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ANALYSIS

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The Network for Emergent Socio-Scientific Thinking (NESST): collaboration for a shared transformative future through STEM Education

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Abstract

Impact networks are formed to address complex social or environmental issues and are often needed to maximize human and financial resources, impact, and scale of individual organizations, including those serving students in Kindergarten through college (K-16). However, contrary to existing network models described by the literature, networks designed to address complex emergent socio-scientific issues such as climate change and biodiversity loss should themselves be emergent. This paper uses a critical analysis to outline our theory of change for one type of impact network—the emergent network—whose structure, function, and purpose are based on the emerging needs of its members and the needs of a changing world; and, whose members work across borders, disciplines, and generations to educate for a shared transformative future. We apply our theory to a case study called the Network for Emergent Socio-Scientific Thinking (NESST), which brings together people with a commitment to think differently about educating youth for the future outlined in the United Nations Sustainable Development Goals (SDGs). Together, through the lens of complexity theory and emergence, we reimagine the future of K-16 Science, Technology, Engineering, and Mathematics (STEM) Education for Sustainable Development (STEM4SD) and demonstrate what collaborative STEM education within the context of SDG 17 and SDG 4.7 can look like.

Policy and practice recommendations

- To achieve the UN Sustainable Development Goals, **emergent networks**, whose structure, function, and purpose are based on the emerging needs of its members and the needs of a changing world, can bring together young people, educators, scientists, researchers, community leaders, and museum and cultural professionals who work across borders, disciplines, and generations to educate for a shared transformative future.

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- **Emergent networks**, using the lens of complexity theory and its concept of emergence, can help individuals and organizations address the biggest global issues of our time as outlined by the UN Sustainable Development Goals. The Network for Emergent Socio-Scientific Thinking (NESST) is one example of an emergent network.

Keywords Impact networks, Emergence, Complexity theory, Critical analysis, STEM education for sustainable development, Socio-scientific thinking

Introduction

STEM education for sustainable development

In the last several decades, a "STEM education" movement has evolved from the idea of teaching four related disciplines—science, technology, engineering and math—to a worldwide sustainability effort that "includes both pedagogical and andragogical activities across all developmental levels—from pre-school to post-doctorate—in both formal and informal settings, which has grown into an international movement to promote peace and human progress" [42].

In 1989–1991, the concept of STEM was formulated by Charles E. Vela [42]. It was then popularized in the early 2000's by the National Science Foundation and Institute of Medicine in the United States (U.S.) to highlight the importance of creating a more scientifically literate citizenry and preparing students for the future workforce [21]. However, the vision for improving science literacy and diversifying the STEM workforce through more targeted STEM education efforts has been difficult to realize [35]. A combination of low-quality STEM teaching practices, rigorous grading, and failure to provide adequate student supports led many STEM undergraduates, especially those less likely to be represented in the STEM workforce, to switch majors or drop out of school altogether [17, 33].

In the mid-2010's, states across the U.S. began to adopt new college and career ready K-12 science standards based on the *Framework for K-12 Science Education,* which called for significant changes in how STEM is taught [36]. The Framework provided a vision of integrated STEM education where there was renewed focus on core ideas (or key points of content learning in each grade), scientific and engineering practices, crosscutting concepts (such as systems and patterns), and student-driven learning opportunities. The goal of the *Framework* was to ensure that all students actively engage in science and engineering practices and apply crosscutting concepts to deepen their understanding of core disciplinary ideas. A focus on inquiry-based STEM education and preparation for a 21st Century workforce was emerging across the globe [13, 20, 26].

Simultaneously, Education for Sustainable Development (ESD) was making headway globally [11]. ESD has two major goals: first, to support changes in knowledge, skills, values, and attitudes to enable a more sustainable and just society for all; and, second, to empower and equip current and future generations to meet their needs using a balanced and integrated approach to sustainable development [50]. Implementation of ESD has had mixed results to date [45]. A global survey conducted in 2023 by the Smithsonian Science Education Center (SSEC) and Gallup revealed wide disparities in the way teachers across five countries reported incorporating ESD topics into their STEM teaching, and many reported avoiding complex socio-scientific topics altogether, such as those outlined in the United Nations Sustainable Development Goals (SDGs) [44]. The survey also found that there was high variability in which nations were including socio-scientific topics (like climate action, clean energy, clean water, sustainable communities, and consumption and production) into the school curriculum. Of the five countries surveyed (Brazil, Canada, France, India, and the U.S.), educators in centralized education systems such as Brazil and India were more likely to report incorporating ESD topics in their curriculum compared to educators from decentralized education systems [7, 39]. Despite this variability, educators were consistent in their perspective that ESD was important because it made learning about STEM more meaningful by connecting students to their local communities and world [44].

To bring STEM education and ESD together, education experts from Germany, the U.S., and Chile co-authored a paper promoting the integration of ESD into the teaching of STEM in preK-12 classrooms with the goal of empowering present and future generations to use STEM skills and reflective reasoning to solve complex sustainability problems [40]. The authors promoted what they called "STEM Education for Sustainable Development" (STEM4SD) situated within a transdisciplinary framework—acknowledging that complex global challenges would require the integration of values, ethics, and worldviews into STEM teaching to build capacity for future generations [40]. A follow up paper by this same group described why **impact networks**—formed to address complex social or environmental issues—were crucial for achieving STEM4SD [30].

Purpose

Using a theoretical framework that draws on complexity theory and emergence, this paper employs a critical analysis to reimagine collaborative K-16 STEM education within the context of SDG 17 (Partnerships for the Goals) and SDG 4 (Quality Education), and in particular Target

4.7 (Sustainable Development and Global Citizenship). It outlines our theory for a new type of impact network—the **emergent network**—whose members work across borders, disciplines, and generations with a commitment to think differently about STEM Education for Sustainable Development (STEM4SD) and the need to educate youth for the shared transformative future outlined in the SDGs. To illustrate, we describe a case study of an emergent network called the "Network for Emergent Socio-Scientific Thinking (NESST)" and provide an overview of how the five pillars identified by NESST's founding members have been informed by complexity theory and emergence. We discuss why emergent networks are needed to achieve STEM4SD, giving voice to youth and educators who participate in the emergent network; and, we describe why emergent networks' structure, function, and purpose are not predefined, but are instead based on the emerging needs of its members and the needs of a changing world increasingly dependent on STEM knowledge, skills, values, and attitudes.

Theoretical framework

Many of the targets outlined in the SDGs can be classified as "wicked problems under conditions of complexity" [p. 975, 1, 54], balanced across both human and non-human (environmental) elements. In this section, we draw on complexity theory and the concept of emergence as our theoretical lens for why emergent networks are needed to bring together educators, youth, and other partners committed to STEM4SD.

Complexity theory

This paper is grounded in **complexity theory**, a perspective that sees the world as operating via complex systems, or dynamic, continuously evolving constellations or networks [46, 48]. Complex systems are comprised of many heterogeneous elements—both human and nonhuman—that interact in unpredictable ways, seemingly giving rise to spontaneous phenomena (or *emergences*) from chaos [46, 48]. For example, both human social activity, like education, and SDG issues, like climate change and biodiversity loss, are produced by complex systems comprised of many different actors, which, through local interactions, collectively generate emergent behavior that cannot be reduced to their constituent parts [9]. We particularly draw on insights from the theoretical work of scholars in the social sciences [e.g., 6, 10, 31, 46, 48] who have applied complexity concepts to both human and environmental activity. According to these scholars, complex systems have several characteristics important for understanding their operation: they exist on the *edge of chaos*, are *nested, porous*, and *interconnected*, are *self-organizing*, and produce collective *emergences*.

A key feature of complex systems is constant disequilibrium, which introduces measures of uncertainty and difference that force the system to respond [hence their dynamic nature). However, complex systems need *just* the right amount of disequilibrium so as not to plunge into total disarray. Waldrop [55], refers to this "just right" recipe as the "edge of chaos," where "the components of a system never quite lock into place, and yet never quite dissolve into turbulence, either…where life has enough stability to sustain itself and enough creativity to deserve the name of life" (p. 12]. As an example, students need to grapple with ideas in STEM activities to produce meaningful learning, so introducing some dissonance is necessary—but too much would likely result in student frustration and/or disengagement.

Complex systems are also **nested**—they are at once made up of smaller networks while also part of a larger Nesting doll of more macro-level constellations—and have fluid, porous boundaries that allow for interactions and exchange of information between systems [10]. Complex systems are therefore characterized by high levels of connectivity [34], both within and without: they are comprised of a number of interacting heterogeneous human and nonhuman elements while also shaping and being shaped by elements from other connected systems—all at the same time [10]. As an illustration, classrooms are systems within larger school systems, which are in turn part of district systems and policy systems. While system interactions are unpredictable, behavior among and between elements and systems tends to create feedback loops [8], or exchanges of information in response to particular system behaviors which either correct or amplify the behavior.

Because of the high level of connectivity and collective behavior, complex systems are decentered—there is not a core entity controlling the system. They are therefore considered to be "self-organizing" or autopoietic [32], although science and technology studies scholars like Haraway [19], have suggested that this collective organizing should not be labeled "auto" (self) but rather "sympoietic" (emphasizing the collaborative part of the co-making). This co-organization or sympoiesis, spurred by interactions, system changes, and forms of disequilibrium, gives rise to new *emergences*.

Emergence

Emergence, which is considered the most significant feature that distinguishes complex from non-complex systems [5], refers to collective scientific phenomena or behaviors in complex adaptive systems that are not present in their more simplistic individual parts. The concept of emergence has been applied to understand new developments across multiple fields—physics, biology, fine arts, and philanthropy, among others.

From the discovery of novel ordered states in quantum matter to eggs cooking, birds flocking (e.g., starlings), collective behavior in ant colonies, the development of consciousness in infants, the latest measurements on the early universe, or global climate change—emergence is all around us [57]. Emergences are co-evolutions of the whole [9], not additive or cumulative, but qualitatively different behaviors or activities that are not attributable to individual elements of the system, nor could be predicted from initial conditions [34, 46, 48].

Complexity, STEM4SD, and emergent networks

Complex systems and its concepts, such as emergence, are highly relevant for STEM4SD. Because STEM4SD is characterized by multi-dimensional or "wicked" problems, the understanding that interactions between people and matter and the environment lead to unexpected consequences and unpredictable behavior (i.e., emergences) is essential for all students as they explore the complexities of the natural and man-made world [29]. For instance, changes in the Earth's climate involve complex interactions between the atmosphere, the ocean, and human behavior (connected systems), which have unexpected effects on global temperatures, migration patterns, rainfall, sea-level rise, disease, and more (the emergences from interactions within and among those systems). This kind of emergent socio-scientific thinking is key to teaching climate change and the related crosscutting concepts of patterns, cause and effect, systems, and energy and matter [36].

However, the teaching of STEM4SD content and skills is not enough. The immensely complex socio-scientific issues (such as climate change) of STEM4SD cut across many different dimensions—economic, social/cultural, environmental, ethical, and political—and require discussions and solutions that consider many different perspectives. Therefore, we also suggest that complexity theory and emergence are useful for thinking about networks that are attempting to influence related educational knowledge and practice, such as impact networks. Impact networks bring people together for shared purposes, such as addressing complex social or environmental issues. They are non-hierarchical with minimal viable structure; support every node in the network; and allow for the ongoing development of a resilient web of relationships, with shifting dynamics, diverse perspectives, and distributed leadership that can respond to change [12, 28, 51].

Impact networks have different functions (e.g., learning networks, movement networks, action networks, scale networks, and resilience networks) [30], which tend to have a form and a structure that can be defined by their degree of connections. They also have some form of centrality, where members are connected in some way: centralized, decentralized, or distributed [3], with critical and central specific nodes in the network [30]. However, in this critical analysis, we argue for a new type of impact network informed by complexity theory and emergence—that is, an **emergent network**—whose structure and function emerges from its members who collaborate to solve complex emergent issues.

While most social impact network types focus on the function (action or operation) or purpose (the reason or outcome of the network exists) [12, 30, 43], we argue that an **emergent network** has no particular pre-defined function, and has no singular pre-defined purpose. Instead, an **emergent network** is constantly shifting as the sum of its member parts defines the whole and the complex socio-scientific issues of a changing world continuously emerge. We argue that networks designed to address complex emergent socio-scientific issues such as climate change and biodiversity loss should themselves be emergent, with the goals of the **emergent network** based on the needs of its respective member organizations and the needs of a changing world.

Methodology

For this paper, we examined the idea that complex socio-scientific issues require emergent networks. We applied a critical analysis of network activities to a case study of one such **emergent network**—the "Network for Emergent Socio-Scientific Thinking (NESST)"—using complexity theory and the concept of emergence. This case study was selected by the authors who are members of NESST. To present our findings from the case study, the authors asked the five self-identified subgroups (described later) within the network to reflect on their experiences as researcher-practitioners [18] and then asked each subgroup to critically analyze how they applied the theoretical framework of complexity theory and the concept of emergence to their practice. By conducting this analysis, we also wanted NESST members to improve their own instructional practice by embracing the theory of complexity and the concept of emergence as a fundamental approach to collaboration and partnership to achieve the SDGs.

This article builds on the multiple convenings and presentations given by the NESST members over the past two years [e.g., 47, 52] and related books and articles published by its members [e.g., 4, 14, 16, 30, 38]. The analysis of this case study is based on the contextualized experiences of each working group and its nested members, who are all part of the larger network.

Findings

Conceptualization and history of NESST as an "emergent network"

NESST was conceptualized during a convening in Colorado by a select number of scientists and educators, led by physicist Dr. David Pines, whose organizations are affiliated with the InterAcademy Partnership (IAP), which represents more than 143 national and regional member academies to support the special role of science (and science education) to seek solutions to address the world's most pressing challenges. The goal of NESST was to create a professional learning community (PLC) that catalyzes critical conversations about science education through the lens of complexity theory and emergence and allows its multi-sector members to identify solutions for engaging youth in understanding complex socio-scientific problems. The inclusion of youth as NESST members was an emergence that occurred as founding members of NESST collectively agreed that the integration of youth as active participants in the network was even more important than educating youth on sustainable development as a goal of NESST.

Realizing this ambitious vision required educators to engage in collaborative conversations around new pedagogies and instructional styles that cultivate hands-on, group learning experiences where students can explore the complex foundations of natural and manmade systems through the lens of **emergence**. But how do you create a network of partners, focused on complex emergent socio-scientific topics, when it is not clear who the members might be, what topics might be the most relevant of the day (such as COVID-19 or climate change), and what needs the members might have as they work across borders, across socio-scientific topics, and across generations? Our answer was to form a network that embraced the construct of emergence and focused on complex socio-scientific topics (that is, an **emergent network**).

Comprised of youth, STEM educators, scientists, university faculty, museum specialists, STEM professionals, and communities committed to thinking differently through the lens of emergence and complexity, NESST reimagines education for life on a sustainable planet. NESST is coordinated through its members who support and respond to the needs of each other. Youth Ambassadors, Teacher Ambassadors, and Scientist Ambassadors provide comprehensive perspectives and are nested within the larger complex system of partnership. Members do not pay a fee to belong. Everyone commits to NESST as an inclusive, collaborative, action-oriented, emergent community of practice [2] supporting STEM education for a sustainable future. NESST values, defined by the founding members, include:

- Commitment to education as a foundational element in a complex changing world
- Inclusion, collaboration, and connection
- Balancing evidence- and research-based practices in STEM education with the practical needs of an emergent socio-scientific world
- Honoring, embracing, and amplifying diverse ways of knowing and understanding
- Engaging and elevating youth as decision-makers in their own communities, and in their own education process
- Embracing emergence in the context of complex socio-scientific issues and in the process of developing the network
- Solutions-oriented approaches to issues of sustainability and other complex challenges
- Valuing process alongside outcomes

Applying complexity theory and emergence to NESST's five pillars

NESST's future-focused, transdisciplinary actions [24] aim to inspire optimism through local solutions to global challenges. To that end, the founding members of NESST self-organized and formed five key working groups (or "pillars") to advance STEM4SD through collaboration and partnership. Like most complex, nested systems, these working groups formed within the larger network, had porous boundaries, and allowed for exchanges within and across the five pillars: scholarship and research, resources and curricular materials, NESST as a professional learning community, engaging youth, and growing the network (see Figure 1). While we acknowledge that a different set of members may have developed a different set of pillars, the important point is that in an emergent network, the infrastructure is defined by its members, who self-organize, are interconnected, and produce collective emergences. The network is dynamic and changes based on the time, needs, and emergent topics addressed by the members.

In the next sections, we describe how each of the five pillars that emerged from this particular case study provided insights into our theoretical framework of complexity theory and emergence. Table 1 summarizes our findings by describing each of NESST's five pillars, outlining the unique methods each applied to NESST's work, and detailing how each pillar applied theory to practice.

Scholarship and research

To create a scholarly underpinning for the work of NESST, the Scholarship and Research pillar was formed to undertake a systematic literature review and create a glossary of NESST terms—including *complexity theory* and *emergence*—to explain how they might be useful for

Fig. 1 The Network for Emergent Socio-Scientific Thinking (NESST): five pillars

different community and education partners. The members used a complexity approach—for example, understanding the ways that different literatures are connected to and inform each other, and pointing out the absence of these connections in socio-scientific issues literature as a gap. After two years of virtual exchanges sharing insights on *complexity* and *emergence* and their application to STEM4SD, the members of this pillar decided to focus on exploring *socio-scientific thinking*, a term co-constructed by the members and identified as a yet-to-be explored area of STEM4SD [47]. While many of the members are prolific scholars, this is the first paper the members—including youth—have written together. By publishing works on STEM4SD, socio-scientific thinking, complexity, and emergence, and creating a glossary of terms through sympoietic co-making, NESST members are developing a shared understanding of the field of emergence and are contributing to a transformative approach to STEM4SD teaching and learning.

Resources and curricular materials
Recognizing the critical role of high-quality instructional materials in STEM4SD, our global survey of educators showed their desire for resources that integrate SDGs and other socio-scientific topics into their core curriculum [44]. To address this need, SSEC conceptualized NESST to connect the 41,000 educators and 4.7 million students across 88 countries who reported using its free STEM4SD curricular resource, *Smithsonian Science for Global Goals* [4, 16, 37]. With that, the Resources and Curriculum Materials pillar was formed, and over a two-year period—in collaboration with the InterAcademy Partnership (IAP)—the members of this pillar conducted a comprehensive analysis of other existing STEM4SD educational resources, initiated a collaborative vision-setting process, and developed a user-friendly decision-making tool for educators [22]. Central to the ethos of an emergent network was the belief in facilitating connections rather than making value judgments. Through the development of the tool, NESST members aimed to help educators find resources focused on emergent topics aligned with the SDGs—global climate change, biodiversity loss, clean energy, infectious disease—classified as "wicked problems under conditions of complexity" [p. 975, 1, 54].

NESST as a professional learning community
Our research also showed teachers across the globe want professional development experiences to advance their expertise in educating for sustainable development [44]. Therefore, a professional learning community (PLC) pillar emerged as a scaffold of NESST that stimulated cross sector collaboration to provide unique approaches to the complex challenges identified within the SDGs. The PLC pillar sought to leverage this unique opportunity by first looking inward to the international multi-disciplinary community of individuals within which NESST was situated. Drawing on the experience of the group's participation within NESST along with academic literature, the members of this pillar created a toolkit for the design,

Table 1 Applying complexity theory and emergence to NESST's five pillars

Position within NESST	Self-Identified working group ("Pillar")	Description	Unique methods applied	Theory applied
Foundational Pillar	Scholarship & Research	Provides a strong theoretical foundation for the network members' interactions	Conducted Systemic Literature Review on "socio-scientific thinking"	Used the sympoietic process of "co-making" to identify a shared understanding of terms related to complexity theory, emergence, and "socio-scientific thinking"
Central Pillars	Curricular Resources	Identifies high quality instructional resources for use in K-16 classrooms and communities to support students' ability to discover, understand, and act on complex socio-scientific issues	Developed a decision-making tool to analyze existing instructional resources that teach emergent socio-scientific topics to K-16 students	Facilitated connections rather than making value judgements; focused on resources aligned with emergent topics classified as "wicked problems under conditions of complexity" (such as climate change)
	Professional Learning Community (PLC)	Supports NESST members as they seek to advance their own practice and understanding of STEM4SD	Applied UNDG Theory of Change (consultative development, foundation in evidence, support for continuous learning) to create a toolkit for the design, delivery and development of an emergent PLC	Operated as a sympoietic community of purpose with a number of interacting heterogeneous human (members) and non-human (toolkit, articles) elements while being shaped by other pillars—at the same time
	Engaging Youth	Ensuring young people are part of the process of their own education, while also informing education for future generations	Analyzed transfer of knowledge through intergenerational learning	Encouraged disequilibrium and difference to force intergenerational partnerships within NESST, without forcing it into chaos; struck a balance between student-driven self-organized actions and adult support
Advancing the Network Pillar	Growing the Network	Advancing the network for continued growth and engagement	Developed matrix of activities across the five pillars to visualize interconnectedness	Promoted nested, dynamic, inter-connected, and self-organizing working groups who catalyze NESST's long-term objective of achieving education for a shared sustainable future

development, and delivery of emergent PLCs [27]. Underpinning the PLC's toolkit are three key principles in the UN's guide for "theory of change": (1) consultative development; (2) foundation in evidence; and (3) support for continuous learning [49]. These principles also undergird how the PLC operated as a sypoietic community of purpose [53]. Development of the toolkit involved a review of articles that focused on PLCs in sustainability education and beyond. Each member reviewed an article ($n=9$) and identified 'what works', 'what does not work' and 'key recommendations' in the context of successfully facilitating PLCs. This stage allowed members a chance to exchange information in response to particular system behaviors, which either corrected or amplified the behaviors in the unique context of each member's cultural context. It also highlighted the gaps between literature and experiences of being part of an emergent network. Each PLC exchange involved a number of interacting heterogeneous human elements (members) and non-human elements (toolkit, articles) while also being shaped by the other connected systems (pillars)—all at the same time [10].

Engaging youth

Dedicated to ensuring youth are part of NESST [4, 56], the Engaging Youth pillar's aim was to convene an international youth council that would increase youth awareness, understanding, and exploration of emergent socio-scientific issues in their own community, and ultimately develop capacity and agency for hopeful and positive action [15, 52]. Based on research demonstrating the power of intergenerational conversations [25], this group sought out ways to integrate youth voices and perspectives into the creation, development, and output of a Youth Ambassador program. These youth collaborated across generations, locations, and contexts through a complex dynamic system of partnerships that were continuously evolving. We encouraged the youth to interact in unpredictable ways, striking a balance between student-driven self-organized actions and adult support.

One such example of developing strong partnerships—not only between youth and adult members of NESST, but with the organizations the youth were affiliated—can be seen through the NESST Intern Exchange Program, where interns from the Smithsonian Science Education Center and the Christa McAuliffe Center were given resources to explore their own initiatives, collaborate with other youth, and learn about other sustainability work. In reflecting on their experiences, NESST interns Rachel Alcazar and Eliana Greenbaum noted the following:

> **Rachel***: As a young person, it is very rewarding to be part of NESST. Through this experience, there were many opportunities to learn from educators, professionals, and scholars in STEM and sustainability education. This intergenerational collaboration inspires youth to explore career paths and develop their socio-scientific interests. As people who are still in school, youth can provide insight and perspectives that may be missed or forgotten by adults when contributing to NESST's important conversations. Providing a space for youth to make connections and energize themselves to address local socio-scientific issues is valuable for the future since education and sustainability work are needed more and more over time. By hearing youth perspectives on how to teach sustainability and helping them to do local projects that contribute to the SDGs, NESST encourages leadership and aims to contribute to SDGs in a very sustainable and self-perpetuating way.*

> **Eliana***: There isn't just the problem that youth voices aren't considered, but also that it's difficult as a young person to know what work is going on in the professional world, how other youth are getting involved and how to get involved yourself. Being a NESST intern taught* **me** *that the connections made between people and their sustainability work is just as, if not more, important than the work itself. There is so much progress that can come from simply collaborating and educating each other on our individual work. A small-scale example of this was getting the chance to work with other interns. Their work focused on researching urban heat islands. This work was completely different from the sustainability education work done by NESST interns, and even though our projects were so different, it was an example of how beneficial diverse networks and connections are.*

A key feature of working across generations, contexts, cultures, and time zones is encouraging just the right amount of disequilibrium and difference to force the system made up of intergenerational partnerships to respond, without forcing it into chaos. As these two interns indicated, creating networks that include both youth and adults are important steps to making progress on SDGs 17 and SDG 4 (particularly, Target 4.7).

Growing the network

NESST is grounded in complexity theory and emergence, while remaining committed to fostering inclusivity, collaboration, and action-oriented objectives. To support this overarching goal, the Growing the Network pillar formed. Its primary focus is on attracting various community groups; maintaining and fostering efforts by different actors who each bring their own perspective to the table; existing on the edge of chaos; and promoting nested, dynamic, inter-connected, and self-organizing working groups who separately and collectively catalyze the long-term NESST objective of achieving a shared sustainable future. Members of the Growing the Network pillar apprehended the dynamic nature of its role and recognized that defining the needs and goals of future NESST members cannot solely rely on today's network members. Its role is vital for NESST's growth and sustainability and will be continuously challenged to maintain a constantly evolving NESST networking with the global community. A matrix of activities from the five pillars was developed to visualize the interconnectedness among activities and suggest ways to align them with the goals of growing NESST. By fostering collaboration, driving innovation, and measuring impact, the group contributes to NESST's mission of creating a sustainable and self-governing yet emergent community dedicated to socio-scientific thinking and STEM4SD.

Conclusion

In this final section, we draw conclusions about the significance of emergent networks like NESST by outlining the values and goals of networks designed to advance STEM education for sustainable development (STEM4SD). We also discuss the implications of such collaborations to achieve a shared transformative future.

Significance: values and goals of emergent networks designed to advance STEM4SD

In this paper, we argue that complexity theory and the concept of emergence were crucial in the governance and management of NESST as an **emergent network**, because the partnerships, relationships, and outcomes of the network could not be disaggregated to simply reflect the individual members. Instead, those who were part of the network were able to form a complex, dynamic system whose outputs could not be predicted. We also argue that NESST and other emergent networks like it can be successful in achieving both SDG 17 and SDG 4 (in particular, Target 4.7) if they place value on bringing together individuals and groups who are committed to building learning environments where its members learn that:

- Emergent strategies are needed to solve complex problems [41].
- Whole-system thinking requires a transdisciplinary approach and a cross-pollination among disciplines, noting that all parts of a system interact to form a more cohesive whole [24].
- Learning emerges from complex behavior and can take place anywhere and is lifelong [46, 48].
- Problems in one's own life have much in common with societal problems; in both cases there is almost certainly no single cause and no single solution, and that this is at the heart of emergent scientific thinking [41].
- The value of collaboration and teamwork includes developing global connections to young people of their own generation through work on community-based projects [23, 33].

Members of emergent networks espouse to define the concept of emergent socio-scientific thinking as it applies to student thinking; create collaborative partnerships among key partners; bring together partners who can collectively seek funds to develop, implement, and test innovative ways to engage students in emergent socio-scientific thinking as it relates to complex problems that face the nation and world; and, communicate regularly and engage—as members–in emergent socio-scientific thinking. As our case study of NESST shows, the members of an emergent network exemplify a commitment to advancing key SDGs, including quality education (SDG 4), partnerships for goal achievement (SDG 17), reduced inequality (SDG 10), sustainable communities (SDG 11), innovation (SDG 9), and gender equality (SDG 5). By fostering collaboration and resource-sharing on a global scale, emergent networks can lay the groundwork for more inclusive and equitable STEM4SD practices worldwide.

There are, however, limitations to consider. For example, given their dynamic structure, emergent networks are difficult to establish (i.e., it takes time to understand the varied cultural context and needs of the members, both as individuals and as a collective); grow (i.e., you need to focus on depth over breadth when topics are complex); and scale (i.e., the network needs to give voice to the youth, educators, and others who are collaborating to transform STEM education for a sustainable future). The structure, function, and goals of emergent networks are not pre-determined; they are based on the make-up of the membership, so members who join, do so without any clear guidance on the path forward and the outcomes they will achieve together. NESST is only one example of an impact network that we would classify as an "emergent network." There may be other emergent networks; and scholars of impact networks may argue that all impact networks are inherently emergent, and therefore, classifying an impact network as emergent may seem redundant.

Implications

To achieve STEM4SD, emergent networks such as NESST must facilitate actions that bring the different efforts of the participating partners into a common framework. They must be willing to catalyze critical conversations on the role of emergence and emergent behavior in solving complex problems through convenings of engaged institutions, scientists, and science education innovators. Participants must inform, connect, and expand their activities based on the needs of its members. Through their collective impact, participants will demonstrate firsthand how socio-scientific learning emerges. The focus will be on cooperation and not competition. Emergent networks must engage more scientists, at every level of their careers, and in science education and give them the tools and guidance to do so effectively. They must raise the stature of outreach, public engagement, and formal and informal science education so that members can communicate and collaborate with one another across traditional and non-traditional boundaries.

By integrating SDG 17 and SDG 4 (with particular emphasis on Target 4.7) through the lens of complexity theory and emergence, NESST and other **emergent networks** like it can identify the grand challenges in engagement that need to be addressed to substantially increase the number of scientists, youth, science educators, university faculty, museum specialists, and industry partners who actively participate in science education, outreach, and communication, and make their engagement more effective and impactful. Together, through such collaboration, we can achieve a shared, sustainable future and demonstrate what collaborative STEM4SD education within the context of SDG 17 and SDG 4 (and specifically Target 4.7) can look like.

Abbreviations

ESD	Education for Sustainable Development
IAP	InterAcademy Partnership
K-12	Kindergarten through 12th grade
K-16	Kindergarten through college
NASEM	National Academies of Sciences, Engineering, and Medicine
NESST	Network for Emergent Socio-Scientific Thinking
NRC	National Research Council
PLC	Professional Learning Community
SDG	Sustainable Development Goals
SSEC	Smithsonian Science Education Center
STEM	Science, Technology, Engineering, and Mathematics
STEM4SD	Science, Technology, Engineering, and Mathematics Education for Sustainable Development
UN	United Nations
UNDG	United Nations Development Group
UNESCO	United Nations Educational, Scientific, and Cultural Organization

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Author contributions

"COD submitted the proposal, drafted the introduction, literature on networks, and conclusion, and serves as the Principal Investigator on the NESST grant. KS wrote the theoretical framework. KB and AD coordinated the writing of each NESST section submitted by the contributing authors, who equally contributed to the five pillar sub-sections. KB wrote the short overview of NESST. KS, AF, and KB wrote the Scholarship and Research section. AF and MS wrote the Resources and Curricular Materials section. VB and AD organized the section outlining NESST as a professional learning community. AM wrote the Engaging Youth section and oversaw the contributions of the student authors (EG and RA). AE and EO wrote the Growing the Network section. COD revised the publication using reviewer feedback. All authors contributed to the revision, read, and approved the final revised manuscript."

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Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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