Network dynamics in developing interdisciplinary research capacity and collaboration: a case study in vector-borne plant virus research.

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ABSTRACT

Vector-borne plant virus research straddles plant virology, entomology, agricultural practices and international trade policies and practices. Reducing crop losses from plant viruses to better secure global food supplies necessitates interdisciplinary collaboration and improvement research capacity. A UK Government-funded research community network, the Community Network for Vector-Borne Plant Viruses (CONNECTED) aimed to increase international interdisciplinary research collaboration and capacity in vector-borne plant virus research through a multi-year programme of activities.

Using network analysis, we show that the provision of CONNECTED's sequenced programme of in-person and online events, involving purposeful networking, training and collaborative projects, in the context of suitable framing conditions, leads to the development of relationships and to higher-order collaborative outputs including peer-reviewed publications. Exploring the evolution of multi-disciplinary clusters of expertise, we demonstrate the emergence of interdisciplinarity within the network via the development of distinct epistemic communities. Our study provides evidence for a new theoretical model for the emergence of collaboration, where in-person and online interactions within and outside events and collaborative projects leads to a dynamic interplay of convergence (closure) and divergence (brokerage) within the network.

Keywords: Collaboration; research capacity; interdisciplinarity; vector-borne plant viruses; network dynamics; epistemic communities.

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INTRODUCTION

Interdisciplinary collaborative research is needed to tackle various aspects of current global food insecurity (Acevedo et al., 2018; Roshania et al., 2023). However, the routes that lead to both effective collaboration and interdisciplinarity are poorly understood (see Ockendon-Powell et al. 2024). Network-based approaches have been supported by various funders in recent years to stimulate research communities in strategic areas, despite their effectiveness typically lacking underpinning evidence.

This paper draws upon research in social network dynamics and recent empirical experience to analyse a food security-focused international research community network which increased interdisciplinary collaboration and capacity through events, training and networking, and funding new research: the Community Network for African Vector-Borne Plant Viruses (CONNECTED).

This work explores the evolution, dynamics and value of social interactions and behaviours in the context of the opportunities and constraints provided by the network setting (Borgatti, Everett & Johnson, 2013), generating insight into the nuances of network member collaborations (Braun et al., 2021, 641). We consider the varying relational needs of participants throughout phases of collaboration that lead to outputs and outcomes, such as peer-reviewed publications and implementation of new applications. The impact of collaborative interactions and processes on the collaborative, innovative and output capacity of the scientific communities that can emerge.

Specifically, we investigate the following: how convergent and divergent activities interact to promote social closure and brokerage during the emergence of collaboration in networks; the relational needs of collaborative network participants at different stages of collaboration development; how participation in convergent and divergent activities drives collaborative outcomes indicating research community capacity; and the role of in-person versus online convergent/divergent activities in the emergence of scientific collaboration.

Our study provides evidence that the intentional facilitation of new connections, interactions and collaborative activities/projects between members of different disciplinary research communities leads to enhanced scientific collaboration, interdisciplinarity and research capacity. We demonstrate that this approach leads to social closure and brokerage in an interdisciplinary research community, generating consolidation in a core of related expertise alongside brokerage between knowledge areas.

We use this context to present a new generalised model of scientific collaboration that considers the dynamism between convergent and divergent interactions in enabling development of social connections and information exchange which lead to both the production of scientific outputs and knowledge integration underpinning interdisciplinarity.

LITERATURE

While the foundations, configurations and impacts of scientific collaboration and interdisciplinarity have been widely researched (see Ockendon-Powell et al. 2024 for a recent review), the processes by which these collaborations develop have received less attention.

A few studies have offered a broad development schema of scientific collaboration supplemented by observations of distinct activities at different stages. The stages are broadly initiation, elaboration, implementation and conclusion (Kraut et al., 1987; Gitlin et al., 1994; Sonnenwald, 2007; Perry-Smith &

Mannucci, 2017). Enabling activities in these schemas involve a combination of cognitive, technical, inter-personal relational, and communication dimensions, the general argument being that different stages in the collaboration process have different needs in each of these dimensions. As the first two (cognitive and technical) dimensions have been well-rehearsed in collaboration studies, there is value in greater examination of the inter-personal relational and related communication dimensions.

Collaboration Networks

A large body of work has detailed many of the relational elements in scientific collaboration, though few have contextualized this in terms of a development process, Perry-Smith and Mannucci (2017) providing a notable exception. Since the relational needs of collaborators differ at each stage of the group development process, the social networks constituted by this social interaction, also differ at each stage.

A long-standing theme of social network research is the contrast between diverse weak social ties as a source of novel information and creativity (Granovetter, 1973) and close, interrelated, strong social ties as a source of trust and effective coordination, 'closure' (Coleman, 1988). However, as there are cognitive limits to the number of weak ties that can be harnessed, the value of additional ties peaks at some point (McFadyen & Cannella, 2004). Yet, Perry-Smith and Mannucci (2017) argue that this cognitive limit can be elided; while the implementation stage of collaborative activities involves social closure around collective objectives, this can be reinforced by outside ties, that is 'network reach' (Tortoriello & Krackhardt, 2010), especially those linking other closed groups, 'small worlds' (Watts & Strogatz, 1998).

In scientific collaboration, weak ties have been found to provide information about the work of other scientists, contributing to new ideas, collaborative projects and outputs (Friedkin, 1982; Cameron & Blackburn, 1981). New members joining a group of collaborators generates novel publication keywords and keyword combinations , albeit less so where there has been prior co-authorship (Chen & Yan, 2023). Burt (1995, 2004) finds that those who bridge structural holes, otherwise disconnected social groups, are better able to creatively combine novel and diverse information, a process known as 'brokerage'. Collaborations spanning structural holes, particularly those involving women, produce more novel and disruptive research (Wang et al., 2023).

While weak ties aid search and discovery of novel information, close interaction is needed to combine this into scientific outputs (Cummings & Kiesler, 2011). The impact of social network structures also varies with the particular resources that the network structure connects, Rodan and Galunic (2004) finding that heterogeneity of knowledge outweighs structural effects in leading to innovation. Gilsing et al. (2008) find that while diversity of contacts provides access to novel information, there is a need for some homogeneity for this information to be effectively absorbed. Thus, the value of exploration is tempered by cognitive similarity; a structural hole is valuable because there is some similarity within the weakly connected cluster. As a result, the value of exploration has an inverse U relationship with network centrality and the network density, that is, the ability to absorb new information (Wuyts et al,. 2005; Xing-Xiu & Hui-Ying, 2022).

Combining these insights with the concept of collaboration as a sequenced process with differing relational needs at each stage, the value of strong and weak ties – the dynamic between 'brokerage' and 'closure' (Burt, 2005) – is likely to vary with each stage of the process. The initiation stage, commencing with diverse participants and idea generation converging on common goals, is likely to shift from initial reliance on brokerage towards closure. The rate at which this occurs is likely to be influenced by partner assessment, trust development and cognitive flexibility and similarities. The elaboration stage centres on closure but also draws information from diverse sources and brokerage between disciplines in novel recombinations. The execution stage again draws on closure but gains greatest effectiveness when combined with network reach.

This dynamic between brokerage and closure in collaborative networks resonates with other explorations of collaborative dynamics. Newell and Swan (2000, p. 1318) found a 'spiralling development of trust in low commitment trust situations', oscillating between companion and competence trust, but without a determined direction. Perry-Smith and Mannucci (2017)'s sequence conceives each stage as a precursor for the next but potentially regressing to the one before if the appropriate social support for the needs of the next stage is not in place. Lindqvist et al. (2000) argue that innovation involves an interaction between divergence and convergence, an 'hourglass model' with divergence (search and experiment) in the initiation of an innovation, convergence in its development, and then divergence again (outreach and customisation) in its commercialisation. So, particularly in new collaborations where uncertainty is high, a fluidity and experimentation in social interactions can be expected amidst a more general dynamic of convergence and divergence, with success or failure in the endeavour depending upon social support and organizing principles.

Communication

Different stages of collaboration also have varying communication needs arising from the different relational needs. Kraut et al. (1987) note that physical proximity and frequent interaction is important for the assessment of potential collaborators and extended face-to-face interactions facilitate the development of project plans. Sonnenwald (2007) argues that as a collaboration consolidates, ICT tends to replace expensive physically proximate interactions.

Proximate interaction provides rapid feedback, multi-channel including non-verbal communication, personal identification, nuance, shared local context, impromptu opportunistic interaction and social bonding, co-reference via gaze and gesture, individual monitoring and control, implicit peripheral cues and spatial references (Olson & Olson, 2003). It exposes the everyday 'ordinary-ness' of partners' work, revealing personal goals, abilities, needs, expectations and fears, particularly important to trust building in novel and cross-cultural collaborations (Bagshaw et al., 2007). This is especially so in academic collaborations, which are inherently challenging due to ambiguity and conflicts in theory, methods, terminologies and practices arising from the disciplinary distinctiveness and individuality of academic training (Siemens, 2010; Fennel & Sandefur, 1983; Newell & Swan, 2000).

Thus, proximate meetings are important at the start of an academic collaboration to reduce ambiguity, conflict and complexity, facilitating non-verbal communication and immediate feedback for clarification, allowing partners to learn about each other, generating trust, commitment and cohesion (Cramton, 2001; Connaughton & Daly, 2004; Jarvenpaa & Leidner ,1999; Kraut, et al. 1987; Poole & Zhang, 2005; Siemens 2010). Formative proximate interaction is associated with idea creation (Cummings & Kiesler, 2005), greater participation and quicker convergence on solutions (Daly, 1993), ECR development (Cummings & Kiesler, 2005) and subsequent co-authorship (Pepe, 2011).

ICT developments have introduced low-cost communications channels for maintaining physically distant collaborative relationships, once commitment and competence trust have been established and uncertainty reduced (Sonnenwald 2007; Newell & Swan, 2000). High users of ICT have higher research outputs (Barjak, 2006; Kaminer & Braunstein, 1998). ICT-mediated social bookmarking, such as Twitter and its internet discussion group precursors, offer many of the benefits of proximate professional conferences, disseminating research outputs outside close contacts and providing access to novel and diverse knowledge (Matzat, 2004). This contrasts with email which tends to be used to communicate with existing contacts rather than to initiate new ones (Carley & Wendt, 1991; Haythornwaite & Wellman, 1998).

While email and electronic document exchange lack the richness of face-to-face communications, developments in videoconferencing now provide many of the benefits of proximate interaction. Even where videoconferencing is limited, collaborators are generally willing to substitute a less effective meeting experience for travelling time and cost; their meeting practice becomes more structured to accommodate the medium, such as turn-taking and using facilitators (Mark et al., 1999; Dourish et al., 1996).

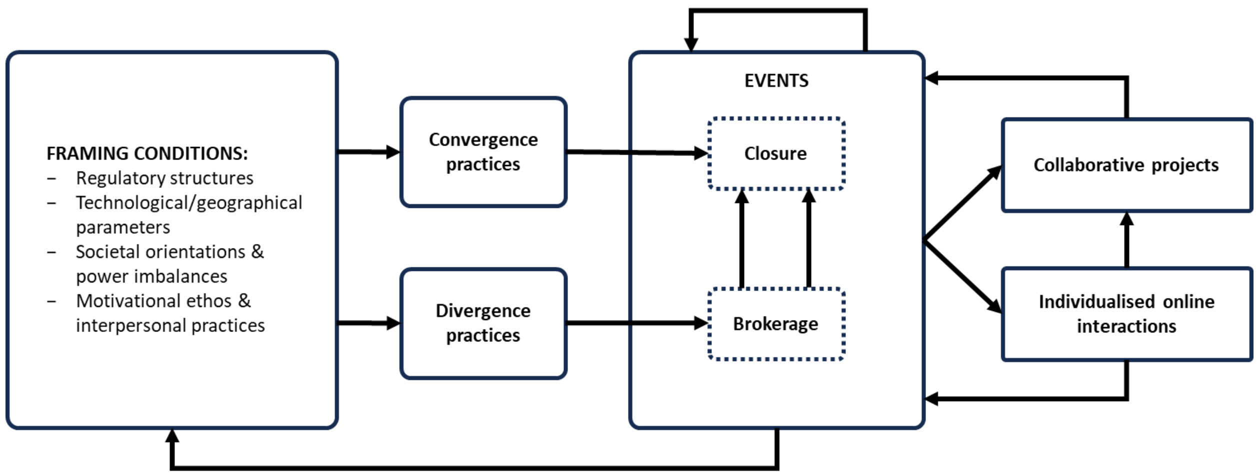
Yet, as widely experienced during the pandemic there is a 'cognitive overhead' in videoconferencing, adding effort for 'explicitly managing themselves, spending time talking about how to manage the work, rather than doing the work.' (Olson & Olson, 2003, p. 33). 'Tightly coupled work', ambiguous or unstructured work requires constant iteration, clarification and synthesis, which are qualities often provided by in-person interactions. Thus, periodic proximate meetings remain important for maintaining or 'replenishing' commitment, pushing past obstacles, and refocusing (Bagshaw et al., 2007, p. 443; Siemens, 2010).

Walther (1992), however, argues that social relationships develop in similar ways whether ICT-mediated or not, with the media used and skills in using it merely influencing the rate of development. Wilson et al. (2006) found that while lower levels of trust were found at the start of computer-mediated collaborations than in face-to-face collaborations, levels were comparable after three weeks. The balance needed between in-person meetings and digitally-mediated communications varies with the composition and the course of a collaboration (Kraut et al., 1987) and can be facilitated by setting expectations about forms of communication (Lawrence ,2006).

Hypothesis Development

From this general review of literature on scientific collaboration, we draw together those streams that consider aspects of the processes by which such collaboration emerges. From broad descriptions of stages in the collaboration process, we note the different relational needs of participants at formational and executing stages of projects; the different patterns of social interactions likely at different stages; the informational implications for collaboration from these different social network forms; and the differing communication needs over the course of a collaborative project, particularly different needs for proximate and ICT mediated interactions over time. But eschewing determinative sequences, we develop a more generalised model of emergent scientific collaboration centred on the dynamic interaction of convergence and divergence in social interaction and information exchange, presented in Figure 1.

Figure 1. Theoretical Model



Framing Conditions and Practices

In this model, framing conditions or parameters place limits on the scale and scope of collaboration. This is particularly so for institutionally-driven collaborations where there are greater demands of accountability for outcomes. Prominent parameters include the vision or strategic goals of the collaboration (Sonnenwald, 2007), its geographic reach (Smith et al. 2023) and available financial and technological resources (Sonnenwald, 2007). These influence the priorities set for the collaboration and the types of practices adopted. Goals supported by limited resources will be best met by rapid convergence on solutions. More extensive goals and resources can favour greater exploration before convergence.

While the framing conditions provide an initial set of parameters that structure the opportunities for social interaction, the actions of participants also impact on the framing conditions (Archer, 1995): in social network analysis this presents a contrast between influence and selection (Leenders, 1997). The experiences of collaborative practices, manifested primarily in collective events, feedback to adjust the framing conditions for further/onward collaboration; resources are shifted from less to more fruitful practices, and strategies are reviewed.

Our initial investigation of the collaborative network in our research setting (Ockendon-Powell et al., 2024) identified processes of framing and reframing and distinctive practices of organisers promoting distinct collaborative behaviours. Convergent practices generally promoted social closure among event participants and divergent practices promoted social brokerage.

In this paper we extend the initial examination of these phenomena to consider the relationship between social closure and brokerage among three broad categories of collaborative activities: events, individualised online interaction, and collaborative projects. Events bring groups of people together physically or virtually, combining collective goals with the potential for interactions among individuals, often 'on the side'. Individualised interactions also take place outside organised events, most readily via ICT channels such as email, chat or social media. Collaborative projects are more specific highly organised interactions among groups of individuals with specific goals such as funding bids, research activity, publications, or social impact. Participation in these, and perhaps also the likelihood of success, can be considered indicators of the capacity of the research community.

Events

As discussed above, the structuring and course of collaborative events combines elements of closure and brokerage. We argue that the practices of participants in the collaborative network, particularly the practices of organisers, determine the prevalence of closure and brokerage in events. A tightly scheduled conference structured around workgroups tasked with many specific outcomes and few social activities will have fewer opportunities for brokerage than one that allows participants to pick and mix among presentations alongside a rich social programme. On the other hand, an insufficiently unstructured event may prompt participant disengagement, limiting opportunities for social closure or brokerage. The way people connect is critical to ongoing interaction (Powell et al.,1996).

Burt (2005) argues that social closure and brokerage are dynamically interrelated. The act of making a connection between two otherwise separate closed groups also generates closure, bringing the two groups together. Groups that are very closed to outside interactions often stagnate or become overly insular, prompting participants to look elsewhere for novel input, i.e. brokerage opportunities. As discussed above, the development of collaboration involves this dynamic of divergence and convergence at each stage.

H1. There is a cycle of social closure and brokerage in events.

Social relationships are characterised by an accumulative advantage (Merton, 1973) or attachment bias (Barabási & Albert, 1999), whereby individuals or organisations with more social connections tend to gain further connections over time. Drivers include functional opportunities for knowledge exchange, social similarity (homophily); status, and 'bandwagon' following of the dominant choices of others (Powell et al., 2005; Storme, 2017). Such processes are likely to lead participants in events to engage in similar subsequent events.

H2. Participation in events promotes participation in further events.

Collaborative Projects

As discussed above, proximate interaction is a critical component of the development collaboration at certain stages. Academic conferences, in particular, provide periodic opportunities to select distant partners in a proximate setting, although this is frequently associated with prior knowledge of the potential collaborator's work (Kraut et al., 1987; Melin, 2000; Freeman et al., 2014). Freeman et al. (2014) found 16 per cent of US external academic collaborations originated in conferences. Melin (2000) found long-standing collaborations had been typically initiated by approaching a speaker at a conference briefly to see if there was mutual interest in a collaboration on a topic; 'The purpose is to make oneself visible to the other' (Melin, 2000, p. 35).

H3. Participation in events promotes collaborative projects among participants.

As discussed above, prolonged engagement, spending time together, is particularly important for trust-building and tight coupling and 'replenishing commitment in academic collaborations. Conferences provide a low-risk opportunity to provide resources and time for international collaboration, particularly where travelling costs are high' (Brew et al., 2013). Thus, collaborators can be expected to seek opportunities for further engagement with partners: academic conferences and similar events provide low-risk opportunities for this.

H4. Participation in collaborative projects promotes participation in further events.

Individualised Online Integration

Physically proximate interaction is challenging for geographically distant collaborators, particularly international collaborations. Developments in ICT provide low-cost communication alternatives for physically distant collaborators and are often substituted for travel even when providing less effective communications. Social bookmarking, such as Twitter, similarly substitute for conferences in accessing novel and diverse knowledge (Matzat, 2004; Radovanovic & Ragnedda, 2012; Sproull & Kiesler, 1986). Academics use social media to maintain an overview of a field (van Noorden 2014), make new contacts and locate collaborators (Jordan & Weller, 2018), sustain existing contacts and follow up with people met at conferences (Gruzd et al., 2012). Participation of scientists in physically proximate conferences is associated with subsequent online communications and collaboration (Cronin et al., 2015; Letierce et al., 2010).

Thus, contacts made, or potential contacts identified during events are likely to be subsequently pursued via individualised online channels, whether low-exposure general information sharing via following, tweets and retweets, or more direct engagement via mentions, joining chat groups, email or instant messaging.

H5. Participation in events promotes individualised online interaction among participants, such as email, Twitter, and WhatsApp.

Event participants who have followed up on contacts or potential contacts via individualised online channels are likely to seek opportunities for further extended interaction such as those provided by events. As discussed above, events provide opportunities for the assessment of potential collaborative partners (Bagshaw et al., 2007; Brew et al., 2013). Email can be used to actively schedule meetups at events, while social media can create a 'buzz' around an event, enhancing its attractiveness as a likely source of encounter or follow-up with contacts, or further information on shared areas of interest (Ang, 2011).

H6. Participation in individualised online interaction promotes participation in further events.

While social media has potential to aid collaboration, it is largely used to share information (Java et al., 2007), a weaker form of collaboration than that involving coordination (Hyde et al., 2012). Twitter(X) has some tools to direct communication to individuals such as retweets and mentions, and it is used in software developed to share 'non-critical' status updates among distributed co-developers (Zhao et al., 2011). But in more classical scientific collaboration, Murthy and Lewis (2015, p. 167) found social media little used for coordination, rather providing 'cohesive glue between events.' Email, with its much greater individuation capacity, remains the principal online coordinating tool for academic collaboration (Aceituno-Aceituno et al., 2019; Ogunjobi & Oyewusi, 2016; Walsh et al., 2000).

There is some purposive use of Twitter(X) to forge scientific collaboration, the Covid-19 pandemic providing a catalyst for collaboration amongst scientists who have not met in person, via open calls for collaborators on a particular topic, especially for review articles (Mukhopadhyay et al., 2021). Lepe et al. (2020) document the emergence of a multi-institution international collaboration from a Twitter(X) interchange. But these examples are celebrated for their exceptionality.

However, social media contributes to collaboration in a wider sense in fostering broad information exchange among specialised interest groups and emerging research areas. There is notable use of social media by marginalised groups to develop mentoring relationships around entrenched hierarchies (Titanji et al., 2022). Social media facilitates the identification of mentors and sponsors from a broader pool than traditional sources (Zheng et al., 2021), provides examples of practice, broadens awareness of a field, allows varying commitment, and eliminates gatekeepers. It allows micro and marginalised interests to develop, celebrate and advocate identities, and geographically distributed participants to seed ideas and collective projects (Titanji et al., 2022).

So, some progression from individualised online interaction among event participants to broad information exchange seems likely, with more purposeful coordination likely via email. There is likely to be progression the other way, from collaboration towards online interaction. But our focus is on the establishment of collaboration.

H7. Participation in individualised online interaction promotes formation of collaborative projects among event participants.

Traditional accounts of academic collaboration emphasise the first row of our model: collaboration strategies favour convergence of academics with similar interests at an in-person conference, seeding ideas and connections for collaborative projects, followed up within project teams and at further general conferences in the field.

We argue that divergent practices are also important to this process, where promoting opportunities for brokerage within in-person events underpins a convergence-divergence dynamic, also contributing to emergence of collaborative projects, indicating increased research capacity. Interaction at events is also likely to spur subsequent interactions in online forums, contributing both to further participation in events and thus to the development of collaborative projects.

METHODS

Research setting

Our study examines the development of the Community Network for African Vector-Borne Plant Viruses (CONNECTED), a UKRI Global Challenges Research Fund (GCRF) funded project based at the University of Bristol from 2017 to 2023. CONNECTED engaged plant virologists, pathologists, entomologists and related experts primarily from the UK and Sub-Saharan Africa. It pursued three interlinked activity streams, comprising networking, pump-priming funding of collaborative projects and training for targeted capacity building, each providing opportunities for social interaction within the membership. The aims, objectives, activity programme, framing conditions and organisational practices are detailed in Ockendon-Powell et al. (2024).

Data collection

1568 people joined CONNECTED by self-enrolment on a website between its establishment in November 2017 and October 2021, especially in the year from November 2018 when a range of funded project and training calls were announced. New members submitted an online form providing individual professional characteristics including country of work, institution, gender, level of experience/ progression, and expertise.

An export of the member directory in November 2021 provided demographic information submitted by 1,447 members (92%) at the time of enrolment. 980 of these reported ORCID identifiers and 328 Twitter(X) user IDs. Those providing Twitter(X) IDs were mainly from Nigeria (82), Kenya (55), UK (44), and Uganda (22). The ORCID identifiers supplied were used to collect member publication data from the ORCID database and Twitter(X) IDs to collect data from Twitter(X). All publicly available Twitter(X) data on tweets, friends and follower data were downloaded for those supplying Twitter(X) IDs.

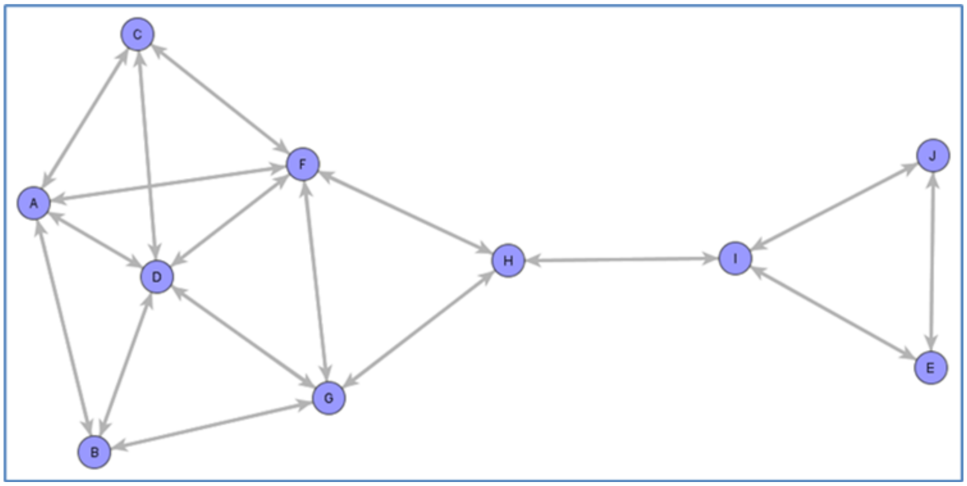
When enrolling, members were asked to list up to five areas of expertise in their own words. Normalised to make spelling and similar categories consistent, 4512 distinct expertise categories were contributed, a mean of 3.1 each. The most common categories were ‘Molecular Biology’, ‘Virology’ and ‘Bioinformatics’. Expert input from the CONNECTED Network identified those self-descriptions that could be meaningly classified as expertise in plant virology/pathology (418), entomology (121) or both (154).

Analytical method

We used a social network analytic approach to analyse the patterns of interaction in the development of CONNECTED, contrasting the two broad patterns of interaction, ‘closure’ and ‘brokerage’. Social network analysis maps individual social interactions in the context of a set of extended relations and models social behaviour from expectations of opportunities and constraints provided by this setting (Borgatti et al., 2018). Figure 2 illustrates such a mapping. The circles represent individual actors and the lines, social interactions among them, such as information transfer.

Theorising that close, repeated social interaction supports the sharing of related knowledge (Coleman, 1990) while more distant, intermittent interactions access novel and diverse information (Granovetter, 1973), social network analysts have explored the tensions between capacity building and diversity in collaboration (Burt 2005). From this perspective an individual’s collaborative behaviour can be deduced from their position in a social network. Individuals at the 10centre of a cohesive group (such as ‘D’ in Figure 2) would be likely to engage in capacity-building, strengthening related expertise. By contrast, those bridging different cohesive groups (such as ‘H’ in Figure 2) would have access to diverse information and thus be a source of novelty and innovation.

Figure 2. Illustration of different individual positions in a social network



Note. Circles represent individuals, lines represent interactions between individuals.

The structure and dynamics of collaboration networks are likely to differ with the type of collaboration. Co-participation in events is a low-order form of collaboration, or even a proxy for interaction, indicating a similarity in interests but may not actually amount to personal interaction. Twitter(X) interaction is a higher but still low-order form of collaboration, that does comprise observable interaction. Co-participation in collaborative projects and co-publication are high-order and observable forms of collaboration. Comparing these forms of collaboration offers richer insight into the evolution of the CONNECTED network than any one alone.

Using a form of network cluster analysis, Newman Community Detection, using the UCINET 6.3 algorithm for this (Borgatti, Everett & Freeman, 2002), we identified the four largest distinct groupings of expertise, 'epistemic communities', at different stages of CONNECTED activity . We compared this engagement and community presence to the pattern of co-authoring and the patterns of Twitter(X) interactions among CONNECTED members.

Path analysis (Wright, 1934) was employed to examine significant correlations between each form of engagement measured each year: event co-participation, Twitter(X) interaction, and co-publishing. Due to the longitudinal nature of these data it was possible to test sequence in the engagement, 2018 event co-participation, for example, preceding 2019 event co-participation and 2019 retweets. The significantly correlated forms of engagement in different years were subjected to multiple regression to determine the relative strengths of each pair of engagement forms, the strongest regression coefficients illustrating the 'backbone' of the process.

RESULTS

Social closure and brokerage in events

Organised events both indicate the sorts of activities members are motivated by and provide opportunities for members to engage with each other. While no comprehensive data exist on actual one-to-one interactions, co-occurrence of members at an event is used as a proxy for interaction. Member participation in events each year is mapped in Figure 3. In each panel, individual members are represented by red circles and each event by a blue square. A line between a member and an event represents the member's participation in that event. The visualisations, created in NETDRAW 2.0, employ an algorithm that positions the most frequent participants in multiple events towards the centre of the figure and those least connected farthest away.

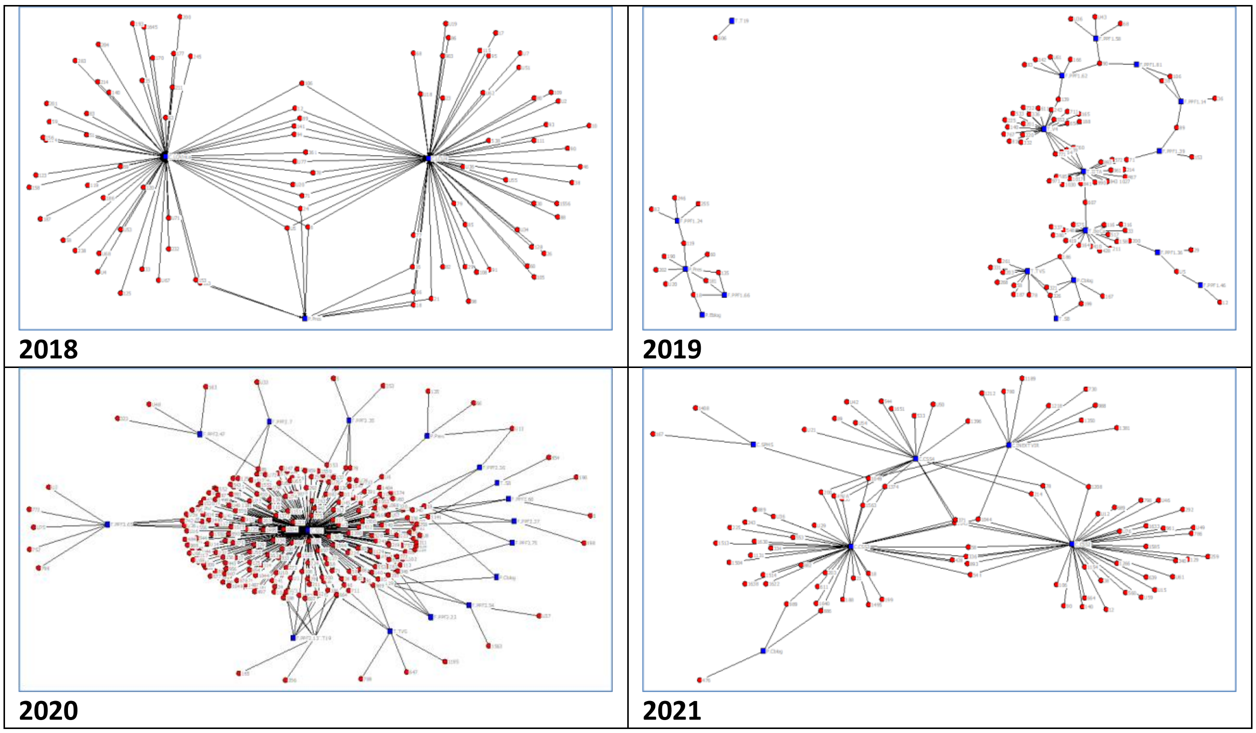


Figure 3. Member co-participation in CONNECTED events by year.

Figure 4 presents changes to three measures of mean network centrality for event co-participation and Twitter(X) interactions among members during the period. There is a small trend towards increased interaction among members (degree centrality), to 2020 in the case of Twitter(X). Initially there is an increased social closure or clustering within these networks, measured by (2-local) eigenvector centrality, to 2019, then decline. This is interweaved by a decline, increase, then decline in brokerage (betweenness centrality).

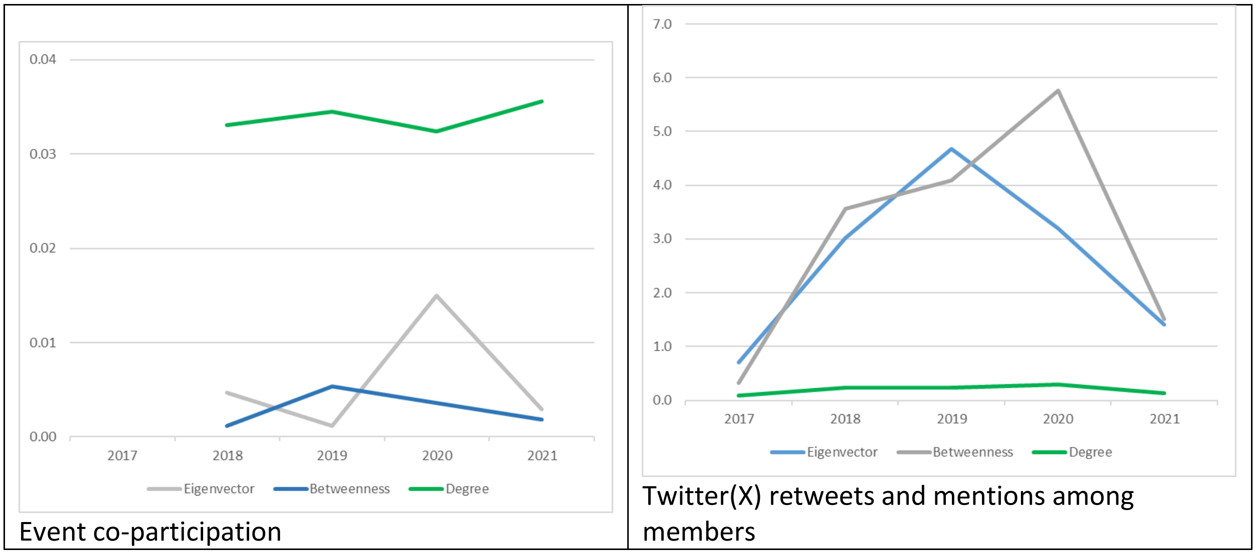
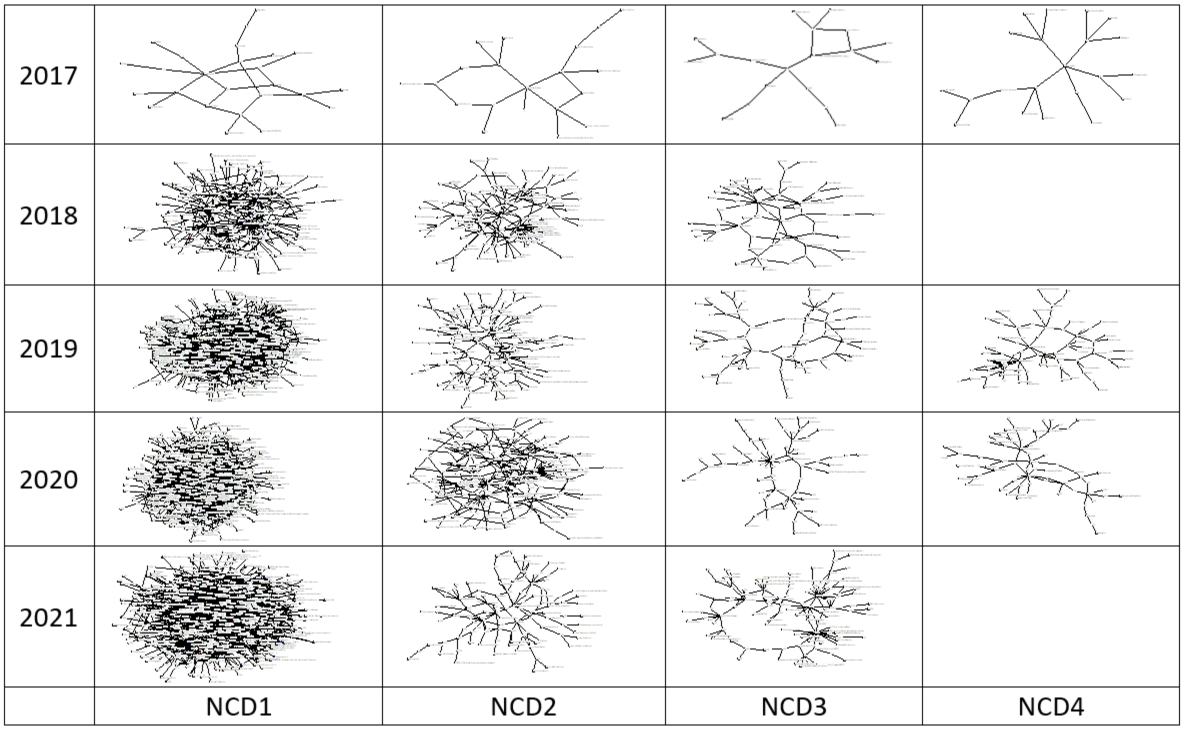


Figure 4. Mean centrality of members in event co-participation and Twitter(X) networks

The visualisations support the hypothesis of a cycle of social closure and brokerage in events. 2018 and 2020 suggest convergence of many members around a small set of events, 2019 and 2021 divergence of smaller groups of members among fewer events. Evidence of both long-term social closure and brokerage occurring within the network can be illustrated by the formation of social groups displaying commonalities in member-cited expertise. These point to related competences and groups of members with similar patterns of expertise to social groups which we describe as 'epistemic communities.' The interrelationships among the expertise of members can be mapped as social networks over time, presenting an 'expertise network'. High overlaps between the expertise of members indicate closure and interlinks between otherwise less connected groups indicate brokerage.

The size and cohesiveness of the largest community, NCD1, increases over time, indicating closure via large overlaps of related expertise (Figure 5). The other large epistemic communities are more dispersed and of variable density, containing more brokerage among different expertise categories, representing transitions from knowledge heterogeneity towards knowledge integration across disciplines to underpin interdisciplinarity.



Note. Calculated using the Newman Community Detection algorithm in UCINET 6.3

Figure 5. Epistemic communities among CONNECTED members.

Figure 6 and Table 2 examine the overlap between these expert categorised specialisms and the word-generated clusters. Plant pathologists accounted for half of NCD1 and NCD2, after the formation year, and NCD3 and the bulk of NCD4 in 2017 and 2019. Entomologists accounted for an increasing proportion of NCD1, a mean of 17%, and a decline share, a quarter overall, of the other three clusters.

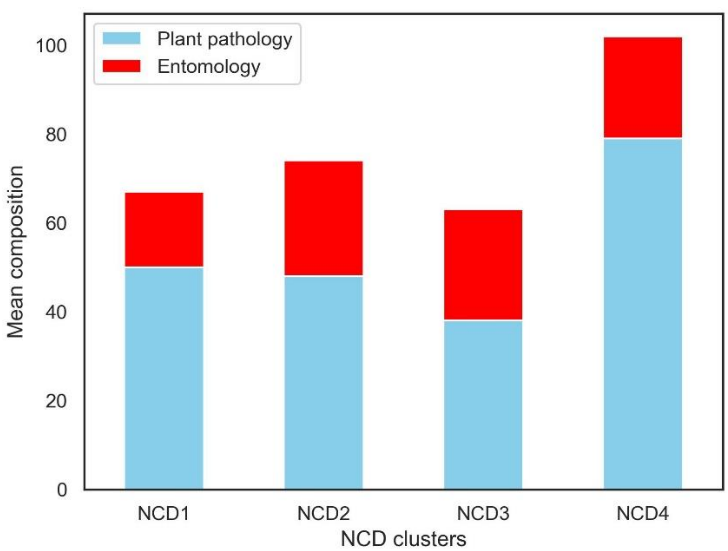


Figure 6. Mean composition of NCD clusters 2017-21 by main disciplines.

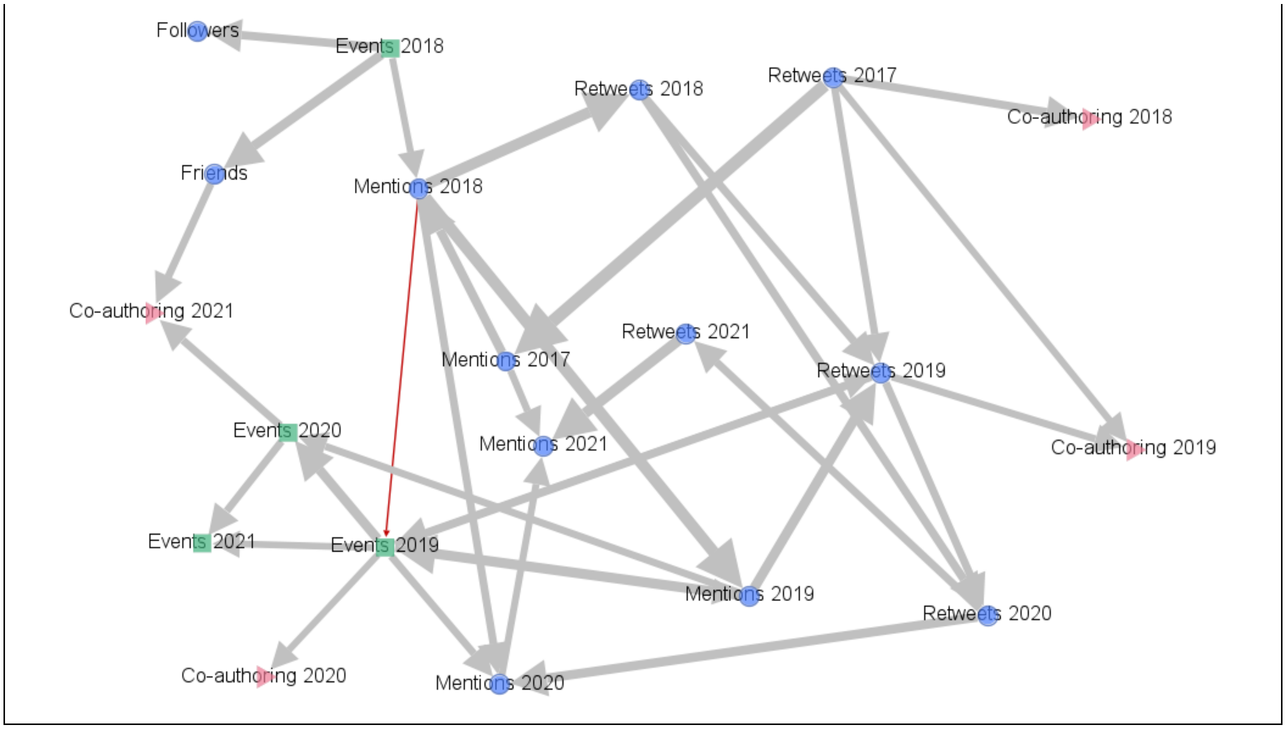
Table 2 Composition of NCD clusters by main disciplines by year.

	NCD1	NCD2	NCD3	NCD4
Plant pathology				
2017	56%	71%	50%	100%
2018	47%	41%	41%	
2019	46%	62%	52%	91%
2020	50%	37%	14%	46%
2021	49%	28%	35%	
Mean	*50%*	*48%*	*38%*	*79%*
Entomology				
2017	11%	57%	33%	17%
2018	17%	7%	59%	
2019	15%	49%	18%	42%
2020	22%	10%	3%	11%
2021	20%	9%	13%	
Mean	*17%*	*26%*	*25%*	*23%*

Note. Totals exceed 100% as participants may hold multiple classifications.

Relationships among different forms of collaboration

Figure 7 presents the results of path regressions among the statistically significant correlated event variables. Wider lines represent higher beta coefficients. Red lines represent negative correlations. The path analysis enables the assessment of the remaining hypotheses. Where correlations are significant both ways in the same year, the arc with the higher coefficient is visualised.



Beta Coefficient and Goodness of fit statistics are reported in the Appendix.

Figure 7 Path regressions among event, Twitter(X) and co-author interactions.

Figure 7 indicates that event participation is the backbone of the interaction, engagement in earlier events driving participation in later events, with the 2019 events contributing to participation in both 2020 and 2021 and co-authoring in 2020. This provides support for H2, participation in events promotes participation in further events.

Participation in the 2018 and 2019 events generated Twitter(X) interactions that were associated with subsequent co-authoring. Participation in 2019 and 2020 events is associated with co-authoring in 2020 and 2021 respectively. Contextual experience evidences this with regard to the generation of expressions of interest (EOIs), and subsequently full proposals for PPF projects: the CONNECTED Network managers reported that each in-person launch conference in 2018 was immediately followed by a funding call to elicit EOIs. The first call received 21 EOIs, 15 of which were invited to full application and 9 awards were made. The second call received 35 EOIs, 24 of which were invited to full application, and 11 awards were made. The short time frame between conference and funding call provided a condensed period of convergence (conferences) and divergence (proposal development) activities, instigating the emergence of directionality, focusing new collaborative teams on producing the requisite outcomes. This evidence provides support for H3, participation in events promotes collaborative projects among participants.

Against expectations, co-authoring is not associated with subsequent event participation, contradicting H4, participation in collaborative projects promotes participation in further events.

The 2018 events are associated Twitter(X) with friends and followers but weakly associated with mentions in 2018, suggesting the events led to contacts then followed up by forwarding tweets to them. 2019 events are strongly associated with 2019 retweets and 2019 and 2020 mentions. Thus, the 2018 and 2019 events generate a subsequent circuit of mentions and retweets:

- Mentions are reinforcing. 2017 mentions drive 2018 and 2021 mentions; 2018 mentions drive 2019 and 2020 mentions; 2020 mentions drive 2021 mentions.
- Retweets are also reinforcing. 2017 retweets drive 2019 retweets; 2018 retweets drive 2019 and 2020 retweets; 2019 retweets drive 2020 retweets; 2020 retweets drive 2021 retweets.
- Retweets and mentions in the same year are correlated, with retweets more strongly associated with mentions than vice versa in all years except 2018 and 2019 (See Table A2).

This evidence is consistent with H5, participation in events promotes individualised online interaction among participants.

2019 mentions and retweets are positively associated with 2019 event participation and 2019 mentions with 2020 event participation. These events are in turn associated with 2021 event participation. However, 2018 mentions are strongly negatively associated with 2019 event participation. This evidence is consistent with H6, participation in individualised online interaction promotes participation in further events.

2018 events are strongly associated with Twitter(X) Friends, which in turn are associated with 2021 co-authoring. 2017 and 2019 retweets are associated with co-authoring in the following year. This evidence provides support for H7, participation in individualised online interaction promotes formation of collaborative projects among event participants.

DISCUSSION

We identified a general cycle of closure and brokerage in the events organised by the Network Team. Inspection of this in terms of epistemic communities saw a general tendency towards closure on the part of the main disciplinary group, plant pathologists, alongside ongoing brokerage leading to more balance between plant pathologists and entomologists, evidencing the development of interdisciplinarity. This is consistent with both Burt's (2005) theory of the dynamic between brokerage and closure but also studies of collaborative dynamics that emphasise non-deterministic cycles (Newell & Swan, 2000; Perry-Smith & Mannucci, 2017; Lindqvist et al., 2000).

We also found evidence generally for the expected interaction between different forms of collaboration, with events leading to more event participation, individualised online interaction and co-authoring, and online interaction leading to co-authoring and further event participation. This is consistent with expectations of homophily, status and bandwagon effects in social interaction (Powell et al., 2005; Storme, 2017), the use of events for social broadcasting (Melin, 2000), the use of events for project development (Brew et al., 2013), the role of online communication in establishing (Ang, 2011; Jordan &

Weller 2018) and maintaining (Gruzd et al., 2012; Cronin et al., 2015; Letierce et al., 2010) in-person contacts.

Our finding of Twitter(X) interaction leading co-authorship adds to the limited research on the role of online communications in facilitating scientific collaboration. However, we were unable to compare this activity with email, which likely retains a much stronger role due to its greater individuation capacity and information bandwidth (Aceituno-Aceituno et al., 2019; Ogunjobi & Oyewusi, 2016; Walsh et al., 2000). Data access limitations also prevented us from comparing Twitter(X) usage with WhatsApp usage, which may provide a more individualised channel for online interaction.

Our findings of a general relationship between event, Twitter(X) and project-based interaction were not universal, however, with some years more important than others. This suggests that there are qualities to these interactions that are important to multi-level collaboration, but which we were not able to measure.

CONCLUSIONS

This case study of the process of fostering collaboration in a scientific community has shown how a sequenced programme of in-person and online events, involving purposeful networking, training and collaborative projects, in the context of suitable framing conditions, led to the development of relationships and to higher-order collaborative outputs including peer-reviewed publications. Importantly, it identified a dynamic interplay between in-person and online interactions involving an oscillation between social closure and brokerage within the emerging social networks among participants.

Drawing on previous literature highlighting the development of collaboration though generic sequential stages, we considered the way relational and communication needs varied with each stage. Broadly, diverse, weak social ties and brokering positions in networks offer advantages at early and middle stages of cooperation where diversity and novel recombination of knowledge is important; social closure is important for elaboration and execution stages where trust and integration of activity comes to the fore. The concrete forms of this dynamic between divergent and convergent activity are influenced by partner specificities, however. We found a general pattern of convergence of CONNECTED participants around a small set of events at the beginning and middle of the period and divergence in-between these events, together with both long-term social closure and brokerage in distinctive epistemic communities.

We also considered the varying communication needs at each stage of the development of collaboration highlighted in the literature, with in-person interaction important at early and mid-stages and ICT-mediated interactions more valuable at other points. We found a dynamic interplay among participation in events, Twitter(X), and co-publication. Participation in events promoted participation in further events, subsequent Twitter(X) interaction and co-publication. Twitter(X) interaction in-turn promoted further event participation and co-publication but collaboration in publications was not associated with further event interaction.

These findings add valuable insight to augment the literature regarding the effectiveness and operation of collaborative research networks. The findings of epistemic community formation over time highlights the value of long-term support for collaborative network initiatives of this kind that aim to increase scientific collaboration and capacity, particularly across disciplinary boundaries. The approach used by CONNECTED demonstrates how it is possible to intentionally develop a core community of technical and experiential expertise, alongside the brokerage across more diverse knowledge areas which enables the transitioning from knowledge heterogeneity towards knowledge integration necessary to lead to interdisciplinarity and innovation (Zhang, 2023). It complements recent work illustrating the increasing diversity and equity in co-authoring that can arise from long-term collaborative networks (Bailie et al., 2021), and goes beyond methodologies for enabling interdisciplinary research (Tobi & Kampen, 2017) which commence once collaborative teams have formed.

The study has empirical limitations: the four year time-span restricted the examination of dynamic interactions and the examination of collaborative outputs that take longer to enter the public domain; only a subset of participants provided Twitter(X) and ORCID identifiers restricting the extent of mapping; no data were available on email or WhatsApp interactions, likely more important channels for individualised online interaction than Twitter(X).

Future research should seek to address these empirical limitations. Alternative analytic models could also be employed to harness developments in longitudinal network analysis such as stochastic actor-oriented models and relational event models. But the methods used in this study can still be readily applied in other empirical settings and contribute to programme evaluation.

APPENDIX

Table A1. Path Coefficients

Source	Destination	Beta	Sig
Events 2018	Mentions 2018	0.14689	†
Events 2018	Followers	0.307912	**
Events 2018	Friends	0.427306	***
Events 2019	Mentions 2019	0.122742	**
Events 2019	Retweets 2019	0.138964	**
Events 2019	Co-authoring 2020	0.141166	***
Events 2019	Events 2021	0.149147	*
Events 2019	Mentions 2020	0.214057	***
Events 2019	Events 2020	0.43279	***
Events 2020	Events 2021	0.214928	**
Events 2020	Co-authoring 2021	0.23263	**
Friends	Co-authoring 2021	0.217929	*
Mentions 2017	Mentions 2021	0.183571	***
Mentions 2017	Mentions 2018	0.376242	***
Mentions 2018	Events 2019	-0.40132	*
Mentions 2018	Mentions 2020	0.250431	***
Mentions 2018	Retweets 2018	0.586557	***
Mentions 2018	Mentions 2019	0.65816	***
Mentions 2019	Events 2020	0.193304	*
Mentions 2019	Retweets 2019	0.457324	***
Mentions 2019	Events 2019	0.490559	**
Mentions 2020	Mentions 2021	0.163938	**
Retweets 2017	Co-authoring 2019	0.164796	†
Retweets 2017	Retweets 2019	0.207816	***
Retweets 2017	Co-authoring 2018	0.290553	***
Retweets 2017	Mentions 2017	0.757685	***
Retweets 2018	Retweets 2019	0.270224	***
Retweets 2018	Retweets 2020	0.300199	***
Retweets 2019	Co-authoring 2019	0.200043	*
Retweets 2019	Retweets 2020	0.25299	***
Retweets 2019	Events 2019	0.312353	*
Retweets 2020	Retweets 2021	0.252311	***
Retweets 2020	Mentions 2020	0.40511	***
Retweets 2021	Mentions 2021	0.544256	***

*Sig. † p < .1; * p < .05; ** p < .01; ***p < .000*

Table A2. Path Regressions Goodness of Fit

	n	R^2	e
Co-Authorship 2018	154	0.0844	0.9569
Co-Authorship 2019	154	0.1086	0.9441
Co-Authorship 2020	755	0.0199	0.9900
Co-Authorship 2021	143	0.1102	0.9433
Events 2018	99	0.0948	0.9514
Events 2019	99	0.2075	0.8902
Events 2020	99	0.3091	0.8312
Events 2021	200	0.0911	0.9534
Followers	99	0.0948	0.9514
Friends	99	0.1826	0.9041
Mentions 2017	233	0.5741	0.6526
Mentions 2018	99	0.5158	0.6958
Mentions 2019	200	0.7360	0.5138
Mentions 2020	200	0.4443	0.7454
Mentions 2021	233	0.4799	0.7212
Retweets 2017	233	0.5741	0.6526
Retweets 2018	233	0.3782	0.7886
Retweets 2019	200	0.6497	0.5918
Retweets 2020	233	0.4980	0.7085
Retweets 2021	233	0.4597	0.7351

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