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ARTICLE



Development of professional networks among environmental educators

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ABSTRACT

Professional development programs provide an opportunity for environmental educators to develop networks to exchange ideas and practices in professional learning communities. This study investigated how diverse educators develop professional networks for exchanging information through online and face-to-face professional development activities. We conducted surveys and social network analysis of three professional learning communities including a state consortium with mostly face-to-face activities, an online-only learning community, and a fellowship program with both face-to-face activities and online interaction. We then used exponential random graph models to examine factors that influenced professional network formation in each community. The results showed that professional development activities including face-to-face meetings and Facebook interactions, and collaborative projects such as co-authoring book chapters, had positive effects on the likelihood of network formation. Results suggest that program leaders can facilitate discussions and collaborative projects to foster network formation in professional development programs, especially those conducted exclusively online.

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Introduction

In addition to helping educators acquire knowledge and skills, professional development programs can encourage exchange of ideas and resources among educators, enabling them to reflect on, improve, and develop innovative practices (Grossman *et al.* 2001, O'Donoghue and Russo 2004, Biggs *et al.* 2010). Such networks also contribute to educators' social development, an important aspect of teacher development (Bell and Gilbert 1996). Similarly, research applying the theory of communities of practice to teacher professional development found that teachers developed networks for the exchange of resources and expertise (Barab *et al.* 2003), which may encourage collaboration (Park *et al.* 2007, Baker-Doyle and Yoon 2011) and help teachers improve their teaching practice (Lotter *et al.* 2014, Pharo *et al.* 2014, Bannister 2015).

Researchers have used social network analysis (SNA) to examine interactions among teachers (Baker-Doyle and Yoon 2011, Moolenaar 2012, Penuel *et al.* 2012) and informal educators (Egg *et al.* 2017) including in online settings (Cela *et al.* 2015). For example, studies measure density and centrality in teachers' face-to-face advice (Penuel *et al.* 2009) and online discussion networks (Sing and Khine 2006). In addition to descriptive analyses of network structure and teachers' positions in networks, research has explored the factors that influence the development of teacher networks (Frank *et al.* 2014). For example, studies have shown that teachers' demographics and network structure, such as density and reciprocity, impact the formation of teachers' advice networks (Penuel *et al.* 2010, Moolenaar *et al.* 2014, Siciliano 2015, Spillane *et al.* 2015).

However, these studies either relied on current existing face-to-face networks or network formation in a totally online environment. No studies have used SNA to examine the impact of a professional development intervention on network formation among educators in both online and face-to-face environments.

From 2011–2016, Cornell University conducted a national professional development program for environmental educators working largely in non-formal settings (Krasny *et al.* 2017). The program was designed around creating learning communities for exchange of ideas and resources among a diverse group of professionals, with the goal to foster innovative practices. The professional learning communities, some of which were conducted exclusively online and others mixing face-to-face and online interactions, provided an opportunity to test ideas about network formation and educational innovation. This article, which is part of a larger study of practice innovation in environmental education, focuses on the development of social networks in three separate learning communities. More specifically, we asked: What were the mechanisms by which professional networks emerged through online and face-to-face activities in these professional learning communities? The results of this study can be used to plan interventions that enable diverse educators to share resources and information, an important component of professional development and practice change.

Theoretical background

Teacher learning communities

Lieberman and Miller (2008, p.2) define a teacher learning community as an ‘ongoing group of teachers who meet regularly for the purpose of increasing their own learning and that of their students’. Research on professional learning communities established to build collegial relationships demonstrated that teachers’ collaboration led to school improvement and teachers’ practice improvement (Stoll *et al.* 2006, Blankenship and Ruona 2007, Hadfield 2009).

Online learning communities also can be used to facilitate teacher professional development (Lock 2006, Macià and García 2016) including through facilitating connections among learners, between learners and instructors, and between a learning community and its learning resources (Goodyear *et al.* 2004, Dresner and Worley 2006, Duncan-Howell 2010). Online networks have been shown to promote peer learning (Holmes 2013), knowledge (Booth 2012), and emotion sharing (Hur and Brush 2009), and to improve teaching practices (Fusco *et al.* 2000). In addition, online interactions enable teachers to develop more diverse networks than they would in their everyday work environment and access resources not available locally (Schlager *et al.* 2009, Lotter *et al.* 2014).

Network formation

Social network analysis (SNA) offers a means to examine interaction patterns (Mcfarland *et al.* 2011, Moolenaar and Daly 2012) and thus to understand how information and resources flow in teachers’ learning communities (Schlager *et al.* 2009, Egg *et al.* 2017). Structural, assortative, and proximity mechanisms (Rivera *et al.* 2010) of network formation can impact the processes of idea exchange in professional learning communities.

Structural mechanisms explain the influence of network structure characteristics, such as reciprocity, transitivity, and existing relationships, on network formation (Rivera *et al.* 2010). In teachers’ work related discussion or advice networks, teachers tend to build reciprocated connections to seek advice from each other (Moolenaar *et al.* 2014, Siciliano 2015). Studies on learners’ interactions in Massive Open Online Courses (MOOCs) found that reciprocity was associated with formation of discussion networks, which indicated that learners tended to interact with peers who replied to their posts (Kellogg *et al.* 2014, Joksimović *et al.* 2016, Zhang *et al.* 2016). Further,

transitivity was observed in online learning networks with teamwork activities (Aviv *et al.* 2005) and in teachers' advice networks, indicating that teachers tended to seek advice from those who shared a mutual connection (Siciliano 2015). Aviv *et al.* (2008) also found that observed values of reciprocity and transitivity were substantially higher than would be expected by chance in online learning networks. Finally, MOOCs studies found a negative relationship between in-degree centrality (popularity) and network formation, indicating most participants had similar levels of popularity (Kellogg *et al.* 2014, Joksimović *et al.* 2016).

Assortative mechanisms focus on individual attributes such as age, gender, ethnicity, and education to examine how two individuals' similarities ('homophily') and dissimilarities ('heterophily') impact the likelihood of their forming a connection (Goodreau *et al.* 2009, Rivera *et al.* 2010). In teachers' advice networks, teachers tend to seek advice from other teachers of the same gender (Frank and Zhao 2005, Spillane *et al.* 2012, Moolenaar *et al.* 2014) and same race (Spillane *et al.* 2012), who teach the same grade (Frank and Zhao 2005, Penuel *et al.* 2010, Moolenaar *et al.* 2014, Siciliano 2015), and attend the same meetings (Penuel *et al.* 2010). Teachers are also more likely to seek advice from those with more years of experience (Moolenaar *et al.* 2014), better at improving student achievement (Wilhelm *et al.* 2016), and who have attended more professional development programs (Spillane *et al.* 2012) and hold leadership positions (Spillane *et al.* 2012, 2015, Moolenaar *et al.* 2014).

Studies of proximity mechanisms, or the tendency of individuals to connect to others who are close geographically (Rivera *et al.* 2010), yield mixed results. Spillane *et al.* (2017) found that school teachers whose workspaces are located closer to one another, and whose paths likely cross more frequently within the school building, are more likely to talk with one another about work. In online learning networks, some researchers found that learners from the same location were more likely to communicate with each other (Yuan and Gay 2006, Kellogg *et al.* 2014) while others found a negative relationship between proximity and communication (Joksimović *et al.* 2016).

Methods

To answer our research questions about network characteristics and formation mechanisms among environmental educators in three professional development programs, we used a mixed-methods approach, including quantitative SNA and qualitative analysis of interviews and project reports.

Professional development programs and participants

From 2011 to 2016, the Expanding Capacity in Environmental Education project (EECapacity) provided online and face-to-face professional development for environmental educators. EECapacity draws from social innovation literature, which suggests that innovations in educational practice emerge through creating platforms for exchanging ideas and resources among educators holding different perspectives and practices (cf. Mulgan *et al.* 2007, Krasny *et al.* 2017). The EECapacity professional development programs that are the focus of this study include: Pennsylvania State Consortium (PASC), Urban Environmental Education Project-based Online Learning Community (PLC), and Community Climate Change Fellowship (CCC) (Table 1). All three programs provided resources and encouraged interactions among a diverse group of environmental education, youth development, and related professionals, but varied in online and face-to-face professional development activities and outcomes.

PASC created a learning community for 27 educators and community and youth development professionals working at nature centers, state agencies, schools, parks, community development organizations, professional associations, and other organizations in Pennsylvania. By fostering exchange among participants, PASC sought to build a new leadership structure for environmental education in Pennsylvania that would include community and youth development in addition to

Table 1. Professional development activities and participants.

	Pennsylvania State Consortium (PASC)	Project-based Online Learning Community (PLC)	Community Climate Change Fellowship (CCC)
Time	March – December 2014	April – December 2014	June – December 2014
Activities	Face-to-face meetings Webinars Facebook group	Online library Webinars Facebook group	Weeklong workshop National conference Webinars Facebook group Action project
Outcomes	New leadership	eBook	
Pre-survey respondents (response rate)	23 (85%)	38 (88%)	26 (100%)
Post-survey respondents (response rate)	19 (70%)	32 (74%)	26 (100%)
Gender			
Female	21 (78%)	32 (74%)	17 (65%)
Male	6 (22%)	11 (26%)	9 (35%)
Race			
White	20 (74%)	30 (70%)	15 (58%)
Non-white	7 (26%)	8 (18%)	11 (42%)
Not reported		5 (12%)	
Age			
Mean		45	40
Working experience in environmental education			
< 10 years		20 (47%)	11 (42%)
≥ 10 years		18 (42%)	15 (58%)
Not reported		5 (12%)	

The Pre-survey was conducted in the beginning of each program, and the Post-survey was conducted after program activities.

environmental education professionals. PASC members did not have structured assignments or collaborative projects during the professional development program period. After the one-year program, the learning community decided to continue sharing ideas and resources through conference calls, and to seek funding to organize additional face-to-face workshops.

PLC was facilitated by a Cornell online instructor and sought to increase educators' capacity to conduct environmental education in cities (Table 1). Of 94 environmental educators and community leaders initially registered, 43 participated in the PLC final project, which involved collaborating in small groups to write eBook chapters on urban environmental education (Russ 2015). Participants worked with youth and adults in urban K-12 schools, after-school programs, community and youth development organizations, faith-based groups, community-based environmental organizations, and urban planning, outdoor education, museum, botanical garden, zoo, and university outreach and teaching programs.

The goal of the CCC fellowship program was to foster leadership, networking, innovation, and strategies for reaching new and under-represented audiences in local climate change education projects (Table 1). CCC involved face-to-face and online exchange of ideas and resources among 26 educators and community leaders from the US, Canada, and Mexico. Participants conducted local climate change education programs in schools, aquariums, community organizations, and other settings, and collaborated on writing an eBook after the formal professional development activities ended.

Social network surveys

We administered social network surveys to participants in PASC, PLC, and CCC in the beginning and after professional development activities. Participants identified how often they went to other program participants for information, advice, or help for their educational programs. In these self-reported advice seeking, professional networks, we defined a directed tie A->B if A named B in the survey, thus generating a whole network. Response rates varied from 70% to 100%. Cross

tabulation and chi-square analysis showed that there were no significant differences between participants who responded to the survey and those who did not respond to the survey in terms of gender, race, and years of professional experience in environmental education or community and youth development (Li 2017).

Social network analysis

To demonstrate how participants' professional networks changed over time, we used the R *igraph* package (Csardi and Nepusz 2006) to visualize the network data, and the R *sna* package (Butts 2008) to measure network structural characteristics. At the group level, we used standard measures to calculate density (ratio of the number of ties to total number of possible ties), reciprocity (ratio of the number of relations that are reciprocated to total number of relations), and transitivity (ratio of the number of transitive triads to total number of possible transitive triads) (Wasserman and Faust 1994). At the individual level, we calculated in-degree centrality (number of ties through which each participant gives out information to others) and out-degree centrality (number of ties through which a participant seeks information) (Knoke and Yang 2008).

Exponential random graph models (ERGMs)

Exponential random graph models (ERGMs) control for the interdependency of networks and can predict the likelihood of tie formation (Robins *et al.* 2007a, 2007b). In this study, we used R *ergm* package (Hunter *et al.* 2008) to explore structural, associative, and proximity mechanisms of network formation (Rivera *et al.* 2010). We conducted diagnostics and chose the models with the best goodness-of-fit, which were indicated by the lowest value for Akaike information criterion (AIC) and Bayesian information criterion (BIC).

For structural mechanisms, we calculated reciprocity (two educators likely to share resources with each other, transitivity (two educators interested in the same topic more likely to connect with a third educator with same interests), and in-degree centrality or popularity (educators seek advice from those who hold more resources) (Table 2) (for details on methods see Li 2017).

Assortative mechanisms included node attributes (individual characteristics including race, gender, work year, number of meetings, and Facebook activities) and edge attributes (tie characteristics including meeting attendance, webinar, Facebook and co-authorship network) (Table 2). PASC was the only program where participants were connected to each other before the professional development program, which provided an opportunity to examine pre-program network as an assortative mechanism. PASC webinar network and meeting network are affiliation networks that indicate whether or not two participants attended the same webinar or meeting.

In PLC and CCC, the number of working years in environmental education was categorized into two groups: less than 10 years and equal or more than 10 years. The edge attribute was Facebook network, which was captured by the online commenting network from the Facebook group (if a participant commented on another participant's posts, there would be a tie between these two participants). The number of participant posts and comments were coded as continuous variables. Because interactions with facilitators were less frequent, the comments to and from the facilitators were coded as binary variables (Table 3). PLC had the additional edge attribute co-authorship. Two participants connected with each other if they co-authored an eBook chapter.

The proximity mechanism was geographic distance measured by the longitude and latitude of each participant's working location.

Table 2. ERGM attributes measured for each of the three programs.

	Pennsylvania State Consortium (PASC)	Project-based Online Learning Community (PLC)	Community Climate Change Fellowship (CCC)
Structural mechanisms	Reciprocity Transitivity Popularity	Reciprocity Transitivity Popularity	Reciprocity Transitivity Popularity
Assortative mechanisms			
Node attributes	Gender Race Webinar attendance Meeting attendance	Gender Race Work Year Facebook post Facebook comments – Participants Facebook comments – Facilitators	Gender Race Work Year Facebook post Facebook comments – Participants Facebook comments – Facilitators
Edge attributes	Webinar network Meeting network Pre-program network	Facebook network Co-authorship network	Facebook network
Proximity mechanism			
Edge attribute	Geographic distance	Geographic distance	Geographic distance

Table 3. Descriptive statistics for Facebook data in project-based online learning community and community climate change fellowship.

	Project-based Online Learning Community (PLC)	Community Climate Change Fellowship (CCC)
Facebook Posts		
Total	180	193
Mean (per person)	4.19	7.42
Median	2	4.5
Range	0–27	0–35
Facebook Comments – participants		
Total	289	167
Mean (per person)	6.72	6.42
Median	5	4
Range	0–42	0–29
Facebook Comments – facilitators		
To facilitators Present	18	18
To facilitators Not present	25	8
From facilitators Present	10	13
From facilitators Not present	33	13

Interviews and reports

To gain a deeper understanding of network formation, we conducted semi-structured interviews with 5 PASC and 7 PLC participants two months after professional development activities. Using a purposive sampling strategy; we chose interview participants who, based on their network surveys, added contacts a lot, some, and not at all. We asked participants if and how participation in professional development activities allowed them to form networks with other educators and instructors. All interviews were transcribed.

To avoid burdening CCC participants who had been extensively interviewed by the program evaluator, we analyzed participants' mid-term and final project reports instead of seeking interviews (23 and 14 reports, respectively). Specifically, we analyzed responses to two questions: 1) Tell us how you have used the fellowship training opportunities or the fellows' network to improve or adjust your fellowship project; and 2) Share a story that illustrates something you have learned or something that was meaningful for you personally or professionally. Although the

questions were not directly about network formation, CCC participants mentioned how they developed professional networks as a result of the training program. For PLC and PASC interviews and CCC reports, we used structural coding methods (Saldaña 2009) to identify network related quotes that showed how participants interacted with each other and exchanged ideas.

Validity

We addressed content validity (Haynes *et al.* 1995) by using previous studies and expert opinions to develop the network surveys. Convergent validity (Campbell and Fiske 1959) was addressed by comparing results from network surveys, Facebook communications, and interviews and reports.

Results

Professional network density increased after professional development activities (Figure 1 and Table 4) and mean values for individual in-degree and out-degree centrality increased across all three groups (Table 4). Network formation mechanisms varied across groups and are presented below.

Mechanisms of network formation

The ERGM results showed that both structural and assortative mechanisms had varying effects on network formation whereas the proximate mechanism had no effect (Table 5).

The structural mechanisms reciprocity and transitivity had significant positive effects ($p < .001$) on formation of network ties in PLC indicating that the connections in PLC tend to be mutual and transitive. In-degree centrality (popularity) had a significant negative effect on tie formation in PLC ($p < .05$) and CCC ($p < .001$) indicating that each tie a participant received significantly decreased the probability that a participant will receive an additional tie.

The assortative mechanisms webinar and meeting attendance and male gender had significant positive effects on likelihood of forming a tie in PASC ($p < .001$), which means participants who attended more webinars or more face-to-face meetings and are male were more likely to form a tie with other participants. Only meeting network showed a significant positive effect on tie formation ($p < .001$) indicating that any two participants who attended the same face-to-face meeting but not the same webinar were more likely to form a tie between them. Further, the pre-program network had a significant positive effect ($p < .001$) indicating that participants who already connected to each other were more likely to keep connecting.

In PLC, Facebook posts had a significant negative effect ($p < .01$) whereas comments to other participants had a significant positive effect ($p < .001$) on the likelihood of forming a network tie, which indicates participants who posted more on Facebook were less likely to connect with other participants but those who made more comments on other's posts were more likely to form ties. Further, Facebook network ($p < .1$) and eBook co-authorship network ($p < .001$) had significant positive effects indicating that two participants who communicated on Facebook and co-authored a chapter were more likely to connect to each other. Finally, homophily by race had a significant positive effect ($p < .01$), indicating that participants of the same race were more likely to connect with each other. Specifically, white race had a significant negative effect ($p < .05$) whereas work year had a significant positive effect ($p < .01$) on network formation, indicating that participants who were not white and with more than 10 years working experience in environmental education were more likely to connect to other participants.

In CCC, Facebook comments from participants had a significant negative effect ($p < .01$) indicating that participants who received more comments from other participants were less likely to form a tie with other participants. In addition, Facebook comments both to ($p < .01$) and from ($p < .001$) facilitators had significant positive effects indicating that participants who interacted with facilitators were more likely to form a tie with other participants. Further, white race had

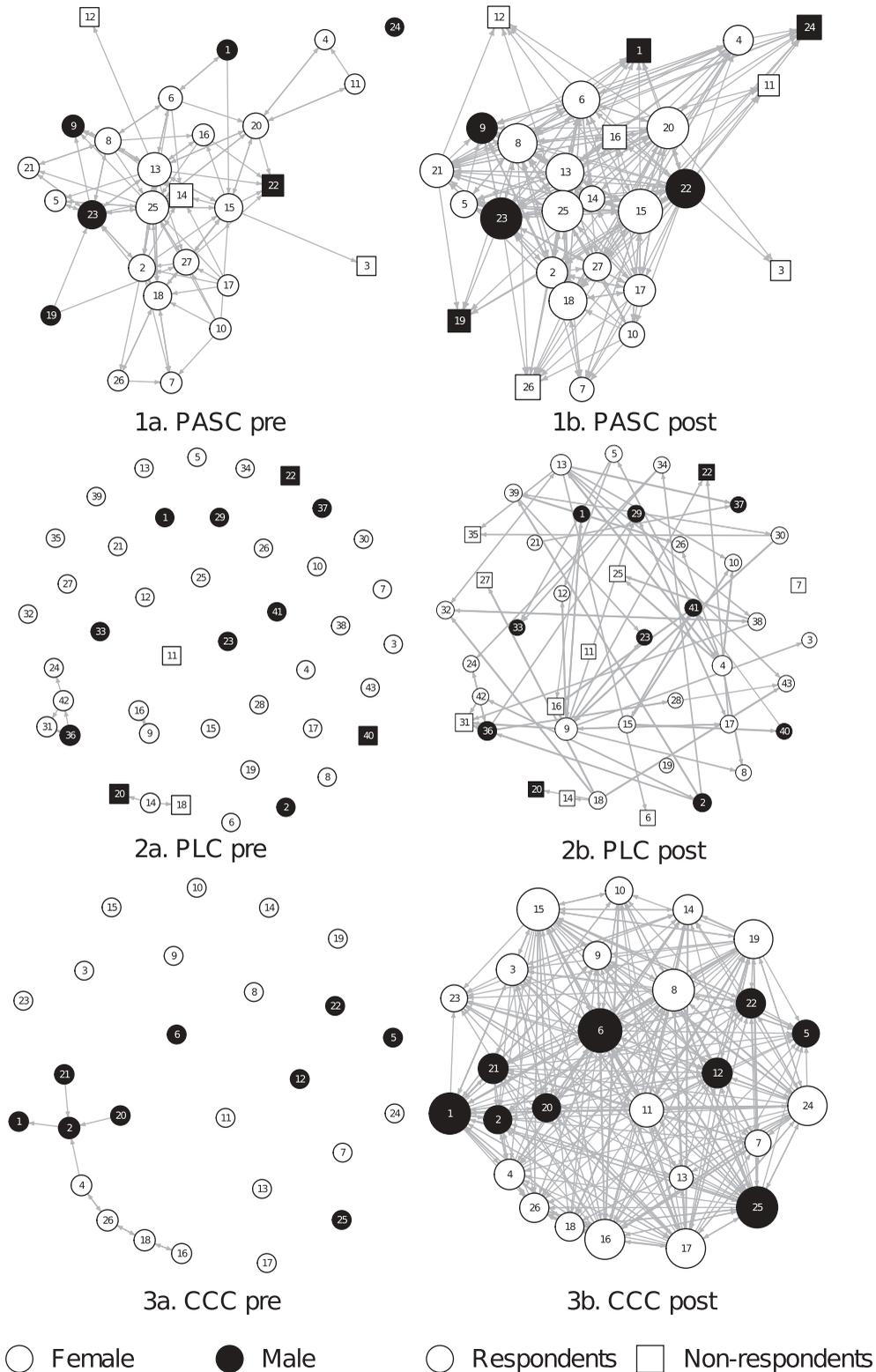


Figure 1. Individual networks in all programs before and after the professional development activities. The size of the node indicates degree centrality and the width of the tie indicates strength.

Table 4. Descriptive statistics of network measures in all programs.

Network metrics	Pennsylvania State Consortium (PASC)		Project-based Online Learning Community (PLC)		Community Climate Change Fellowship (CCC)	
	Pre	Post	Pre	Post	Pre	Post
Nodes	27	27	43	43	26	26
Edges	112	468	9	72	10	327
Group density	.16	.37	.01	.04	.02	.50
In/out degree mean	4.15	9.63	.21	1.67	.39	12.00
In-degree median	3	9	0	2	0	12
In-degree range	0–13	2–16	0–2	0–5	0–3	10–18
Out-degree median	2	7	0	1	0	8.5
Out-degree range	0–15	0–26	0–2	0–10	0–2	0–25

Table 5. Results of exponential random graph models.

	PASC	PLC	CCC
Edges	–4.690 (.502)***	–2.542 (1.149)***	6.212 (1.940)**
Structural mechanisms			
Reciprocity		2.981 (.763)***	
Popularity		–1.072 (.478)*	–1.695 (.406)***
Transitive triples		.305 (.085)***	
Assortative mechanisms			
Webinar attendance	.559 (.091)***		
Meeting attendance	.433 (.125)***		
Meeting network	.984 (.300)***		
Pre-program network	2.291 (.426)***		
Facebook Post		–.059 (.021)**	
Facebook comments to participants		.053 (.013)***	
Facebook comments from participants			–.046 (.015)**
Facebook comments to facilitators			.856 (.188)***
Facebook comments from facilitators			.905 (.173)***
Facebook network		.796 (.415)#	
EBook co-authorship		4.265 (.624)***	
Gender Male	1.440 (.251)***		
Homophily Race		.780 (.290)**	
Race-White		–.554 (.243)*	.848 (.177)***
Work Year ≥10 years		.645 (.214)**	–.954 (.159)***
AIC		445.5	387.9
BIC		470.7	455.6
			794
			825.3

*** $p < .001$; ** $p < .01$; * $p < .05$; # $p < .1$

a significant positive effect ($p < .001$) meaning that white participants were more likely to form a tie with other participants, whereas work year had a significant negative effect ($p < .001$)

indicating that participants with more than 10 years working experience in environmental education were less likely to connect to other participants.

Interviews and reports

Analysis of the interviews and reports similarly pointed to network formation varying among the three professional development programs. PASC participants talked about how the face-to-face meetings helped build connections, PLC participants emphasized the importance of Facebook interaction and co-authorship, and CCC participants mentioned about both face-to-face and Facebook interaction. Both PLC and CCC participants also shared the importance of their interactions with facilitators in helping them to collaborate with other participants and improve their programs. Further, participants from all three programs mentioned that their existing connections were strengthened, their networks expanded beyond each program, and they would like to build more local partnerships.

A PASC co-leader talked about how they started the program to engage participants from different regions and how participants developed connections among each other through face-to-face meetings:

Even when I was writing the grant, I wanted to make sure that people across the state of Pennsylvania were involved... The very first meeting, you bring in 23 people together. Some of them knew each other but the majority did not... And people just came in and just started talking to each other as if they have been best friends for their whole lives. I heard people saying oh yeah, I will let you know what I have about this, and so on that personal basis. I have seen that.

A PASC participant also explained how face-to-face meetings rather than webinars help build connections among participants:

Face to face meetings are always the best... That's where you develop the relationships. It's hard to develop relationships through webinars, it's hard to develop them over a phone call or a chat. You know you have to develop them face to face and you've to not only do activities, you have to do examples of programs that are working and not just talking about those examples but show them actually, you know get them involved in the particular practice you know that you are doing... so they can get a better understanding for the work that you're doing...

In the online only PLC, a participant mentioned how she connected to other participants through Facebook interaction, which led to an initial conversation and collaboration on co-authoring an eBook chapter.

You know because she saw that we had similar interests based on the things that we were posting in the group, and then he [another participant] found his way to me based on my postings things about global climate change and ... that we had an initial conversation. And then [another participant] reached out to me... So I think in the short run we all came together very organically just through an initial connection and an initial connection making another initial connection and so forth and so on. We had not worked together previously.

CCC participants mentioned that the program created opportunities for them to develop networks among each other. A participant explained how the first workshop helped her connect to other participants, and how she continued networking with some of the participants:

The weeklong training in West Virginia helped me to hear about others' projects and to better-clarify my own, as well as to network with and learn from some of the most amazing and positive people I know... Since then, there are three or four fellows with whom I have remained in consistent contact either to provide them with resources, share CC101 PowerPoint [on climate change] and information, or to get their feedback on what I am doing.

CCC participants also connected to each other and shared resources on Facebook.

It has been very helpful and supportive to have a network of other environmental educators on the same path in many different locations, working on meaningful projects in each of their communities. Specifically, [a participant] has been very helpful through the number of resources she has shared over our Facebook community.

In addition to networking among themselves, PLC participants mentioned their individual conversation with the program facilitator to help engage co-authors:

[facilitator] and I would have conversations outside of the group of four or so folks that were in our chapter and then I would go back to those and trying to smooth things over and eventually develop a good relationship with all the ladies that were in my group...

CCC participants also mentioned their interactions with the program facilitators and receiving advice from the program facilitators:

I feel the greatest benefit of the fellowship for me was the chance to work with the 25 other fellows and to begin building a community of people dedicated to improving climate change education. I will continue to support and gain support from the talented fellows in this program, in addition to the amazing contributions and organizational skills of [facilitate 1] [facilitate 2] and [facilitate 3].

Participants who knew each other before the program were more likely to maintain connections during the program. A PASC participant mentioned how she was invited by another participant to join the program:

I was invited to participate in this collaborative by [another participant] ... She and I have a long history of a professional relationship in a number of capacities...and she thought that my perspective coming from a community based organization that's also doing work in the environmental realm that it would be a nice addition to the community of learners.

She continued explaining how her network was strengthened through the professional development activities:

I think it has certainly strengthened my relationship or at least continued to strengthen my relationships particularly with the people that are in closest proximity to me that I would ... more likely collaborate with on a project or a program.

For those who knew each other previously, CCC helped them strengthen their relationship. One participant explained how their local partnership was reinforced through the program:

It has also allowed and inspired me to reinforce existing partnerships and create new ones, in particular with fellow [name]'s [organization name] and an NGO we work with ...

Through connecting with each other, participants expanded their networks beyond the programs. A PASC participant mentioned that his networks expanded at the local and national level:

It's actually added more partners to our existing coalition and it allowed us to increase our own organization's awareness and outreach on a broader scale to a not only a regional level or in a more localized level in some of these other counties, but it's actually helped us on a national level...

Although the ERGM results showed no proximate effect on network formation, participants from all three programs expressed an interest in building local connections. A PLC participant mentioned:

I mean the distance is a little bit of a barrier... And it's good to collaborate we know, but again because I'm part of a bigger machine...I wonder who we could talk to locally to make the impact because locally is where we need to concentrate our efforts and I think that's part of why I'm not as readily reaching out as well.

A CCC participant also showed her interest in exploring ways to continue networking and sharing with others to deepen relationships:

I think I am also feeling a little challenged how to make some mutual support "Fellowship friends" across distance, etc. The sporadic check-ins and Facebook themselves are not sufficient to deepen those mutual support connections...I would love to know if there are other things I could be sharing that would help support others' work as well.

Discussion

Through examining network structure and formation mechanisms in professional learning communities using SNA, this study demonstrated that both face-to-face and online learning activities can build connections among educators. However, it appears that supplementing online interactions with face-to-face activities enabled participants to build denser networks and stronger connections throughout the network, and project-based learning forged stronger connections among members of a co-author group.

In PASC, the result that going to the same face-to-face meeting increased the likelihood of participants connecting to each other, is consistent with findings from previous research showing participating in the same meetings increased the likelihood that teachers sought advice from one another (Penuel *et al.* 2010). In CCC, participants mentioned the importance of attending a face-to-face workshop and conference in shaping their networks in addition to Facebook and webinars. In an online graduate course, Haythornthwaite (2001) also found that a short face-to-face interaction session had a catalytic effect on social and emotional exchanges among students.

Whereas in PASC and CCC, face-to-face meetings were important in network formation, eBook chapter co-authorship was influential in network formation in PLC with only online interactions. The significant positive effect of transitivity on network formation in PLC suggested that a participant tended to connect to another participant who shared a mutual contact (Siciliano 2015). PLC participants collaborated in small groups to write, which may have led them to form transitive triangles sharing a mutual interest in their chapter topic; reaching consensus in writing the chapter may have reinforced these transitive connections (Aviv *et al.* 2005). The finding that chapter co-authors formed stronger ties relative to ties with all PLC participants, suggests that project-based collaborative work has the potential to develop stable connections for information exchange.

Further, this study found how Facebook networks as part of professional development activities impacted participants' professional advice network formation, thus adding to research that uses network models to explore formation of advice networks among teachers (Moolenaar *et al.* 2014, Siciliano 2015, Spillane *et al.* 2015) and online discussion networks in online courses designed for teacher professional development (Kellogg *et al.* 2014). PLC participants who posted less but commented more on each other's Facebook posts were more likely to form connections, suggesting that engaging in conversation by commenting instead of only posting could foster network formation. However, posting and commenting on Facebook showed no significant impacts on tie formation in CCC. A possible explanation is that participants relied on Facebook interaction to learn about each other in PLC, while participants in CCC could learn about each other through face-to-face meetings and webinars.

The result that participants' comments to and from facilitators increased the likelihood of network formation between participants in CCC supports findings by De Laat *et al.* (2007) and Li *et al.* (2014) that instructors or facilitators of online learning communities play a key role in promoting networking among participants. However, interacting with facilitators on Facebook in PLC showed no effect on tie formation among participants; one explanation is that compared to CCC, which had strong facilitation by experienced program leaders, PLC had one facilitator who coordinated the group-writing project individually rather than interacting with participants on Facebook as mentioned in a participant interview.

The result for homophily by race indicated a significant positive effect in the PLC, meaning that participants with the same race were more likely to connect with each other. In teachers' face-to-face advice networks, Spillane *et al.* (2012) found that teachers tend to seek advice from other teachers of the same race. In the PLC, participants of the same race may have found common interests in a particular topic or in writing a chapter, and thus were more likely to connect with each other. The fact that the proportion of non-whites varied among the programs (e.g. 30 white and 8 non-white in the PLC, and 15 white and 11 non-white in the CCC) might explain the lack of consistent patterns between race and social ties across the three programs.

In an online professional development course, Li *et al.* (2014) found that participants with fewer years of work experience were more likely to intend to adapt ideas to their practice. Similarly, in CCC, less experienced participants were more likely to connect with others, perhaps to find ideas and resources that could be applied to their projects. In PLC, more experienced participants may have reached out to other participants to coordinate collaborative writing activities, suggesting that the goal of the professional development, to create new practices in CCC versus to write a book chapter in PLC, may impact how people seek information from others.

In contrast to previous studies which showed that participants whose location were closer to each other were more likely to communicate with each other in face-to-face (Van Duijn *et al.* 2003) and online settings (Yuan and Gay 2006, Kellogg *et al.* 2014), geographic distance showed no impact on network formation in this study. Similar to how the students in a MOOC from one country were more likely to communicate with students from another country (Joksimović *et al.* 2016), participants connected to each other across the state in PASC, and across the country in PLC and CCC. For environmental educators, networking with participants from different regions and with different professions may provide them with diverse perspectives, which may foster innovation in practice (Mulgan *et al.* 2007, Biggs *et al.* 2010). However, in terms of long-term collaborations, participants may prefer local connections. PLC and CCC participants mentioned in the interviews that they met with or would like to meet with other participants close by, which suggests the need for online learning communities to create local groups for future collaboration.

Previous studies used the community of practice framework to understand the importance of social context in teachers' learning (Akerson *et al.* 2009, Bannister 2015). This study applied SNA to examine specifically how educators interacted with each other for the exchange of ideas and practices, which helps us understand mutual engagement in communities of practice (Wenger 1998). Further, previous studies relied on descriptive analysis when using SNA to examine teachers' interactions through face-to-face (Penuel *et al.* 2009) and online activities (Sing and Khine 2006). The results of this study add to the literature on network formation and structure in educator professional development by conducting ERGMs to understand the mechanisms of network tie formation. Finally, adding to research that used network models to explore formation of advice networks among teachers (Moolenaar *et al.* 2014, Siciliano 2015, Spillane *et al.* 2015) and online discussion networks in online courses designed for teacher professional development (Kellogg *et al.* 2014), this study explored how Facebook networks as part of professional development activities impacted participants' professional advice network formation.

Limitations

Having only three professional development programs with different goals and numbers of participants makes it difficult to directly compare network characteristics and formation mechanisms between groups and generalize findings to broader settings. Also the relatively low response rates in PASC and PLC resulted in missing ties in the networks, which impacted network measures. Further, the post-surveys were conducted right after the professional development activities and thus we do not know if participants maintained their connections after the programs, although the interviews conducted two months after surveys indicate that this was a strong possibility. In addition, we counted the number of Facebook posts and comments, but we did not analyze post or comment content or commenter-commenter interaction, which may also influence advice network formation. Finally, we were not able to capture all the participant interactions, which may have occurred through other communication means such as emails and phone calls.

Conclusion

By conducting ERGMs, we were able to examine the relationship between professional development activities and formation of professional networks. Both online and face-to-face professional

development activities were associated with the development of networks albeit to varying degrees and through differing mechanisms. Our results suggest implications for future professional development programs. In particular, the fact that CCC participants who interacted with program facilitators tended to connect to other participants, and PLC participants who posted more on Facebook were less likely to connect to other participants, suggests a role for program facilitators in guiding participants in discussion with other participants, including through online platforms such as Facebook. In addition, co-authoring an eBook chapter provided a chance for PLC participants to develop professional network ties to exchange ideas in depth, which suggests including collaborative projects in future professional development programs that seek to foster idea exchange, especially those conducted exclusively online.

For researchers, the results leave open questions about the impact of professional networks on professional practice and innovation. For example, what kinds of shared information and resources through networking in professional learning communities contribute to innovative practice? How do network position and structure impact innovation in environmental education practice? These questions are further explored in related papers that explore the relationship between networks and practice change.

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