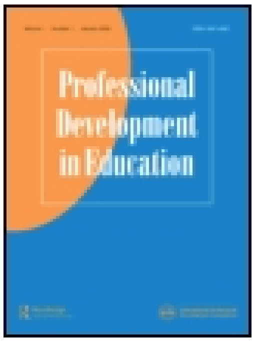

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The impacts of professional learning communities on science teachers' knowledge, practice and student learning: a review

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The purpose of this article is to provide a review of empirical studies investigating the impact of professional learning communities (PLCs) on science teachers' practices and knowledge. Across 14 articles that satisfied the definition we embraced, most were devoted to the change in science teaching practices, disciplinary content knowledge (DCK) and pedagogical content knowledge (PCK) of K–12 science teachers. Although a small number of studies have implicit focus on comparing measures of student learning, we set out to examine the studies in science education and present how teachers engaged in PLCs focusing on examining and exploring strategies to promote student learning. Analysis of the related studies resulted in the following: PLCs can help teachers increase their PCK and DCK; increases in PCK and DCK may facilitate the change in teacher practices from traditional into more inquiry-based approaches; science teachers collaboratively focusing on student learning in PLCs are more likely to change their practice; and studies do not embrace student learning as an essential feature of PLCs. Methodological flaws and future directions along with implications for science teachers' professional development are discussed.

Keywords: professional learning communities; professional development; science education; teacher practice; teacher knowledge

Introduction

Systems and structures to support science teacher professional development (PD) are crucial to student achievement in science. The need for effective science PD has been heightened by current reform efforts in K–12 science education which require science teachers to have different knowledge and skills. The literature is replete with descriptions of differing models of PD, most of which include activities that focus on job-embeddedness (Learning Forward 2011), developing teacher leaders (Killion and Kennedy 2012), reviewing learning and teaching strategies (Saito 2012), one-to-one interaction between two teachers in the form of coaching (Kennedy 2005) and collective participation towards school change (Garet *et al*. 2001). While there is a consensus on what constitutes 'high-quality' PD activities (Desimone *et al*. 2002), today's standard-driven educational environment requires the deepening of science teachers' content knowledge alongside the development of subject-specific teaching practices consistent with how children learn. Many PD activities do not adequately consider how teachers make sense of their experiences (Drago-Severson 2012), do

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not include provisions for long-term support and do not offer challenges that promote teachers' learning in ways that would allow for growth (Moller and Pankake 2007, Kegan and Lahey 2009). More often, PD appears fragmented and disconnected from the recurring problems of improving practice (Morrissey 2000, Borko 2004, Little 2006). Arguably, these attempts have been futile in effecting significant gains in teaching and learning, thus raising issues for policy-makers and administrators who allocate PD funds to improve science teaching and learning.

Over the last two decades, much credence has been given to the development of professional learning communities (PLCs) as a means of supporting and improving teacher knowledge and skills leading to increased teacher efficacy for meeting students' needs (Rosenholtz 1989, Hord 1997, Donaldson 2008, Cohen *et al*. 2009, Drago-Severson 2012). Research indicates that when done well, PLCs have the potential to enable a local focus, and to build the respect, trust and collegiality conducive to teachers becoming more effective in their work (Little 1982). While there is no universally accepted definition of PLCs (Hord 1997), early research on PLCs provided evidence that strong learning communities of teachers were important contributors to instructional improvement and school reforms (Morrissey 2000, Little 2002). Furthermore, Crawford (2007) contends that PLCs as dynamic and purposeful entities elicit 'the voices of teachers in the context of their practice.' She also advocates that a learning community 'offers a powerful vehicle for synergy, collaboration, and creation of an environment in which change is possible' (2007, p. 638). When teachers collaborate to solve issues of practice, they develop multiple ways that are directly related to their students' learning. It is such immediate diagnosis and actions that can reconceptualize the process of PD and teacher learning. By focusing on student achievement and allowing teachers to collaborate and address daily problems of practice in their own classrooms, advocates indicate that PLCs provide a strong conceptual framework for transforming educational practices.

Guided by Dufour (2004) and Hord (1997), we used the following working definition of a PLC for this paper: in PLCs, teachers commit to a common vision of improving student learning, teachers work collaboratively to find solutions to problems of practices and improve their teaching practices, and teachers evaluate the success of their efforts to improve their pedagogy based on student achievement. Student learning is both the purpose and mechanism for a PLC. Members work together to study levels of student learning, identify specific goals for improvement and develop strategies to achieve these goals. Furthermore, members use evidence of student learning such as student work samples and test scores heavily in their interactions. They use such evidence to make claims about current student understandings and the impact of changes in their teaching practices. One of the early proponents (DuFour 2004) cautions that the preservation of the fundamental concepts of PLCs requires educators to critically reflect on the merits of student learning and the development of a culture of collaboration.

Championed by support from the National Science Foundation/Math Science Partnership over the last decades (Hamos *et al*. 2009), PLCs have become a cornerstone of systemic reform efforts supporting science teachers' learning and heralded as a vehicle for collaboration among science teachers with the ultimate goal to improve student achievement. As such, a core characteristic of the vision of science PLCs is an undeviating focus on students' learning (Louis and Kruse 1995), in which analyses of students' work become the focus among community members. Thus, PLCs as an infrastructure in which teachers collaboratively engage in the analysis of teaching and learning, analyze student work and obtain feedback about their teaching are a crucial cost-effective measure given the shift in vision for quality science teaching. Despite institutionalization within state and nationally funded programs in science education, very little systematic research has explored the extent to which the salient features of PLCs are operationalized across these programs as well as their effects on science teacher knowledge and teaching practices, and impacts on students' science learning. Our literature review therefore seeks to examine the studies in science education that have embraced PLCs in their PD efforts, to deconstruct how they have integrated the essential feature of PLCs, and to delineate the impacts on teachers' and students' learning.

In this article, our reference to teacher 'change' as a result of involvement in PD includes 'knowledge and skill development' (Hargreaves and Fullan 1992) and shifts in practices. We believe that teacher knowledge and practices, affective characteristics and student learning are crucial components of teacher change within the context of PLCs (Guskey 2002, Desimone 2009). Therefore, our operational definition of teacher change in practice is the incorporation of instructional techniques, integration of new materials, curriculum implementation or basic improvements in teaching process and classroom settings (Guskey 2002). Our review also uses two domains of teacher knowledge: disciplinary content knowledge (DCK); and pedagogical content knowledge (PCK). DCK refers to a knowledge domain which includes specific subject matter, facts and concepts within a discipline (Wilson *et al*. 1988). PCK refers to another knowledge domain which contains subject-specific teaching methods, principles that facilitate learning and instructional conditions necessary to overcome students' misconceptions (Shulman 1986). In addition, we are using 'affective characteristics' to refer to additional changes teachers experience as a result of PD participation in the form of values, beliefs, attitudes, behaviors or perceptions. King (2014) identifies two main categories of affective outcomes: attitudes and beliefs about teaching and how students learn; and attitudes and beliefs about collaboration. Self-efficacy would be included under the first category because it involves the beliefs of teachers in their ability to explore and enact new practices such as inquiry-based science teaching (Cakiroglu *et al*. 2012). Attitudes and beliefs about collaboration would include the dispositions and expressed values of teachers about participating in collaborative PD and promoting or leading change (Jones *et al*. 2013).

Method

The purpose of this article is to provide a review of empirical studies investigating the impact of PLCs on science teachers' knowledge, practice and affective characteristics. We examine the studies as they relate to two research questions: how are science teachers impacted by their participation in PLCs; and in what ways do science teachers in PLCs focus on student learning?

To begin our study, a comprehensive search was conducted of the following peer-reviewed educational databases: Academic Search Premier, ERIC, Professional Development Collection, and Web of Knowledge. The reason for choosing four databases is to cover as many educational areas of sources as possible and not to miss any PLC manuscripts. Studies relating to science education and including the term 'professional learning community' were identified in the initial search. However, because PLCs can be associated with other terms, we chose our search terms (both singular and plural) as 'professional communities,' 'communities of practice,' 'learning communities' and 'critical friend groups.' We also added 'science,' 'teachers,' 'biology,' 'chemistry,' 'physics' and 'student' as qualifiers. In addition, we focused on individual search terms and all the relevant combinations of these terms in the title, abstract and whole text of the articles within the databases that served as the primary sources for the relevant literature. This initial search resulted in 60 peer-reviewed articles.

After an initial perusal, we excluded articles that did not contain relevant empirical results about teacher knowledge and practice. For example, we excluded the study by Shernoff *et al*. (2011) from our sample because the paper investigates the satisfaction, needs and perceptions of teachers who participated in PLCs, which is not the main focus of this article. Furthermore, we excluded studies that used technology as the only medium for supporting collaborative activities among science teachers. We kept articles including information regarding either teaching practice or knowledge. While there was a plethora of articles connecting learning communities and science teachers, not many embraced the notions of PLCs as an ongoing process in which educators work collaboratively in recurring cycles of inquiry or reflective dialogue to increase students' science learning.

In a second screening, we read all the abstracts of the articles, noted their definition of PLCs and individually made a judgment on the extent to which PLCs were a feature of the research article. Furthermore, our criteria for article selection included: science teachers were clearly engaged and in attendance in PLCs which focused on student learning; PLCs were characterized by ongoing opportunities for collaboration and interaction among teachers; and the article provided evidence regarding the extent to which the teachers' knowledge and/or practices were impacted. After this selection, additionally we identified the articles in which the impact of PLCs on student learning was studied. In our follow-up discussion, guided by our description of PLCs, we engaged in intense negotiation and arrived at consensus on those articles that needed to be eliminated. We eliminated articles that did not conform to the definition we embraced by Dufour (2004) and Hord (1997). After a careful reading, followed by further negotiation and arriving at consensus, the process resulted in 14 articles that met the criteria for inclusion in this literature review as shown in Table 1.

Results

Consistent with our view of PLCs as a mechanism for science teachers' professional learning, we presented our results according to two research questions. The articles providing details about a particular research question are emphasized further in following the sections. Sufficient details about each paper are presented for a clear understanding of the studies and the role that PLCs played in each unique context.

The impacts of professional learning communities on science teachers

We place credence in understanding the extent to which PLCs enable science teachers to change their science teaching practices, enhance their knowledge and develop other relevant affective characteristics. This section addresses our first research question: how are science teachers impacted by their participation in PLCs? The findings

Table 1. Descriptive information related to the reviewed articles.

Reference	Methods used	Part of larger PD project	Description of PLC activities	Number of teachers / subject / level / voluntariness
1. Crippen *et al.* (2010)	Mixed / achievementtests	Yes	Collaboration with university faculties, mentoring, sharing ideas, plan and implement action research, readings, reflection, review, online discussion and support	50 / science / ninthgrade / purposefully
2. Diacanu *et al.* (2012)	Mixed / surveys, observations	Yes	Experience practice, mentoring, reflective journals, studying practices, support	80 / science / elementary / random assignment
3. Jones *et al.* (2013)	Qualitativesurveys / interviews	No	Discussion and examination of student test scores, facilitator / leadership, sharing ideas and strategies	65 / science / elementary / yes
4. Lakshmanan *et al.* (2011)	Mixed / observations	Yes	Design instruction, review best practices, discuss experiences, content and pedagogy	46–63 / science / elementary and middle / yes
5. Nelson and Slavit (2007)	Qualitative / observations, interviews	No	Inquiry Cycle, design / plan action research, peer observation, support and facilitator, implementation, discussion, exploring their own conceptions, sharing ideas, examination of data and test results	45 / science and mathematics / sixth to eighth grades / purposefully
6. Brown *et al.* (2011)	No info / achievement tests	Yes	Review and analyze student data, develop instructional innovations	No information / science / K–12 / no information
7. Woolhouse and Cochrane (2009)	Mixed / surveys	Yes	Sharing experiences, discourse, online discussion	23 / science / third to fifth grades / yes
8. Richmond and Manokore (2011)	Qualitative / interviews	Yes	Reflection and discussion enacted lesson, plan curricula and assessment and enact these, motivation, share their practice, facilitation / leadership, investigate their own teaching, examining published research,	8 / Key Stages / first and fourth grades / yes

(*Continued*)

Table 1. (*Continued*).

Reference	Methods used	Part of larger PD project	Description of PLC activities	Number of teachers / subject / level / voluntariness
			explore curricula and assessment, debriefing, analysis of student work	
9. Clark *et al.* (2008)	Qualitative / video records	No	Speaking with meaning, discourse, peer facilitator, discussion about learning and teaching concepts of the given courses, two different PLCs, reflection	5 / science and mathematics / secondary / purposefully
10. Nelson (2009)	Qualitative / observations, interviews	No	Inquiry cycle, evaluation of teaching practice, facilitation, exploring their belief and perceptions about learning and teaching, analyzing videos of lessons and guided discussion	45 / science and mathematics / sixth to 12th grades / purposefully
11/12. Rahman (2011a, 2011b)	Qualitative / questionnaire, surveys, interviews	No	Peer pairs, post-teaching discussion, sharing success and failures in practice, classroom teaching practice and observation, exploring problems in their own practices and reflection	14 / science / secondary / yes
13. Mintzes *et al.* (2013)	Mixed / reflections	No	Lesson Study, Demonstration Laboratories, discuss, analyze, plan, implement and assess inquiry-based science lessons, facilitated discussion, teacher observation on students, reflection and revision	116 / science / K–5 / no information
14. Guzey *et al.* (2014)	Qualitative / teacherartifacts	Yes	Facilitator, discussion, designing activity, reflection, sharing, engineering content, presentation	198 / science and mathematics / third to sixth grades / no information

reveal, although they are not consistent across all studies under review, that there are noticeable changes in teachers' science teaching practices and knowledge as well as affective characteristics.

Changes in teacher practices

Changes in teacher practices imply that teachers, as a result of participation in PLCs, improved their use of reform-based science teaching practices, including shifting to a more student-centered approach through facilitation and scaffolding of student inquiry (National Research Council 2000). In this analysis, 12 of the 14 studies explicitly or implicitly examined teachers' enactment of inquiry-based teaching practices and concluded that teachers participating in PLCs experienced noticeable changes in their practices. However, the authors of these 12 studies differed in how they attributed the role of PLCs to specific shifts in teacher practices.

Professional learning community-enhanced professional development. Three of these 12 studies used PLCs as a component of comprehensive PD efforts that also included formal university coursework, summer institutes and year-long teacher workshops (Woolhouse and Cochrane 2009, Crippen *et al*. 2010, Guzey *et al*. 2014). The authors of these studies did not attempt to assert that changes in teacher inquiry-based practices stemmed exclusively from participation in PLCs. In contrast, another three studies utilized PLCs in similar comprehensive PD efforts but did assert that the changes in teacher practices were attributable to their participation in PLCs (Lakshmanan *et al.* 2011, Richmond and Manokore 2011, Diaconu *et al*. 2012). For example, Diaconu *et al.* (2012) used PLCs in the four-year Rice Elementary Model Science Lab PD program to create classroom culture for science teaching. Teachers, one full day each week, participated in workshops and PLC meetings related to science content, inquiry-based practices and use of the 5E instructional model (Bybee 1997). This group of teachers was the treatment group. The other group of teachers who were not involved in PLC workshops was the control group. The authors showed that, based on the survey results, the teachers in the treatment group during 2008–2010 reported greater improvements in their use of inquiry-based science teaching practices and the 5E model compared with the control group. Additionally, qualitative data from classroom observations yielded similar evidence of shifts in practices towards inquiry-based teaching for the program during 2008–2010.

The other two studies are particularly important in understanding the difference between studies of pedagogy-focused, PLC-enhanced PD and studies of content-focused, PLC-enhanced PD. In a three-year PD program using a combination of content knowledge courses and Educator Inquiry Groups, Lakshmanan *et al.* (2011) documented significant improvements in the extent to which elementary and middle school science teachers incorporated inquiry-based teaching practices using classroom observations. The authors posited that participation in PLCs in the PD program can help teachers improve their instructional methods in the classroom. However, the authors did not provide specific empirical evidence to support this claim. On the other hand, Richmond and Manokore (2011) provided some evidence supporting their claim that PLCs were important for changing teacher practices. In their PD model, elementary science teachers were engaged in summer institutes, were provided with facilitator support and studied a curriculum unit that focused on core scientific concepts including fossil records, along with strategies for incorporating them into inquiry-based science instruction. Teachers in the interviews mentioned that in PLCs they encouraged each other to try new instructional practices, adjust their teaching methods based on deliberations in the group, develop reform-based instructional strategies to use in interdisciplinary teaching and be 'change makers' (2011, p. 564).

Professional learning community-only professional development. The remaining six articles used PLCs exclusively as their method of PD and asserted that participation in PLCs were responsible for changing teacher practices. Jones *et al.* (2013) documented the findings from the implementation of PLCs guided by DuFour (2003). Specifically, the PLCs that Jones and colleagues studied followed a step-by-step procedure starting with examining state science standards, reviewing test scores and discussing ways of adjusting teaching and assessment practices based on the test score evidence. They collected data, using surveys and interviews, from 65 randomly-sampled elementary science teachers participating in the PLCs. Teachers reported the greatest changes in their use of formative assessment strategies in science, followed by the way they designed their lessons, although the data were based on self-reported perceptions of the teachers. Rahman (2011a, 2011b) described how a group of secondary science teachers started using one inquiry-based teaching strategy, prediction–observation–explanation (POE; White and Gunstone 1992), in their practices while being engaged in a PLC. Rahman analyzed data from an open-ended questionnaire, focus group interviews, researcher's field notes and classroom observations. The findings indicated that teacher participation in PLCs enabled the science teachers to adopt the inquiry-based teaching strategy (i.e. POE), which was not familiar to these teachers at the beginning of the study. Although how the teachers were introduced to POE was somewhat unclear, the author noted that PLCs helped the teachers improve understanding of POE and how to implement this strategy in their teaching in effective and efficient ways.

Related to the PD project Partnership for Reform in Secondary Science and Mathematics, Nelson (2009) focused on three of the total 10 PLCs to document the nature of PLC-related work in middle and high schools. The analysis of peer observations, interviews and video-recordings of 35 PLC meetings indicated variability in how teachers were engaged in the PLCs as well as how their practices were impacted. In the first case, the author noted that the four physical science teachers implemented science lab writing activities for students and created 'some of the tools for inquiry-based teaching' (2009, p. 563). The teachers developed lessons requiring students to use and apply data during earth science study. However, there was no salient information regarding further changes in other inquiry-based teacher practices. For the second case, a total of eight sixth-grade to 12th-grade mathematics and science teachers worked across disciplines and grade levels to figure out how to do classroom-based inquiry. One of the teachers in this PLC admitted that 'we didn't change [instructional] strategies throughout the year, we've kept our same strategies' (2009, p. 568). In the third case, science teachers developed and implemented their new instructional plan across all six classes. The practices they used were a science writing assessment strategy and a comprehensive in-class activity to teach how to develop scientific conclusions. Most importantly, the PLC members including teachers having different teaching experiences decided that they would continue to develop and implement new strategies that would address different students' needs in the seventh and eighth grades. In spite of the absence of explicit indicators of change in teacher practices, two of the cases showed evidence of change in teacher practices based on self-reported teacher data.

As for the second article related to the PD project Partnership for Reform in Secondary Science and Mathematics, Nelson and Slavit (2007) examined five cases (including cases from the first article) of 10 PLCs in which the teachers were engaged in a collaborative cycle of inquiry. Although this second article did not examine each case individually, it had more tangible teacher-reported evidence on what teachers did or did not do in their classrooms related to PLC work. The synthesis of interviews, field notes, video records and teacher reports demonstrated important findings. The first and second groups of PLCs talked about how to increase inquiry-based instruction in their mathematics and science classrooms and succeeded in implementing inquiry teaching. The second PLC case focused more on one of the essential elements of inquiry: questioning. The third PLC group developed and used a rubric to score students' error analysis activity, which was a regular process for some of the teachers in the group. There was no evidence from the fourth and fifth PLC groups regarding change in teaching practices.

In our final review of the six PLC-only PD articles, Mintzes *et al*. (2013) conducted a mixed and non-equivalent control group experimental study in which changes in elementary science teacher practices were examined. Based on the teachers' own reflections, the authors found that the teachers moved from didactic and text-based instruction to more inquiry-based instruction. One of the teachers in this study stated that 'I'd say my pedagogy has changed a bit – trying to use more of a discovery learning for science.' The other teacher was more specific in her reflection that:

> We do a lot more science in small groups … I think just using science in small groups has been something that we've done more that we didn't do before. It seems like before it was whole group, use your textbook, read the textbook together – that kind of thing. (Mintzes *et al*. 2013, p. 1214)

Through participation in PLCs, these elementary science teachers made changes to their practices as they incorporated hands-on strategies, group work, discovery learning and the use of learning stations.

Summing up, our review indicates that nine of the 12 articles (two out of 14 did not examine teacher practice) we reviewed reported changes in teaching practices as a result of science teacher participation in PLCs. In most of the studies, changes were alluded to without giving specific evidence of the impact of PLCs on teacher practices. Some studies, however, documented what science teachers tried to implement in their classes after participation in PLCs. For example, science teachers began to implement inquiry-based instructional and formative assessment strategies after being engaged in PLCs. It should be noted that in all of the articles, with the exception of Diaconu *et al.* (2012), information about changes was based on teachers' self-reported data. None of the PLC-enhanced PD studies in our review articulated whether these changes could be ascribed explicitly to the teacher participation in PLCs. Instead of reporting individual impacts of PLCs, these studies documented the impacts of PD holistically.

Changes in teacher knowledge

For our review purposes, we embrace changes in teacher knowledge to include improvements in both their DCK and their PCK. In our review, we noted that two studies reported increases in both DCK and PCK of teachers participating in PLCs. Two studies reported an increase only in teachers' DCK (Brown *et al.* 2011, Guzey *et al.* 2014). Three studies demonstrated increases only in teachers' PCK. However, four of the 14 articles did not examine either PCK or DCK (Clark *et al.* 2008, Lakshmanan *et al.* 2011, Rahman 2011a, Mintzes *et al.* 2013).

Two articles notably provided evidence that teachers increased both their DCK and their PCK through participation in PLCs. In the study by Jones *et al.* (2013), the researchers aimed to develop teachers' science DCK and science-specific pedagogical skills through series of PLC meetings. The authors demonstrated that 11 teachers reported that participating in the PLCs caused them to increase their science DCK. The researchers also found that, although the study did not refer to PCK explicitly, participating in PLCs probably impacted aspects of teachers' PCK. Based on the survey results, significant numbers of teachers reported that participation in the PLCs positively impacted their understanding of how to plan science lessons (41.9%), various assessment strategies (43.5%), science resources (33.9%), science curriculum (27.9%) and student thinking in science (27.4%). The findings about PCK were supported by interview data which reported that teachers had benefitted from PLCs in gaining confidence in teaching science and having different perspectives related to teaching. Likewise, Richmond and Manokore (2011) documented the findings of their PD cycle, which includes summer learning institutes to provide time for teachers to work on their content before participation in PLCs. The researchers claimed, based on their interview analysis, that participants learned about their subject matter and specific PCK, despite their lack of specific measurements to document these changes. In particular, the self-reported data of participating science teachers acknowledged that they learned science content and science-specific pedagogy from the interactions with their peers. In addition, during the PLCs, teachers noted the importance of learning about appropriate assessments, science concepts and specific differentiation strategies to meet the learning needs of all students.

Three of the 14 studies in our review documented an increase in PCK of science teachers engaged in PLCs. In Rahman's (2011b) study, science teachers acknowledged that they refined their ideas about an inquiry-based teaching strategy (POE) and how it can be implemented effectively with the help of their peers in the PLCs. Nelson and Slavit (2007) and Nelson (2009) did not intentionally examine PCK or provide evidence for change in pedagogy. However, the sixth-grade to eighth-grade science teachers reported that they learned how to improve students' written communication skills in mathematics and science, how to encourage high-quality questioning by students, how to help students reflect on their own work and how to increase their use of inquiry-based teaching. These teachers also studied how to support scientific investigation and language in their classes and used various formative assessments as part of their involvement in PLCs. Six teachers in the project further stated that participation in PLC meetings helped them to become aware of the essential characteristics of inquiry-based teaching.

Changes in teachers' affective characteristics

Along with changes in teachers' knowledge and practices, changes in affective characteristics of science teachers participating in PLCs are also an important finding that requires closer examination. These additional changes reported in the studies under review were teacher confidence, self-efficacy, leadership skills, collegiality, sense of accountability, change in culture of professional practice and empowerment. Five of the 14 articles did not report any additional changes (Nelson and Slavit 2007, Nelson 2009, Crippen *et al.* 2010, Brown *et al.* 2011, Guzey *et al.* 2014). One of the remaining nine studies concluded that teachers increased their leadership skills, which refer to teachers' activities as a campus science leader such as attending and presenting at PD activities, applying funding and grants (Diaconu *et al.* 2012). However, there was no sound evidence to claim that teachers developed some affective characteristics due to their participation in PLCs. Eight articles attributed the changes to the efforts and experience that the teachers were engaged in during the PLCs. In one of these studies, Jones *et al.* (2013) concluded that PLCs impacted the teachers' creativity and innovation in instruction (n = 24), their knowledge of science resources (n = 21) and their confidence in their science teaching (n = 16). Lakshmanan *et al.* (2011) also found that an important benefit gained from participation in PLCs was an increase in middle and elementary science teachers' self-efficacy. In Woolhouse and Cochrane's (2009) study of the third and fifth grades, science teachers reported on their personal development. The teachers expressed that they developed their confidence, interest in their subject matter and friendships among colleagues as a result of participating in PLCs.

In another study, Richmond and Manokore (2011) demonstrated that developing confidence in content knowledge, teaching practice and a sense of accountability emerged among first-grade and fourth-grade teachers who were engaged in PLCs. Results from the research conducted by Clark *et al.* (2008) reported that the PLC participants began to establish their own criteria for an acceptable argument and what constituted 'speaking with meaning.' In addition, they developed a framework to help teachers improve the quality of their discourse among individuals engaged in discourse in PLCs. Rahman (2011a, 2011b) demonstrated that 14 secondary science teachers increased their confidence in using collaborative activities, developed feeling of comfort in exploring their own problems about their teaching practice, and changed the culture of their professional practice from traditional to a more constructivist approach after working in PLCs within and across schools. Mintzes *et al.* (2013) also supported the finding that participation in PLCs enabled science teachers to increase their personal self-efficacy. In addition, this study pointed out that there were significant shifts in teachers' outcome expectancy (expectation of desirable performance), emotional reinforcement (a support source of self-efficacy) and empowerment (project-found term for self-confidence), which were ascribed to their participation in PLCs.

Ways science teachers in professional learning communities focus on student learning

The literature contains tangible evidence that PLCs can have an impact on science teachers. Consistent with our definition of PLCs, their value as an effort in PD is related to their impact on student learning. At present, improvements in student learning usually refer to achievement in subject matter. Although PLCs are defined by a triangle of teacher collaboration, focus on student learning and focus on results (Dufour 2004), most of the studies conducted do not embrace PLC's focus on student learning nor do they examine the impacts of PLCs on student achievement. Therefore, it is important to look at the impact of PLCs on student learning and the ways science teachers in PLCs focus on student learning.

How teachers focus on student learning in professional learning communities

In our review, we tried to understand the extent to which the PLCs in these studies focused on student learning. Of the 14 articles we reviewed, nine explicitly discussed the focus of PLCs on student learning. Eight of the articles reviewed focused on student learning but did not examine whether there were changes in the student achievement as a result of teacher participation in PLCs. In one of these articles, Diaconu *et al.* (2012) studied high-poverty and high minority students in their comprehensive Rice Elementary Model Science Lab project. Although the researchers did not address student achievement as an outcome variable, they documented that the teachers in PLCs 'had opportunities to practice with their students and brought the results and their questions back into their PLCs' (2012, p. 869) and reflected on and shared student works with their colleagues. Additionally, teachers were mentored and supported in their implementations and practices. In a similar way, Jones *et al.* (2013) discussed that elementary science teachers engaged in PLCs focused on working to improve students' standardized test scores and ensuring that each student would achieve a standard for a particular science topic. Towards reaching this aim, with facilitator and leadership support, the teachers examined the students' scores on district-level science assessment. They collaboratively identified the science topics in which the students received low scores, and discussed the strategies to improve these scores in PLC meetings. Although the model of PLCs in this study addressed how students learn and examined the difficulties they experience during the process, some teachers in this study indicated that during the PLC meetings they were mainly focused on science test scores and how to raise scores for the school, rather than focusing on how to teach students science in more meaningful ways.

Nelson (2009) and Nelson and Slavit (2007) in each article explicitly noted that the teachers examined student learning by analyzing the student work and reflecting on the impact on students' achievement. In their inquiry cycle, a framework used in the project, teachers asked questions related to students such as 'Will the deliberate and systematic use of learning targets improve student achievement?' and 'How can we help our students build higher order thinking skills when learning science vocabulary concepts?' (Nelson 2009, p. 553). The teachers were supported by facilitators as they designed action research, analyzed the videos of their peers, implemented what they learned and shared, explored and discussed their own conceptions about learning and teaching. In addition, Nelson acknowledged that teachers were involved in collective decision-making processes on what actions to take in their classrooms. Nelson and Slavit (2007) also indicated that the teachers drew on data-driven discussion in their PLC meetings to impact students' learning. Here, 'the work of the PLCs entails more than selecting a focus, examining data relevant to that focus, taking action to change something in the classroom and looking at the impact of that action on student learning' (2007, p. 36). The other study focusing on student learning was conducted by Mintzes *et al.* (2013). These researchers established grade-level PLCs in which teachers met biweekly to discuss, analyze, plan and implement inquiry-based science instruction. In Demonstration Laboratories, the teachers observed their students and elicited prior knowledge and their understanding of scientific concepts. Results from this research indicated that elementary science teachers discussed critical issues of student learning in Lesson Study sessions and revised their instruction based on what they learned from their observations.

In the California Partnership for Achieving Student Success study, Brown *et al.* (2011) documented findings of science professionals' (science teachers and professors) use of student data to shape the ways instruction and assessment were planned. In the PLCs they identified students' shared needs based on regional data and developed innovations to meet these needs. The researchers then investigated the difference between pre and post innovations. One of their innovations was the development of biology, chemistry, English language arts and algebra courses, in which significant improvements were observed in seventh-grade, eighth-grade and ninth-grade students. Although this study seems a little bit different from other studies we reviewed, the importance of this study is that science professionals in the California Partnership for Achieving Student Success examined student data and developed new actions collectively to improve student achievement.

Richmond and Manokore (2011) also provided evidence about PLCs focusing on student learning. In this study, the teachers in the PLCs carefully investigated student understanding by bringing selected work to the PLC meetings, examining research papers on students' ideas with respect to science concepts, and analyzing student work collaboratively using formative and summative assessments. The researchers also documented that the teachers discussed how well students were responding in the implemented lessons; specifically the ways they were engaged in and motivated in the class, the common learning difficulties they experienced and the misconceptions they had. These discussions led teachers to think of ways to adjust their science teaching to improve student achievement on district and state examinations.

In their engineering-focused PD project Mathematics and Science Teacher Partnerships, Guzey *et al.* (2014) qualitatively investigated the effects of their general PD project and worked with 198 third-grade through sixth-grade science and mathematics teachers. In this PLC-enhanced project, teachers participated in PD to support the development of a collaborative culture in their school. Working with facilitators, 'teachers explored students' conceptions of engineering by assessing student knowledge on engineering before and after they implemented an engineering lesson' (2014, p. 143). Teachers in PLCs examined student assessment protocols to determine students' knowledge of engineering practices. The researchers indicated that teachers collaboratively designed engineering activities, shared and reflected on what they learned from using the assessment protocols. Most importantly, teachers in this study discussed their students' work to understand student thinking and explored ways to improve instruction.

Impact of professional learning communities on student learning

It is worth highlighting here that only one study among our PLC papers examined the changes in student academic achievement (Crippen *et al.* 2010). In Project Proficiency and Success in Science, science teachers analyzed and developed strategies to improve students' performance on a statewide high school proficiency examination for science. The study compared the scores of three groups of students using two different assessments: the Nevada High School Proficiency Exam; and the Iowa Test for Educational Development. These groups were composed of students whose teachers fully participated in the PD program (treatment group), students whose teachers demonstrated limited participation (partial treatment group) and students who were not involved in either of the two groups (comparison group). Although univariate analysis using the Iowa Test for Educational Development as a covariate showed no significant difference between the three group marginal means, a more positive pattern emerged in which the treatment group outperformed the comparison group. However, the treatment group did not exceed the performance of the partial treatment group in these analyses. Furthermore, the authors reported that students whose teachers participated fully in Project Proficiency and Success in Science were more than twice as likely to be successful on the state science examination.

Even though the focus on student learning and the ways in which teachers focus on student learning were not explicitly examined in the study by Crippen *et al.* (2010), the researchers incorporated some activities into the PLCs. In these activities, teachers collaborated with and were mentored by university faculties. Together they were involved in an action research project in which they prepared an action research proposal. Teachers also shared their ideas with peers about inquiry-based teaching and developed a collective sense of responsibility for student learning. During the PLCs, they also read, reflected on and discussed the important issues about conceptual change theory and self-regulated learning theory in PLCs.

Five of the 14 articles (Clark *et al.* 2008, Woolhouse and Cochrane 2009, Lakshmanan *et al.* 2011, Rahman 2011a, 2011b) did not report an explicit focus on student learning or evidence of changes in student achievement. However, in nine studies teachers focused on student learning in a number of ways in their PLC meetings. The most common ways were to collaboratively examine and analyze student work, review student data based on test scores and to reflect, discuss and share strategies on how to improve student learning. Our review identified only one study investigating the impact of participation of science teachers in PLCs on student achievement, and the authors themselves did not attribute improved student achievement to teacher participation in PLCs. There is therefore insufficient evidence to conclude in this review the extent to which PLCs impact student achievement.

Discussion

PLCs have been acknowledged as a means to improve teacher and student learning by many scholars and educators (Dufour 2004, Vescio *et al*. 2008, Loucks-Horsley *et al.* 2009). In this review, we sought to validate these perceptions as we examined science teachers' engagement in PLCs and the focus on student learning. Our selection process was therefore guided by specific inclusion criteria and a deliberate focus on empirical studies of PLCs involving science teachers. In the resulting 14 studies we reviewed, PLCs were enacted as either one component of a larger, comprehensive PD project or were the sole method through which the PD activities were conducted.

Recent research shows that effective PD focuses on developing a community in which teachers' professional learning is supported (Darling-Hammond 1997, Wenger 1998, Garet *et al.* 2001, Stoll *et al*. 2006, Desimone 2009, Loucks-Horsley *et al.* 2009). Research also indicates that learning communities can have significant impact on changing teacher practice and instructional improvement (Little 1993, 2002, Darling-Hammond 1995). A learning community component added to PD offers a shift in thinking about PD and learning. The findings in this review provide some support for Little's (2003) claim: PLCs are beneficial for shifting teachers' perspectives and helping teachers form a culture in which they engage in improving their own practice and knowledge.

Recently the focus of PD efforts has been changed to professional learning of teachers from teacher development. As Dufour (2004) indicates, every community focusing on teacher learning promotes positive outcomes. We identified many possible positive outcomes in this review. Findings from our review provide some support for the claim that participation in PLCs improves science DCK and PCK in ways that may translate into change in teacher practices. However, additional evidence is needed to conclude that the more teachers learned about their content and/or pedagogy, the more they changed their practices (Hord 1997, Garet *et al.* 2001).

Considering change in teacher knowledge and practice, participation in PLCs provided science teachers with important opportunities to develop PCK and DCK required to implement rigorous, content-driven, inquiry-based curriculum and instruction. Furthermore, as members of PLCs, teachers had access to rich and deep subject matter knowledge in science and research-based instructional strategies used in science education through the excitement of learning in a collaborative community. The knowledge gained was further reinforced when, in discussion, the teachers shared their classroom experiences and developed other views about science teaching. As teachers enhanced their knowledge in communities by collaboration and active participation (Fishman *et al*. 2003), teachers probably also improved their practice (Desimone 2009). This connection between knowledge and practice can only be established on the condition that PLCs are well organized and include structured work towards student learning. However, further research is needed to explore the extent to which the documented changes in teacher practice resulted from the combined efforts to improve DCK and PCK or a sole mechanism of either content or pedagogy.

The common change in our PLC studies was that science teachers started to use more inquiry-based learning methods and assessments. We can explain this change with the argument that teachers in PLCs drew upon their expertise to have a fruitful conversation and gained new perspective about teaching and learning when they came together in a learning community (Putnam and Borko 2000). The other reason for this change is that 'learning motivates change' (Morrisey 2000, p. 24). As teachers learn in PLCs, they are motivated to make necessary changes in instructional plans. Bryk *et al*. (1999, p. 771) also argue that the change mostly stems from 'an environment that supports learning through innovation and experimentation,' which we witnessed in most of our reviewed PLC cases. Teachers participating in PLCs in these kinds of environments also used their higher thinking, communication, knowledge-gathering, connection with the real world and leadership skills (Louis and Marks 1998). PLCs can be regarded as a unifying entity for science teachers to gain knowledge about science and science teaching, in turn helping them to improve their practice. Teachers in PLCs invest in their own learning and adapt what is needed to meet all of the students' need (Morrisey 2000).

Across the studies in which PLCs were incorporated as an additional mechanism into a comprehensive PD, university coursework, summer institutes and teacher workshops were common activities that engaged the science teachers in learning about DCK and PCK. Although changes in teaching practices were reported, most of these changes were not defined. Therefore, the limited information presented in the reviewed studies refers one important conclusion: participating in science PLCs may not guarantee changes in science teachers' practice.

It is not surprising that the science teachers in the reviewed studies experienced not only cognitive but also affective changes. Most of our studies claimed affective changes in science teachers, such as confidence in teaching and a sense of community. Although our samples did not suggest any cause for additional changes, a careful screening shows that nine of the articles attribute the changes to the participation in PLCs. Because of the rich culture of collaboration, teachers have the chance to learn from and with each other (Dunne 2002). Collaborative culture not only influences the relationship among teachers, but also enables science teachers to develop affective characteristics as additional changes of PLCs. We note that change is more likely to occur in cases where teachers experience communal feeling and collaborate with others who are open to trying innovations in the classroom in PLCs (McLaughlin and Talbert 2001, Crippen *et al.* 2004).

Our review provides some support that science teachers who focus on student learning in PLCs are more likely to change their practices, which is supported by Vescio *et al.* (2008). Research also draws attention to the significance of the emphasis on analyzing student work and their learning (Guskey 1997, Little *et al*. 2003). Science teachers who changed their practices were engaged in examining classroom artifacts, which inform the knowledge base for improving their practices. Such shifts in science teachers' practices contributed to the enhancement of student learning (Little 2003).

From an international perspective, our sample included two non-US studies. These articles from the United Kingdom and Bangladesh contained valuable information about teachers' perceptions and how they were impacted by their participations in PLCs. While we garnered information from only two international endeavors, they provided other perspectives that can contribute to our understanding of the impact of PLCs on science teachers. For example, teachers stated that initially they felt shy and hesitant about sharing in PLCs; however, gradually they realized that sharing helped them improve their teaching. In addition, the findings can provide a framework for broadening the scope of investigation around science teachers from various cultures.

Methodological flaws might shed doubt on findings of professional learning community research

The belief that PLCs result in new knowledge in teachers, which then will translate into student achievement, is implicit in the design of PLC-enhanced PD (Hamos *et al.* 2009). The important questions to ask are: how do we, as researchers, know that participation in PLCs results in change in science teacher knowledge; and does teacher participation in PLCs benefit students? As Hamos *et al.* (2009, p. 21) indicate, 'rigorous assessment of the impact that professional development has on teachers and their students requires the development of tools and instruments accompanied by piloting, revision, and field-testing.' Therefore, we need to pay more attention to the methodologies of PLC studies. We identified two flaws related to methodologies used across our articles: PLC research is based mostly on self-reported teacher data; and there is much confusion about the role of PLCs in general PD findings.

Most of our articles capitalize on data from teachers' own reflections and views about their own practice and knowledge. However, self-reported data may have reliability and validity problems. In educational research, teachers are apt to over-report certain change in their practices (Porter *et al*. 1993). Furthermore, teachers may find it hard to remember past actions accurately (Yu 2014). Because questionable findings about PLC research will not inform us about the possible benefits for teachers or students, it is important to validate self-report data on teacher practice along with additional data sources such as direct observation (Penuel *et al*. 2007).

As Desimone (2009, p. 188) acknowledges, observations are regarded as 'the most unbiased form of data.'

In the reviewed articles, the authors also differed in how they attributed the role of PLCs to shifts in teacher practices and knowledge. Some studies focused only on case-study methods of studying PLCs and others used PLCs as a component of PD for enhancement. Within these PLC-enhanced PD, some studies did not specify the role of PLCs in the PD model nor how teachers were engaged in PLCs. This lack of information prevented us from understanding whether or not, for example, an increase in teacher DCK stems from participation in PLCs. The other flaw is that some studies did not explain the structure of PLCs in a clear and detailed way. We believe that essential features such as how teachers specifically studied student learning should have been presented to the readers. This information would enable readers to better understand the impacts of PLCs on teaching and learning science.

These observed methodological issues in the articles under review also have implications for the ways in which the readers interpret the report findings. Researchers should be careful in reporting their methods and data-gathering measures with a clear description of the possible limitations. Several of our studies lacked important information in the methods section, such as weakly defined research design, selection of teacher participants (as volunteers) and the nature of interviews. All such information is needed for researchers to evaluate the credibility of our findings in the review.

In conclusion, we have provided a review of empirical studies that reported the impact of PLCs on science teachers. We claim that, provided particular conditions – a focus on student learning and collaboration – PLCs might have the potential to change teachers' habits of mind and capacity to improve student learning. The most important condition for fully-functioning PLCs is the focus on student learning. Yet we believe that further research is still needed to more fully justify the expansion of PLCs for science teachers and rigorous research designs are needed to provide information to increase our knowledge of PLCs and their role in PD among science teachers. Many questions still remain unanswered: what are best practices for engaging science teachers in PLCs; how did outside experts and teachers negotiate roles within the PLCs; and what is the relationship between student achievement and teachers' participation in PLCs that attend to students' work?

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