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Exploring Teacher Participation and Engagement: Climate Change Professional Development and Collaboration

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ABSTRACT

Sustainable WATERS addressed the critical need to support Title I middle school teachers and students by creating a community of practice (CoP) around modeling and field exploration of climate impacts on Southwest Florida's watershed. The program integrated virtual and field environments to grow access to tools, technology, and expertise in STEM, allow for teacher and student asynchronous participation, and facilitate a long-term connection. The aim of the professional development program was to create a CoP and network of continued engagement and resource support to support climate change education opportunities for students and six middle school STEM teachers in underserved schools. The study outlines the participatory involvement and outcomes of each participant throughout the course of the study.

Keywords: community of practice, climate education, teachers' professional development

Introduction

Creating equitable access to STEM programs is complex due to economic disparities, geographic isolation, cultural bridges, language barriers, and socio-economic differences amongst districts (Munn et. al., 2018). Inequity in access to high-quality science education occurs especially within Title I schools (Jones & Stapleton, 2017). These schools are typically low-resourced; and situated in low-income communities with a high number of students underrepresented in STEM fields (Banilower et al., 2013; Chen & Weko, 2009; National Research Council, 2013).

Sustainable WATERS is an interdisciplinary program that provides teacher training, supplies, and digital resources to improve watershed literacy in Southwest Florida (SWFL). The overarching goal of the project is to improve educators and students' watershed literacy through the use and building of models, leading to a greater knowledge of and sense of agency in creating solutions to the impacts of climate change in SWFL. Each lesson within the program has a clear scientific focus, opportunities for field or lab work, data analysis, and model building all related to the learner's own backyard. As part of Sustainable WATERS' teacher training, a professional development (PD) Communities of Practice (CoP) program was developed that focused on teacher development and understanding the local impacts of climate change in Title I middle schools. The program transitioned from in-person PD to an online format as a result of the COVID-19 pandemic. It leveraged access to virtual tools to increase teacher and student access to modeling and climate change expertise relevant to SWFL communities. Sustainable WATERS' CoP engaged teachers and students in locally-focused climate education by integrating models and modeling.

Communities of Practice (CoP) in Education

A CoP is a is a social learning system where individuals come together to fulfill individual and group goals of a common interest (Cambridge et al., 2005). CoPs focus on sharing best practices and creating new knowledge to advance a professional practice. Ongoing interactions are an important part of CoPs, and many virtual CoPs (vCoPs) rely on face-to-face meetings as well as virtual collaborative environments to communicate, connect, and conduct community activities (Cambridge et al., 2005). CoPs are social learning systems, where members define competence around a discipline or practice by combining three elements: a sense of joint enterprise, mutually defined norms and relationships, and a shared repertoire of communal resources they create and can draw upon to further their competence (Wenger, 2010). We used a CoP approach as a PD partnership model to connect university researchers and K-12 teachers. In this study, CoP serve as the primary theoretical framework, to examine how teachers engage in professional development in climate education. CoP provides a structured approach to understanding teacher learning as a social process, where participants develop expertise through interaction, collaboration, and sustained engagement within a professional learning community.

School-university partnerships provide opportunities for collaboration with mutual benefits (Lynch & Smith, 2012; White et al., 2010). The benefits associated with these partnerships include "built-in support networks" for the teachers (Darling-Hammond, 2006, p.110). However, challenges and barriers exist when implementing school-university partnerships, including sharing space, time, and resources required (Green et al., 2020). Existing connections to the community and school district partners in watershed education allowed for us to grow the CoP to deepen teachers' skill, content knowledge, and participation in watershed education.

Within CoPs, the members can participate at different levels and can move between levels of engagement throughout their participation. *Core* members define CoP norms and create and share knowledge. *Active* members frequently participate in the CoP but may not be leaders or creators of knowledge and artifacts. *Peripheral* members participate less frequently but can move to be active or core when they develop their knowledge and contribute to the CoP. Core members can legitimize peripheral members as they develop (Borzillo et al., 2011). Participation in a CoP enhances teachers' self-efficacy by providing opportunities for mentorship, collaboration, and real-world application of new instructional strategies. According to Bandura (1997), self-efficacy is shaped by mastery experiences, social persuasion, and observational learning, all of which occur naturally within a CoP. As teachers progress from peripheral to core members, their confidence in teaching climate-related content increases, reinforcing their belief in their ability to facilitate student learning effectively.

Climate Change Education

Science education communities advocate for a climate-literate public equipped with the scientific knowledge and skills needed to make informed decisions about global climate change (GCC) (McNeal et al., 2014). For this study, we define *climate literacy* as the ability to apply scientific knowledge to advance understanding and engagement in climate science (McNeal et al., 2014). However, climate change is inherently complex; the global nature of the issue makes it challenging to observe climate change at the local level, limiting its relevance to students' daily lives and the need for long-term analysis and projections makes it challenging for science educators to fully understand and effectively communicate the processes behind GCC (Nation & Feldman, 2022). Science educators recognize that teaching climate change science is necessary to produce a citizenry that understands the causes of

GCC and ways to both mitigate it and prepare for its effects (ChewHung, 2022; Gutierrez et al., 2008) Teachers must integrate GCC into their curriculum, and students need to develop a deeper understanding of its causes and impacts. Adding climate change content to existing science curricula, however, is not enough. Teachers require preparation through PD in effective pedagogical strategies to teach climate-focused content meaningfully (Nation & Feldman, 2021).

The Next Generation Science Standards (NGSS Lead States, 2013) emphasize the importance of analyzing evidence for climate change (HS-ESS3-1) and using climate models (HS-ESS2-6, HS-ESS3-5). However, studies have shown that educators, both at universities and K-12 schools, often lack confidence in their subject knowledge and feel unprepared to adequately teach climate change (Oversby, 2015). Filho and Hemstock (2019) argued that educational institutions should actively pursue initiatives that promote awareness and encourage local solutions. The Sustainable WATERS program aims to bridge this gap by engaging teachers and students through locally focused models and simplified climate modeling, fostering connection to the material and enhancing comprehension of GCC's complexity for beginners. Models can be powerful tools to help educators and students describe, represent, and predict climate phenomena (Cartier et al., 2001), though these models must often be simplified to illustrate climate change effects on a local or regional scale. Climate models are critical for scientists studying global climate trends. The program seeks to make these models more accessible for students and secondary science teachers, helping them understand the complex interactions associated with GCC. Research by Holthuis et al. (2014) indicated that instructional approaches focused on modeling climate data can improve both teaching effectiveness and student understanding of climate change. Additionally, Bhattacharya et al. (2020) found that students' ability to analyze complex climate science and climate literacy can improve when they use multiple modeling methods. In later sections, we describe the types of models used within the Sustainable WATERS curriculum and their integration with existing science standards.

Professional Development

The impact of PD on efficacy and student learning is well-documented (Althauser, 2015; Fischer et al., 2018; Rutherford et. al, 2017). PD is vital to help teachers gain skills and knowledge to teach about current environmental and social issues (Borko, 2004; Guskey, 2002). While many PD opportunities are available to science teachers, most are not designed specifically for teaching and learning of climate science or to advance teacher understanding of this complex issue (Schneider & Plasman, 2011). For complex issues, such as climate change, research suggests that educators need PD that presents content paired with specific teaching strategies to build confidence and better incorporate the topic into their curriculum (Hestness et al., 2017; Kunkle & Monroe, 2018; Plutzer et al., 2016). This specific type of PD can increase teachers' subject matter knowledge (SMK), pedagogical content knowledge (PCK), and self-efficacy to enable them to teach climate change more effectively (Nilsson, 2014; Van Driel & Berry, 2012). For the purpose of this study, self-efficacy is defined as "beliefs in one's capabilities to organize and execute the courses of action required to produce given attainments" (Bandura, 1997, p. 3). PD programs can increase educators' self-efficacy (Bandura, 1997; Chesnut & Burley, 2015; Holden et al., 2011; Morris et al., 2017) and teachers with greater self-efficacy tend to be more open to new ideas and willing to experiment with new methods to meet the needs of their students (Gavora, 2010).

Li et al. (2021) document a gap in the literature, in that while many climate change education PD programs are implemented, little empirical evidence of effective PD approaches specific to climate change education have been documented. Desimone (2009) offers five critical features for successful PD, of which the following were implemented in the Sustainable WATERS teacher training experiences including:

1. **Focus on content**: Sustainable WATERS incorporated the use and creation of models to communicate and represent their understanding of the problematic trends associated with the impacts of climate change in SWFL
2. **Opportunities to engage in active learning between and among the participants**: teachers engage with each other, experts in the field, (including Marine and Environmental Scientist and GIS specialists) and local ecosystems to learn about the impacts of climate change in local watersheds and their home environments.
3. **Coherence between new learning and teachers' knowledge and beliefs, collective participation:** data collected via Climate Literacy survey and virtual check-ins determined the progression of each learner.
4. **Extending the PD over an appropriate duration of time**: Sustainable WATERS took place over one Academic Year (AY) and weekly check-in

As PD models continue to evolve, vCoPs have emerged as powerful tools for supporting teacher learning, collaboration, and instructional confidence (Ghamrawi, 2022; Schwarzhaupt et al., 2021). Building on this foundation, our project applied a CoP model specifically rooted in climate-related watershed issues, focused on teachers' self-efficacy and the impacts of climate change in SWFL through participation in PD designed in the Meaningful Watershed Educational Experiences (MWEE) framework employed by the National Oceanic and Atmospheric Administration (NOAA, 2021). This model responds to the growing demand for equitable, high quality, climate change PD that supports content knowledge and instructional confidence across diverse educational settings and can be readily adapted to other geographic regions by contextualizing climate impacts to their local ecosystems.

Research Questions

1. How does participation in the professional development community of practice affect teachers' climate literacy and self-efficacy in climate education?

2. What elements of a hybrid professional development program foster the development of a community of practice and how?

Materials and Methods

A mixed methods design was used to examine relationships between program participation, CoP engagement, and climate literacy through the data collected via surveys, interviews, and meeting notes. A mixed methods approach was chosen to allow for a comprehensive exploration of both quantitative trends and deeper contextual insights vial qualitative data that would not be possible with either method alone. Given that this study aimed to assess both objective measures (e.g., CoP engagement levels, climate literacy growth) and subjective experiences (e.g., teachers' perceptions of their participation and self-efficacy), a mixed methods approach was the most suitable. Specifically, this study employed a sequential explanatory mixed methods design (Creswell & Plano Clark, 2018), where quantitative data were collected first, followed by qualitative data to provide deeper insight into initial findings and identify patterns in CoP engagement and climate literacy through surveys, interviews, and meeting notes to contextualize patterns within teachers' experiences.

To elicit teachers' perceptions of their program participation and CoP membership, we used a phenomenographical approach (Marton, 1986). By using a phenomenographical approach, we gained insights into the different ways the teacher participants perceived and engaged with the program and CoP. A phenomenographic approach was selected to explore the diverse ways teachers experienced and interpreted their participation in the PD and CoP and allowed for a deeper understanding of variations in teachers' experiences, beliefs, and levels of engagement, contributing to a richer analysis of the impact of the PD program on teachers' perceptions and practices related to climate change education within Sustainable WATERS. We examined teachers' understanding of the impacts of climate change in SWFL, perceptions of teaching confidence, perceptions of their CoP membership, and their actual participation.

Sustainable WATERS took place over two years, beginning in Fall of 2021. This study focuses on the experience of the first cohort. Sustainable WATERS supported teachers within a large district, both in student population and geographically. Over half the students identify as economically disadvantaged. 38% of the student population identifies as Hispanic, 15% Black, and 43% White.

Participants

Teachers were recruited through noncompetitive selection and the district partnership dissemination of applications. Six STEM teachers applied to participate in the first cohort, thus, all were selected as participants in the CoP Teacher PD. All participants worked in Title I middle schools within the district. Because the group was small and selected through an invitational process, findings may not be generalizable to all teacher populations or contexts.

Intervention

The program supported the key parts of a CoP: working together, sharing goals, and building resources through the following: teachers worked together through virtual check-ins and in-person sessions, exchanging ideas, offering feedback, and reflecting on classroom implementation. The program centered around a shared goal of improving climate literacy instruction using the NOAA MWEE framework, fostering a common sense of purpose and direction. Participants also contributed to a growing set of tools and resources, which were shared and refined throughout the PD.

Teachers were selected to participate as teams for an entire school year, between PD and classroom implementation to foster long-term engagement in the program. They had weekly communication with teachers from other schools through field experiences and synchronous weekly virtual check-ins for collective participation. Each week was designed to take approximately 10 hours of the teachers' time. The 32-hour hybrid program, included the following elements (see supplemental materials):

In-person Kick-off: Teachers were provided supply kits for curriculum training, introduced to the program's outdoor activities on local beaches (surveying local beaches for the impacts of erosion) and classroom activities (hurricane dynamics).

Virtual instruction: Modules contained videos, text instruction, and models to support teachers' engagement in curriculum activities in the classroom and schoolyards. Each module focused on one of four major impacts of climate change in SWFL- habitat shift, increased extreme weather events, sea level rise, and saltwater intrusion- through field studies, data collection and analysis, and using and creating models. Each was developed through inquiry-based activities aligned with the NOAA MWEE framework, facilitating four activities for students and teachers: Issue Definition and Background Research, Outdoor Field Activities, Synthesis and Conclusions, and the execution of Stewardship Action Project. For a detailed examination of NOAA's MWEE framework see: https://www.noaa.gov/education/explainers/noaa-meaningful-watershed-educational-experience

Synchronous, virtual check-ins**:** Weekly one-hour check-ins provided facetime with project partners, time for sharing climate change education resources, successes and challenges with other teachers, and a platform for collaboration. Table 1 describes each climate-related module and the MWEE elements included to support learner-centered practices in climate change education.

Table 1:

Sustainable WATERS content and MWEE alignment

CLIMATE IMPACT	ISSUE DEFINING QUESTION	OUTDOOR FIELD ACTIVITY	MODELS FOR SYNTHESIS AND CONCLUSIONS	COMMUNITY ACTION ACTIVITIES
Habitat Shift	How are organism populations changing as climate changes?	Schoolyard plant surveys and measurement, with data sharing, phenology surveys	Spatial models of plant location and characteristics	Defined by teacher
Increased Extreme Weather	How does increased storminess impact our watershed dynamics?	Schoolyard elevation surveys: Map Your Watershed	Schoolyard topography maps to identify vulnerabilities	Defined by teacher
Sea Level Rise	How does sea level rise impact our watershed dynamics?	Schoolyard elevation surveys: Map Your Watershed	Spatial map of sea level rise scenarios; NOAA Sea Level Rise Simulator	Defined by teacher
Saltwater Intrusion	Why are our mangroves "walking" inland?	Schoolyard plant surveys and measurement, with data sharing, phenology surveys; schoolyard surface and groundwater quality analysis	Spatial models of plant location and characteristics and potential change; combined water quality data portal with other participating schools	Defined by teacher

Data Collection

To measure the participation in the CoP affecting teachers' climate literacy, teachers were surveyed via pre- and post-Climate Literacy Survey (see Appendix A). The participants were surveyed on GCC content knowledge and perceptions, their experience teaching climate topics, using models in their instruction, and self-efficacy teaching climate topics and using models in their instruction. Post-PD, they were asked their perceptions of PD effectiveness, recommended changes, and resources needed for effective curriculum implementation.

Teachers completed feedback surveys (see Appendix B) after each module. They provided their implementation plan, recommendations for improvement and best classroom practices, and reported on their implementation experience. All responses were anonymous to ensure protection of identities.

Weekly virtual check-ins were recorded, during which the program coordinator probed teachers' perceptions of their participation, challenges to participation, and how it impacted their classroom practice. They were asked about their perceptions of the hybrid format, and how it supported or challenged their PD. These recordings were transcribed and coded for analysis using interrater reliability among three researchers on the team.

Analysis

Recordings of weekly check-ins, informal meeting observations, and surveys were analyzed through thematic coding and the development of learning progressions to understand how the teachers' climate literacy and perceptions, self-efficacy, and CoP engagement developed throughout the PD. To analyze the qualitative data collected, we used the concept of learning progressions as a framework to guide our thinking about how the teachers' knowledge progressed over time (Schneider & Plasman, 2011). Applying the framework from Feldman et al. (2021), to document the progress of each participant over the course of the PD. Learning progressions are used to describe the process of how learning becomes increasingly sophisticated about a topic over time (Duschl et al., 2007; Heritage, 2008; Smith & Wiser, 2015). The use of teacher learning progressions helps illustrate the development of pedagogical and content knowledge, and role within CoPs related to the climate-centered PD.

To construct each progression, we examined years of experience, what they hoped to gain from the PD, change in climate literacy and self-efficacy, type of engagement in activities, level of implementation of curriculum, impact on practice, perception of the PD, and their role for their future participation in the program. We assessed the change in understanding of concepts and skills over time to construct the progressions as opposed to making a single summative assessment upon completion (Wilson, 2009). We mapped the progressions, constructed the progressions as grouped instances, and then reformulated them into narratives. This informed our understanding of the teachers' progressions as a trajectory of development rather than a series of discrete events (Heritage, 2008). Each teacher was evaluated as an active or peripheral member of the CoP, based on their participation (Baker & Beames, 2016). Inter-researcher reliability was ensured through consensus of the research team of each progression. Member checking occurred throughout via check-ins, interviews, and opportunities for feedback.

Results

The following themes were identified through the analysis:

1. Confidence and a result of increased understanding: Participants showed varying levels of initial knowledge and confidence in teaching climate change topics. Post-program, there was a noticeable increase in their climate content knowledge and confidence in teaching these topics effectively.
2. Perceptions of anthropogenic-induced climate change: Participants' beliefs about climate change evolved throughout the program, with most shifting towards a stronger belief that climate change is happening, caused by humans, and supported by scientific consensus. This shift also included increased concern about the impacts of climate change.
3. Impact on Teaching Practice: The program had a positive impact on participants' teaching practices. They reported feeling more prepared, using new teaching strategies, and integrating climate change topics effectively into their curriculum. However, some participants faced challenges in implementation due to time constraints or other barriers.

4. Role of Mentorship: Mentorship played a role in supporting participants' engagement and learning. Mentorship contributed to increased engagement and confidence among mentees.

The PD program yielded varied outcomes for participating teachers, highlighting differences in engagement, growth in climate literacy, shifts in climate change perceptions, and contributions to the CoP (see table 2). Participants entered the program with diverse teaching experiences and confidence levels regarding climate change instruction. The case studies examined below provide insights into how teacher engagement, prior experience, and active collaboration can influence the effectiveness of climate change education initiatives in professional development settings.

Table 2
Overview of Teacher Participants

Participant	Gender Identity	Years of Teaching Experience	Same School as Another Participant	CoP Participation Status	Pre-Test Score	Post-Test Score
Monica	Woman	16	Yes (with Rachel & Mark)	Active	69	77
Rachel	Woman	2	Yes (with Monica & Mark)	Active	62	77
Mark	Man	2	Yes (with Monica & Rachel)	Peripheral	62	62
Francine	Woman	4	No	Active	92	85
Georgina	Woman	7	Yes (with Ashley)	Peripheral	62	62
Ashley	Woman	1	Yes (with Georgina)	Peripheral	54	85
					M: 66.83 SD: 13.21	M: 74.67 SD: 10.44

Learning Progressions for Participants

Monica and Rachel (Mentor/Mentee) - taught at the same school. Monica had 16 years of teaching experience. Prior to participation, she implemented climate change curriculum with her students frequently and felt somewhat comfortable teaching those topics. Monica believed climate change was happening and caused by humans, that there was scientific consensus to support it, and was very concerned about the impacts.

Monica's climate content knowledge increased from 69% to 77%. Post-PD, she felt completely comfortable in her climate content knowledge and ability to teach climate topics. Monica maintained climate change was happening and caused by humans, there was scientific consensus to support it, and was very concerned about the impacts.

Monica participated in all opportunities for engagement, she attended the in-person kick-off day, all virtual weekly check-ins, completed the pre- and post-PD assessment, and all four requests for feedback during the program. She implemented lessons within one month of completion. Monica was a key contributor to community dialogue, she shared plans to implement activities, suggested improvements, commented on content accuracy, coached the team on technology barriers, requested clarification and material supply provision. She perceived herself as connected to the CoP, stating she engaged most through the weekly virtual check-ins. Monica was satisfied with the program and felt it was a success for her. She felt the program was well-organized, relevant to her classroom practice, and developed her teaching skills. She was evaluated as an *active* CoP member.

Rachel had two years of teaching experience. Prior to participation, she implemented climate change curriculum frequently and felt confident in her teaching ability for climate topics. Initially, Rachel was somewhat sure climate change was happening and caused by humans, that scientists disagreed about the phenomenon, and was somewhat concerned about the impacts. She hoped to "gain more hands-on activities to increase student engagement".

Rachel's climate content knowledge increased from 62% 77%. Post-PD, she felt completely comfortable in her climate content knowledge and ability to teach climate topics. Rachel's climate perceptions shifted from pre- to post-PD. Post-PD, Rachel believed climate change was happening and caused by humans, there was scientific consensus to support it, and was very concerned about the impacts.

Rachel also implemented lessons within one month of program completion. Rachel was a key contributor to community dialogue, she shared implementation plans, experienced implementing activities in her classroom, suggested activities that would enhance curriculum and classroom strategies, and perceived herself as connected to the CoP; stating weekly check-ins were most useful for connecting with the rest of the cohort. Rachel felt the program was well-organized, relevant to her classroom practice, and developed her teaching skills. She specifically requested a field experience for the students as a way of making local climate issues meaningful for and memorable to them. She was evaluated as an *active* CoP member.

Mark - was at the same school as Monica and Rachel and taught for two years. Prior to participation, he implemented climate change curriculum frequently and felt confident in his teaching ability on the topic. At the beginning of the program Mark was very sure climate change was happening, was caused by humans, and there was scientific consensus about the phenomenon but was not at all concerned about the impacts. Through the PD, Mark hoped to integrate more environmental science projects into his curriculum and to deepen students' knowledge of environmental issues and stewardship.

Mark's climate content knowledge remained the same, at 62%. Post-PD, he felt completely comfortable in his climate content knowledge and his ability to teach climate topics. Mark's climate concern shifted from not at all concerned to very concerned.

Mark taught at the same school as Monica and Rachel. However, he did not collaborate, share supplies, or participate in a peer mentor relationship. He was reserved and would often "see how went with their implementation" before fully implementing the curriculum. Mark only went to two of the PD sessions and largely participated as an observer with limited contributions to the greater community. While being an enthusiastic member of the community, he didn't actually complete any of the modules and had limited responses to emails, check-ins, and has yet to implement any parts of the curriculum with his students. Mark found the timing of the program to be difficult for his students due to the testing schedule his students were participating in. That said, all participating members experienced the same testing period within the same school district.

Mark perceived himself as connected to the CoP but could not describe how he interacted with the community. He had no plans for implementation, but stated the other CoP teachers at his school were developing a plan and a timeline. Mark was evaluated as a *peripheral* CoP member.

Francine - was the third *active* member of the CoP, while not as central as Monica and Rachel to the community, she maintained active participation over the course of the semester. Francine had four years prior teaching experience. Prior to the PD, Francine frequently taught climate change and felt confident teaching concepts of GCC. She hoped to gain ways to incorporate the 5E model with climate change content from the PD. Francine participated in university-led PD two years prior.

Francine's climate content knowledge decreased from 92% correct on a content assessment to 85% correct. Post-PD, she felt completely comfortable in her climate content knowledge and her ability to teach climate topics. Francine maintained climate change was happening and caused by humans, there was scientific consensus to support it, and was very concerned about the impacts.

She actively participated in the PD but went to one less session than the other *active* members of the group. When she did participate, she was able to share new insights, and new resources she created related to the curriculum with the rest of the group. In one instance, during a discussion of how to incorporate mangroves with life science, she created her own photosynthesis game and sent a photo to the rest of the CoP. She was also the only member of the PD who was considering an Environmental Action Plan with her students for Earth Day. While she wasn't able to complete it, she did have initiative to use the PD to inform her practice in real-time.

Francine responded "I don't know" when asked if she was connected to the CoP, and also when asked to describe how she interacted with the community. Despite her engagement level in the community, Francine felt only somewhat prepared to implement the curriculum in class. Post-PD feedback revealed she only somewhat agreed the program supported her PD in this content. The number of activities and the limited amount of time were her primary barriers. Nonetheless, Francine was evaluated as an *active* CoP member.

Georgina and Ashley (Mentor/Mentee) - participated from the same school. Pre-PD, Georgina infrequently taught climate change in her class and felt "neutral" in her comfort level teaching GCC. She was somewhat sure climate change was happening and was caused by humans, felt there was disagreement among scientists about climate issues, and was somewhat worried about the phenomenon. She hoped to gain "useful classroom resources to engage students in real life experiences."

Georgina's climate content knowledge remained constant at 62%. Post-PD, she felt completely comfortable in her climate content knowledge and her ability to teach climate topics. Georgina's perceptions of climate changed from pre- to post-PD: she was sure climate change was happening and caused by humans, there was scientific consensus to support it, and was very concerned about the impacts.

While Georgina did have seven years teaching experience, her time was split between teaching science and technology, so she did not have the opportunity to practice the implementation of the curriculum as much as others. Georgina perceived herself as a CoP member and stated she participated by sending emails asking questions, discussing failures and successes, sharing information, attending meetings. She served as an informal mentor to Ashley. Based on her actual participation however, she was evaluated as a *peripheral* CoP member.

Ashley was a new teacher, pre-PD, Ashley never taught climate change subjects in her class and felt "neutral" in her comfort level teaching them. At the beginning of the program Ashley believed climate change was happening and caused by humans, there was scientific consensus to support it, and was very concerned about the impacts. She hoped to gain expanded knowledge on climate change and new ways to incorporate real life situations in the classroom.

Ashley's climate content knowledge increased from 54% 85%. She maintained her perceptions on climate change as happening, important, and human caused. Post-PD, she felt completely comfortable in her climate content knowledge and in her ability to teach climate topics.

one meeting, she was able to document her experience implementing the sea level rise module and give feedback to the rest of the community, particularly timing tips. However, her participation with the rest of the PD beyond that meeting was limited. She did not attend half of the virtual check-ins, and did not implement the rest of the curriculum beyond the sea level rise module. Ashley perceived herself as a CoP participant, stating teachers in the cohort "were all in the same boat with students." Based on her actual participation however, Ashley was evaluated as a *peripheral* CoP member.

Discussion

The results of the program reveal diverse outcomes among the six participating teachers, influenced by variations in experience, climate knowledge, and levels of engagement. There were distinct differences in actual CoP participation level that divided the group. Three teachers (Monica, Rachel, Francine) were *active* participants and three were *peripheral* (Mark, Georgina, Ashley), based on their PD completion, virtual meeting attendance and level of participation, survey responses, and program implementation. Monica and Rachel, highly active in the CoP, saw meaningful gains in climate content knowledge, increased confidence, and readiness to implement the curriculum. Both reported feeling deeply connected to the CoP, actively contributing ideas and resources. In contrast, Mark and Ashley, who engaged minimally, showed limited progress; they were evaluated as peripheral members and faced challenges in curriculum implementation. Francine and Georgina had moderate participation and displayed steady, though varied, impacts on their teaching. Francine maintained high engagement, but felt only somewhat prepared to teach the curriculum, Georgina balanced her role in the CoP with limited classroom implementation.

None of the participants were evaluated as *core* CoP members. Core members typically plan, coordinate, and lead other members to engage them in the CoP shared enterprise (Borzillo et al., 2011). Sustainable WATERS, was a new university-school partnership, *core* CoP membership was catalyzed through a university program coordinator, who maintained constant contact and support for new CoP members. This was essential to program success, however, for long-term impact, core participation from teachers is necessary. In the future, there should be a focus on how *active* members can move to the *core* of periphery as they gain experience with the curriculum.

Findings suggest teachers' actual participation with the program did not align with perceptions of CoP participation. All teachers, except Francine, felt connected to the CoP. It should be noted Francine was the only teacher participant who did not have a peer teacher at her school. While Mark felt connected, he could not describe what he did to participate, and while he did have peer teachers at his school, he did not collaborate with them as often as they collaborated with each other.

Monica and Rachel were active CoP members; both demonstrated an increase in their climate content knowledge over the course of the PD. Francine was an *active* member of the CoP, but did not perceive herself that way. She was the only participant to demonstrate a decrease in content knowledge over the course of the program. *Peripheral* members, Mark and Georgina, demonstrated no change in their climate content knowledge. Ashley, another *peripheral* member, had the largest increase of the CoP participants. However, it should be noted, she began the program with the lowest score. Examining the progression of individuals, and as a whole, we suggest both actual and perceived participation in a CoP can affect development of content knowledge over time. This can have future impact on the design of virtual environments and potential research questions - which are most likely to support actual CoP participation, and which are most likely to foster a *perception* of connectedness?

Active CoP members, Monica and Francine's climate perceptions were both considered alarmist and anthropogenic induced prior to the PD. Rachel did not begin the program as concerned, although completed it that way. Her mentor/mentee relationship with Monica may have contributed to the change (McCauley & Guthrie, 2007). The relationship within the program highlights the impact of school-based teacher teams participating. According to Vescio et al., (2008) participants are more likely to persist and contribute to CoPs through co-learning and collaboration when participating with other teachers from their home school. Our findings suggest that while vCoPs provided an essential platform for continuity, virtual meetings present challenges in forming peer connections. This aligns with Jocius et al. (2022), who found that face-to-face interactions create more opportunities for spontaneous collaboration and relationship-building. Future CoPs should prioritize hybrid models that blend the flexibility of virtual engagement with the relationship-building benefits of in-person collaboration that are particularly important to novice teachers.

There was no discernible pattern to changes in self-efficacy related to CoP membership, perceived or actual among the participants. Pre-PD, two teachers (one active, one peripheral) reported high levels of confidence teaching with models and teaching climate change topics. Four teachers (two active, two peripheral) reported medium levels of confidence. Post-participation, all participants reported high levels of confidence teaching GCC, aligning with previous studies indicating the use of vCoPs for in-service teacher PD can increase self-efficacy through increased opportunity for social networking, collaboration, and overcoming barriers typical to implementation of in-person PD (Boling & Martin, 2005; Kirschner & Lai, 2007; Moore & Barab, 2002). Sustainable WATERS virtual and in-person interactions supported these practices and positively affected self-efficacies for all participants.

Years of teaching experience played an important role in shaping CoP participation and its impact on climate literacy. More experienced teachers, such as Monica, demonstrated greater confidence in engaging with the CoP, likely due to her prior pedagogical expertise and familiarity with PD settings. Conversely, early-career teachers such as Ashley and Mark often remained in peripheral roles, citing uncertainty in both climate content knowledge and instructional strategies. These findings suggest scaffold PD, including mentorship or differentiated pathways, may help support early-career teachers fully integrating into CoPs.

Community Participation and Virtual Tools

All teachers participated in the in-person kick off day and completed pre- and post-PD surveys. Only Monica completed all module feedback surveys. Weekly virtual check-in participation matched overall CoP participation: *active* members attended most frequently and contributed most to the conversation. *Peripheral* members attended 50% of the meetings and were less engaged during their attendance. For successful CoP, members develop their own ways of contributing and mechanisms for CoP development outside of program coordination.

Participants described their participation in the CoP through discussions with other teachers, collaborative planning or implementation, and virtual check-ins, which was the mechanism for communication and collaboration. No one described CoP interaction beyond the university team set up. Therefore, none of the teachers were evaluated as *core* members based on the literature. Because core members are typically schedulers and coordinators, we situated the core position and associated responsibilities within the university program coordinator. The expectation is as *active* members participation deepens; they will become *core* members of the CoP. Future follow-up with participants is needed to determine if this occurred after the completion of the PD.

All interactions described by teachers were ones in which they received immediate feedback and acknowledged their contribution in real time. Ekici (2018) found online CoPs boosted self-efficacy as participants were able to compare their experiences to others and recognize their problems and struggles were similar to what others experienced; similar to in-person CoP development, participants typically report meetings, curriculum training, and social events as most impactful to their belonging (Fernández et al., 2003; Lee, 2008; Puchner & Taylor, 2006). This suggests leveraging virtual tools that mimic in-person interactions and provide immediate feedback will have the greatest positive impact on CoP development. To achieve this, when survey tools are used to shape resources, practices, and norms, contributors should see the result of their feedback in community resources immediately.

Previous research supports the importance of groups of teachers from the same schools participating together for increased persistence and incorporation of PD into practice. vCoPs can increase teachers' self-efficacy by connecting novice and veteran teachers who may not otherwise get a chance to collaborate (Ghamrawi, 2022; Lieberman et al., 2011; Schwarzhaupt et al., 2021). Our program aimed to do this by partnering teachers from the same schools, however, future recruitment efforts should ensure that all participants have support from peer teachers. Mark and Francine were not partnered with another teacher, and were the only participants who could not describe the ways in which they interacted with the group. Georgina and Ashley were both evaluated as peripheral members, while Monica and Rachel were both identified as active. These relationships suggest that a strong mentor-mentee relationship can help facilitate growth and development of a new teacher and lead to active participation.

This study offers additional insights for designing hybrid vCoPs, particularly in the post-pandemic era, building on the work of Ghamrawi (2022). Variability in knowledge gains, engagement levels, and perceived CoP participation suggests that virtual and hybrid PDs must be designed to actively bridge participation gaps and tailor support for different participants.

Conclusion

This study explores the complex dynamics of climate literacy, and climate participation within a CoP framework. As with previous research, the differences in both actual and perceived CoP participation levels among the teacher participants, had implications for their climate content knowledge, self-efficacy, and engagement. Core CoP membership, characterized by planning, coordination, and leadership within the community, was facilitated primarily through the program coordinator, thus, crucial to fostering sustained engagement among future PD (Baker & Beames, 2016; Borzillo et al., 2011; Wenger et al., 2002). However, for long-term impact of climate change PD programs, it is clear that for teachers to transition from peripheral to core participation roles as they gain experience with the curriculum, ongoing support and mentorship is necessary, and PD programs should consider interventions that can bridge this gap, including pairing teachers from the same school to build in-person peer support, incorporating structured mentorship to guide early-career teachers, and leveraging hybrid models that blend virtual flexibility with school-based collaboration.

While most of the participants within the study reported feeling connected to the CoP, lack of perceived connectedness may be influenced by isolation from peer teachers at her school. This further supports the need for peer collaboration in fostering a sense of belonging and active engagement within CoPs, aligning with previous research and the importance of school-based teacher teams in sustaining participation.

The study revealed variations in climate content knowledge development among participants, with active members demonstrating increases in knowledge while some peripheral members showed no change or even decreases. These findings suggest differences between actual and perceived participation in shaping learning outcomes within CoPs. Additionally, mentor-mentee relationships highlight the potential for peer support to influence participants' climate perceptions and engagement levels, suggesting the need for structured support mechanisms within CoPs. While the development of mentor/mentee relationships was not intentional in the recruitment process, they were impactful on engagement. Future design should consider a nested CoP structure, in which each school has a predetermined core or active teacher to draw other peripheral teachers in and provide on-site support to positively influence teacher participation. As the program norms and practices evolve, program leaders should emphasize in-person collaboration within school environments and support expert teachers within a group to share expertise.

The role of virtual tools in facilitating CoP with virtual check-ins served as the primary mechanism for communication and collaboration among participants, the COVID-19 pandemic bolstered the case for virtual CoPs. Jocius et al. () uncovered unique impacts of online CoPs when the pandemic forced them to shift their face-to-face teacher PD to a virtual platform. Previous in-person sessions had high levels of engagement, so they worried "switching to a virtual experience might limit opportunities for community building" (p. 11). We had similar concerns as Sustainable WATERS was forced to shift modes. We found that interactions were initiated primarily by the university team, indicating a need for interventions to foster deeper engagement and collaboration beyond this framework. Leveraging virtual tools that mimic in-person interactions and provide immediate feedback may enhance CoP development and support participants' sense of belonging and self-efficacy.

Our findings suggest the connection between hybrid CoP participation, climate literacy, and teacher self-efficacy are useful tools. However, more research is needed to define how and with what specific tools this is fostered. That said, what happens at schools as they interact in-person may be more impactful than the CoP, as teachers' perceived CoP participation was aligned with school team participation. CoP impact hinges on teachers' abilities to contribute to and receive feedback in real time, therefore, hybrid and virtual programs should be designed with tools that enable that type of interaction.

Future Research

Overall, the study outlines the complex interactions between participation and climate literacy within CoPs. Future research should examine strategies for promoting active participation and mentorship within CoPs, as well as the effectiveness of virtual tools in fostering collaboration and knowledge sharing among participants. Additionally, efforts should be made to incorporate peer support structures and on-site collaboration within school environments to enhance teacher engagement and learning outcomes within CoPs.

Declaration of Interest Statement

No potential conflict of interest was reported by the authors.

Data availability statement

This study was approved by the University's Human Subjects' IRB. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to restrictions as information could compromise the privacy of research participants.

Supplemental online materials

https://sites.google.com/view/sustainablewaters

Appendix A:

Pre-Assessment: https://forms.gle/QEzaacGDmdwoTmZZ8

Appendix B:

Post-Assessment: https://forms.gle/8hJzMPg43nGTsiwD7

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