International Journal of Science and Mathematics Education
https://doi.org/10.1007/s10763-023-10421-7

Collective pedagogical content knowledge for teaching sustainable development

Annika Forsler[1] · **Pernilla Nilsson**[1] · **Susanne Walan**[2]

Received: 19 July 2023 / Accepted: 25 September 2023

Abstract

It is vital that upper secondary students gain a rich and deep knowledge of sustainability issues, as they will enter adulthood and working life within a short time. The students belong to a generation that will be intensely involved in managing several environmental issues to achieve sustainable development for our Earth. However, earlier research indicates that many teachers have a low self-efficacy for teaching sustainability issues. This study aimed to explore how science teacher teams in Swedish upper secondary schools can develop their knowledge and expertise in sustainable development (SD) through collective reflections with the support of the reflective tool Content Representation (CoRe). Science teachers' pedagogical content knowledge (PCK) development in teaching SD was examined. Twelve in-service science teachers participated in the study. The qualitative research design included semi-structured interviews and science teacher teams' collective meetings. The findings covered four themes about how the collective reflections with support of the CoRe tool stimulated teachers' PCK development: (1) creating structure and a focus for learning conversations, (2) modification of the teaching approach, (3) development of new content knowledge and pedagogical knowledge in SD, and (4) shared language to stimulate equal opportunities for students to learn SD. The conclusion is that with the support of CoRe, the teacher team's collective PCK in SD was developed; therefore, we recommend that decision-makers within the school system organize regular meetings in science teacher teams and introduce CoRe to the teachers.

Keywords Content representation · Pedagogical content knowledge · Sustainable development · Teacher knowledge

Extended author information available on the last page of the article

Published online: 04 November 2023

Introduction

Sustainable development (SD) is a continuously developing topic, and it is crucial for the future of our earth that young people have good knowledge of sustainability issues. However, as school students are continually affected by these issues, teaching SD can be perceived as demanding. Research indicates that many teachers have a low self-efficacy for teaching SD (Evans et al., 2016; Redman et al., 2021). To meet students' learning needs, as well as the rapidly changing society, teachers need to plan and conduct their teaching of SD in a way that is closer to the students' reality and everyday experiences. Therefore, it might be valuable for science teachers who teach SD to reflect systematically and collaboratively on their teaching and learn from each other's best practices. In 1986, Shulman introduced the concept of pedagogical content knowledge (PCK) to draw attention to the value of the special amalgam of content knowledge and knowledge of general pedagogy that a teacher needs to promote students' learning. PCK is a well-researched concept for teachers' professional knowledge and expertise (e.g. Hume et al., 2019; Loughran et al., 2012; Schmelzing et al., 2013). However, capturing teachers' knowledge is a complex issue involving an understanding of the key components that influence the teaching and learning process, as well as how these components are implemented in the classroom. To articulate, develop, and enhance teachers' PCK, Loughran and his colleagues (Loughran, Mulhall & Berry, 2004) introduced Content Representation (CoRe). The CoRe is a reflective tool designed to stimulate teachers to reflect on how to teach a specific science topic to promote students' learning. It raises teachers' awareness of teaching a certain content and engages them in reflection and decision-making around their enactment in the classrooms (Nilsson & Loughran, 2012). Research has demonstrated the effectiveness of the CoRe as a tool to capture and develop teachers' PCK (Bertram & Loughran, 2011; Hume & Berry, 2013; Kind, 2009; Phihlo & Rollnick, 2018; Rollnick et al., 2008; Van Driel & Berry, 2017).

SD includes three dimensions: environment, economy, and society (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2006). Those dimensions are present in the curriculum for the upper secondary school in Sweden. The curriculum is not governed in detail, which gives teachers the space and freedom to design the teaching. However, the curriculum states that teaching in science shall include different aspects of SD, such as resource utilization and resource distribution, carrying capacity of ecosystems, energy, climate, and human rights. The curriculum also states that the teaching should highlight how our way of life and work can be adapted to create sustainable development (Swedish National Agency for Education, 2023a, 2023b).

The main purpose of this study was to explore how science teacher teams in Swedish upper secondary schools can develop their knowledge and expertise in SD by working collectively with the support of the CoRe design. In the study, the CoRe tool was used to support teachers' collective reflections on their teaching of SD in upper secondary school. The research question that guided this investigation was as follows:

How can science teachers' PCK in SD be developed through collective reflections with the support of the CoRe tool?

As such, the outcomes of this study have the potential to provide valuable insights for science teacher teams regarding organizational structures and instructional approaches that facilitate the cultivation of their collective and personal knowledge for teaching SD. This, in turn, is expected to foster enhance student outcomes in the domain of SD.

Background

Collective knowledge formation

The notion that human beings acquire knowledge and enhance both their individual and collective understanding through social interaction and mutual learning is widely acknowledged and firmly established in the field of educational science. This concept can be traced back to the foundational theories of Vygotsky and Dewey, who explored the relationships among knowledge acquisition, learning processes, communication, and reflection extensively (Dewey, 1916/1966, 1933; Vygotsky, 1978; Wertsch, 1985). Wells (1999) explored collective knowledge formation, and in the model, *The spiral of knowing*, he presented some guiding principles. The model comprises a spiral with four quadrants: (1) experience, (2) information, (3) knowledge, and (4) understanding. The spiral consists of cycles that start with experience and end with understanding. Wells claimed that all individuals bring previous experiences to new situations, forming the basis for building new knowledge. New information is added from the environment, in the form of representations produced by others through speech and writing. The information is then integrated with the individuals' earlier beliefs based on interpretations of previous experiences. Such integration often involves a dialogical formation of knowledge with others to reach the end goal — understanding (Wells, 1999).

In recent years, collegial learning and collective knowledge formation have been developed as research fields, all of which have in common that collaboration and reflective conversations between teachers are important and have the potential to be successful. An example is the extensive research on professional learning communities (e.g. Dogan et al., 2016; Friedrichsen & Barnett, 2018; Voelkel & Chrispeels, 2017). Another example is the research on how participation in learning studies and lesson studies (Bravo & Cofré, 2016; Mårtensson, 2019; Mok & Park, 2022; Nilsson, 2014) influence teachers' science PCK. However, to our knowledge, there is, so far, little research about how science teachers develop PCK in teaching SD through reflections and collegial discussions. This article addresses a research gap identified by Park (2019), who emphasized that "little is known about how teachers' PCK evolves through interaction with other members of the profession" (p. 126). The aim of this article is to fill this gap by examining science teachers' collective PCK, specifically within the context of SD.

Collective PCK

PCK is a complex knowledge that teachers develop through experience over time and is about teaching a particular content in a specific way to improve students' understanding (Gess-Newsome, 2015). Teachers' PCK is often described as tacit and being complicated to capture and express. Despite its complexity, capturing and expressing PCK is essential for developing and improving teaching (Bertram & Loughran, 2011). Furthermore, as reported in several studies within science education that teachers' PCK affects students' learning (e.g. Alonzo & Kim, 2016; Gess-Newsome et al., 2019; Keller et al., 2017; Rollnick et al., 2008), and capturing and defining PCK is valuable for teaching. Since Shulman's (1986) introduction, the concept of PCK has developed a lot over the years. The latest model, which international researchers in science education involved in PCK have agreed upon, is the Refined Consensus Model (RCM) (Hume et al., 2019). The RCM has three distinct realms of PCK: enacted PCK (ePCK), personal PCK (pPCK), and collective PCK (cPCK). When teachers plan, perform, and reflect on the teaching, they utilize ePCK. A teacher's pPCK is the cumulative PCK of an individual teacher that contains the reflection of the teacher's teaching and learning experiences. Many processes are combined in developing pPCK, such as formal education, teaching experiences, and professional sharing and reflection. The cPCK refers to PCK knowledge that is held collectively. cPCK can range in size from discipline-specific to topic-specific to concept-specific. Knowledge exchange operates between the realms of PCK. Except for the three realms of PCK, RCM also includes the aspect of learning context and is held together by professional knowledge bases such as content knowledge, pedagogical knowledge of students, curricular knowledge, and assessment knowledge (Carlson et al., 2019).

This study primarily investigates the interplay between pPCK and cPCK, focusing on their knowledge exchange and potential development. Park (2019) posited that when teachers engage in collaborative discussions to collectively learn from each other by sharing their pPCK, this process contributes to the development of both pPCK and cPCK:

> A significant insight to research on teachers' PCK for science teaching drawn from the RCM is the importance of professional communities and shared expertise to the development of PCK. This insight implies collaborative interactions among teachers become essential for the development of a teacher's PCK for science teaching because those interactions encourage teachers to make their knowledge public and understood by colleagues (Park, 2019, p. 128).

Earlier research concerning development of cPCK

As described above, there is research on how teachers develop their PCK in collegial settings, but to our knowledge, research which uses RCM for identifying teachers'

cPCK is limited. However, Ellebæk (2021) aimed to provide insights into cPCK-development, perceived by teachers as narratives. The findings showed that local collegial learning conversations and significant colleagues influenced cPCK-development. Furthermore, Buldu and Buldu (2021) investigated pre-service early childhood teachers' cPCK and pPCK in scientific processes. The case study included 36 teachers who, at the start of a 13-week science-focused course, had their prior knowledge of scientific processes determined individually through a form and an interview. At the end of the case study, post-interviews and the form were applied again; moreover, the teachers completed a CoRe. The CoRe was completed collectively based on their science activities, designed at the end of the science course. The findings showed that the teachers' pPCK and cPCK development was supported by the science-focused course and the collaborative CoRe design. In addition, Mok and Park (2022) studied cPCK-development through a case study performed as a lesson study. The research explored how a lesson study might help primary teachers develop their cPCK in teaching mathematics. The findings showed that the lesson study led to cPCK-development, as the interactions between the teachers provided a deep reflection that consequently clarified the mathematic concepts. Instead of a lesson study, Cooper et al. (2022) used a reading group in their qualitative research to examine the development of pPCK and cPCK for science teachers. The results revealed that participation in the reading group developed the teachers' pPCK and cPCK by (a) creating conditions for meaningful links between theory and practice, (b) encouraging the adoption of an inquiry stance as a means for purposive engagement with professional knowledge, and (c) initiating a transformation in the teachers' contemporary understandings of science and science education.

Methods

Local context and participants

In Sweden, students between 16 and 19 years old attend upper secondary school, and almost all students learn science. The national curriculum delineates the interdisciplinary nature of the science subject. The science curriculum substantially emphasizes SD content (Swedish National Agency for Education, 2023b).

Twelve in-service science teachers participated in the study: six women and six men. The teachers worked in two upper secondary schools in two different municipalities in mid-Sweden. Seven of the twelve teachers worked in one school and were organized into one teacher team concerning the science subject. The other five teachers worked in the other school and were also organized into a teacher team concerning the subject of science. The teachers in both teacher teams knew each other and had meetings a few times per year. The meeting agenda in both teacher teams usually concerned administrative tasks, for example, book purchases, instead of learning conversations about teaching.

CoRe as a tool to stimulate reflection

In this study, the CoRe design was used to stimulate teachers' collective reflections on their teaching of SD. The CoRe was developed by Loughran et al., (2004) to meet the need for an articulated PCK. Cooper et al. (2015) described a teacher's PCK as a tacit form of teachers' professional knowledge that was usually subject-, person-, and context-specific. According to Cooper et al. (2015), the CoRe was developed to capture, document, and portray this knowledge, so that it might be useful from a teacher's point of view (Cooper et al., 2015). Loughran et al. (2004) believed that CoRe would create opportunities for sharing this knowledge within the professional community in a useful and valuable way for science teachers and researchers.

The tool's design implies that science teachers articulate some Big Ideas in a content area and respond to eight reflective questions for each Big Idea. The Big Ideas represent the central idea and concepts within a particular science content area. (In this study, the given content area was SD). The reflective questions cover different aspects that are important for teaching a particular content to a particular student group (see Figure 1).

Many science education researchers have used CoRe as a research tool for collecting data. They describe CoRe as successful since it clarifies and makes different visible dimensions of and connections between knowledge of content, teaching, and learning about a specific subject area in science (Bertram & Loughran, 2011; Hume & Berry, 2013; Kind, 2009; Mazibe et al., 2020; Nilsson & Loughran, 2012; Nilsson & Karlsson, 2019).

	Big Idea 1	Big Idea 2	Etc.
What do you intend the students to learn about this idea?			
Why is it important for students to know this?			
What else do you know about this idea (that you do not intend students to know yet)?			
What are the difficulties/limitations connected with teaching this idea?			
What is your knowledge about students' thinking that influences your teaching of these ideas?			
Are there any other factors that influence your teaching of these ideas?			
What are your teaching procedures (and particular reasons for using these to engage with this idea)?			
Specific ways of ascertaining students' understanding or confusion around this idea (include a likely range of responses).			

Fig. 1 The content representation template (Bertram & Loughran, 2011, p. 1029; Loughran et al., 2004, p. 376)

Overall research design and data collection

The research design contained different activities (see Figure 2). First, the teachers completed a CoRe concerning SD individually and sent it to the first author. As a preparation, all the teachers were similarly informed about the CoRe tool. The first author had an interview with each teacher, which encompassed an in-depth discussion about their CoRe. Thereafter, the first collective meeting was held for each school's science teacher team. In this meeting, the teachers were instructed to

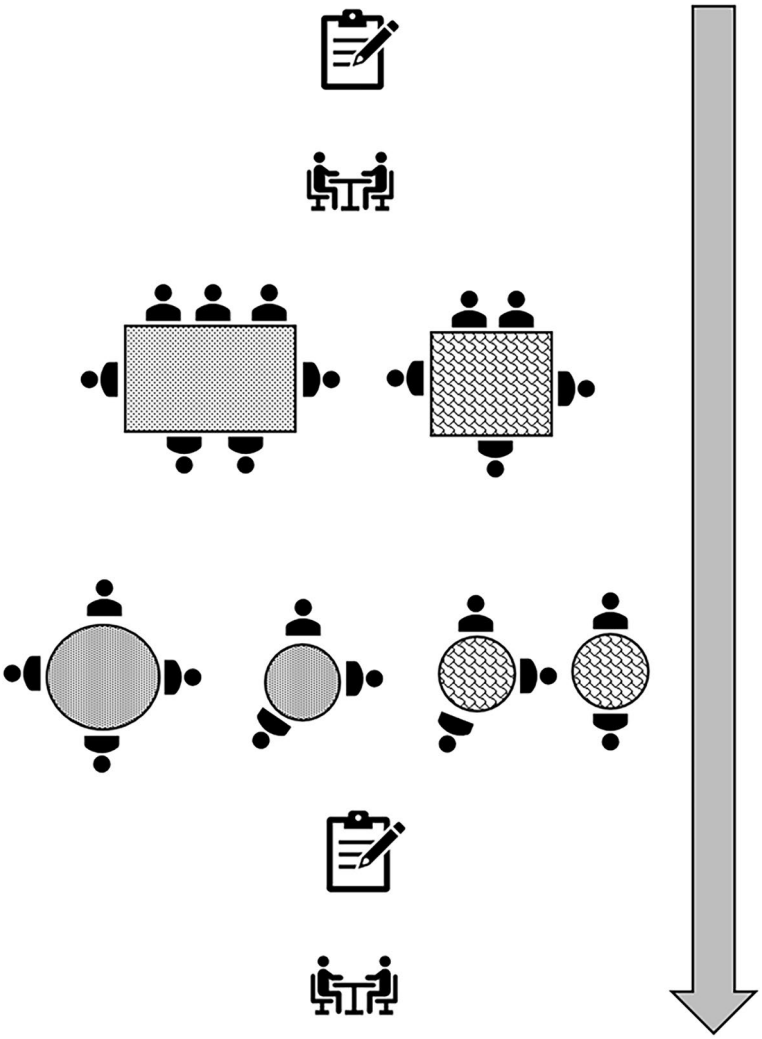

Fig. 2 The figure presents the six steps in the research design: (1) individual CoRe, (2) interview, (3) first collective meeting for each school's science teacher team, (4) second collective meeting, (5) revised Core, and (6) interview

present their Big Ideas and reflect together on the similarities and differences. In the second collective meeting, the teacher teams were divided into smaller groups, and the teachers were instructed to talk about one Big Idea similar to all the teachers in that group. They told each other what they had written in their CoRe prompts for that specific Big Idea, and they were instructed to reflect together and learn from each other. After the meeting, the teachers were asked to revise their CoRe individually and send it to the first author. In the final step of the research design, the first author had a semi-structured interview for approximately 60 min with each teacher. In the interview, the teachers described their revisions in their CoRe and shared their perspectives and experiences regarding the research question.

Throughout the various stages in the research design, the teachers engaged in teaching related to their respective CoRe. All interviews and collective meetings were audio recorded. The presented findings in this article primarily draw upon data obtained from the final interview session.

Data analysis

All activities were held in the teachers' mother tongue, Swedish. The last interviews for each teacher were transcribed verbatim. A thematic analysis was performed according to Braun and Clarke's (2006) description. In the first phase of the analysis, the first author read and re-read the data and noted the initial ideas. In the second phase, preliminary interesting data features were coded systematically, and relevant data were collated into each code. In the third phase, codes were collated into potential themes, and all data pertinent to each potential theme was gathered. Subsequently, in the final step, all authors discussed and reviewed the themes and generated clear labels. Excerpts were chosen to present the findings and were translated into English.

Ethical considerations

The handling of the data followed the ethical guidelines of scientific research recommended by The Swedish Research Council (2017). Informed consent was obtained from all subjects involved in the study. In the findings presented in this article, the teachers have been given pseudonyms to keep their identities anonymous.

Findings

The findings showed a knowledge exchange between pPCK and cPCK and vice versa, which allowed PCK development for teaching SD. Four themes were identified on how the collective reflections with support of the CoRe tool stimulated teachers' PCK development: (1) creating structure and a focus for learning conversations, (2) modification of the teaching approach, (3) development of new content knowledge and pedagogical knowledge in SD, and (4) shared language to stimulate equal opportunities for students to learn SD. The following sections address the four themes.

Creating structure and a focus for learning conversations

The first theme related to the CoRe as a supportive tool, both for the teachers themselves and together with teacher colleagues. None of the twelve participating teachers had previously encountered the CoRe tool. First, the findings showed how the CoRe tool had supported the teachers in capturing and expressing their pPCK in SD. As teachers' knowledge is often tacit, the CoRe helped the teachers to make their knowledge explicit and share it with their colleagues. Elliot and Charlotte expressed that CoRe was helpful and that it will make it easier to share their good teaching practices with their colleagues.

> Elliot: I have missed that you cannot always make explicit in words what you do. I cannot say why I do everything. And maybe it is good enough when I am alone, but not in a meeting with colleagues.
> Charlotte: This CoRe helped me because that is how it looks inside my head, but I have had such a hard time sharing it with someone else before.

The teachers expressed that the CoRe was helpful because it created a structure and a focus in the learning conversations about teaching SD. John stated that the CoRe made it easier to explain his demarcations in teaching SD to his colleagues:

> John: You can also explain to others what is important and what is not important. It is the understanding that I want. With the CoRe, you can be more specific or clear about what you want to present and what you do not want to show.

Charlotte, Sara, and Elliot expressed that CoRe gave them a structure when they had discussions, which was valuable for the science teacher team. Structuring their ideas within their CoRe helped them to focus on the particular Big Ideas and the important content of SD for the students to learn.

> Charlotte: With this project, we have come a lot further than we have ever done before. I feel that we can use this as a template when having a conversation.
> Sara: It is a good way for us teachers to structure our discussions about a subject area. Because if we only talk about SD, it is so easy to slip away and talk about different things without noticing it, but with CoRe, it becomes more accessible because it provides a structure from which we can talk.
> Elliot: It is good to have a template like the CoRe because then you stick to the topic when you talk.

Consequently, in the first theme, the CoRe was a support to capture and express the teachers' pPCK in SD. The CoRe-tool also created a structure and a focus in the learning conversations. This made sharing knowledge between colleagues successful, which, in turn, created opportunities for developing cPCK.

Modification of the teaching approach

The second theme showed that teachers can be influenced by other teachers in such a way that they modify their approach to their teaching in SD. Charlotte

expressed that she, thanks to the collective meetings, realized that she wanted to modify her teaching so that all three dimensions of SD (the environmental, social, and economic dimensions) are discussed in relation to eutrophication in her teaching.

> Charlotte: I have been more into teaching the students about eutrophication and the details of that and why it is so unique in the Baltic Sea. To make it a little more connected to the three dimensions in SD and highlight that complexity (that it is not only the biological problem that causes it to be the way it is), I will add some questions that the students can discuss to help them see that complexity. I feel I was not helping the students with those dimensions in that way before.

Jim and Jessica discussed teaching about global warming linked to SD in two different collective meetings. Jim gained new perspectives from the collective meeting regarding the students' climate anxiety and revised his CoRe.

> Jim: I have added in my revised CoRe: students who have climate anxiety. I probably thought about it a bit before but did not write it down, and it was something that the other teachers had brought up. I wanted to include that in my CoRe, as you have to respond to it in some way in the teaching.

Jessica received support from her colleague regarding the nuance of the threat of global warming in her teaching. She did not want to scare the students, but she wanted them to understand the seriousness of global warming.

> Jessica: We are talking about if it is 40 degrees Celsius in heat waves, people can die, and in Spain and France, it has already started to happen. We have talked about that, but not the worst. I am also not saying to the students that people in Bangladesh might drown or people in Africa might get heat stroke and die. That is not what I am saying, either. [She makes the comparison with her colleague].

While comparing his first and second CoRe, Robin reflected on the impact that his work with the CoRe and the collegial reflections, which led to his revised CoRe, will have on his future teaching in SD.

> Robin: My first CoRe and my revised CoRe may affect the teaching because you become a little more aware of what you do and reflect more broadly on these questions; why must the students know exactly this? It becomes more concrete when you write it down and revise what you have written down; it even becomes more tangible. What do I want them to learn about this particular area, and what do I know more about it that the students do not need to learn right now? You become more aware when planning and teaching.

Consequently, in the second theme, the findings stated that learning conversations in SD with the support of CoRe benefited the knowledge exchange between

the pPCK and cPCK and vice versa, regarding the modification of teachers' approach in teaching in SD.

Development of new content knowledge and pedagogical knowledge in SD

The third theme proved that the collective meetings gave the opportunities for the teachers to develop their pPCK. Jacob described the opportunity with the collective meetings to provide each other with new content knowledge concerning SD.

> Jacob: It may be teachers who shed light on something that you had not thought of before. And then a teacher may need to read up on specific content. In that way, the students benefit. It is a development for teachers to perhaps broaden their content knowledge with the help of others. In this way, there will be a broadened content competence.

Tom described that he revised his CoRe concerning his teaching about energy through the inspiration from his colleagues in the collective meeting. He expressed a desire to renew his teaching due to the collective meeting.

> Tom: It was the Big Idea of "how energy is produced" that we talked about at the meeting. On the first question: what do I expect the students to learn? I added what opportunities and limitations they will face. I had not even thought about that aspect when sitting alone. There is, of course, a large part that will affect the students; that students learn more about what future electricity production might look like and which future energy sources might become available. Because it is a change now, a lot is happening, so of course, they need to know the possibilities and limitations there. That is why I added it.

Emma described the opportunity with the collective meetings concerning teachers to provide each other with new pedagogical knowledge concerning SD. She exemplified this with a revision she made in her CoRe after the collective meeting concerning eutrophication. Her colleagues helped her to reframe her teaching to make the chemical elements more concrete for the students.

> Emma: Regarding the question of what I expect the students to learn about this Big Idea, my colleague talked about the different chemical elements: carbon, nitrogen, oxygen, and sulfur. In my teaching I will introduce the students to the chemical elements and to make them more concrete. Why do we need these chemical elements or nutrients? I think it would be more apparent to the students because I always talk about nitrogen and phosphorus, as they are central to eutrophication and algal blooms. So that was my thought; this is a clarification I took with me from the meeting.

Consequently, in the third theme, the findings stated that learning conversations in SD with the support of CoRe benefited the knowledge exchange between the cPCK and pPCK, both regarding specific content knowledge and pedagogical knowledge concerning SD.

Shared language to stimulate equal opportunities for students to learn SD

The fourth theme demonstrated how the teachers' collegial reflections strengthened the ability of teachers to stimulate equal opportunities for students to learn SD. For example, the learning conversations about teaching SD strengthened the science teacher team in that they came to develop a "shared language" in relation to their teaching of SD.

> Emelie: Many times, when we have science teacher team meetings, there will be practical things we have to solve and so on. But discussing the what, how, and why of teaching is very valuable, and this was an excellent form and way of doing it. It inspired me to discuss with colleagues and hear what they thought and what they included in their CoRe. The school is changing, and the students do not look the same now as they did 15 years ago. I think this project has been great!
> Denise: I think this project has been very positive, and I learned a lot. That we have done this together in the science teacher team can contribute to our thinking in a new way and help us focus more on aspects that are important for teaching and learning SD.
> Elliot: I feel that we have started to talk more to each other because we have started to talk more about what and why we do certain things.
> Charlotte: It has given us something in the science teacher team. Knowing what will come out of it is not clear. It could become something more, a shared language among us teachers, a way of talking.

The teachers' reflections indicated how their collective learning conversations helped them become more aware of their own and their colleagues' teaching of SD in relation to students' learning. Their shared language helped them make explicit aspects in their practice and share it with others. When engaging in discussions around their CoRe design, they provided each other with teaching resources and ways of dealing with the content of SD. The way the teachers shared their personal experiences and their knowledge, as expressed in their CoRe, indicated a development of cPCK among the teacher team.

Sara emphasized that reflecting through the CoRe in a collective setting enables awareness and consensus in teaching SD.

> Sara: We can compare with each other, and then we may get a better quality because we have been inspired by each other and develop a consensus about what we teach and how.

At the first collective meeting, when the teachers were sharing their Big Ideas, it was discovered in the science teacher team that all of Jim's colleagues did not include global warming in their CoRe. That surprised Jim: he reasoned about the importance of providing the students with the same opportunities for learning.

> Jim: For me, global warming has always been the most critical aspect to address in SD. Of course, it might differ between teachers, but in my world, it is good to have a consensus. At least, it is good to be aware of what others are

> teaching. It is perhaps a least common denominator: that it is possible to do this in other ways as well, my way is not the only way. There are other ways to focus or prioritize what is important. I believe this kind of awareness and consensus is essential for achieving quality teaching. It will be a way to ensure the quality of teaching. With these discussions, we somehow ensure a reflection of the content being taught. If everyone else brings this up, why don't I? It is important, and I hope we continue to reflect on these issues more. I think we could use this model to achieve a consensus in the future. It is vital that students are provided with the same learning opportunities. I think it would improve teaching, leading to better results.

Tom was more concrete as he wanted to reduce differences in the selection of teaching content and, as such, provide equal learning opportunities for students by producing a CoRe with his colleagues.

Tom: We have said we would like to sit down and produce a joint CoRe.

Finally, the teachers wanted to continue with learning conversations based on the CoRe tool in the future.

> Emma: If I had the choice, I would like to have more opportunities with the science teacher team to continue to work like this.

Consequently, in the fourth theme, the findings indicated that learning conversations with the CoRe-tool in science teacher teams can develop teachers' awareness about the what, how, and why of teaching SD in upper secondary school. The teachers claimed that the learning conversations about teaching SD had strengthened the science teacher team, which may lead to improved opportunities for students to learn SD. The findings showed that the knowledge exchange between pPCK and cPCK and vice versa allowed the PCK development for teaching SD.

Discussion

According to UNESCO (2018), teaching SD should (1) provide the students with knowledge about the ever-changing planetary conditions and environmental issues as well as their risks and causes. The teaching should (2) empower students to make informed decisions and to take responsible actions for environmental integrity, economic viability, and for the society for both the present and future generations. Finally, teaching should (3) prepare students to cope with and find solutions to problems that threaten the planet's sustainability and social systems. These three recommendations conform with the guideline for teaching SD in the Swedish curriculum (Swedish National Agency for Education, 2023a, 2023b). Despite this, the curriculum gives teachers the freedom to design the teaching based on their own interests and knowledge, which can result in students not being provided with equal opportunities to learn about SD. Research states that it requires a complex approach to teaching in order to empower students with the necessary competencies to deal with and act regarding the complexity of sustainability issues (Breiting & Mogensen, 1999; Sass et al., 2020). Teaching SD is a challenge connected to complex educational

principles, such as holism and action orientation (Sinakou et al., 2019). As sustainability issues are wicked problems characterized by high complexity, uncertainty, and value conflicts, they are complex for teachers to manage (Rittel & Webber, 1973). Teaching SD can be emotional, as some students may have climate anxiety and other concerns linked to SD. These emotions can cause tensions in the classroom (Ojala, 2015; Ojala et al., 2021), as SD is characterized by wicked problems for which there are no simple solutions. The students belong to a generation that will be involved in managing several environmental issues to achieve SD, and a deep understanding of how the rapidly changing society influences the earth is important. To develop students' engagement in and understanding of SD issues, the role of the teacher is crucial. Furthermore, as research indicates that many teachers have a low self-efficacy for teaching SD (Evans et al., 2016; Redman et al., 2021), teachers need well-structured learning opportunities concerning the teaching and learning of SD. This study aimed to investigate how such learning opportunities can be designed in light of the theoretical framework of PCK. The research question was: How can science teachers' PCK in SD be developed through collective reflections with the support of the CoRe tool?

The findings showed a knowledge exchange between pPCK and cPCK and vice versa, which allowed PCK development for teaching SD. The teachers viewed CoRe as an excellent tool for capturing and expressing pPCK in SD and felt that it provided a structure and focus for the science teacher teams. This result is consistent with previous research which has also shown that CoRe has good potential to support teachers in making the tacit PCK explicit and possible to share with others (Bertram & Loughran, 2011; Hume & Berry, 2013; Kind, 2009; Mazibe et al., 2020; Nilsson & Loughran, 2012; Nilsson & Karlsson, 2019). The findings also showed that using CoRe to structure and support learning conversations meant that the teachers' pPCK was strengthened, as they gained more content knowledge in SD and developed new pedagogical strategies for teaching SD in order to meet students' learning needs. The exchange of knowledge that took place in the discussions in the science teacher teams also meant that teachers, to some extent, modified their approaches to teaching SD. Finally, the findings showed that the learning conversations were not only rewarding for the teachers themselves and their pPCK, but also for the group as such. It thus strengthened cPCK in the science teacher team and created conditions for equal opportunities for students to learn SD. The findings relate to Wells' theory of collective knowledge formation and his model of the spiral of knowing (Wells, 1999). Similar to Wells' model, the teachers have experience and knowledge (pPCK) about teaching SD when they started the learning conversations with their colleagues in the science teacher team. This knowledge served as a base for building new knowledge. In the conversation with colleagues, where CoRe served as a support for identifying and being able to express their pPCK, teachers shared their pPCK, and new knowledge was formed (i.e. cPCK). The new information became integrated with the teacher's previous pPCK in SD. Such integration involved a dialogical formation of knowledge with others (cPCK), resulting in a new and richer knowledge for teaching SD, congruent with Wells' theory.

According to RCM (Carlson et al., 2019), the two realms of PCK (pPCK and cPCK) can be developed continuously when exchanging knowledge. The findings

of this study provide empirical evidence for Park's (2019) argument that shared expertise is necessary for the development of PCK. The findings from this study also align with previous research, such as Ellebæk (2021), who concluded that learning conversations influenced cPCK development.

Similar to this study, previous research has focused on the realms of pPCK and cPCK and the knowledge exchange between and development of cPCK (e.g. Buldu & Buldu, 2021; Cooper et al., 2022). However, research on cPCK is still sparse, and this study contributes to research on the realm of cPCK. We claim that research on cPCK is an important complement to the research in collective knowledge formation, such as professional learning communities (e.g. Dogan et al., 2016; Friedrichsen & Barnett, 2018; Voelkel & Chrispeels, 2017).

Implications

Based on the findings of this study, we strongly recommend that principals and other decision-makers within the school system organize regular meetings in science teacher teams. We also want to advise science teachers to use CoRe with colleagues in a structured way in learning conversations, as it has a great potential to support and develop their teaching in SD. This would benefit the teaching quality and equal opportunities for students to learn. When the teachers' pPCK in SD and the teacher teams' cPCK in SD become developed, it is assumed to lead to increased knowledge, skills, and abilities linked to SD for the students. Consequently, this factor is expected to contribute modestly, yet effectively, to the pursuit of SD on Earth.

Acknowledgements We would like to thank all the participating teachers.

Author contribution All authors contributed to the study's conception and design. Annika Forsler performed the data collection. The analysis was performed by Annika Forsler, Pernilla Nilsson, and Susanne Walan. The first draft of the manuscript was written by Annika Forsler, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by Halmstad University. This work was supported by the Swedish Research Council [2019-04419].

Declarations

Competing interests The authors declare no competing interests.

References

Alonzo, A. C., & Kim, J. (2016). Declarative and dynamic pedagogical content knowledge as elicited through two video-based interview methods. *Journal of Research in Science Teaching, 53*(8), 1259–1286. https://doi.org/10.1002/tea.21271

Bertram, A., & Loughran, J. (2011). Science teachers' views on CoRes and PaP-eRs as a framework for articulating and developing pedagogical content knowledge. *Research in Science Education, 42*, 1027–1047. https://doi.org/10.1007/s11165-011-9227-4

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bravo, P., & Cofré, H. (2016). Developing biology teachers' pedagogical content knowledge through learning study: The case of teaching human evolution. *International Journal of Science Education, 38*(16), 2500–2527. https://doi.org/10.1080/09500693.2016.1249983

Breiting, S., & Mogensen, F. (1999). Action competence and environmental education. *Cambridge Journal of Education, 29*(3), 349–353. https://doi.org/10.1080/0305764990290305

Buldu, E., & Buldu, M. (2021). Investigating pre-service early childhood teachers' cPCK and pPCK on the knowledge used in scientific process through CoRe. *SAGE Open, 11*(2). https://doi.org/10.1177/21582440211025564

Carlson, J., Daehler, K. R., Alonzo, A. C., Barendsen, E., Berry, A., Borowski, A., Carpendale, J., Chan, K. K. H., Cooper, R., Friedrichsen, P., Gess-Newsome, J., Henze-Rietveld, I., Hume, A., Kirschner, S., Liepertz, S., Loughran, J., Mavhunga, E., Neumann, K., Nilsson, P., & Wilson, C. D. (2019). The refined consensus model of pedagogical content knowledge in science education. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 77–94). Springer. https://doi.org/10.1007/978-981-13-5898-2

Cooper, R., Loughran, J., & Berry, A. (2015). Science teachers' PCK: Understanding sophisticated practice. In A. Berry, P. J. Friedrichsen, & J. J. Loughran (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 60–74). Routledge.

Cooper, R., Fitzgerald, A., & Carpendale, J. (2022). A reading group for science educators: An approach for developing personal and collective pedagogical content knowledge in science education. *International Journal of Science and Mathematics Education, 20*, 117–139. https://doi.org/10.1007/s107-022-10260-y

Dewey, J. (1916/1966). *Democracy and education. An introduction to the philosophy of education*. Free Press.

Dewey, J. (1933). How we think: A restatement of the relation of reflective thinking to the educative process.

Dogan, S., Pringle, R., & Mesa, J. (2016). The impacts of professional learning communities on science teachers' knowledge, practice and student learning: A review. *Professional Development in Education, 42*(4), 569–588. https://doi.org/10.1080/19415257.2015.1065899

Ellebæk, J. J. (2021). Primary science teachers' narratives about significant colleagues in light of collective PCK. *International Journal of Science Education, 43*(10), 1167–1684. https://doi.org/10.1080/09500693.2021.1927235

Evans, N. S., Tomas, L., & Woods, C. (2016). Impact of sustainability pedagogies on pre-service teachers' self-efficacy. *Journal of Education for Sustainable Development, 10*(2), 243–261. https://doi.org/10.1177/0973408216650953

Friedrichsen, P. J., & Barnett, E. (2018). Negotiating the meaning of Next Generation Science Standards in secondary biology teacher professional learning community. *Journal of Research in Science Teaching, 55*, 999–1025. https://doi.org/10.1002/tea.21472

Gess-Newsome, J. (2015). A model of teacher professional knowledge and skill including PCK: Results of the thinking from the PCK summit. In A. Berry, P. J. Friedrichsen, & J. Loughran (Eds.), *Re-examining Pedagogical Content Knowledge in Science Education* (pp. 28–42). Routledge.

Gess-Newsome, J., Taylor, J. A., Carlson, J., Gardner, A. L., Wilson, C. D., & Stuhlsatz, M. A. M. (2019). Teacher pedagogical content knowledge, practice, and student achievement. *International Journal of Science Education., 41*(7), 944–963. https://doi.org/10.1080/09500693.2016.1265158

Hume, A., & Berry, A. (2013). Enhancing the practicum experience for pre-service chemistry teachers through collaborative CoRe design with mentor teachers. *Research in Science Education, 43*, 2107–2136. https://doi.org/10.1007/s11165-012-9346-6

Hume, A., Cooper, R., & Borowski, A. (2019). *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science*. Springer. https://doi.org/10.1007/978-981-13-5898-2

Keller, M. M., Neumann, K., & Fischer, H. E. (2017). The impact of physics teachers' pedagogical content knowledge and motivation on students' achievement and interest. *Journal of Research in Science Teaching, 54*(5), 586–614. https://doi.org/10.1002/tea.21378

Kind, V. (2009). Pedagogical content knowledge in science education: Perspectives and potential for progress. *Studies in Science Education, 45*(2), 169–204. https://doi.org/10.1080/03057260903142285

Loughran, J., Mulhall, P., & Berry, A. (2004). In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. *Journal of Research in Science Teaching, 41*(4), 370–391. https://doi.org/10.1002/tea.20007

Loughran, J., Berry, A. K., & Mulhall, P. (2012). *Understanding and developing science teachers' pedagogical content knowledge*. Sense Publishers.

Mårtensson, P. (2019). Learning to see distinctions through learning studies. Critical aspects as an example of pedagogical content knowledge. *International Journal for Lesson and Learning Studies, 8*(3), 196–211. https://doi.org/10.1108/IJLLS-10-2018-0069

Mazibe, E. N., Coetzee, C., & Gaigher, E. (2020). A comparison between reported and enacted pedagogical content knowledge (PCK) about graphs of motion. *Research in Science Education, 50*(3), 941–964. https://doi.org/10.1007/s11165-018-9718-7

Mok, I. A. C., & Park, Y. H. (2022). Integrating research into practice: The growth of collective pedagogical content knowledge for primary mathematics via lesson study. *Asian Journal for Mathematics Education, 1*(2), 187–203. https://doi.org/10.1177/27527263221105111

Nilsson, P. (2014). When teaching makes a difference: Developing science teachers' pedagogical content knowledge through learning study. *International Journal of Science Education, 36*(11), 1794–1814. https://doi.org/10.1080/09500693.2013.879621

Nilsson, P., & Karlsson, G. (2019). Capturing student teachers' pedagogical content knowledge (PCK) using CoRes and digital technology. *International Journal of Science Education, 41*(4), 419–447. https://doi.org/10.1080/09500693.2018.1551642

Nilsson, P., & Loughran, J. (2012). Exploring the development of pre-service science elementary teachers' pedagogical content knowledge. *Journal of Science Teacher Education, 23*(7), 699–721. https://doi.org/10.1007/s10972-011-9239-y

Ojala, M. (2015). Hope in the face of climate change: Associations with environmental engagement and student perceptions of teachers' emotion communication style and future orientation. *The Journal of Environmental Education, 46*(3), 133–148. https://doi.org/10.1080/00958964.2015.1021662

Ojala, M., Cunsolo, A., Ogunbode, C. A., & Middleton, J. (2021). Anxiety, worry, and grief in a time of environmental and climate crisis A narrative review. *Annual Review of Environment and Resources, 46*(1), 35–58. https://doi.org/10.1146/annurev-environ-012220-022716

Park, S. (2019). Reconciliation between the refined consensus model of PCK and extant PCK models for advancing PCK research in science. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 117–128). Springer.

Phihlo, P. M., & Rollnick, M. (2018). Exploring the development of novice unqualified graduate teachers' topic-specific PCK in teaching the particulate nature of matter in South Africa's classrooms. *International Journal of Science Education, 40*(7), 742–770. https://doi.org/10.1080/09500693.2018.1446569

Redman, E., Murphy, C., Mancilla Mendez, Y., Mallon, B., Kater-Wettstaedt, L., Barth, M., Ortiz-Martínez, G., Smith, G., & Kelly, O. (2021). International scaling of sustainability continuing professional development for in-service teachers. *Interdisciplinary Journal of Environmental and Science Education, 17*(3), e2243. https://doi.org/10.21601/ijese/10936

Rittel, H. W., & Webber, M. W. (1973). Dilemmas in a general theory of planning. *Policy Sciences, 4*, 155–169. https://doi.org/10.1007/BF01405730

Rollnick, M., Bennett, J., Rhemtula, M., Dharsey, N., & Ndlovu, T. (2008). The place of subject matter knowledge in pedagogical content knowledge: A case study of South African teachers teaching the amount of substance and chemical equilibrium. *International Journal of Science Education, 30*(10), 1365–1387. https://doi.org/10.1080/09500690802187025

Sass, W., Boeve-de Pauw, J., Olsson, D., Gericke, N., De Maeyer, S., & Van Petegem, P. (2020). Redifining action competence: The case of sustainable development. *The Journal of Environmental Education, 51*(4), 292–305. https://doi.org/10.1080/00958964.2020.1765132

Schmelzing, S., van Driel, J. K., Jüttner, M., Brandenbusch, S., Sandmann, A., & Neuhaus, B. J. (2013). Development, evaluation, and validation of paper-and-pencil test for measuring two components of biology teachers' pedagogical content knowledge concerning the "cardiovascular system. *International Journal of Science and Mathematics Education., 11*(6), 1369–1390. https://doi.org/10.1007/s10763-012-9384-6

Shulman, L. S. (1986). Those who understand: knowledge growth in teaching. *Educational Researcher, 15*(2), 4–14.

Sinakou, E., Boeve-de Pauw, J., & Van Petegem, P. (2019). Exploring the concept of sustainable development within education for sustainable development: Implications for ESD research and practice. *Environment, Development and Sustainability, 21*(1), 1–10. https://doi.org/10.1007/s10668-017-0032-8

Swedish National Agency for Education. (2023a). Curriculum for upper secondary school. Retrieved March 8, 2023, from https://www.skolverket.se/undervisning/gymnasieskolan/laroplan-program-och-amnen-i-gymnasieskolan/laroplan-gy11-for-gymnasieskolan

Swedish National Agency for Education. (2023b). Science subject syllabus. Retrieved March 8, 2023, from https://www.skolverket.se/undervisning/gymnasieskolan/laroplan-program-och-amnen-i-gymnasieskolan/gymnasieprogrammen/amne?url=-996270488%2Fsyllabuscw%2Fjsp%2Fsubject.htm%3FsubjectCode%3DNAK%26version%3D3%26tos%3Dgy&sv.url=12.5dfee44715d35a5cdfa92a3

Swedish Research Council. (2017). Good research practice. Retrieved October 4, 2023, from https://www.vr.se/english/analysis/reports/ourreports/2017-08-31-good-research-practice.html

United Nations Educational, Scientific and Cultural Organization [UNESCO]. (2006). Framework for the UNDESD International Implementation Scheme. Retrieved May 5, 2023, from https://unesdoc.unesco.org/ark:/48223/pf0000148650

United Nations Educational, Scientific and Cultural Organization [UNESCO]. (2018). *Issues and trends in education for sustainable development*. Retrieved April 20, 2023, from https://unesdoc.unesco.org/ark:/48223/pf0000261445

Van Driel, J. H., & Berry, A. K. (2017). Developing pre-service teachers' pedagogical content knowledge. In D. J. Clandinin & J. Husu (Eds.), *The SAGE handbook of research on teacher education* (pp. 561–576). SAGE Publications Ltd.

Voelkel, R. H., Jr., & Chrispeels, J. H. (2017). Understanding the link between professional learning communities and teacher collective efficacy. *School Effectiveness and School Improvement, 28*(4), 505–526. https://doi.org/10.1080/09243453.2017.1299015

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.

Wells, G. (1999). Dialogic inquiry: Towards a sociocultural practice and theory of education. *Cambridge University Press.* https://doi.org/10.1017/CBO9780511605895

Wertsch, J. V. (1985). *Vygotsky and the social formation of mind*. Harvard University Press.

Authors and Affiliations

Annika Forsler[1] · Pernilla Nilsson[1] · Susanne Walan[2]

✉ Annika Forsler
Annika.forsler@hh.se

Pernilla Nilsson
Pernilla.nilsson@hh.se

Susanne Walan
Susanne.walan@kau.se

[1] Department of Education, Humanities and Social Sciences, Halmstad University, 301 18 Halmstad, Sweden

[2] Department of Environmental and Life Sciences, Karlstad University, Karlstad, Sweden