


ANALYSIS

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How a multidimensional ecology education approach can enhance college curricula to implement the United Nations Sustainable Development Goals

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Abstract

Sustainability, i.e., effective management of natural resources to maintain ecological balance, is taught in formal post-secondary and nonformal education for students of all ages, but is often left out of the basic college and university life sciences coursework. To achieve the United Nations' 2015 Sustainable Development Goals (SDGs) we must provide students with ecological knowledge and skills to enhance sustainability. Beginning in 2014, Ecological Society of America (ESA) educators developed an integrated, four-dimensional curricular framework (Core Ecological Concepts, Ecological Practices, Cross-Cutting Themes, and Human-Environment Interactions) (4DEE) to generate ecologically literate college students. Here we investigated all possible connections between 4DEE and the SDGs, to determine whether instructors could teach both in context of one another - to the betterment of both sustainability and ecology education. Analysis of the subcomponents of 4DEE arrayed against the Targets in SDGs 13 - Climate Action, 14 - Life Below Water, and 15 - Life on Land, revealed good to strong SDGs connections to each of the 4DEE dimensions. Curricula following the 4DEE approach can better address the SDGs. By integrating this multidimensional framework and connections to the SDGs and their Targets in our classroom, lab, and field experiences on and off campus, educators can help form the next generation of teachers, workers, policymakers, and citizens in ecological literacy and responsible sustainable decision-making. Applying the multidimensional thinking and training of the ESA 4DEE with interdisciplinary collaborations in our institutions and off-campus community partnerships will increase both the ecological literacy and SDG-literacy of present and future generations.

Science highlights

- The 4DEE curriculum can facilitate integrating SDGs learning for students, the environmental workforce, and academicians.
- Multidimensional thinking and interdisciplinary collaborations are needed for SDG-literate citizens.
- Community partnerships in environmentally-focused projects are essential to provide real-world learning experiences in integrating SDGs to environmental education.

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Policy and practice recommendations

- University graduates should be both ecology-literate and SDG-literate to address local to global sustainability issues.
- Policy and pedagogy must promote multidimensional thinking and interdisciplinarity, for effective partnerships.
- Promoting community-engagement on SDGs should involve formal and nonformal education partnerships.

Keywords ESA 4DEE curricular framework, Diversity, Climate justice, Integrating SDGs into college curriculum, Sustainability, Core ecological concepts, Ecological practices, Cross-cutting themes, Human-environment interactions

Introduction

Humans are leading lives that are environmentally unsustainable for future generations, especially with regard to energy consumption and overdevelopment – contributing to climate change and other misuse of terrestrial, marine, and aquatic ecosystems. Most cultures recognize the need for sustainability that dates to antiquity and have educated their adherents through their sacred writings on care for the earth, using goods in moderation, and ensuring the livelihood of future generations. Today's education must preserve these sustainable values to understand the complexity of human and environmental interactions, and to keep pace with equipping students with the knowledge and skills to address the global challenges at multiple scales.

In 2015, the United Nations (UN) took the lead on worldwide sustainability issues. Representatives of all 193 member states adopted a set of Sustainable Development Goals (SDGs) until 2030 “to end poverty, protect the planet, and improve the lives and prospects of everyone, everywhere” [1]. The seventeen SDGs include initiatives to eliminate hunger and poverty, promote gender equity, promote good health and wellbeing, and advocate for responsible consumption and production [2]. They retain the human development aspects of the former Millennium Development Goals, while explicitly adding dimensions pertaining to the sustainable human-natural environment balance. This is a significant opportunity for natural scientists, as Goal 4 addresses education, Goal 7 addresses affordable and clean energy, while Goals 13, 14, and 15 have direct relevance to the field of ecology – because they deal with climate change, marine ecosystems, and terrestrial systems like forests and deserts. Goal 17 speaks to the collaborations and partnerships that are increasingly engaging ecologists and other scientists. Progress towards achieving the UN SDGs in a timely fashion has been slow to meet the 2030 Agenda and avert climate impacts [3], so promising avenues for achieving an informed citizenry must be explored.

The 2030 SDGs Agenda recognizes that education is important, because having an accurate, inclusive, and equitable awareness of sustainability issues is a first step toward converting unsustainable attitudes and actions to those that are better aligned with sustainability goals.

We investigate this new opportunity for bridging ecology literacy frameworks with the SDGs. We also explore how existing education-centered networks can be used to enhance awareness, educational formation, curriculum development, and implementation of SDGs in higher education.

Improving ecological literacy

The need to improve ecological literacy, especially for undergraduate college students, was discussed in the literature beginning in the latter 1980s [4–9]. Recognizing that the voters, workforce, educators, influencers, and policy-makers of tomorrow are in today's classrooms, a task force of education-focused members of the Ecological Society of America (ESA - the world's largest professional association of ecologists [10]) began in 2014 to produce a formalized ecological literacy framework for undergraduate education. An initial version of the ecological literacy framework was collaboratively fine-tuned during subsequent special sessions of broad, interactive discussion including academics and environmental professionals at several ESA conferences. The result organized the teaching of essential ecological knowledge and skills into four dimensions – and hence was called the Four-Dimensional Ecology Education (4DEE) curricular framework [11, 12].

The ESA's multidimensional approach was informed by the U.S. Next Generation Science Standards (NGSS) [13] and K-12 Science Education Framework [14]. The 4DEE's four dimensions are: (1) Core ecological concepts (CEC), (2) Ecology practices (EP), (3) Human-environment interactions (HEI), and (4) Cross-cutting themes (CCT), which are taught in integrated ways in classroom and field settings.

The 4DEE's multidimensional approach (not to be confused with *multidisciplinary* modes of teaching and thinking) is important because it integrates multiple ways of studying the environment. It elevates and integrates the human dimension in the teaching of ecology along with the teaching of the Core Ecology Concepts like populations, communities, and ecosystems. Thus, the human dimension is not just included as an addendum to a course, as so often happens. Relevant to the SDGs, 4DEE provides for the increasing emphasis on human dependence on the environment, ecosystem management,

and related ideas that highlight the relevance of ecological knowledge to human welfare. The framework aids in developing policies and practices that address current global environmental problems, especially those affecting otherwise disenfranchised groups (environmental justice and climate justice concerns). Moreover, the inclusion of multiple dimensions beyond just Core Ecological Concepts allows integration of various ways of thinking and doing ecology with teaching big ideas (e.g., population processes, community theory, transfer of nutrients and energy in ecosystems) in the discipline [11, 12].

The 4DEE framework was endorsed in 2018 by the ESA's Governing Board and has become a springboard for developing new ecology pedagogy that is more culturally responsive and that is meeting the training needed for today's environmental workforce.

Linking SDGs and 4DEE: an opportunity

An examination of the Goals and Targets of the SDGs and the Dimensions of 4DEE begs the question as to whether the two can inform each other. Specifically, is there a benefit for ecology educators to incorporate SDGs into their courses? Conversely, is there a benefit for sustainability educators to incorporate the 4DEE framework into their courses? And what might be the benefit for environmental science educators to incorporate both into their courses? Any linkage between SDGs and the 4DEE framework could benefit three (admittedly overlapping) populations of college instructors and their students. This benefit of integrating multiple ecological and social knowledge dimensions is especially important at a time of development of new Sustainability and Environmental Studies programs. The ESA's 4DEE framework promotes multidimensional thinking, interdisciplinary collaborations, and hands-on learning, while the SDGs provide a set of goals and targets to enhance sustainability thinking and practice including promoting partnerships at local to global scales. Together, they could help produce a citizenry that is sustainability-aware and ecologically literate.

Challenges to integrating SDGs into formal and nonformal sustainability curricula

Understanding and implementing the SDGs in sustainability, ecology, and environmental science education requires elevating awareness of the importance of human-environment interactions in the management of natural resources. In the United States today, sustainability is increasingly being discussed in formal post-secondary and nonformal environmental education settings for various ages [15], but is only part of a handful of state K-12 public education guidelines [16]. These guidelines include NOAA's Bay Watershed Education and Training (B-WET) grant program [17] and the North American

Association for Environmental Education's (NAAEE) programs for developing State Environmental Literacy Plans [18], supporting districts in infusing environmental literacy into curricula [19]. These efforts reach relatively few K-12 students, leaving a higher responsibility with college education. Rarely is there integration of the physical, biological and social components that are needed to provide a clear road map for communities and the environmental workforce to respond effectively to sustainability challenges.

Educational partnerships with local and regional environmentally-focused organizations are also needed within schools and universities to create a comprehensive approach to learning about sustainability. Partnerships with nonformal education providers, such as museums and nature centers, which provide general public education and educator training, can help generate a broader community-engaged understanding of sustainable environmental practices for all.

Considerably more effort has been devoted in countries other than in the United States toward integrating sustainability and the SDGs into education. These developments span formal and nonformal education programs, integrating SDGs into science disciplines' college coursework (e.g., Science, Technology, Engineering and Mathematics (STEM) college teaching), K-12 teacher preparation, and interdisciplinary curricular collaborations to promote global sustainability literacy across educational levels [20–25]. The global college focus has been on curricular, structural, and functional changes to help universities lead the process of promoting integration of sustainable development goals in the training of all college students and future teachers. The ultimate goal is to develop a population that understands the need for critical thinking, interdisciplinary approaches, and community collaborations to implement the SDGs.

A hopeful development is that many universities are promoting their engagement in sustainability education by assessing their curricular, co-curricular, and operations sustainability activities using the international Association for the Advancement of Sustainability in Higher Education (AASHE) Sustainability Tracking Assessment Rating System (STARS) [26]. This STARS rating approach promoted by AASHE has been in place for more than 20 years and has now been upgraded to align the integration of SDGs with university activities including student engagement [27]. This new rating shows much promise for institutions themselves to serve as real-world sustainability education learning labs where students can apply their classroom learning to improve campus sustainability.

Exploring ESA-4DEE Ecology literacy Framework for Teaching the SDGs

Overall, the SDGs provide a broad, worldwide framework for validating the importance of ecology literacy, as the future of human life depends on our adaptation and resilience to climate change, and living in harmony with natural ecosystems. The 4DEE framework's human-environment interactions dimension serves as a lens to all the SDGs when discussing ethics, equity, and environmental justice issues.

The SDGs and ESA's 4DEE developed on parallel time-tracks with comprehensive holistic aims. The 4DEE could be a complementary means for furthering achievement of the SDGs.

Rationale and goals

Our aim for this paper was to examine the relationships between the elements of the two frameworks as they pertain to ecology and sustainability education, which to our knowledge has not previously been done. In particular we asked whether the SDGs can be taught using the ESA's 4DEE - especially at the undergraduate level. If doing so is possible, numerous opportunities for partnering with a variety of stakeholders can open up.

Our first goal was to evaluate the use of the ESA 4DEE curricular framework as a means for connecting college student education with the SDGs. Specifically, we explored whether and how the ESA's 4DEE framework can be used to teach the SDGs, and focus particularly on SDGs 13–15 - because they appear to be the most ecologically relevant.

Secondly, we aimed to show how the ESA 4DEE can be a resource that both nonformal and formal educators might use at all levels as key ecological components to sustainability literacy, through connecting with the human-environmental dimensions of the SDGs.

Thirdly, we explored examples of how partnerships within the academy, with other science-focused organizations, and with nonformal education centers facilitate identification of sustainability teaching goals and understanding of the relationships between the human and environmental dimension in implementing SDGs. Since the SDGs also give broader perspective to local community partnerships for understanding sustainability principles, integrating the SDGs into the undergraduate curricula can promote informed citizens for the next generation. Such collaborations can help equip learners for a future where addressing sustainability challenges will be increasingly more important to everyday household, workplace and civic activities.

Methods

To determine whether the SDGs could be taught using the 4DEE framework, we created a matrix of the two systems and topic connections that are presented in Additional files 1–4 in the Supplemental Data section.

An initial examination of all seventeen SDGs found that three were most relatable to 4DEE. They included SDG 13 – Climate Action, SDG 14 – Life Below Water (mainly oceans and other marine - saltwater ecosystems), and SDG 15 – Life on Land (primarily terrestrial and freshwater ecosystems).

To facilitate the analysis, SDGs 13, 14 and 15 were each classified into subcategories based on the SDG statements in the UN website. The subcategories consisted of a mix of *issues* presented as background on the main webpage for each goal, along with the *targets* for each goal. For example, SDG 13 [28] included five issues taken from the infographics, as well as five targets [29].

That examination yielded 35 subcategories: ten for SDG 13, ten for SDG 14, and fifteen for SDG 15. In contrast, an examination of the 4DEE framework yielded 22 subcategories: seven for Core Ecological Concepts, seven for Ecology Practices, four for Human-Environment Interactions, and four for Cross-Cutting Themes [30].

We created a matrix where the SDG categories and subcategories were arrayed in 35 columns, and the dimensions and subcategories from the 4DEE framework were arrayed in 22 rows. For easier table display, we created a shorthand version of each SDG issue and target. For example, SDG 13 - Climate Action contains the issue “Global climate finance flows reached an annual average of \$803 billion in 2019–2020”, which was classified as a subcategory, and reworded for the analysis as “Global climate finance flows.”

We continued this approach for SDGs 14 and 15. The full list of subcategories on the UN website for SDG 14 - Life Below Water (five issues and ten indicators) and SDG 15 - Life On Land (four issues, twelve indicators), and the shorthand versions used in the analysis are presented in Additional file 1. The entire matrix consisted of 770 possible interactions (Additional file 2).

To determine the degree to which the 4DEE framework could be used to teach at least SDGs 13–15, we placed an X in each cell where a clear relationship between the SDG subcategory and the 4DEE subcategory was present. In other words, can that particular SDG subcategory be taught using that particular 4DEE subcategory? For example, within SDG 13 is the category “The world will get warmer.” was determined to be teachable using the “Organisms” subcategory within the Core Ecological Concept dimension of 4DEE (organisms would be expected to be affected by their habitat getting warmer). Conversely, “Global climate finance flows” from SDG 13, was determined to lack a direct relationship to any of

the subcategories within Core Ecological Concepts, and those cells were left blank (Additional file 2).

To determine the percent overlap between the four 4DEE dimensions and the three SDGs, we condensed the matrix in three ways. The first was by condensing the 4DEE subcategories, leaving the SDG subcategories expanded (Additional file 3). The second was by condensing the SDG subcategories, leaving the 4DEE subcategories expanded (Additional file 4). The third was by condensing both the SDG and 4DEE subcategories (see Table 1 in the Results section). The latter analysis shows the number of positive connections for each combination of SDGs against each 4DEE Dimension, divided by the number of possible combinations, as well as the percentage of each combination showing connection against the number possible – again for each goal against each dimension. Those percentages were then classified into a scale of five Strength of Connection categories (see Table 1). We then computed composite measures for each 4DEE dimension across all three SDGs, and for each goal across all four dimensions. Finally, a comprehensive strength of connection value was computed by combining all goals and dimensions.

To illustrate how to specifically follow the 4DEE curricular approach for integrating SDGs 13–15 into the college curriculum, we developed three college-level lessons as examples (one for each Goal). They are presented in Additional file 5. For each lesson, we took a particular Target, explained the scenario, and then laid out what the students would learn for each of the four 4DEE dimensions.

To facilitate a broader understanding of the human-environment interactions associated with the ESA 4DEE curricular framework, we also created a second matrix consisting of all of the targets for all seventeen SDG goals arrayed against the 4DEE subcategories. This allowed us to examine the targets as they pertained to ecology, and we then determined which were teachable using the 4DEE framework. We listed examples of SDG targets for Goals 1–12 and 16–17 that can be incorporated into college coursework across the curriculum, and in nonformal

educational partnership activities (Table 2 in the Results section).

Results

Examining connections between the SDGs and 4DEE frameworks

The matrix comparing the UN's SDGs 13, 14, and 15 and their subcategories against the subcategories within the ESA's 4DEE framework (Additional file 2 - SDGs and 4DEE both expanded) showed a large number of strong connections that facilitate the integration of SDGs 13–15 into the undergraduate ecology curriculum. Looking at the full matrix, many of the cells were marked with an X – indicating that the SDG subcategory could easily be taught using that part of the 4DEE framework.

Looking at the matrix version where the SDGs remain expanded, but the 4DEE dimensions were condensed (Additional file 3) reveals a few patterns that can facilitate teaching of the SDGs. For SDG 13 - Climate Change, more linkages were noted between science-based SDG subcategories (World will get warmer, sea level will rise) connecting with 4DEE's CEC, than SDG subcategories dealing strictly with human impacts or response (global climate finance flows, Integrate Climate Change into national policies).

A close examination of Additional file 4 (where SDGs were condensed and 4DEE categories remained expanded) revealed other meaningful patterns useful for class discussions. For example, in CEC, linkages were particularly strong for the community level of the hierarchy in SDG 15. For HEI, linkages were strong for all three SDGs in the 4DEE subcategories of Human accelerated environmental change, Humans shape and manage resources, and Ethics. For CCT, linkages were strong for all subcategories with respect to SDGs 14 and 15 (Additional file 4).

The analysis in which both 4DEE and SDG subcategories were condensed (Table 1) showed the strength of linkage between each dimension and each goal. For example, the intersection between SDG 13 (Climate Action) and 4DEE Dimension 1 - Core Ecological Concepts had

Table 1 Summary of the strength of connections between SDGs 13–15 and 4DEE curricular dimensions

4DEE Curricular Dimensions	SDG 13 Climate Action	SDG 14 Life under Water	SDG 15 Life on Land	Combined
Core Ecological Concepts (CEC)	26/70 = 37.1%**	38/70 = 54.3%**	38/105 = 36.2%**	102/245 = 41.6%**
Ecology Practices (EP)	30/70 = 42.9%**	47/70 = 67.1%***	61/105 = 58.1%**	138/245 = 56.3%**
Human-Environment Interactions (HEI)	29/40 = 72.5%***	33/40 = 82.5%***	52/60 = 86.7%***	114/140 = 81.4%***
Cross-Cutting Themes (CCT)	12/40 = 30.0%*	35/40 = 87.5%***	32/60 = 53.3%**	79/140 = 56.4%**
Combined	97/220 = 44.1%**	153/220 = 69.5%***	183/330 = 55.5%**	433/770 = 56.2%**

Total # of subcategories for SDG 13 = 10, for SDG 14 = 10 and for SDG 15 = 15. Total # of sub-categories for the 4DEE dimensions are CEC = 7, EP = 7, HEI = 4, CCT = 4

Each fraction represents the number of connections divided by the number possible – followed by the percentage. The **strength of linkage** was defined as follows: 0–4.9% - no linkage, *5–33.3% - linkage present, **33.4–66.6% - good linkage, ***66.7% - 94.9% - strong linkage, **** > 95% - very strong linkage

Table 2 Examples of additional SDG Targets 1–12 and 16–17 that can be discussed in college coursework across the curriculum and nonformal educational activities using 4DEE to promote human–environment interactions awareness and encourage appropriate sustainability-focused behavior. Goals are in boldface; Targets (summarized from original wording) are in normal typeface

1. No poverty

1.5 Build resilience of the poor to climate related extreme events, and other problems.

2. Zero hunger

2.3 Double agricultural productivity.

2.4 Ensure sustainable food production systems, implement practices to maintain Ecosystems.

2.5 Maintain genetic diversity of seeds and agronomic plants.

3. Good health and well-being

3.9 Reduce illnesses from air, water, and soil contamination.

4. Quality education

4.3 Ensure access to quality technical or college education.

4.4 Ensure readiness for employment, decent jobs and entrepreneurship.

4.6 Ensure everyone achieves literacy and numeracy.

4.7 Create a population educated for sustainability and good world citizens.

4.b Improve vocational and scientific education in L.D.C.s.

4.c Increase the supply of qualified teachers.

5. Gender equality

5.5 Promote women's participation in decision-making in political, economic and public life.

5.c Leverage policies and legislation to empower women.

6. Clean water and sanitation

6.3 Improve water quality by reducing pollution.

6.5 Implement universal integrated water resources management.

6.6 Protect and restore water-related ecosystems.

6.b Help local communities improve water and sanitation management.

7. Affordable and clean energy

7.2 Increase share of renewable energy.

7.3 Improve energy efficiency.

8. Decent work and economic growth

8.4 Decouple economic growth from environmental degradation.

8.9 Promote job-creating sustainable tourism.

9. Industry, innovation and infrastructure

9.1 Develop sustainable infrastructure to support human well-being.

9.2 Promote inclusive and sustainable industrialization.

9.5 Enhance scientific research and technological capabilities, especially in developing countries.

10. Reduced inequalities

10.7 Facilitate safe, orderly, regular and responsible migration of people.

11. Sustainable cities and communities

11.5 Reduce impacts caused by natural disasters.

11.6 Reduce environmental impact of cities especially to air quality and waste.

11.b Improve ability of cities to respond to climate change and natural disasters.

12. Responsible consumption and production

12.4 Safely manage chemicals and all wastes throughout their life cycle.

12.8 Provide information to all regarding sustainability and living with nature.

16. Peace, justice, and strong institutions

16.7 Ensure fair and effective decision-making.

16.b Promote non-discriminatory laws for sustainable development.

17. Partnerships for the goals

17.6 Countries share scientific and technical knowledge and innovation.

17.7 Disseminate environmentally sound technologies to developing countries

17.9 Support targeted capacity-building in developing countries.

17.15 Let each country determine its path to sustainability & poverty reduction.

17.17 Promote public, private & civil society partnerships

17.18 Enhance capacity-building through effective data.

70 possible linkages, with 26 of them deemed to be useful for teaching (Table 1). Thus, the strength of linkage was 37.1% (Table 1), which we classified as a “good” linkage. Conversely, the intersection between SDG 15 (Terrestrial and Freshwater Ecosystems) and 4DEE Dimension 3 (Human-Environmental interactions) had 52 out of 60 (86.7%) cells determined to be connected (or linked) - denoting a “strong” linkage.

According to Table 1, SDGs 13, 14, and 15 could all be taught by using the 4DEE framework. Each goal had at least 30.0% of the intersecting cells that were connected. Eleven of the twelve SDG-4DEE combinations had at least 36.2% denoting good - or better - linkages.

When the linkages for all the SDGs and 4DEE dimensions are combined, a few additional patterns emerge. Notably, all of the linkages between the three SDGs and the HEI dimension were determined to be “strong” at 81.4%, whereas those for the other dimensions were in the “good” range. Considering the SDGs combined over all the 4DEE dimensions, SDG 15 had the highest composite linkage at 69.5% (strong linkage), while SDG 13 had the lowest at 44.1%. The overall linkage between SDGs 13–15 and the four 4DEE dimensions was 56.2%, demonstrating a “good linkage” between them.

Among the SDGs that were not largely directly related to ecology, we found at least one target that could be teachable using the 4DEE framework in every SDG (Table 2). Those SDGs that had at least four 4DEE-teachable Targets included: #4 - Quality education, #6 - Clean water and sanitation, and #17 - Partnerships for the goals. Each of those Targets had components that involve ecological knowledge or its understanding. Many of the selected Targets were chosen based on our recognition of the role we have as educators who model equity, inclusion and empowerment by how we teach. Also, we recognize that we are preparing the next generation to have an impact in their home places and cultures.

We created examples of lessons showing how each SDG can be taught using the 4DEE framework (Additional File 5). The lesson relating to SDG 13 has the students conducting a Google Earth investigation to determine sea level rise. The lesson relating to SDG 14 asks the students to visit a coastline (in person or virtually using photos or videos), take or obtain various measurements, and compare those measurements to historical data. The lesson relating to SDG 15 asks the students to visit a surface-mined site (again in person or virtually), determine current ecological conditions, and then assess different reclamation techniques (Additional File 5).

Discussion

ESA's 4DEE is a curricular framework for teaching the SDGs

Our analyses revealed that the ESA's 4DEE framework is highly relevant for teaching the SDGs. Our specific focus

on the goals most likely to have elements already taught in college and university classrooms, Goals #13 - Climate Action, #14 - Life Below Water (Ocean Conservation), and Goal #15 - Life on Land (Conservation of Terrestrial Ecosystems), showed that the SDGs encompass all four dimensions in 4DEE.

Among the 4DEE dimensions, Human-Environment Interactions (HEI) had the strongest linkages with SDGs 13, 14, and 15. Moreover, Targets within the other SDGs that relate to human equity, inclusion, and environmental justice were determined to be teachable using the 4DEE framework. That is perhaps to be expected, considering that the SDGs are largely human-oriented. Overall, our examinations show much potential for using 4DEE to integrate the SDGs into a variety of environmentally-focused courses across the curriculum, for global applications of ecological knowledge, and the interactions with humanitarian concerns.

Applications of 4DEE for educators in environmental fields

Our findings have clear applications for those who teach sustainability, environmental science, or ecology - especially to undergraduate college students. For example, an instructor seeking to teach SDG 13 - Climate Action from a 4DEE perspective could incorporate all dimensions as follows: CEC through discussing impacts of rising temperatures and sea levels on any level of the ecological hierarchy (see Additional file 2), EP (Ecological Practices) through global education in SDG 13, HEI by bringing in the impacts of climate change on humans, climate justice - disproportionate impacts on the disadvantaged, and efforts to reduce the root causes of climate change, and CCT (Cross-Cutting Themes) - especially systems and spatial / temporal scale through warming effects, education and planning in SDG 13.

Instructors who want to focus on SDG 14 - Life Under Water could utilize the numerous linkages between SDG goals and 4DEE items. In terms of topics (Additional file 2), those within SDG 14 that are the most ecological / environmental in nature yielded linkages with items in the CEC, HEI, and CCT dimensions. They included coastal eutrophication, ocean acidification, ocean warming, plastic pollution, and overfishing. Conversely, those involving economic and social issues - such as small-island developing states and tourism - yielded links only within HEI and CCT.

Instructors wishing to focus on terrestrial ecosystems would see that the matrix involving SDG 15 and 4DEE yielded a pattern similar in some ways to that of SDG 14. Those subcategories in SDG 15 that were ecological or biological in nature linked well to items within the CEC, HEI, and CCT (and EP to an extent) dimensions (Additional file 3). Conversely, those SDG 15 items that were economic, sociological, or attitudinal (Additional file 3)

linked to items in the HEI dimension – especially the way in which humans manage nature and ethics.

The take-home message is that the UN SDGs that relate to Climate Change, Oceans, and Terrestrial Ecosystems can be easily taught using the ESA's 4DEE framework - a finding that has not been previously reported. Instructors can craft their own specific lessons, based on the exact combination of connections between SDG and 4DEE subcategories that they would select and relevant local or global environmental issues they want to explore.

The three potential lessons that were created to illustrate how SDGs 13–15 could be taught using 4DEE (Additional File 5) represent just three possibilities of many that could be developed by creative instructors. Location and available resources would certainly determine the exact nature of the lesson. The key is to have the students address the topic from a multidimensional perspective, including at least three of the 4DEE dimensions and seek out ways in which those dimensions interact. Instructors are then encouraged to share their lessons with others through outlets like ESA's EcoEd.net digital library [31], the Bulletin of the Ecological Society of America [32], or other journals and conferences devoted to promoting higher education reform and sustainability education. Indeed, combining SDGs with 4DEE opens a universe of opportunity for instructors to develop and publish their innovative lessons.

These educational examples would count toward the college-wide AASHE and STARS and assessment rubrics for sustainability implementation [26, 27] and would be available for educators online at the ESA 4DEE resources website [33].

Being able to incorporate 4DEE into undergraduate environmental coursework provides a way to help students connect the different goals within the SDGs to ecology - and vice versa. The 4DEE framework promotes integrating information from more than one discipline and focuses the educator and learner on addressing the major sustainability issues of the UN SDGs in today's real-world context, as well as on how we do science and how we interpret the science relevant to current human-environment interactions knowledge. There have been previous efforts to determine how interdisciplinarity and systems thinking can be used to build student agency in sustainability [34, 35]. But unlike our 4DEE curricular approach, these did not provide specific ways to incorporate multidimensional thinking into existing ecology college curricula, and could be of benefit to many sustainability courses and programs.

The 4DEE framework does not address how to prioritize taking action in solving real-world environmental problems that focus on sustainability. The process of determining what is the best environmental solution for a local community to address the UN SDGs must mutually

involve the community in the process of research project planning and implementation. It requires knowing the community and partnering with a diverse group of collaborators that represent community interests [36]. Practices and toolkits for successful partnerships between scientists, youth, and local communities including faith communities are increasingly available for implementing the SDGs [37]. As we teach, we must remind educators and students of the need to work as mutual partners with each community in any decision-making that addresses implementation of SDGs [37].

The finding that numerous Targets distributed across the other SDGs were amenable to being taught using the 4DEE framework (Table 2) is noteworthy because they would be useful in broadening discussion of human-environment interactions, but it would be harder to develop a lesson plan integrating the four dimensions of 4DEE in the traditional ecology or biology major coursework ecological concepts discussion outside of SDGs 13–15. The difficulty stems from addressing the interdisciplinary nature of the problems from within the disciplinary confines of the more traditional college departments. Human behavior is not within the realm of traditional ecology, but is deeply grounded in sociology and psychology, and other social sciences. However, the rapidly emerging discipline of human ecology does address this integration. Although that area is often not part of biology or ecology departments, those who study human ecology would make valuable partners for broadening ecology education. Another campus partner would be environmental sociologists who study the social factors that cause environmental problems, the societal impacts of those problems, and efforts to solve the problems.

Environmental Studies and Human Ecology departments promoting interdisciplinary environmentally-focused majors are slowly growing in numbers to essentially follow the integrative approach required to implement the SDGs. The increasing number of human dimensions engagements in the projects, organizational development and meeting activities of professional societies is a hopeful sign and asset to educators. For example, the Ecological Society of America has initiatives integrating human diversity with education and member Sections include the fields such as Agro-Ecology, Applied Ecology, Communication and Engagement, Environmental Justice. Human Ecology, Policy, Restoration Ecology, and Traditional Ecological Knowledge, which bridge the natural sciences and humanitarian dimensions for achieving the SDGs [10].

Partnerships for facilitating integration of SDGs into formal post-secondary education

To provide the hands-on experience that students and faculty need to see the connections between SDGs and

college environmental education, it is important to develop community-engaged partnerships in environmentally-focused projects. Individual educational subject areas have not always kept up with teaching approaches that strive to meet societal needs [38]. However, universities are increasingly motivated by student prompting, desire for national recognition (e.g., increasing AASHE STARS ratings), or economic demands to demonstrate best practices in saving paper, recycling energy, managing campus landscapes, pursuing sustainable practices in cafeteria food services and promoting sustainability education across the curriculum [26]. Within universities, Green Campus committees form to integrate the Facilities, Maintenance and Food Services staff with faculty and students in generating a more sustainable approach to campus resource management and providing internships for departmental coursework on sustainability implementation. Often university departmental partnerships occur with local community food gardens or food collaboratives to help integrate the concerns of the SDGs in practice and further classroom discussion. Such interest serves to guide and train students to be better sustainably-minded citizens and also develops partnerships that respond rapidly to change in community environmental needs. Universities also benefit from their participation in AASHE STARS rating systems that allow them to be validated in their efforts to integrate sustainability across the curriculum and facilities operations [27]. AASHE has many resources including online materials, workshops and annual conferences that promote engagement of students, faculty and staff at all academic and operations levels [26].

In the United States, many research-focused state universities maintain an Extension Service department, often associated with the College of Natural Resources, that provides their university students with academic conservation ecology opportunities [39]. The Extension faculty also partners with professionals in nonformal education centers, such as museums and nature centers, on conservation and sustainability educational outreach [40]. Depending on the community's demographics, some university Extension agents are involved in leading events such as Latino Conservation Week, or Black Birders week, and enhancing the connection to nature that is already part of the local community cultural ethnic groups. These partnerships also help in promoting the understanding and implementation of essential principles needed to meet UN SDGs by promoting goodwill, and alerting policy makers to their importance in local governance. Additionally, the values and mission of many academic institutions already facilitate integration of the SDGs, since they align with moral and ethical dimensions. For example, faith-based organizations regionally and globally are increasingly engaging the SDGs, and

provide a way for learners to put into practice the integration of values and knowledge [37].

Additional community partnerships that engage students in greater understanding of SDGs are often teacher-preparation focused. These education enhancement programs may focus on watershed environmental stewardship, preparing future teachers to take students outside to observe, record, monitor and build understanding of the importance of water and climate on the quality of life in their communities. This type of community partnership often involves professional development of current and future teachers on climate and energy principles to be embedded in high school science coursework.

Integrating SDGs into environmentally-focused curricula

To enhance how we align SDGs and ESA 4DEE in sustainability education, we suggest that educators engage in developing and promoting college activities that help increase awareness of how the SDGs relate to their community at large, research and teacher preparation, not only in STEM disciplines but across the curriculum. To that effect we encourage U.S. colleges to become leaders in the implementation of the SDGs.

We suggest at least five approaches that can enhance local SDG alignment to education efforts through partnerships, such as: (1) convene existing and potential community partners who are already engaged in promoting SDGs awareness such as in faith-based institutions, community-engagement educational projects, or sustainability-focused NGOs or government agencies, (2) offer specific examples of lesson plans at education-focused meetings that fit college coursework across the curriculum, for majors and non-majors, (3) connect college student organizations to SDGs and Green Campus sustainability initiatives, (4) develop SDGs curriculum projects in partnership with existing university community-engagement service-learning and partnership activities, and (5) promote SDGs awareness by offering virtual presentations on the meaning of SDGs and how to integrate them into community sustainability efforts. Boorse and Jablonski [37], summarize partnership history and potential with faith-based organizations, scientist and youth/young adult learning and action.

Most curriculum changes require that college administrators consider incentives such as time-release, team-teaching or stipends for faculty willing to modify their teaching activities and this can present a demanding challenge in a time of low resources. This is where enhancing partnerships with SDG-focused networks, and including student organizations in the process can lead to motivating college administrators to support the resource allocation required for SDG-focused change. The more that community partnerships and student activities are

generated and cultivated to promote SDGs implementation, the more resilient the campus will be. It will be less likely that any single change in college administration or that one financial challenge event precipitates elimination of those activities.

It is always a challenge to motivate interdisciplinary collaboration for meeting societal urgent needs outlined in the UN SDGs. Youth and young adults today feel the urgency of a climate crisis and want to put environmental knowledge into action. Strong student interest and partnerships with networks that already validate the value of SDG-focused work can secure continuous integration of SDGs into college curriculum efforts and gradually transform the institution as a whole.

Conclusions

Elevating the human dimensions in all aspects of environmental education to promote a better understanding of sustainability and meet the UN SDGs requires integrating information and skills from multiple sources, and partnering with existing community-engagement activities to promote appropriate action. ESA's 4DEE framework that promotes multidimensional thinking, interdisciplinary collaborations and hands-on learning in community-engaged projects can facilitate college coursework, pedagogy and ultimately an SDG-informed citizenry. The work to support implementation of the UN SDGs requires connecting across all elements involved in successful community partnerships that support sustainability principles. Literacy efforts alone are not enough. Partnerships that focus on evaluating the progress must be developed to prompt the generation of innovation in modifying formal and nonformal curriculum, promote equitable community engagement, and celebrate steps taken towards achieving the UN SDGs.

Abbreviations

4DEE	Four dimensional ecology education
AASHE	The Association for the Advancement of Sustainability in Higher Education
CEC	Core Ecological Concepts
CCT	Cross Cutting Themes
EP	Ecology Practices
ESA	Ecological Society of America
HEI	Human-Environment Interactions
LDCs	Least developed countries
NGO	Non-governmental organizations
NGSS	Next Generation Science Standards
NOAA	National Oceanic and Atmospheric Administration
SDGs	Sustainable Development Goals
STARS	Sustainability Tracking & Rating System
STEM	Science Technology Engineering Mathematics
UN	United Nations

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Supplementary Material 4

Supplementary Material 5

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Author contributions

All authors were equally involved in the conception of the article and in analysing the potential ways to integrate SDGs through using the 4DEE curricular framework. KMK initiated the detailed analysis of the interactions between SDGs and 4DEE, developed the three lessons, and contributed to writing all sections; CRC was the organizer and editor; LMJ provided partnership perspective and experience along with writing and editing. DH provided expertise in best practices for nonformal education and community-engaged future teacher preparation to enhance understanding of sustainability.

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All data and materials used to serve the purpose of this research are provided within.

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Competing interests

The authors declare that they have no competing interests.

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