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STEM education K-12: perspectives on integration

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Abstract

This commentary was stimulated by Yeping Li's first editorial (2014) citing one of the journal's goals as adding multidisciplinary perspectives to current studies of single disciplines comprising the focus of other journals. In this commentary, I argue for a greater focus on STEM integration, with a more equitable representation of the four disciplines in studies purporting to advance STEM learning.

The STEM acronym is often used in reference to just one of the disciplines, commonly science. Although the integration of STEM disciplines is increasingly advocated in the literature, studies that address multiple disciplines appear scant with mixed findings and inadequate directions for STEM advancement. Perspectives on how discipline integration can be achieved are varied, with reference to multidisciplinary, interdisciplinary, and transdisciplinary approaches adding to the debates. Such approaches include core concepts and skills being taught separately in each discipline but housed within a common theme; the introduction of closely linked concepts and skills from two or more disciplines with the aim of deepening understanding and skills; and the adoption of a transdisciplinary approach, where knowledge and skills from two or more disciplines are applied to real-world problems and projects with the aim of shaping the total learning experience.

Research that targets STEM integration is an embryonic field with respect to advancing curriculum development and various student outcomes. For example, we still need more studies on how student learning outcomes arise not only from different forms of STEM integration but also from the particular disciplines that are being integrated. As noted in this commentary, it seems that mathematics learning benefits less than the other disciplines in programs claiming to focus on STEM integration. Factors contributing to this finding warrant more scrutiny. Likewise, learning outcomes for engineering within K-12 integrated STEM programs appear under-researched. This commentary advocates a greater focus on these two disciplines within integrated STEM education research. Drawing on recommendations from the literature, suggestions are offered for addressing the challenges of integrating multiple disciplines faced by the STEM community.

Keywords: STEM integration, STEM research, Multidisciplinary, interdisciplinary, and transdisciplinary integration, Mathematics education, Engineering education

Background

International concerns for advancing STEM education have escalated in recent years and show no signs of abating. Educators, policy developers, and business and industry organizations, to name a few, are highlighting the urgency for improving STEM skills to meet current and future social and economic challenges (e.g., Caprile et al., 2015; Honey et al., 2014; Marginson et al., 2013; Prinsley and Baranyai, 2015; The Royal Society Science Policy Centre, 2014). The almost universal preoccupation with STEM education in shaping innovation and development is evident in numerous reports. In the USA for example, the 2013 report from the Committee on STEM Education stressed that "The jobs of the future are STEM jobs," with STEM competencies increasingly required not only within but also outside of specific STEM occupations (National Science and Technology Council, 2013, p. vi). Developing competencies in the STEM disciplines is thus regarded as an urgent goal of many education systems, fuelled in part by perceived or actual shortages in the current and future STEM workforce (e.g., Caprile et al., 2015; Charette, 2013;

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Hopkins et al., 2014; The Royal Society Science Policy Centre, 2014), as well as by outcomes from international comparative assessments (e.g., OECD, 2013).

Although global interest in STEM from educational and workforce perspectives has proliferated in recent years, the acronym was coined in the USA during the 1990s by the National Science Foundation (USA). The combining of the disciplines was seen as “a strategic decision made by scientists, technologists, engineers, and mathematicians to combine forces and create a stronger political voice” (STEM Task Force Report, 2014, p. 9). Since this time, the debates and dilemmas surrounding STEM employment shortages and STEM education in general have compounded.

Perspectives on the nature of STEM education and on the competencies requiring development are mixed, however. With the increased focus on STEM integration (e.g., Honey et al., 2014; Johnson et al., 2015), it appears timely to consider issues pertaining to STEM and its disciplinary integration and consider some research recommendations for advancing the field.

Perspectives on STEM and STEM integration

One of the problematic issues for researchers and curriculum developers lies in the different interpretations of STEM education and STEM integration. As indicated in numerous articles, STEM education has been defined variously ranging from disciplinary through to transdisciplinary approaches (e.g., Burke et al., 2014; Honey et al., 2014; Moore and Smith, 2014; Rennie et al., 2012; Vasquez, 2014/2015; Vasquez et al., 2013). In acknowledging the lack of an agreed-upon definition, the California Department of Education (2014) provides a broad perspective on STEM education, namely, “[STEM]… is used to identify individual subjects, a stand-alone course, a sequence of courses, activities involving any of the four areas, a STEM-related course, or an interconnected or integrated program of study” (http://www.cde.ca.gov/PD/ca/sc/stemintrod.asp).

In his editorial for the journal’s first issue, Yeping Li introduced the publication as “a brand new, forward looking journal that will add the multidisciplinary perspectives needed to complement current disciplinary-focused journals in the field of STEM education” (Li, 2014, 1:1). In doing so, Li emphasized the need for researchers to “span disciplinary boundaries.” Boundary crossing is a primary feature of integrated STEM perspectives, although the extent of disciplinary crossing in definitions of integration varies considerably. In their National Academies Press report, *STEM integration in K-12 education: Status, prospects, and an agenda for research*, Honey et al. (2014) provide a basic definition of integration as “working in the context of complex phenomena or situations on tasks that require students to use knowledge and skills from multiple disciplines” (p. 52). A more comprehensive perspective on STEM integration is featured in Vasquez et al.’s work (2013; Table 1), where different forms of boundary crossing are displayed along a continuum of increasing levels of integration, with progression along the continuum involving greater interconnection and interdependence among the disciplines.

An increased commitment to interdisciplinary and transdisciplinary STEM integration has appeared in recent years in several US documents. For example, the STEM Task Force Report (2014) adopts the view that STEM education is far more than a “convenient integration” of its four disciplines, rather it encompasses “real-world, problem-based learning” that links the disciplines “through cohesive and active teaching and learning approaches” (p. 9). The Report argues that the disciplines “cannot and should not be taught in isolation, just as they do not exist in isolation in the real world or the workforce” (p.9). Likewise, the California Department of Education adopts the axiom that “the whole is more than the sum of the parts” in its call for an increased focus on STEM integration (http://www.cde.ca.gov/PD/ca/sc/stemintrod.asp). More in-depth connections among the STEM disciplines are further advocated in the US *Common Core State Standards for Mathematics* (http://www.corestandards.org/Math/) as well as the *Next Generation Science Standards* (http://www.nextgenscience.org/).

Given the various interpretations of STEM education and STEM integration, it is little wonder that confusion can arise when researchers and policy developers refer to STEM education but differ considerably in their perspectives. Although the STEM acronym was initially coined to highlight the importance of the respective disciplines, the interdisciplinary nature of the world in

Table 1 Increasing levels of integration (adapted from Vasquez et al., 2013)

Form of integration	Features
1. Disciplinary	Concepts and skills are learned separately in each discipline.
2. Multidisciplinary	Concepts and skills are learned separately in each discipline but within a common theme.
3. Interdisciplinary	Closely linked concepts and skills are learned from two or more disciplines with the aim of deepening knowledge and skills.
4. Transdisciplinary	Knowledge and skills learned from two or more disciplines are applied to real-world problems and projects, thus helping to shape the learning experience.

which we live and work demands a broadening of STEM education and research (Hoachlander, 2014/2015). Interdisciplinary and transdisciplinary approaches to STEM research are emerging in the literature; however, the presence of integration as a distinct field of study is in its embryonic stages (Honey et al., 2014).

Inequitable STEM discipline representations

Although each of the integrative approaches in Table 1 has value in advancing learning, as Vasquez et al. (2013) pointed out, a major concern is that of inequitable discipline representations in STEM research and learning outcomes (English, 2015; English and Kirshner, 2016; Hoachlander, 2014/2015; Honey et al., 2014; Marginson et al., 2013; Moore et al., 2014; Shaughnessy, 2013). As one example of this uneven representation, of the 141 regular papers presented at the 2014 STEM conference in Vancouver, 45 % were devoted to science, 12 % to technology, 9 % to engineering, 16 % to mathematics, and interestingly, the remaining 18 % were classified as "general" with several papers in this category addressing two or more of the STEM disciplines (http://stem2014.ubc.ca/presentations/).

As several researchers have lamented (e.g., Barrett et al., 2014; Honey et al., 2014), the effectiveness of integrated STEM education in developing students' knowledge of core content is relatively under-researched. More studies are needed to identify ways in which learning across the disciplines might be more evenly distributed so that student achievement in one area does not overshadow or reduce gains in others. As Marginson et al. (2013) expressed metaphorically, "we need to lift the level of the peaks of the STEM mountain range, and broaden and elevate the whole of the range at the same time" (p. 72).

While acknowledging that reference to science could be interpreted as encompassing the other disciplines, especially mathematics, the STEM acronym itself is frequently defined as simply "science" (e.g., Office of the Chief Scientist, 2014). Many nations also refer to the role of STEM education as one that fosters "broad-based scientific literacy," with a key objective in their school programs being "science for all" in efforts to lift science education in the elementary, middle, and secondary school curricula (Marginson et al., 2013, p. 70). As Marginson et al. indicated, STEM discussions rarely adopt the form of "mathematics for all," even though mathematics underpins the other disciplines: "the stage of mathematics for all should be shifted further up the educational scale" (p.70). Likewise, Shaughnessy (2013) warned of programs that are merely a STEM veneer, that is, where approaches do not genuinely integrate the disciplines and thus may be devoid of important learning especially in mathematics. Even the rise in engineering education, beginning in the early school years (e.g., Lachapelle & Cunningham, 2014), would appear to be oriented towards the science strand with less emphasis on mathematics. Hoachlander (2014/2015) reiterates the above concerns:

> Despite more than a decade of strong advocacy by practitioners, employers, and policymakers, STEM education in US schools leaves a great deal to be desired. In too many schools, science and math are still taught mostly in isolation from each other, and engineering is absent (p. 74).

Although several policy and curriculum documents are now recognizing the important role of the respective disciplines in STEM integration, including engineering, a focus on connecting core content knowledge and processes across the disciplines still appears limited.

Advancing integrated STEM education research

Given the global importance accorded to STEM achievements as measured by national and international assessments, it is not surprising that many nations are questioning the quality of their curricula and the strategic actions needed to enhance the STEM disciplines. If we are to advance STEM integration and lift the profile of all of its disciplines, we need to focus on both core content knowledge and interdisciplinary processes. Nations that enjoy high international testing outcomes as well as strong STEM agendas have well-developed curricula that concentrate on twenty-first century skills including inquiry processes, problem-solving, critical thinking, creativity, and innovation as well as a strong focus on disciplinary knowledge (English and Gainsburg, 2016; Marginson et al., 2013; Partnership for 21st Century Skills, 2011). The need to nurture generic skills, in-depth conceptual understandings, and their interdisciplinary connections is paramount.

Making STEM connections more apparent

Developing students' understanding and appreciation of how integrated content, skills, and modes of thinking interact, including how they support and complement one another, is not an easy task (Honey et al., 2014; Moore et al., 2014). As Moore et al. (2014) noted, just because these connections might be emphasized in a curriculum, there is no guarantee that students will identify them or make the connections on their own. Consequently, the desired integrated STEM learning may well be lost. Likewise with respect to mathematics, Shaughnessy (2013) stressed that the "M" must be made "transparent and explicit." We cannot assume that all students will "see" the mathematics that is inherent in a particular problem (p. 324). More research is called for on ways to help students make STEM connections more transparent and meaningful across disciplines, including how this might be achieved at different grade levels. At the same time, further research is required on ways of assisting teachers to foster these connections, especially when appropriate curriculum frameworks and resources might be lacking.

Targeting student outcomes

Research on student outcomes in STEM integration appears limited and inconclusive, especially from a long-term perspective. A number of research issues arise including how integrated STEM programs might encourage more student engagement, motivation, and perseverance (Honey et al., 2014). Unfortunately, Honey et al.'s review of research reports indicated that such aspects, especially from a long-term view, are rarely measured in evaluations of these programs. Their review revealed that "few data convincingly correlate integrated STEM education with student outcomes" (Honey et al., 2014, p. 136). This finding is of particular concern, especially with respect to students' achievements in each of the STEM disciplines at different grade levels. Studies have yielded varied results. For example, Becker and Park's (2011) meta-analysis of studies investigating the possible differential effects of integration types on students' learning showed a large effect size (1.76) when all disciplines were integrated. In contrast, the effect size for integrating engineering and mathematics was small (0.03), as was the case when mathematics was integrated with science and technology (0.23).

Given that a number of studies analyzed by Becker and Park (2011) did not report on students' mathematics achievements, there remains the problem of inadequate research on the effects of integrative approaches on mathematics learning. Honey et al.'s (2014) review suggests that mathematics achievement is difficult to promote through STEM integration. If this is the case, then possible reasons for this need further investigation including whether a sequenced and structured approach to mathematics instruction hinders in-depth learning within STEM integration (Honey et al., 2014; Lehrer and Schauble, 2000).

Lifting the profile of mathematics in STEM integration

Recent concerns for the often diminished focus on mathematics include how its concepts and practices can contribute more effectively to an understanding of the remaining STEM disciplines (e.g., English, 2015; English and Kirshner, 2016; Fitzallen, 2015; Rennie et al., 2012; Shaughnessy, 2013). As Fitzallen (2015) highlighted, many reports claim that STEM provides contexts for fostering mathematical skills but these reports do not acknowledge the reciprocal relationship between mathematics and the other STEM disciplines. That is, the ways in which "mathematics can influence and contribute to the understanding of the ideas and concepts of other STEM disciplines" (p. 241) are not being addressed.

Coupled with the above is how we might best develop in-depth understanding of core mathematics content and processes within STEM experiences, while at the same time acknowledge that not all of mathematics can or should be learned within an integrated program (Honey et al., 2014). An inadequate focus on assisting students (and teachers) to recognize and make mathematics connections to the remaining disciplines further contributes to undermining mathematics learning within STEM. Making explicit the role of mathematics by repeatedly foregrounding the desired content and temporarily backgrounding other STEM content is one way in which the discipline might be advanced (Silk et al., 2010).

One example of how mathematics could provide core foundations and promote learning in the other disciplines is through a focus on mathematical literacy (English, 2015). Mathematical literacy was a core feature of PISA 2012 (OECD, 2013), where "meeting life needs… through using and engaging with mathematics, making informed judgements, and understanding the usefulness of mathematics in relation to the demands of life" were emphasized (Thompson et al., 2013). Mathematical literacy is foundational to STEM education, where skills in dealing with uncertainty and data are central to making evidence-based decisions involving ethical, economic, and environmental dimensions. Furthermore, with the exponential rise in digital information within STEM, the ability to handle contradictory and potentially unreliable online data is critical (Lumley and Mendelovits, 2012). Mathematics thus warrants increased recognition for its role in developing students' abilities to analyze and reason with data in making informed decisions and to engage in constructive debate about local and global issues (The Royal Society Science Policy Centre, 2014).

Lifting the profile of engineering in STEM integration

Although engineering across K-12 is emerging as a significant research area in its own right (e.g., Johri and Olds, 2014; Purzer et al., 2014; *Journal of Pre-College Engineering Education*), its presence within integrated STEM education deserves heightening. Engineering design and thinking, recognized as major components of K-12 engineering education, provide foundational linking processes across the STEM disciplines and are not just confined to engineering (Bryan et al., 2015; Lucas et al., 2014; *Next Generation Science Standards [NGSS]*, 2014; The National Academies, 2014). The NGSS specifically includes core practices and concepts from engineering alongside those for science, highlighting the interrelated nature of science and engineering education.

Broadening the role of engineering design and elevating it to the same level as scientific inquiry, the NGSS defines engineering design practices as those that all citizens should develop. Core features of engineering design are commonly described as comprising iterative processes including (a) defining problems by specifying criteria and constraints for acceptable solutions, (b) generating a number of possible solutions and evaluating these to determine which ones best meet the given problem criteria and constraints, and (c) optimizing the solution by systematically testing and refining, including overriding less significant features for the more important. Although there is increasing research demonstrating ways in which engineering can link the mathematics, science, and technology disciplines, mathematics still requires greater recognition in these experiences. In the next section, I provide one example of how both mathematics and engineering can be elevated within a modeling with data activity.

Engineering-based modeling with data

Modeling with data addresses the mathematical literacy domain addressed previously and comprises important learning features that facilitate different forms of integration including the interdisciplinary and transdisciplinary approaches of Table 1. As displayed in Table 2, modeling with data involves several features that support engineering within integrated STEM approaches including design processes, problem-solving and thinking, and testing, revising, and improving generated products.

In a collaborative research project (English and Mousoulides, 2015), 48 students from two sixth-grade classes (12-year-olds) in a K-6 urban public school in Cyprus worked a problem that addressed the 2007 structural failure of the 35W Minneapolis Bridge in Minnesota (adapted from Guzey et al., 2010). Developing models to rebuild the damaged bridge was a new experience for the students.

The problem commenced with an introductory session (35–45 min) where students studied a newspaper article about the bridge collapse as well as a video clip; they then answered questions to establish their understanding of the context and its data. In the second session (1 h 20 min–1 h 30 min), students were presented with two tables of data, together with the problem description. The first table of data comprised the key characteristics of the four main bridge types (truss, arch, suspension, cable-stayed), namely, the advantages and disadvantages of each bridge, the span range, the main materials used in construction, and the design effort (low, medium, high). The second table contained two samples of each of the major bridge types and some of their key features including the total length, the number of car lanes, the construction difficulty, and the building costs (in current values).

The problem stated that the Minnesota Public Works Department urgently needed to construct a new bridge in the same location given specific parameters including a highway length of approximately 1000 ft and a deck of four lanes with additional side lanes. Students were to assist the Department by creating a way (model) for comparing the different bridge types so as to choose the appropriate one to build across each span.

Working in small groups of 3–4 (mixed-achievement in school mathematics), the students drew on the given data to generate, refine, and document their models. The groups were to develop a model that (a) included calculating the cost for each one of the four bridge types (using the given characteristics of the four main bridge types) and (b) would enable selection of the best possible bridge type for the reconstruction of the collapsed bridge. All possible factors related to bridge type, materials used, bridge design, safety, and cost were to be taken into consideration. In the final session (40–50 min), each student group explained to their peers the models they had generated and their key findings, which they documented in a poster.

Data from 13 audiotaped student groups were analyzed together with videotapes of all whole-class discussions. The data sources also included students' worksheets and the researchers' field notes. Interpretive techniques (Miles & Huberman, 1994) were used to analyze the data, with detailed analysis of all data sources enabling identification of the mathematization and statistical reasoning processes students applied during solution. Students' phases of model development, reflecting aspects of engineering design, were identified through iterative refinement cycles of analyses to generate more in-depth evidence of students' learning (Lesh and Lehrer, 2000).

Students' models varied in the number of problem factors considered (cost per surface unit of bridge deck, aesthetics of the various bridge types, bridge design effort, construction difficulty, length), as well as in how they reasoned with these data, and in the sophistication of their models. Excerpts from one student group's model development, where they reasoned with multidisciplinary components, are presented next.

This group began the problem by excluding a truss-type bridge explaining that, "The collapsed bridge was a

Table 2 Features of modeling with data (adapted from English, 2015)

- Exploring, posing, and refining investigative questions within STEM contexts
- Applying discipline-based concepts and engineering design in formulating and solving problems
- Testing, revising, and improving products generated
- Planning and undertaking investigations
- Analyzing and representing data in multiple ways
- Developing, applying, and assessing evidence-based models
- Understanding informal inference involving variation and uncertainty
- Critically evaluating data-based arguments and conclusions
- Sourcing, evaluating, and communicating information
- Thinking in creative, flexible, and innovative ways

truss one" (student A) and "Selecting the truss type bridge would make people feel insecure and bring back all those bad memories" (student B). The group then decided that a cost model for ranking the different bridge types was needed, but after developing an initial model that involved calculating the average cost (money per ft^2) for each bridge type, they decided that it was not the most appropriate solution. The group concluded that the substantial variation in their results for bridges of the same type could be addressed by integrating more factors within their initial model:

Student C: Our calculations are correct. There is nothing wrong. The cost is very different.

Student D: There are other things (factors) that are important and influence the cost … for those (bridges) that are close to sea it is more difficult.

Student C: Yes, like in the Golden Gate Bridge. It is so expensive and not that long.

Student B: Cost is not proportionally related to the surface of the bridge (deck), but also the level of difficulty in constructability, just like in the Golden Gate, is an important factor.

On returning to the key characteristics of the four major bridge types (advantages, bridge span etc.), the group concluded that all types had their advantages as well as disadvantages. It was thus decided that a suitable bridge type could not be determined from this set of data alone. This realization prompted the next phase of model development as students examined further data. Students' reflections on their prior discussion regarding an initial cost model also contributed to their movement towards a more comprehensive model.

The group's next phase of model development involved a consideration of engineering, scientific, and societal factors. The group decided that these should be incorporated within their earlier model. These additional data included the necessary extra lanes for bridges, bikes, and pedestrians, as well as the difficulty level for each bridge construction. The last factor was determined by dividing the estimated final cost per square feet by 1.5 for the given examples of the four major bridge types. The group referred to this as the "difficult constructability" factor, which they specifically created to provide the same basis of comparison for all bridge types.

The refined model ranked the bridge types from cable-stayed as most favored, followed by the arch, truss, and suspension bridge types. In deciding on their final model, however, the students were aware of scientific and engineering issues and thus selected the arch type as the best possible solution. They were still concerned about the stability of a cable-stayed bridge for long-span bridges.

Students' reasoning in working the above problem illustrates how they drew upon multiple disciplinary features, reflecting Charette's (2014/2015) sentiments on STEM integration: "If we truly want students who can think critically, solve problems, and communicate their thoughts clearly, then some kind of systematic, cross-disciplinary instruction is required" (p. 82).

Discussion

In this commentary, I have argued for a greater focus on STEM integration, with a more balanced focus on each of the disciplines. Specifically, I have maintained that mathematics and engineering are underrepresented in studies claiming to address STEM education. Identifying ways in which we might achieve a more equitable representation of the disciplines is a complex endeavor, especially given the lack of a globally accepted definition of STEM education, as well as the different perspectives on and approaches to STEM integration within and across nations. Vasquez et al.'s (2013) continuum of disciplinary through transdisciplinary approaches to integration, with increasing interconnection and interdependence among the disciplines, provides one framework for addressing STEM integration. Developing and implementing integrated STEM programs, however, is challenging especially if one is to ensure that the respective core concepts and skills are given due attention. Different approaches to teaching each of the disciplines, such as a sequenced and structured approach to mathematics, could hinder some learning outcomes during integrated experiences.

Although STEM integration is receiving increasing emphasis in many curriculum documents and policy reports, there appears inadequate research that yields substantive evidence of desired learning outcomes. Existing studies of integrated STEM education rarely document in sufficient detail the curriculum or program being implemented including the nature of the integration and ways in which it was supported. The form of evidence collected to demonstrate whether the intervention goals were achieved is also frequently lacking (Honey et al., 2014).

Clearly, there remain many research questions regarding STEM integration, as documented by Honey et al. (2014) and others (e.g., Kimmel et al., 2014). In an effort to provide much-needed direction to future research, Honey et al. (2014) developed a descriptive framework of core features and subcomponents of integrated STEM education incorporating *goals* and *outcomes* for students and educators, together with the *nature and scope of integration* and features of *implementation* (p. 32). Emanating from this framework, their recommendations include as a necessary starting point a consistent use of terminology that establishes a common STEM language. The development and application of substantial theoretical frameworks, and a better delineation of the nature of STEM integration programs, including how evidence for learning is gathered and the types of learning supports provided, are also essential to advancing the field.

With respect to program implementation, I noted previously the need to investigate ways to make connections among the STEM disciplines more transparent for both students and teachers. One expectation of effective STEM education programs is that students are encouraged to make new and productive connections across two or more of the disciplines, which may be evidenced in improved student learning and transfer as well as interest and engagement. These learning outcomes require students to be competent with specific discipline content as well as discipline representations, together with "representational fluency" in translating among these representations (Honey et al., 2014, p. 144). These competencies may require teacher scaffolding especially for younger learners. The research of Dorie et al. (2014) demonstrated how appropriate adult scaffolding can promote the "natural" engineering talents of young learners. The question of how much scaffolding should be provided, however, warrants further investigation. English and King (2015) recommend that such support needs to be balanced in terms of establishing an understanding of core concepts and allowing students to apply this learning in ways they choose during problem solution.

Conclusion

Integrated STEM education continues to raise more questions than there are presently answers. It is hoped that this commentary has prompted further avenues for research and discussion on how we can advance the STEM field including keeping abreast of the exponential growth in technology. The multifaceted ways in which technological advances can enhance student outcomes are expanding rapidly (Johnson et al., 2013), opening up new directions and challenges in our STEM research endeavors.

Competing interests

The author declares that she has no competing interests.

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