Computational Thinking to Learn Environmental Sustainability: A Learning Progression

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Abstract
Current environmental problems are the primary focus for environmental science students and researchers. Sustainable environmental solutions require interdisciplinary thought processes, which pose difficulty to both students and the public. Computational thinking is an emerging term emphasized by progressive science curricula. Computational thinking and environmental science are both interdisciplinary by nature. Learning about sustainable environmental solutions requires students to partake in computational thinking. These ideas lend toward an expansive learning progression that encourages scaffolded and differentiated student progress in both computational knowledge and environmental knowledge. The learning progression, which emerges from the conceptual framework, emphasizes the spheres of sustainability, research, education, and economic perspectives to support environmental science learning through computational thinking. Computational thinking emphasized by the computational components (input, integration, output, and feedback) support learning about environmental solutions within the learning progression. The learning progression promotes application and implications for educators, students, researchers, and environmental scientists.

Keywords Environmental education · Sustainability · Computational thinking · Learning progression · Interdisciplinary

Introduction
Gus Speth who was the former Dean of Forestry and Environmental studies at Yale University and top U.S. advisor on climate change claimed: “I used to think the top environmental problems were biodiversity loss, ecosystem collapse, and climate change.” He was hopeful that 30 years of science advancement would lead toward environmental solutions. “I was wrong. The top environmental problems are selfishness, greed, and apathy.” He now feels that alongside the science “We need a cultural and spiritual transformation… We scientists don’t know how to do that” (Trudgill, 2022, p. 6). Environmental Science (ES) is a unique field in which its participants study interactions within and between various disciplines (Grundmann & Rodder, 2019). The pace of efforts to combat environmental problems such as climate change, ecosystem degradation, and resource depletion is slow; therefore, environmental and health problems continue to grow more rapidly than society’s ability to identify and correct them. As a result, ES terms such as environmental worldviews (Miller & Spoolman, 2012) and the precautionary principle have arisen (Kriebel et al., 2001) to emphasize the overall theme of sustainability.

A change in public perceptions which systemically integrates various domains such as economics, law, and cultural factors is essential for environmental solutions (Valero et al., 2021; Bosselmann & Engel, 2010). This is particularly important due to the increase in prevalence of science denial (Sinatra & Hoffer, 2021). Both the physical sciences and economics have framed current public perspectives on climate change (Grundmann & Rodder, 2019). In parallel to increased public concern, advanced technologies and data management have become integrated into environmental studies (Hernandez et al., 2012). For the technology revolution to be useful toward sustainable solutions, scientists, researchers, educators, and professionals (Valero et al., 2021) should consider various domains and sociocultural perspectives (Van Kerkhoff & Pilbeam, 2017). Evolving technology provides innovative avenues for scientists to explore our natural world, while educators are expected to lay the foundation in preparing students for these tasks using innovative methods such as computational thinking (CT) (National Research Council, 2013).
The most popular foundational definition of CT is the use of problem-solving methods that involve formulating solutions in ways that a computer can execute (Aho, 2012). Computational science is the intersection of computer science, mathematics, and a scientific discipline in which students use a combination of computational tools combined with mathematical principles to solve a problem using content knowledge (Shiflet & Shiflet, 2014). Student use of CT to learn ES is critical in the development of skills that support interdisciplinary sustainable environmental solutions. I posit that computational thinking should be used to teach environmental science.

CT is emphasized across curricula (Collegeboard, 2022; National Research Council, 2013), yet it is weakly defined for educators (Lyon & Mangana, 2020) and not commonly nor systematically used in classrooms. Computational science can be taught as a stand-alone subject; however, most curricula present it as a tool to emphasize specific content due to its interdisciplinary nature and importance within domains. The interdisciplinary nature of CT and having the potential to emphasize critical connections for ES students emphasize sustainability (Schoolman et al., 2012) and improve technological competency at a variety of levels. A gap in research exists in combining CT with ES overall (Gunkel et al., 2022), but also particularly considering the interdisciplinary theme of sustainability combined with computational complexity. For example, modern economics has not considered that economic benefits have natural costs and if technology is reoriented, environmental solutions are feasible (Valero et al., 2021). Tools, which emphasize interdisciplinary study using CT, can alleviate these associative difficulties for ES students.

The following conceptual framework approaches ES from (1) a sociocultural perspective which emphasizes current misconceptions, social and political contexts, emotions, and societies’ failure to think interdisciplinary; (2) as a subject of study from a teaching and learning lens through both the NGSS (Next Generation Science Standards; the k-12 US content standards which set expectations for what students should know and be able to do) and current ES classroom expectations; and (3) sustainability’s importance as an interdisciplinary backbone due to interrelated concepts for both study and practice (Moldan et al., 2012). The interdisciplinary aspects are supported by both ES problem-solving concepts (ESPSCs) and sustainability spheres (SS) as derived from a rigorous ES curriculum. The purpose of this framework is to emphasize that CT is critical for both ES learning and implementing sustainable environmental solutions. A learning progression (LP) combining CT and ES emerges from this framework. Environmental science content was paired with CT components to generate a LP that spans from simple toward complex. Implications of this LP for both education and research are presented in the conclusion.

Conceptual Framework

Sociocultural Perspective of Environmental Science

ES learning and decision-making take place in diverse social, political, and cultural contexts (Van Kerkhoff & Pilbeam, 2017). These sociocultural factors have an impact on science learning, truths, emotions (Lutz & White, 1986), and understanding and should specifically be considered when unpacking cross-disciplinary topics as related to sustainable learning. A scientifically literate society can better understand the mechanisms which lead to environmental problems, the urgency it poses as well as widespread impacts of global changes (Miller & Spoolman, 2012). Scientifically literate citizens are those who consider that natural capital (the world’s stocks of natural assets) matters, our ecological footprints are large and expanding, and ecological tipping points are irreversible (Miller & Spoolman, 2012). Scientifically literate individuals are more likely to advocate their position on controversial science topics (Drummond & Fischoff, 2017), and this is particularly important with increased technology use.

Durnova (2019) redefines truth in our society today as a negotiation in public discourse between the interplay of values, beliefs, and facts and claims that unveiling emotion’s role in knowledge-making is imperative. Public misunderstanding of science topics requires researchers to understand motivations and emotions while assessing misconceptions (Sinatra, 2022). ES is a discipline that can bridge the gap between social and natural sciences for students, alleviating overall public misconceptions of what science is and does. Assessing public conceptions on environmental topics may lend toward solutions that are more realistic. There is a common misconception that emotions and science are mutually exclusive (Barbalet, 2002); however, this is not reality. Emotions do play a role in the scientific process (Sinatra et al., 2014) and an even larger role than knowledge specifically for ES learning (Carmi et al., 2015); therefore, emotions should be addressed to get a true understanding of learning and decision-making in ES (Barbalet, 2002). Environmental conflicts are based on differing logical viewpoints, the individuals’ engagement on a topic, and their related emotions. Buijs and Lawrence (2013) claim emotions are sources of diverging views, influential in processing information and a motivation for social movements. In ES classrooms where emotions are common, learning some emotions can broaden understanding while others can narrow understanding (Quigley, 2016). Computational thinking can be used as a tool to facilitate scientific and logical discussions while maintaining awareness of sociocultural differences and emotions through the use of LP’s and proper scaffolding.

In order to solve environmental problems, they must first be fully articulated and adjudicated through political means before science can play an effective role in resolving them (Sarewitz,
is the students’ willingness to assess what they know about the interdisciplinary nature or complexity of these issues (Higgins, 2019). In some cases, prior knowledge is a barrier to conceptual change, especially in dealing with misconceptions (Sinatra et al., 2008). The Dunning–Kruger effect describes that some students tend to overestimate their own knowledge particularly when it comes to information literacy (Mahmood, 2016) and experience alone does not lead individuals to more accurate self-assessment (Schlösser et al., 2013). Science has always required its participants to look at evidence in front of them in order to seek and acknowledge truth, especially in the light of new evidence (Durnova, 2019). Environmental scientists have access to contemporary arrays of data such as NOAA’s (National Oceanic and Atmospheric Administration) climate data or The National Center for Environmental Information, new ways to access the public, and innovating software and progressive modeling and visualization systems.

Easterbrook (2014) claims that technology, human behavior, and environmental impacts are highly inter-related and systems thinking is essential in driving realistic sustainable solutions. Society’s failure to think systemically is a critical weakness. Easterbrook (2014) proposes that lack of knowledge related to CT is a major limiting factor in responding to environmental dilemmas such as climate change, food production, water management, pollution, environmental health, and the end of cheap energy. Our society should learn to address these dilemmas systemically rather than solving individual problems, as they cannot be approached independently.

### Environmental Science: as a Discipline

#### NGSS: Computation and Environmental Science

The NGSS have been adopted by 20 US states and four additional states use a similar framework. The NGSS is composed of (1) disciplinary core ideas, (2) cross-cutting concepts, and (3) science and engineering practices (National Research Council, 2013). Disciplinary core ideas and science and engineering practices focused on both ecosystem interactions and computational thinking in environmental science within standard HS-LS2 are.

1. “Ecosystems: Interactions, Energy and Dynamics” (National Research Council, 2013, p. 89) and
2. “Science and Engineering Practice 5: Using Mathematical and Computational Thinking” (National Research Council, 2013, p. 1).

According to the NGSS, students should specifically be able to.

1. “Use mathematical and/or computational representations to support explanations of factors that affect carrying capacity of ecosystems at different scales.” (National Research Council, 2013, p. 89),
2. “Use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales.” (National Research Council, 2013, p. 89).
3. “Use mathematical representations to support claims for the cycling of matter and flow of energy among organisms in an ecosystem.” (National Research Council, 2013, p. 89).
4. “Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere.” (National Research Council, 2013, p. 89).
5. “Evaluate claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable conditions, but changing conditions may result in a new ecosystem.” (National Research Council, 2013, p. 89) and
6. “Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity.” (National Research Council, 2013, p. 89).

Components within the NGSS such as environmental concepts, interdisciplinary learning, and emphasis on sustainability are heavily supported in curricula outside the USA. This encouraged the use of the NGSS as a standard lens to frame arguments throughout the manuscript. For example, The Australian Curriculum aimed to prioritize a cross-curricular policy which prioritizes sustainability (Skamp & Green, 2022).

One of the criticisms of the NGSS is that teachers play more of a passive role rather than an active one, as students become more involved in their learning through skill building, such as computational processes. Other criticisms of the NGSS include the lack of teaching a single specific “scientific method,” while others argue there is no single scientific method universally employed by all, just various processes (Emden, 2021). Science relies on various processes to develop scientific theories and all domains feature data and evidence as holding a primary position in deciding any issue. The NGSS heavily emphasizes assessment and evaluation of data. Gunkel et al. (2022) presented successful models for learning about water flow using both CT and the three cross-cutting concepts of the NGSS to emphasize an appropriate learning progression in environmental learning. Current research places emphasis on learning progressions, lessons, appropriate scaffolding, and assessment based around CT due to its emphasis within the NGSS (Covitt et al., 2020; Mayes et al., 2013; Rebitzer et al., 2003). The open-ended nature of the NGSS leaves research on CT vague and distant from educators.

As one would use scientific thinking to describe thinking about science, CT is used analogously to describe thinking about computational science. Collectively, Wing (2006) and Weintrop et al. (2016) emphasize CT as a cognitive process that intersects (1) science-specific content such as biology or environmental science; (2) mathematical principles such as Simpson’s diversity index, statistical comparisons, and correlations; and (3) computational tools such as software programs, data sets, and hard coding (Christensen & Lombardi, 2020; Shiflet & Shiflet, 2014). Computational components are defined as (a) input, (b) integration, (c) output, and (d) feedback (Weintrop et al., 2016; Christensen & Lombardi, 2020). Use of CT components lends to student embodiment and alleviation of misconceptions, and encourages learners to think like scientists (Wilenksy & Reisman, 2006). There are additional research gaps in computation-based assessment and domain-specific CT definitions in STEM education (Wang et al., 2021; Angeli & Giannakos, 2020). Research integrating CT and educational curricula usually emphasize computational thinking for student success, yet definitions, assessment, and scaffolding are not presented.

**Post-Secondary Environmental Science Expectations**

Edelson (2007) claims that although ES is most often offered as an elective for high school students, it is (1) important for students and society, (2) an opportunity for students to experience applied science, and (3) a particularly engaging context for learning fundamental science. According to the Education Commission of the USA, students are required to earn credits for two science courses (one life science and one physical science) in order to graduate. For example, in New Jersey, high school science requirements include 15 credits requiring one laboratory/biology life science; one laboratory/inquiry-based science course such as chemistry, ES, or physics; and a third laboratory/inquiry-based science course. Many districts in the USA offer ES as an alternative to physics and any instructor with a science certification can teach the course.

College Board is an organization that prepares and administers standardized tests that are used in college admission and placement. College Board offers advanced placement (AP) courses, in which high school educators teach college-level courses. The ES expectations of the LP were approached using the APES (AP Environmental Science) curriculum and standards. This curriculum specifically explores the interaction between society, economics, science, and culture (Collegeboard, 2022) while emphasizing sustainability. This curriculum is an international measure that standardizes what intro ES post-secondary students should be proficient in. APES is one of the most rigorous ES courses, which is globally standardized through international examinations. Student enrollment in AP courses has increased; however, over the last 20 years, test scores have been dropping drastically (Judson & Hobson, 2015). Using the NGSS combined with the APES standards is beneficial because it emphasizes both the requirements of k-12 teachers (NGSS) as well as a standardized rigorous introductory college course–level curriculum (APES) to support interdisciplinary ideas that can be addressed through CT.
According to the College Board, APES is one of the more popular science courses. About half of the students who take the APES examination pass with at least a three out of five or higher and the mean score is a 2.67. The mean score and passing rate are lower than average as compared to other AP examinations. Scores on the AP examination is the determining factor in if students earn college credits for the course. The topics within the course include ecosystems, diversity, populations, earth systems, land and water use, energy resources, pollution (atmospheric, terrestrial, and aquatic), and global change (Collegeboard, 2022). The skills and science practices students must be able to exhibit include concept explanation, visual representations, text analysis, scientific experiments, data analysis, mathematical routines, and environmental solutions (Collegeboard, 2022). By the end of the course, students should be able to (1) explain environmental concepts and (2) processes and models presented in written format; (3) analyze visual representations of environmental concepts and processes; (4) analyze sources of information about environmental issues; (4) analyze research studies that test environmental principles; (5) analyze and interpret quantitative data represented in tables, charts, and graphs; (6) apply quantitative methods to address environmental concepts; and (7) propose and justify solutions to environmental problems (Collegeboard, 2022). In the free response section of the final APES examination, students are to display their competence of the expectations listed above. Students are presented with authentic environmental scenarios, model/visual representations, and quantitative data and expected to (1) design an investigation, (2) analyze environmental problems and propose solutions, and (3) perform calculations as an environmental scientist would (Collegeboard, 2022). Computational thinking is required for students to mimic these practices and develop the related skills, yet CT skills themselves are not directly imbedded into the curricula.

**Sustainability as an Interdisciplinary Backbone for Environmental Science**

**Sustainability Spheres**

Sustainability is a major theme in ES which contains three spheres (Miller & Spoolman, 2012). The environmental sphere includes items such as natural resource use, environmental management, and pollution prevention. The economic sphere includes concepts such as profit, cost savings, economic growth, and research development. For example, Nikanorova and Stankeviciene (2020) introduced the circular economy which aims to save the environment by eliminating waste and efficiently using resources by applying recycle, reuse, repair, remanufacturing, and recycling strategies. The social sphere includes topics such as standard of living, equal opportunity, public awareness, equity, participation, and social cohesion (Murphy, 2012). Interestingly, these sustainability spheres are used within other disciplines (e.g., corporate pillars of sustainability).

The U.S. Army Corps of Engineers’ (2020) Sustainability Plan presented interactions between these three spheres. The interaction between the spheres of environmental and social aspects includes social-environmental concepts such as environmental justice and local and global natural resource stewardship. Standards of living should be bearable and topics include socio-ecological possibilities. The interaction between environmental and economic spheres includes the environmental economic concepts such as subsidies and incentives for use of natural resources. Ideas should be viable and should consider environmental necessities. The overlap between social and economic spheres include business ethics, workers’ rights, and fair trade which should be equitable and involve socio-economic solutions. Due to the nature of overlap, the study of ES requires case studies and consequences past laboratory or field work not only to understand the issues but also to successfully solve them. The APES curriculum emphasizes this holistic interdependent approach.

The Australian Curriculum, Assessment and Reporting Authority (2020) has put major emphasis on sustainability. This curriculum suggests that sustainability education develops the knowledge, skills, values, and world views necessary for people to act in ways that contribute to more sustainable patterns of living while it also allows individuals and communities to reflect on ways of interpreting and engaging with the world. This method of education is future oriented and focuses on protecting environments and creating an ecologically and socially just world through informed action (Australian Education for Sustainability Alliance, 2014). The curriculum also states that support of more sustainable patterns of living require consideration of environmental, social, cultural, and economic systems and their interdependence. Walker (2017) calls for greater attention and structure of environmental knowledge transmission to inform sustainability education to promote social sensitivity. Five ethical guidelines for a more sustainable society from Miller and Spoolman (2012) include the following: (1) do not deplete natural capital, (2) do not waste matter or energy, (3) protect biodiversity, (4) repair ecological damage, and (5) leave the earth in as good a condition as we found it.

Systems approaches have been applied to sustainability education (Porter & Cordoba, 2009; Easterbrook, 2014). Jarabeen (2012) presented a framework for teaching sustainability which was interdisciplinary. Thus far, research which lends to the development of ES learning progressions have a specific phenomenon covered; however, these progressions are not goal oriented in solving ES problems. As students consider and engage with computational components,
it allows them to bridge connections within and between domains (e.g., between biological levels in biological evolution learning for students; Christensen & Lombardi, 2020). In learning about sustainability, these domains include economic, societal, and scientific content and perspectives (Saviano et al., 2019). This is because computational outputs, and in turn feedback, should directly correlate to solving the problem at hand which achieved the highest levels of the learning progression. These ideas emphasize that scientists need to understand societal, cultural, and economic problems to holistically approach major scientific problems (Bosselmann, 2010). Computational outputs may provide data and insight as to what is occurring in the world, but solving these problems requires additional scaffolding by teachers to promote interdisciplinary skills for future problem solvers.

**Interdisciplinary Problem Solving Concepts of Environmental Science**

The introductory unit in most science courses presents the scientific method, introduces variables, and sets students up for understanding the nature of scientific content. Environmental science is unique in that most problems are presented due to what the earth or society requires of us. To solve environmental problems, we need not only traditional scientific perspectives but also (1) research concepts, (2) regulation concepts, and (3) education concepts. These three environmental problem-solving concepts (ESPSCs) are the major aspects required to approach ES problems. Relevant student-based examples are shown in Table 1. These concepts may be stand-alone or integrated. New approaches, such as citizen science, have emerged to solve environmental problems through merging various disciplines. For example, ozone monitoring has been done by the public to provide data to scientists, educate the public, and influence regulations (Agathokleous et al., 2020), and mobile apps have been developed to both monitor biodiversity and educate the public (Luna et al., 2018). TreeSnap is an application to connect tree enthusiasts and tree scientists (Crocker et al., 2020). The popular eBird application has been used by scientists to study seasonal and migration patterns of thrush (Chen et al., 2022). Johnston et al. (2019) have already started working on standardizing data from eBird applications so that citizen science can be more commonly accepted and used by scientists.

If a post-secondary student is studying to be an environmental scientist, coursework includes not only science and math classes, but also other domains such as environmental law or public health. When students are taught to think like scientists, this often includes design, execution, and analysis of laboratory and field work; however, a holistic approach applied to these designed studies is required to solve ES problems. The AP environmental curriculum emphasizes this approach.

**Table 1** Environmental science problem-solving concepts, aspects, and student examples

| ES problem-solving concepts | Aspects to approach problem | ES examples |
|----------------------------|-----------------------------|-------------|
| Research                   | Natural Science             | – Evaluation of a population over time  
 |                            |                            | – Relationship between physical environment and population (tolerance)  
 |                            |                            | – Test of an environmental solution to anthropogenic impacts  
 | Social                     | Cultural importance of a specific species or specific practice (which may affect environment)  
 |                            | Willingness to move toward sustainable solutions  
 |                            | Autonomous knowledge of personal ecological impacts  
 | Regulation                 | Law Development             | – Process of developing legislature that may provide environmental relief  
 |                            |                            | – How laws are implemented under different contexts  
 |                            |                            | – Evaluating the most pressing environmental concerns which require legislature to promote environmental justice  
 | Law Enforcement            |                            | – Methods for how laws can realistically be enforced  
 |                            |                            | – Evaluating impacts environmental laws have on economy  
 |                            |                            | – How companies may be affected vs. individuals due to enforcement  
 | Education                  | Formal                      | – How should environmental education be incorporated into curriculums?  
 |                            |                            | – Do environmental experiences contribute to sustainability?  
 |                            |                            | – Can feasible ES solutions be incorporated into curriculums?  
 | Informal                   |                            | – Are environmental scientists responsible for outreach?  
 |                            |                            | – What are the best practices to advocate for environmental regulations or more sustainable practices?  
 |                            |                            | – What are best practices to reach a majority of the public?  
 |                            |                            | – What misconceptions does the public have?  

Aspects is the lens students use to approach the environmental examples.
It is common for students and the public to incorrectly refer to scientists, public officials, or lawmakers etc. as they. Students typically are unable to distinguish between different types of science, research, and associated scientists including (1) university scientists who commonly partake in peer-reviewed science projects, teach, and write for grants, (2) government science including programs such as NASA and DEP as well as (3) industry science or science done by companies for profit. Understanding the difference between these three entities may better get students to understand the complexity of scientific problems from the research ESPSC.

For example, overfishing is a major global issue, and the following processes outline how NOAA fishing regulations are developed. (1) A council meets and gathers information from the public and stakeholders which include options impacts and opinions. (2) An oversight committee is developed. (3) Public hearings are held so the public can voice alternative. (4) A committee makes a recommendation which gets submitted to the council; if council decides to accept, it goes to NOAA fisheries management. (5) NOAA Fisheries reviews the council action for compliance with federal laws and then proposes a regulation by issuing a Notice of Proposed Rulemaking which is listed in the Federal Register (FR). (6) Once public comments are considered, NOAA revises the regulation as needed and issues a final rule which becomes published in the Federal Register. (7) The regulation is then codified in the CFR (Olson, 2005). This is a complex process related to the regulation ESPSC which also heavily involves the public and both the natural and social science research ESPSC.

Similarly, outlined processes are presented for declaring an endangered species. The current endangered species act requires that listing determinations be based solely on the best scientific and commercial information available based on items such as habitat destruction and disease. The species may not be listed based on economic impacts. The petition process starts when the U.S. Fish and Wildlife department receives a petition from a person or organization requesting that the species be listed as threatened or endangered (or reclassified and or delisted and these requests may be internal or external). Once the petition is received, there is a 90-day review where a positive finding may be initiated, the findings are made public, then it undergoes a status review and peer review. If a 12-month finding is warranted, the proposed rule is published and then it undergoes one or more public hearings where it either becomes withdrawn or published (U.S. Fish and Wildlife, 1997). This is a regulatory ESPSC although public education, involvement, and research are required for the completion of the process. Not only may these ESPSCs be explored separately but they may also be interrelated as shown in Table 2.

**APES Research Concepts** The APES curriculum requires students (practice 4: scientific experiments) to analyze research studies that test environmental principles. By the end of the course, students should be able to (1) evaluate the validity of conclusions from an ES source or research study (Skill 3.E), (2) identify a research method, design, or measure used (Skill 4.5), (3) describe an aspect of a research method design and or measure used (Skill 4.C), (4) make observations or collect data from laboratory setups (Skill 4.D), and (5) explain modifications to an experimental procedure and how it may alter results (Skill 4.E). Computational components may be used at a variety of levels to address each of these research skills (Collegeboard, 2022).

**APES Regulations Concepts** The APES curriculum requires students to identify and understand 10 environmental pieces of legislation and environmental policies. It is critical that students understand the impact of these policies and why they are necessary as well as why they were created as solutions. Students should also identify the impact of these policies on stakeholders as well as benefits and drawbacks of these solutions and how they are applied in different contexts (AP Environmental Science CED, 2021). For example, students are expected to understand why laws are created to protect endangered species (EIN) or the relationship between the availability, price, and governmental regulations as well as the influence that has on which energy sources people use and how they use them (ENG-3B.5). Students should understand strategies to protect animal populations including criminalizing, poaching, animal habitats as well as the associated legislation (Collegeboard, 2022).

**APES Education Concepts** Within big idea four of the APES curriculum (Collegeboard, 2022), students are to understand the role of cultural, social, and economic factors as it is vital to the development of environmental solutions. Students should identify that there are cultural services provided by the environment (ERT-2.B.1) and that humans’ populations change in reaction to a variety of factors including social and cultural factors (EIN-1). The curriculum requires students to identify how educational opportunity for women is connected to human population change (EIN-1.B.1).

In order to get students from understanding basic concepts within ES toward answering advanced ES questions with the goal of sustainability in mind, they need to make connections between the three spheres of sustainability as well as ESPSCs as shown in Table 3. Students should experience a logical yet pliable progression in both environmental content (sustainability spheres, ESPSCs), the relationship between content, and the integration of CT. Computational thinking can be used to learn sustainability, which is an overarching theme in ES. This can be done through the interdisciplinary nature of both ESPS, sustainability spheres, and computational tools.
A Learning Progression for Computational Thinking to Support Sustainability

Berland and McNeill (2010) describes learning progressions as requiring (1) a developmental progression for how understanding develops, (2) a progression in increasing levels of complexity of disciplinary knowledge and practices, as well as (3) use of pathways to support student learning. Analysis of disciplinary knowledge is essential for identifying big ideas in sustainability, which is the primary focus of learning progressions (Yao and Guo, 2016). The specific outlined progression is called learning sustainability through computational thinking (LSTCT) and is a modified version of Berland and McNeill (2010) framework which is grounded in both disciplinary practice and research on student learning. The LSTCT focuses on merging dominant ideas in sustainability through the use of CT practices specifically through the interdisciplinary nature of (1) the sustainability spheres and (2) the ESPSCs. The LSTCT is geared toward secondary and post-secondary students; however, very simple aspects and or very complex aspects of the progression may span well past those learning stages and can be used to direct students toward specific sustainability or computational aspects.

Computational Thinking Complexity and Environmental Science

Proper scaffolding is required for all aspects of learning; it encourages the interdisciplinary nature of sustainability, lending toward the mastery of ES as shown in Table 4. The LSTCT shows simple through complex aspects of the (1) instructional context, the (2) computational product, and the (3) computational process. Learners will naturally start their progressions at the simple end and progress toward the more complex end of each of these three components. Simple aspects relate to early learners whereas complex aspects relate to the types of processes that environmental scientists perform. Educators have the most influence on the instructional context as shown in Table 4. This scaffolding includes the context of both ES concepts as well as computational knowledge. Easterbrook (2014) encourages systems thinking to support sustainability in realistically solving environmental problems. The definition of CT implemented here is a practical tool that is systematically implemented and may be quantified to encourage this type of systems thinking.

The computational product is the resulting artifacts created by the student which can also be described as simple through complex. A computational product at the complex stage may involve software used by others in the field or predicted solutions to a problem (with supporting data) using interdisciplinary means whereas a simple product may be a single number representing a variable. Most research studies that claim to involve computation around a subject area
involve premade user-friendly interfaces such as Netlogo (simple to moderate) or video games (Kudayeva et al., 2018) rather than more advanced types of programs such as MATLAB or R.

The computational process describes the complexity in which students relate environmental concepts spanning from simple through to complex. Simple computation would involve premade computer simulations and video game interfaces to learn sustainability and ES concepts as well as elementary data manipulation within Google Sheets or Excel. Complex computation would be representative of problems and solutions that environmental scientists face such as finding source data, data manipulation, and statistical analysis using computer languages. The learning biological evolution through computational thinking learning progression (Christensen & Lombardi, 2020) emphasizes increasing the complexity of both the content (biological evolution) and the computation (simple, moderate, or advanced) gradually. The LSTCT uses a similar framework of increasing complexity but emphasizes the content of ES as well as computation.

### Spheres of Sustainability, Integration, and Computation

The three overlapping sustainability spheres can use computational components of input integration, output, and feedback to solve ES problems. For example, solely in the sphere of environmental research, the input may be temperature data and abundance of a certain economically important marine species. Integration may be the correlation between temperature and abundance of the species whereas the output may be a graph and corresponding data representing tight correlation. If students were asked how anthropogenic influence on water temperature might affect the economy of an area (economic sphere), they would need to initially understand the previous interaction between water temperature and fish abundance (as one potential approach to the problem). The learner would also realize that the input of temperature change or declining individuals (integration) of this economically important species would produce an output of a decline in profit for anglers in the area and increased prices for consumers using a supply-and-demand computational model (feedback). However, if the students were provided data (input) that anglers were losing money (economic sphere) based on declined catch of this economically important species, students would work in the opposite direction to identify the environmental cause (environmental sphere). Students need to identify which spheres and respective variables are associated with their input, integration, output, and feedback in order to better understand the holistic nature of ES as shown in Table 5. Introductory courses tend to focus on the science aspects (simple computation), but more advanced courses explore two spheres simultaneously such as environmental law or environmental economics. Students with a degree are expected to have studied multiple aspects of their major which can be emphasized through advanced computation.

| ES problem-solving concept | Sustainability sphere | Example | Specific student example |
|---------------------------|-----------------------|---------|--------------------------|
| Research                  | Environmental         | Environmental science research aimed at ecological sustainability | Student assessing a population change in fishes (e.g., growth, spawning, seasonality, behavior, population size, ecosystem effects, life history) |
|                           | Economic              | Research aimed at optimizing both profit and sustainability | Student identifying the economic impacts of a decline in a population of fishes |
|                           | Societal              | Research aimed at understanding societal and cultural norms and perspectives | Students identifying the cultural norms of a society which relies on fishing (e.g., public opinions, wants and needs) |
| Regulation                | Environmental         | Developing regulations aimed at promoting environmental protection | Developing fishing regulations (e.g., enforcement, corruption) |
|                           | Economic              | Developing regulations aimed at promoting economic and environmental protection | Developing fishing regulations which would minimize economic impacts (e.g., quotas, subsidies) |
|                           | Societal              | How understanding the cultural norms of a society may contribute to environmental regulations | Identifying how receptive the public would be to new regulations |
| Education                 | Environmental         | Identifying how environmental education should be incorporated into curricula | Identifying when and how students should learn overfishing |
|                           | Economic              | How company or individual choices may impact the economy and environment concurrently | Educating fishing companies about their most viable fishing options |
|                           | Societal              | Developing practical ways to inform public of environmental issues | Developing outreach programs on overfishing (e.g., museums, PSAs) |

The table represents environmental integration and solving environmental problems from a classroom perspective.

### Table 3  ESPSCs combined with sustainability spheres with specific student examples

| ES problem-solving concept | Sustainability sphere | Example | Specific student example |
|---------------------------|-----------------------|---------|--------------------------|
| Research                  | Environmental         | Environmental science research aimed at ecological sustainability | Student assessing a population change in fishes (e.g., growth, spawning, seasonality, behavior, population size, ecosystem effects, life history) |
|                           | Economic              | Research aimed at optimizing both profit and sustainability | Student identifying the economic impacts of a decline in a population of fishes |
|                           | Societal              | Research aimed at understanding societal and cultural norms and perspectives | Students identifying the cultural norms of a society which relies on fishing (e.g., public opinions, wants and needs) |
| Regulation                | Environmental         | Developing regulations aimed at promoting environmental protection | Developing fishing regulations (e.g., enforcement, corruption) |
|                           | Economic              | Developing regulations aimed at promoting economic and environmental protection | Developing fishing regulations which would minimize economic impacts (e.g., quotas, subsidies) |
|                           | Societal              | How understanding the cultural norms of a society may contribute to environmental regulations | Identifying how receptive the public would be to new regulations |
| Education                 | Environmental         | Identifying how environmental education should be incorporated into curricula | Identifying when and how students should learn overfishing |
|                           | Economic              | How company or individual choices may impact the economy and environment concurrently | Educating fishing companies about their most viable fishing options |
|                           | Societal              | Developing practical ways to inform public of environmental issues | Developing outreach programs on overfishing (e.g., museums, PSAs) |
Table 4 Increasing complexity of the instructional context, computational process, and product

| Dimension of LP | Simple | Complex |
|-----------------|--------|---------|
| **Instructional context** | – Environmental question/problem narrowly defined | – Environmental question/problem has multiple potential answers |
|                  | – Results are limited, predictable, predetermined, and/or scripted | – Answers can be used to generate new environmental questions |
|                  | – One sphere of sustainability | – Students define or develop data set which can come from multiple sources (e.g., database, public, sampling) |
|                  | – One ESPSC | – Data set(s) contain irrelevant data and require modification |
|                  | – Data set is provided and limited | – Little to no computational or disciplinary scaffolds |
|                  | – Computation and associated disciplinary content is highly scaffolded | – Multiple problem-solving perspectives |
|                  | – Simple platforms/interfaces (e.g., Google Sheets, Microsoft Excel, developed “plug and play” websites and software) | – Multiple spheres of sustainability |
|                  | – Data set is large and multifaceted and may require manipulation | – Interaction between spheres of sustainability and ESPSCs complex |
|                  | – Moderate computational and disciplinary scaffolds | – Computational representation is used (e.g., MATLAB, R, C++) |
|                  | – Multiple environmental problem-solving perspectives | – Computational representation has various forms which represent environmental content appropriately |
|                  | – Multiple pillars of sustainability | – Computational design is appropriate, understood and efficient for audience |
|                  | – Interrelationships between spheres of sustainability and ESPSCs are simple | – Student able to produce various types of open-ended written components describing computational process as it relates to ES content |
|                  | – Computational platform(s) involve some coding (e.g., SPSS, MAPLE) | – Student spontaneously develops computational ideas and outputs which are highly appropriate and relevant to ES |
|                  | – Environmental question/problem has multiple potential answers | – Student able to describe input and data modification/synthesis is highly appropriate based on ESPSC and sphere of sustainability |
|                  | – Answers can be used to generate new environmental questions | – Student uses highly appropriate combinations of mathematical/statistical components |
|                  | – Students define or develop data set which can come from multiple sources (e.g., database, public, sampling) | – Student develops new connections between computational aspects, spheres of sustainability, and ESPSC |
|                  | – Data set(s) contain irrelevant data and require modification | – Model has capability to reform itself and other models and may contain various output methods |
|                  | – Little to no computational or disciplinary scaffolds | – Student able to develop new computational processes and ideas associated with ES content |
|                  | – Multiple problem-solving perspectives | – Computational process and ES content can be shared with various audiences (e.g., public, ES scientists, economists, etc.) |
|                  | – Multiple spheres of sustainability | |
|                  | – Interaction between spheres of sustainability and ESPSCs complex | |
|                  | – Computational representation is appropriate but may not be efficient | |
|                  | – Multiple designs considered for output | |
|                  | – Student able to produce some written component describing computational process | |
|                  | – Some appropriate interrelationships between sustainability spheres and or ESPSCs | |
| **Computational product** | – Computational representation, design or output may be inappropriate | – Computational representation is appropriate but may not be efficient |
|                  | – Environmental content may inaccurate (e.g., involve misconceptions) | – Multiple designs considered for output |
|                  | – Student unable to produce written component describing computational process | – Student able to produce some written component describing computational process |
|                  | – Sustainability sphere may be represented inappropriately | – Some appropriate interrelationships between sustainability spheres and or ESPSCs |
|                  | – ESPSC may be represented inappropriately | |
| **Computational Process** | – Little to no data (input) modification or synthesis | – Moderate development and modification of input and adequate synthesis (e.g., data modification) |
|                  | – Weak or inappropriate development of applied ES integration (e.g., mathematics and statistics) | – Appropriate use of relevant ES mathematical/statistical component |
|                  | – Student unable to make connection spheres of sustainability/ESPSCs | – Student able to internalize connection between spheres of sustainability, ESPSC and computation (e.g., produce written component) |
|                  | – Computational representations unable to re-inform themselves (e.g., no feedback) | – Computational representations able to re-inform itself (e.g., some feedback) |
|                  | – Student unable to produce written component describing computational process, spheres of sustainability and or ESPSC | |
|                  | – Appropriate use of relevant ES mathematical/statistical component | |
|                  | – Student able to internalize connection between spheres of sustainability, ESPSC and computation (e.g., produce written component) | |
|                  | – Computational representations able to re-inform itself (e.g., some feedback) | |
|                  | – Moderate development and modification of input and adequate synthesis (e.g., data modification) | |
|                  | – Appropriate use of relevant ES mathematical/statistical component | |
|                  | – Student able to internalize connection between spheres of sustainability, ESPSC and computation (e.g., produce written component) | |
|                  | – Computational representations able to re-inform itself (e.g., some feedback) | |
|                  | – Student able to describe input and data modification/synthesis is highly appropriate based on ESPSC and sphere of sustainability | |
|                  | – Student uses highly appropriate combinations of mathematical/statistical components | |
|                  | – Student develops new connections between computational aspects, spheres of sustainability, and ESPSC | |
|                  | – Model has capability to reform itself and other models and may contain various output methods | |
|                  | – Student able to develop new computational processes and ideas associated with ES content | |
|                  | – Computational process and ES content can be shared with various audiences (e.g., public, ES scientists, economists, etc.) | |
For example, when considering the environmental example of overfishing, input may include data manipulation on temperature (or other anthropogenic changes), abundance of commercially important species, or obtaining data from local fishermen. Integration would include statistics, data management, and correlations. Output may be the correlation between temperature and species abundance, number of fish predicted, and amount of money lost based on declines. Feedback may involve exploration of population dynamics equations to drive future fish populations, the population numbers available to or from anglers, and the fish population changes’ predicted or real effect on economy. This example provides obvious interaction of sustainability spheres including the environmental sphere to environmental sphere, the environmental sphere to economic sphere, and the environmental sphere to economic sphere.

Another example includes assessment of declines in populations of sensitive shore birds due to anthropogenic habitat destruction. In this example, input may be the data on amount of available habitat, the current population size, or obtaining data from public willingness to conserve habitat. Outputs may be the correlation between amount of available habitat and the population change predicted based on available habitat whereas the feedback would be the population dynamics equations to drive future population sizes or bird population numbers based on human population. In these two examples, all three spheres are considered, and students are not only considering what the computational components are (i.e., what data is being used for input), but how they interact (using algorithms in integration) and what possible solutions are represented as their output. Complex programming allows students to immerse themselves in the interdisciplinary thought process and work through and in between these ES concepts. The students’ role based on ES knowledge and practices has computational components associated for infinite environmental examples as shown in Table 5. Computational components can also be addressed for both computational knowledge as well as student communication as shown in Table 5.

**Construct Maps: Sustainability Spheres and ESPSCs**

To break down the LSTCT, further four construct maps representing student learning of sustainability through CT are shown in Figs. 1, 2, 3, and 4. These maps represent what students should be learning between both the sustainability spheres as well as the ESPSCs and the interaction between them. These have been developed by adapting Plummer and Krajcik (2010) learning progression for lunar motion and spatial reasoning to sustainability and computational thinking. These maps represent a process of the complete interdisciplinary understanding of sustainability with increasing levels representing increased understanding. This idea of progression is supported by CT and the interdisciplinary nature can further enhance learning. Figures 1 and 2 focus on sustainability learning through ESPSCs focused on the AP environmental science curriculum.

Figures 3 and 4 focus on sustainability learning through the spheres of sustainability focused on the NGSS standards associated with ES concepts and computation. Each of these multi-leveled progressions (Figs. 1 and 3) can be used on their own or coupled with each other. As students navigate toward being able to solve environmental problems in the way that environmental scientists do, they attain skills toward the higher levels (level 5) and have mastered the lower levels (level 1). Computational thinking, specifically using the computational components, works as a tool for students to master these levels.

**Piping Plover Example**

Previous AP Environmental Science examination questions are made by professional educators, researchers, and scientists and involve intersections of sustainability spheres as well as ESPSCs. A previous free-response AP Environmental Science examination question (2019) presented a topographical map with data on nesting piping plovers (a shore bird) from 1999 to 2009. Students were to look at the presented data and identify (1) the preferred nesting habitat for piping plovers and (2) the change in number of piping plovers during this time as well as a likely reason for the change. These particular questions involve the intersection of the environmental sphere and research ESPSC.

The next prompt in the series reads: “Special beach restrictions can help piping plovers during nesting season” (AP Environmental Science Scoring Guidelines, 2019). Students were to describe one restriction that could reasonably be implemented to help prevent the destruction of plover nests by human actions. Accepted answers included.

“Post warning signs/fencing/barrier tape/boardwalks around the nesting area, place wire enclosures/other barriers over active nests, limit specified recreational activity on beaches with plover nests (prohibit kite flying, fireworks, etc.), implement motor vehicle restrictions (limit times, size of vehicles, raking, etc.) etc.” (AP Environmental Science Scoring Guidelines, 2019).

This question involves research ESPSC in knowing that beach restrictions “improve” plover populations, the regulation ESPSC through modification and implementation of public behavior, as well as the social sphere by understanding cultural perspectives (e.g., if these are feasible solutions).

The next prompt asked students to identify one economic impact (on coastal communities) due to of rising sea levels. Accepted answers included.
| Component of computational thinking | Input | Integration | Output | Feedback |
|------------------------------------|-------|-------------|--------|----------|
| Student role based on environmental scientific knowledge and practices | – Decision of variables to include | – Ongoing understanding of how variables contribute to body of knowledge or practice | – Which ES concepts and practices should be applied | – Use of results to support or contradict working ES knowledge |
| Sustainability sphere examples | – Water temperature and fish abundance data obtained from field sampling (e.g., from catch records) | – Developing tools (e.g., code) to relate water temperature and fish abundance | – Identifying the potential largest causes of poaching in an area |
| – Environmental – Economic – Social – Computational knowledge | – Understanding fish abundance data obtained from field sampling (e.g., from catch records) | – Using data from surveys (e.g., pre- and post-tests) to determine the types of information which generate public awareness | – Using results to support or contradict working ES knowledge |
| – Economic | – Developing tools to evaluate which fishes are experiencing highest demands | – Generating CCFP for various species | – Making quantitative predictions as to what methods would encourage OSY practices and future predictions of fish populations |
| – Social | – Obtaining data from the public to best understand awareness on climate change and its effects on fish populations | – Using culturally relevant data to develop hierarchy of educational methods to the public | – Making predictions about future fish populations |
| – Computational knowledge | – “Type” of variable (e.g., number, string, binary) | – Representing variables in a program | – Ensuring robustness of the solution |
| – Communication | – Complexity and interface type | – Use for solving problem only, or for communication/education purposes | – Developing a complete package |

**Table 5** Components of computational thinking and student roles.

Examples provide a better perspective of what interactions of the spheres and ESPCs may look like when combined with computation.
“Decrease of tourist revenue, decrease of property value, increase in damage to property, land, or infrastructure requiring repair or replacement, increase in insurance costs, loss of agricultural land or aquaculture operations resulting in financial loss, loss of fish nurseries in wetland areas leading to less revenue for commercial fisheries, increase in jobs in infrastructure/construction to repair damaged structures and properties, and increase in costs associated with preventative measures (building sea walls, raising building etc.).” (AP Environmental Science Scoring Guidelines, 2019).

This question involves the intersection of the economic sphere, social sphere as well as regulation ESPSC, and included consideration of both positive and negative impacts. There are multiple outputs which could be explored through computation.

The final question reads “Describe two methods that may be used locally to protect coastal communities from rising sea levels.” (AP Environmental Science Scoring Guidelines, 2019). This question is an applied approach, which considers all three spheres and all three ESPSCs. Accepted answers included “Raise structures to prevent water damage, plant vegetation along coastline to reduce erosion, replenish sand to address problems from erosion or increase width of beach, install pumps etc.” (AP Environmental Science Scoring Guidelines, 2019). This examination is a short comprehensive test, which reflects on a multitude of ES knowledge and skills that students develop through the year. It is evident that interdisciplinary thought processes are required to properly answer the example-based questions. The interdisciplinary nature of CT would emphasize the interdisciplinary nature of these problems through student use of the computational components: input, integration, output, and feedback.

Using the concepts maps from above (Figs. 1, 2, 3 and 4), a student may be at level 2 in the ESPSC aspect of the progression if they construct evidence from analysis of research studies (e.g., are able to quantify the change in piping plovers). Students may be at a level 4 in the sustainability sphere of the progression if they apply sustainably spheres to evaluate claims that the piping plover population would be changing due to unstable conditions (anthropogenic habitat changes). If this was a classroom activity rather than an assessment, students may use raw data provided by instructors and computational processes to derive their answers. If the level were simple, data would be provided with heavy scaffolding whereas a complex level would involve students doing their own research, or sampling to find data with little scaffolding and open-ended questions, lending toward more robust solutions. Environmental scientists identify their own methods and are often determining how their variables relate as well as the best ways to write code to derive their solution. Researchers often reach out to colleagues, such as a programmer or a chemist for tasks outside their realm of specialty. As the complexity of this assignment increases toward sustainable solutions, it becomes evident that CT is required in the learning process. Simultaneously, as students moved up in the progression, not only would the computational aspects become more complex but additional disciplines would be considered and eventually mastered.

Overfishing Example

Another free-response AP Environmental Science examination question (2006) prompted students with a graph showing the decline in the catch of ground fish (such as cod, haddock, and flounder) from George’s Bank from 1965 to 1995. This eventually resulted in a closure of large portions of the fishery. Students were initially asked to identify the 5-year period during which the greatest rate of decline in the fish harvest took place and perform calculations regarding the rate of decline in the fish harvest. Students were expected to identify the period of greatest decline from the graph and then perform calculations based on the data presented, a process which relies heavily on application and interpretation of the environmental sphere and research ESPSC.

The next question prompted students to choose and describe two commercial fishing practices as well as the role they play in the depletion of marine organisms. Accepted answers included.

“Bottom trawling drags a net along the ocean bottom and catches many non-target species and contributes to habitat destruction or purse seins are large nets drawn up to capture fish in large schools near the ocean surface which catches large quantities of fish (whole schools) or sonar which uses sound waves to locate fish which allows ships to locate large schools relatively quickly.” (AP Environmental Science Scoring Guidelines, 2006).

This question relied heavily on the understanding of the environmental sphere as well as the economic sphere and implied solutions that rely on both the economic sphere and regulation ESPSC.

The next problem asked students to: “Identify one international regulation or United States federal law that applies to the harvesting of marine food resources and to explain how that regulation or law helps to manage marine species.” (AP Environmental Science Scoring Guidelines, 2019). Accepted answers included the endangered species act which prohibits the harm or harvesting of endangered species or the CITES act which prevents trade of threatened or endangered marine species. This question prompts students to use the regulation ESPSC and apply knowledge from the social sphere to derive solutions.
**Fig. 1** Student understanding of sustainability via ESPSCs at increasing complexity

| Level 5 | Accurately explains sustainability through ESPSCs. Apparent similarities, differences and reasoning between solutions are described through environmental concepts using multiple lines of evidence. |
|---------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Level 4 | Construct applications to support explanations as to why environmental laws and regulations are created, the impact of these policies, why they are necessary and created as solutions to environmental policy (including effects on stakeholders and benefits and drawbacks of the solution). |
| Level 3 | Constructs explanations on the role of cultural, social and economic factors (as it is vital to the development of solutions) and that there are cultural services provided by the environment and that human populations change in reaction to a variety of factors including social and cultural factors. |
| Level 2 | Constructs evidence from analysis of research studies that test environmental principles (may include evaluation of the validity of conclusions of a source or research study, identification of research methods, design or measure used, description of an aspect of a research method design and or measure used, observations or collect data from laboratory setups, or explanation of modifications to an experimental procedure that will alter results). |
| Level 1 | Constructs explanations based on evidence for how ESPSCs lead to sustainability |

**Fig. 2** Computational thinking associated with ESPS. Students should be increasingly engaged in computation as a multi-step process of manipulating environmental information. Students will be exploring and producing evidence for sustainability as explained by the ESPSCs through computation.

Goal: Increasingly engaged in computation as a multi-step process of manipulating computational information. Students should be relating ES concepts associated with ESPSCs at various disciplines to describe sustainability using computational tools.

- Considers sustainability within different disciplines. The relationship between ESPS can be described through methods of computational thinking.
- Constructing explanations that connect sustainability across disciplines. Increasingly sophisticated interdisciplinary connections allows students to understand and distinguish how disciplines within ES will interact between ESPS.

Sustainability based frame of reference: increasing sophistication in understanding the interactions that take place in Environmental systems between disciplines.
**Fig. 3** Student understanding of sustainability via sustainability spheres

| Level 5 | Accurately explains sustainability through the 3 sustainability spheres using multiple lines of evidence. Students design, evaluate, and refine a solution(s) for reducing the impacts of human activities on the environment and biodiversity |
| Level 4 | Constructs applications using sustainability spheres which evaluate claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable conditions, but changing conditions may result in a new ecosystem |
| Level 3 | Constructs or supports explanations based on evidence using mathematical and/or computational representations based on evidence about factors affecting biodiversity and populations in ecosystems using sustainability spheres |
| Level 2 | Constructs evidence from sustainability spheres using mathematical and/or computational representations to support explanations of factors that affect carrying capacity of ecosystems |
| Level 1 | Constructs explanations based on how application of sustainability spheres leads to sustainability |

**Fig. 4** Computational thinking associated with sustainability spheres. Students should be increasingly engaged in computation as a multi-step process of manipulating environmental information. Students will be exploring and producing evidence for sustainability as explained by the sustainability spheres through computation. **Goal:** Increasingly engaged in computation as a multi-step process of manipulating computational information. Students should be relating ES concepts associated with sustainability spheres at various disciplines to describe sustainability using computational tools.

- Considers sustainability within different disciplines. The relationship between sustainability spheres can be described through methods of computational thinking.
- Sustainability spheres based frame of reference: increasing sophistication in understanding the interactions that take place in environmental systems between disciplines.
- Constructing explanations that connect sustainability across disciplines. Increasingly sophisticated use of embodiment allows students to understand and distinguish how disciplines within ES will interact between sustainability spheres.
The final question prompted students by claiming that the oceans of the world are often referred to as a commons. Students were to give an example of other such commons and asked to explain how human activities affect that commons as well as one practical method for managing said commons. Acceptable answers included the atmosphere or air, and students were to state the fact that humans increase greenhouse gases in the atmosphere by combusting fossil fuels and a practical method to manage this issue may include education of the public. This question represents a combination of the interaction of all three spheres as well as ESPSCs.

Although this overfishing problem was used as a problem on a comprehensive test, there are similar real-life ES problems that can be used as a teaching tool which require all spheres and ESPSCs. A current ES problem in Kenya results due to overfishing its local lakes. Women are prohibited from owning and operating boats. For women to make an income, they must obtain fish from fishermen, prepare the fish, and sell them at the market for a profit. “Jaboya” is a system in which sex is used for leverage to ensure that women obtain fish to sell. To develop a realistic solution to this problem, all three of ESPSCs as well as spheres of sustainability need to be assessed, applied, and interconnected. This particular issue also evokes emotions and opinions.

**Implementations for Research and Teaching**

The learning progression allows for student progression from simple toward complex sustainability solutions under the context of ES learning with CT. Computational knowledge as well as separate components (and interrelationships) of the spheres and ESPSCs may be explored by researchers. For example, certain interrelationships may be more contusive to learning than others or CT may be more useful for student learning of certain types of interrelationships. Researchers may quantify if and how students are learning sustainability and ES through computation, and these ideas may span across other domains. Although the examples at hand are geared toward high school and college students, the concepts may be expanded and differentiated based on how much students already understand about each of the ESPSCs, sustainability spheres, and computation. For example, some students (or professionals) may be versed in computation or a certain sphere, but the learning progression may be tailored for these student (or course)-specific limitations. In science laboratories, it is not uncommon for statistics or programming experts to help content knowledge experts (scientists). Ideally, with the use of the learning progression, ES students can learn the role of both.

Typical computational programs used by environmental scientists in the field include SPSS, R, MATLAB, and Python. Environmental science graduate students struggle with skills such as programming and implementing statistics to solve environmental problems (Theobald & Hancock, 2019). Various colleges have already identified that students must have knowledge of computer science in order to solve environmental problems in an increasing technological world. For example, the University of Rochester requires ES majors to take a computer science course and Northeastern University offers a Bachelor of Science in computer science/environmental science that focuses on solving the world’s environmental problems through technology. Integrating CT into domain-specific coursework may allow for greater student knowledge gains within specific fields lending toward overall realistic solutions to environmental problems.

Formal and informal educators are increasingly expected to use CT in their instruction. Although CT would benefit students in learning content, learning programming, the most robust and complex type of computation, is time consuming for both educators and students. Theobald and Hancock (2019) identified in learning programming in ES education, students’ required peer support, seeking out a singular “consultant,” and learning through independent research experiences (e.g., applying statistics in their own research). The LSTCT allows for educators and students to tailor their specific learning goals (with use of interdisciplinary concepts) while improving computational skills. Communication between educational researchers, environmental scientists, and educators may lend toward lessons based on the LSTCT. These lessons may be geared toward students based on their regional ES problems, specific interests, and ability levels.

**Conclusions**

Computational thinking should be used to learn sustainability, which is an umbrella theme in ES. The interdisciplinary nature of both ES (ESPSCs and sustainability spheres) and CT allows students to uniquely process information lending toward environmental solutions. Environmental Science solutions are interdisciplinary in nature, and application of interdisciplinary tools (i.e., programming in computational thinking) allow both students and practicing scientists to develop thinking about sustainable environmental solutions in an interdisciplinary manner. Computational thinking within domains has become an arms race due to technological advances. The LSTCT learning progression can allow both educators and researchers to become more efficient. If CT were implemented within science courses at an early age, it would encourage both enhanced understanding of ES as well as increased technological skill for college students. As applications and technologies are created for ES purposes, these advancements encourage the interaction and...
collaboration of researchers, educators, and students (especially if they all have computational skills).

The father of wildlife ecology, Aldo Leopold, claims that there are spiritual dangers in not owning a farm. He claims that people assume “breakfast comes from the grocery and that heat comes from the furnace.” One of the reasons we have environmental problems is because people do not understand the relationships between the earth and the everyday luxuries that we have, the related economic consequences, and resulting environmental changes. He also claims that one of the consequences of an ecological education is that once someone becomes educated about environmental problems, they live alone “in a world of wounds, much of the damage inflicted on land is quite invisible to laymen.” Using computation to support these connections is one of the most advanced solutions we have to support ES learning and sustainable solutions and, most importantly, protect the integrity of the planet for future generations.

Declarations

Informed Consent  Informed consent not required.

Research Involving Human and Animal Participants  No research on humans or animals.

Conflict of Interest  The author declares no competing interests.

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