soil systems

Article

Integrating United Nations Sustainable Development Goals in Soil Science Education

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Abstract: The United Nations (UN) Sustainable Development Goals (SDGs) offer an opportunity to improve soil science education on sustainability because they provide specific context to educate faculty and students from various disciplines, including Science, Technology, Engineering, and Mathematics (STEM) about SDGs. Soil science is a STEM discipline with a wide range of applications in the SDGs. The objectives of this study were to use a matrix approach (framework for presenting options for discussion and implementation) to integrate SDGs into an existing introductory soil science course taught to undergraduate students from different STEM fields (environmental and natural resources; wildlife biology; and forestry). The course was enriched with a lecture on SDGs and students were asked to link soil properties and class activities to specific SDGs. A post-assessment survey revealed an increase in students' familiarity with SDGs, and their relevance to soil properties and course activities. Students acknowledged the importance of soils and individual actions for achieving the SDGs. There was an overall increase in student familiarity (+59.4%) with SDGs. Most students agreed (46.7%) and strongly agreed (23.3%) that the course activities were an effective way to learn about SDGs with examples from soil science. Identified learning gaps in subject matter found through the surveys on SDGs were clarified during later classroom discussions. The advantage of this teaching approach is that it seamlessly integrates SDGs with existing course materials while relying on students' critical thinking skills to effectively analyze soil science information and form a judgement on how it relates to SDGs.

Keywords: course; environment; higher education; laboratory; learning; science; social; university

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1. Introduction

The 17 United Nations (UN) Sustainable Development Goals (SDGs) and their numerous targets and subtargets were adopted by 193 countries with the aim of directing humanity towards sustainability by 2030 [1] (Table 1). Surveys of students at higher education institutions (HEI) worldwide often indicate highly variable results in terms of knowledge about UN SDGs. For example, a study in Spain indicated that students have limited knowledge about UN SDGs and sources of this knowledge are scarce [2]. Students at the University of Malaya (Malaysia) demonstrated "a high knowledge and positive attitude towards SDGs" but "low performance in practicing SDGs" [3]. Higher education institutions are often expected to develop teaching, research, and outreach activities associated with UN SDGs at various organizational levels within the education system (e.g., courses, subjects, research centers, etc.) [4]. There are various examples of using SDGs in educational settings in different subject matters, including STEM (Science, Technology, Engineering, and Mathematics) [5–7]. One of the main challenges identified in using SDGs in HEI is their broad and general scope [8]. The integration of SDGs in HEI is often subject matter-specific and requires a prior detailed analysis of integration options and implementation methods (Figure 1). There are several pathways for integrating soils with SDGs using the concept of ecosystem services (ES) provided by soils [9]. The concept of ES [10] is often used to "capture" the economic value provided by the ecosystems and their components (e.g., soils), which encompasses provisioning (e.g., food), regulating/supporting (e.g., carbon sequestration), and cultural (e.g., monuments) ES. The concept of ES views soil as natural capital (stock) providing a flow of goods and services, which can be defined, quantified, and valued [9]. Soil properties are related to soil functions, which provide ES necessary to achieve SDGs (Figure 1). For example, soil texture (proportion of sand, silt, and clay, %) is a physical property with the function of storing, filtering, and transforming nutrients in the soil, which provides regulating ES necessary to achieve several SDGs (e.g., SDG 2, 6, 7, and 15). Table 1 provides a selection matrix [11] that shows all the SDGs, as well as examples of typical ES by category which could be used to help identify which ES supports achieving specific SDGs. After one or more ES are selected, then it is possible to highlight relevant domain STEM topics. For example, SDG 6. Clean Water and Sanitation is dependent on a regulating ES (water purification), which is directly related to soil physical properties such as soil texture and saturated hydraulic conductivity (Ksat). Previous research on integrating sustainability into management and business education demonstrated the use of a matrix approach (framework for presenting options for discussion and implementation) [11] in decision-making, which is useful not only in curriculum planning but also in selecting STEM (e.g., soil science) subject matter for integration with SDGs.

Table 1. Possible selection matrix for integrating United Nations (UN) Sustainable Development Goals (SDGs) with ecosystem services (ES), where ES are not aligned with specific SDGs to provide multiple selection options.

United Nations (UN) Sustainable Development Goals (SDGs)	**Ecosystem Services**		
	Provisioning	**Regulating/Supporting**	**Cultural**
1. No Poverty 2. Zero Hunger 3. Good Health 4. Quality Education 5. Gender Equity 6. Clean Water and Sanitation 7. Clean Energy 8. Economic Growth 9. Infrastructure 10. Reduced Inequality 11. Sustainable Cities 12. Responsible Production and Consumption 13. Climate Action 14. Life Below Water 15. Life on Land 16. Peace 17. Partnerships	**Examples:** Food Wood fiber Genetic resources Biochemicals Freshwater	**Examples of Regulating Ecosystem Services:** Air purification Water purification Climate regulation Flood regulation Erosion regulation Pollination **Examples of Supporting Ecosystem Services:** Primary production Nutrient Cycling Soil formation Biodiversity	**Examples:** Recreation Education Aesthetics

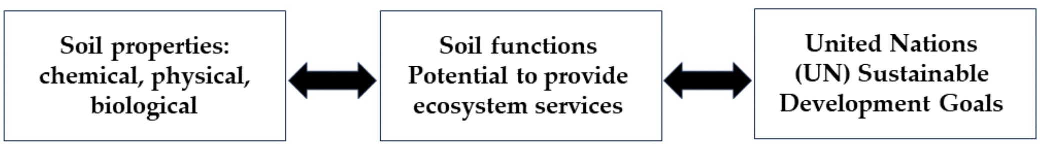

Figure 1. Integration of soil science subject matter with United Nations (UN) Sustainable Development Goals (SDGs) to enrich learning experiences.

Soils play an important role in almost all SDGs [12,13] but are particularly relevant to the following SDGs: SDG 2. Zero Hunger; SDG 6. Clean Water and Sanitation; SDG 7. Responsible Consumption and Production; SDG 13. Climate Action; and SDG 15. Life on Land [14]. The integration of SDGs into soil science education can enrich learning experiences not only for soil science students but also for students from other STEM disciplines (e.g., forestry; wildlife biology; and agriculture), especially since introductory soil science is often a required course in their curriculum. For example, Noguera et al. (2021) [15] integrated the subject matter of cation exchange capacity (CEC) with SDGs within a soil science laboratory where students were asked to relate their newly acquired knowledge to relevant SDGs with most students selecting SDG 2. Zero Hunger as the most relevant SDG.

This study hypothesizes that integrating SDGs in STEM education helps students understand the importance of subject matter (e.g., soil science) in achieving these goals. In addition, the SDG framework is becoming a teaching tool, that can identify learning gaps. The objectives of this study were to: (1) use a matrix approach to integrate the SDGs into an introductory FNR 2040: Soil Information Systems course taught at Clemson University in the Fall of 2023, and (2) assess the impact of this integration on student learning. This course included students from multiple STEM disciplines (forestry; wildlife biology; and environmental and natural resources). The SDGs are relevant to various course objectives structured around fundamental soil science definitions, concepts, and soil analysis techniques in both lectures and laboratories.

2. Materials and Methods

2.1. Design

An existing introductory soil science course (FNR 2040) was enriched with an SDGs lecture, which gave students information on SDGs enabling them to identify how soil properties and course materials are related to specific SDGs. This study used a series of reusable learning objects (RLOs), which are self-contained digital modules utilized in e-learning. In this study, the following sequence of RLOs was used in a Learning Management System (Canvas): (1) pre-assessment web-based survey (Google Forms); (2) lecture on SDGs in PowerPoint and video formats; (3) exercises (e.g., laboratory, assignments) in various formats; and (4) post-assessment web-based survey (Google Forms) (Table 2).

Table 2. Design steps of the study, which used various reusable learning objects (RLOs).

Steps	Description of Activities
1. Pre-assessment	Students complete a general Google Forms web-based survey of familiarity with the United Nations (UN) Sustainable Development Goals (SDGs) at the beginning of the semester.
2. Lecture on SDGs	Students are presented with a lecture on SDGs entitled “United Nations Sustainable Development Goals” in PowerPoint and video formats.
3. Lectures, laboratory, and field exercises on soil science topics	Students are presented with lectures, laboratory, and field exercises on various soil science topics in PowerPoint and video formats. Students complete exercise(s) on soil science topics related to various SDGs. Students complete non-graded quiz questions on which SDGs were relevant to soil properties and laboratory exercises and if those activities were an effective way to learn about SDGs.
4. Post-assessment (non-paired to individual pre-assessment responses)	Students complete a follow-up general Google Forms web-based survey of familiarity with the United Nations (UN) Sustainable Development Goals (SDGs) which matches the pre-assessment except for two additional questions about students’ role in SDGs and the effectiveness of course activities in learning about SDGs at the end of the semester.
5. Follow-up discussion	Classroom discussion and activities to help fill in learning gaps.

A non-graded pre-assessment was designed to gauge student prior knowledge about the SDGs. The lecture on SDGs contained information for all 17 SDGs based on material available on the UN website (https://sdgs.un.org/goals) (accessed on 8 November 2023) [16] but did not provide specific information or discussion on the role of soils in these SDGs. This study used an effective way of integrating subject matter with SDGs within an existing soil science course material, which does not disrupt course flow. A matrix approach (framework for presenting options for discussion and implementation) was used to identify linkages between soil properties and related laboratory and field exercises to multiple SDGs (Table 3). Table 3 gives an expert determination of which SDGs are most closely tied to soil properties and exercises which were subsequently compared to pre-assessment students' answers. This comparison was used to identify gaps in student learning when students' answers deviated from the expert determination (Table 3) of the relationship between course material and SDGs.

Table 3. A matrix approach for expert selection of science subject matter (e.g., soil science) for teaching integration with the United Nations (UN) Sustainable Development Goals (SDGs).

Soil Property	Society		Economy	Environment	
	SDG 2	**SDG 6**	**SDG 7**	**SDG 13**	**SDG 15**
Soil texture	+	+	+	-	+
Bulk density	+	+	+	-	+
Porosity	+	+	+	-	+
Saturated hydraulic conductivity (Ksat)	-	+	+	-	+
Available water capacity (AWC)	+	-	+	-	+
Soil organic matter (SOM)	+	+	+	+	+
CEC and ECEC	+	+	+	+	+
Soil reaction (pH)	+	+	+	-	+
Calcium carbonate ($CaCO_3$)	+	-	+	+	+
Base saturation (BS)	+	-	+	-	+
Laboratory and Field Exercises					
Soil texture	+	+	+	-	+
Bulk density and compaction	+	+	+	-	+
Soil organic matter (SOM)	+	+	+	+	+
CEC and ECEC	+	+	+	+	+
Soil nutrient analysis and liming	+	+	+	+	+
Field interpretation ("soil judging")	+	+	+	-	+

Note: SDG 2. Zero Hunger, SDG 6. Clean Water and Sanitation, SDG 7. Responsible Consumption and Production, SDG 13. Climate Action, and SDG 15. Life on Land. CEC = cation exchange capacity, ECEC = effective cation exchange capacity for soils with soil reaction (pH) less or equal 5.5. A positive sign (+) indicates a strong relation to an SDG, while a negative sign (-) indicates less relation to an SDG.

This matrix approach allows the targeting of specific SDGs that are most related to existing course material, with the potential to prioritize specific SDGs with high relevance to core course topics. Ten soil properties and six laboratories were selected for this study based on a matrix approach analysis (Table 1). Soil properties include both physical (soil texture, bulk density, porosity, saturated hydraulic conductivity (Ksat), available water capacity (AWC), soil organic matter (SOM)) and chemical properties (CEC and ECEC, soil reaction (pH), calcium carbonate ($CaCO_3$), and base saturation (BS)). These properties, field, and laboratory exercises are commonly taught in the USA [17–20]. It should be noted that information about these soil physical and chemical properties can be easily obtained in the tabular form for most soils found in the USA using the USDA-NRCS Web Soil Survey (https://websoilsurvey.nrcs.usda.gov/app/ (accessed on 8 December 2023)) [21]. In addition, definitions, and examples of uses of these properties can be found in most soil science textbooks [18]. Below are summaries of property definitions, units, and uses [18]:

1. **Soil texture** is defined as a proportion of sand, silt, and clay; **Units:** %; **Use:** Determination of soil texture class (e.g., loam, etc.).
2. **Bulk density:** $\rho_b = Ms/Vb$ = (mass of soil/volume of bulk soil sample); **Units:** g/cm^3 or g/cc; **Use:** Determination of soil compaction.
3. **Porosity:** Porosity = $[1 - (\rho_b/\rho_d)] \times 100$, where ρ_b is bulk density and ρ_d is particle density (ρ_d of quartz: 2.64 g/cc); **Units:** %; **Use:** Determination of soil compaction.
4. **Available water capacity:** AWC = $\theta_{fc} - \theta_{wp}$ (the water held between field capacity and the permanent wilting point); **Units:** in/in or cm/cm (units of depth of available water per unit depth of soil); **Use:** Irrigation management.
5. **Soil organic matter (SOM):** SOM is a component of soil that consists of animal and plant tissue at different stages of decomposition; **Units:** %; **Use:** Soil colloid.
6. **Saturated hydraulic conductivity:** Ksat = $(q/A) \cdot (L/\Delta H)$, where q is the volume of water (cm^3) per unit of time, A is a cross-sectional area (cm^2), L is the length of the flow path (cm), ΔH is the hydraulic head or potential causing flow (cm); **Units:** in/h or cm/h; **Use:** Septic suitability in the field, "perc" test.
7. **Soil pH:** pH = $-\log [H^+]$; **Units:** n/a; **Use:** Measure of reaction (Note: Does **not** indicate the amount of lime to apply).
8. **Cation exchange capacity:** CEC = The sum of the exchangeable cations that soil can adsorb. ECEC = effective cation exchange capacity for soils with soil reaction (pH) less or equal 5.5; **Units:** meq/100g; **Use:** Measure of soil fertility and nutrient retention capacity.
9. **Calcium carbonate:** $CaCO_3$ = soil inorganic carbon (SIC), naturally present liming material; **Units:** %; **Use:** Raises pH.
10. **Base saturation:** BS = $((Ca^{2+} + Mg^{2+} + K^+ + Na^+)/CEC) \times 100\%$; **Units:** %; **Use:** Proportion of exchange sites occupied by cations such as Ca^{2+}, Mg^{2+}, K^+, Na^+. Soil fertility. Differentiation between soil orders (e.g., Mollisols have >50% base saturation [18]).

For the post-assessment survey, only five of the soil-related SDGs (SDG 2. Zero Hunger, SDG 6. Clean Water and Sanitation, SDG 7. Responsible Consumption and Production, SDG 13. Climate Action, and SDG 15. Life on Land) were provided for relating to soil properties and the associated course activities (Table 3). Students were requested to use their critical thinking skills to relate SDGs and "to write a paragraph or more describing one or more laboratory and field activities that relate to an SDG of your choice and describe what specific knowledge and skills you have acquired from these hands-on activities that could improve your contribution to sustainable development (SD) personally and/or professionally." Identified learning gaps in subject matter found through the surveys on SDGs were used as topics for a follow-up classroom discussion.

2.2. Background of "Test" Course

"Test" course: Soil Information Systems (FNR 2040) is a 4-credit course in the Department of Forestry and Environmental Conservation at Clemson University, Clemson SC, USA [22]. FNR 2040 is "an introductory soil course that focuses on the input, analysis, and output of soil information utilizing geographic information technologies (Global Positioning Systems, Geographic Information Systems, direct/remote sensing) and soil data systems (soil surveys, laboratory data, and soil data storage). Soil Information Systems course is a required course for forestry; wildlife; and environmental science majors" [22]. General information about the course based on the survey indicated that students (n = 58, 18 females and 40 males) were from forestry (20), environmental science (16), and wildlife biology (22) majors at the sophomore—2nd year of studies (21), junior—3rd year of studies (33), senior—4th year of studies (4), and other levels. Forty-seven students were from South Carolina (SC), and 11 students were from various other states (e.g., Florida, Maryland, Massachusetts, North Carolina, Ohio, Pennsylvania, Virginia, and West Virginia). Most students (79%) did not have any previous experience with soils.

3. Results

3.1. Responses in the Pre-Testing Online Survey

The non-graded pre-testing online survey was intended to evaluate overall students' prior background knowledge of SDGs before posting a lecture on SDGs in the course materials. Responses to the pre-testing survey questions, which focused on overall familiarity with the concepts of SDGs, showed that most students were "not at all familiar" (46.6%) and "slightly familiar" (31.0%) with SDGs (Table 4). Less than half of all students knew the total number of SDGs and the deadline for reaching them. Almost all students acknowledged the role of soil in the SDGs.

Table 4. Pre- and post-assessment results from course activities on United Nations (UN) Sustainable Development Goals (SDGs) in the FNR 2040: Soil Information Systems course.

Survey Questions and Answers	Responses		
	Pre-Assessment (%) (n = 58)	Post-Assessment (%) (n = 50)	Difference (%)
Please, rate your familiarity with the United Nations (UN) Sustainable Development Goals (SDGs) on the following scale:			
1 = not at all familiar	46.6	1.7	−44.9
2 = slightly familiar	31.0	18.3	−12.7
3 = somewhat familiar	15.5	31.7	+16.2
4 = moderately familiar	6.9	40.0	+33.1
5 = extremely familiar	0.0	8.3	+8.3
What is the total number of United Nations (UN) Sustainable Development Goals (SDGs)?			
10	36.2	3.3	−32.9
5	8.6	0	−8.6
20	5.2	5.0	−0.2
15	8.6	8.3	−0.3
17	**41.4**	**83.4**	**+42.0**
What is the deadline for reaching the United Nations (UN) Sustainable Development Goals (SDGs)?			
2025	6.9	5.0	−1.9
2030	**44.8**	**56.7**	**+11.9**
2035	25.9	30.0	+4.1
2040	5.2	1.7	−3.5
2050	17.2	6.7	−10.9
Do soils play a role in the United Nations (UN) Sustainable Development Goals (SDGs)?			
Yes	**98.3**	**100.0**	**+1.7**
No	1.7	0	−1.7
Are your individual actions as a member of this country important for achieving the United Nations (UN) Sustainable Development Goals?			
Yes	-	95.0	
No	-	5.0	
The course activities were an effective way to learn about the United Nations (UN) Sustainable Development Goals with examples from soil science:			
1 = strongly disagree	-	1.7	-
2 = disagree	-	5.0	-
3 = neither agree nor disagree	-	23.3	-
4 = agree	-	46.7	-
5 = strongly agree	-	23.3	-

Note: Correct answers are indicated in bold. Post-assessment was not paired with individual pre-assessment responses.

3.2. Pre- and Post-Testing Comparison of Responses in the Online Surveys

After completing the pre-testing survey students were presented with a lecture on SDGs that contained information for all 17 SDGs based on material available on the UN website (https://sdgs.un.org/goals) (accessed on 8 November 2023) [16] but did not provide specific information or discussion on the role of soils in these SDGs. Although this study was focused on five SDGs most related to soils (Table 3), the lecture material was a complete overview of all 17 SDGs (Table 1) so that students were introduced to how the goals can be used to improve sustainability and address global challenges. Survey results indicated that the participants "agreed" (46.7%) or "strongly agreed" (23.3%) that the course activities were an effective way to learn about the UN SDGs with examples from soil science (Table 4). There was an increase in number of students who classified themselves as "moderately familiar" (+33.1% increase from pre-assessment) and "extremely familiar" (+8.3% increase from pre-assessment) (Table 4) with SDGs. Students increased their knowledge of the total number of SDGs (+42.0% increase from pre-assessment) and the deadline for reaching the SDGs (+11.9% increase from pre-assessment). Students agreed that both soils and students' actions as members of the USA are important in achieving the SDGs. For the post-assessment survey, only five of the soil-related SDGs were provided to the students for relating to soil properties and the associated course activities (Table 5).

Table 5. Comparison of expert (in parenthesis) to the students' responses on the relevance of the United Nations (UN) Sustainable Development Goals (SDGs) to soil properties and laboratory exercises in the FNR 2040: Soil Information Systems course after SDG lecture and course activities (total number of students in post-review: 50).

	Society		Economy	Environment	
	SDG 2	**SDG 6**	**SDG 7**	**SDG 13**	**SDG 15**
List one or more SDGs that are the most relevant to each soil property.					
Soil texture	12 (+)	10 (+)	12 (+)	5 (-)	31 (+)
Bulk density	18 (+)	8 (+)	14 (+)	3 (-)	19 (+)
Porosity	13 (+)	30 (+)	14 (+)	2 (-)	14 (+)
Saturated hydraulic conductivity (Ksat)	13 (-)	48 (+)	14 (+)	6 (-)	28 (+)
Available water capacity (AWC)	13 (+)	42 (-)	8 (+)	1 (-)	5 (+)
Soil organic matter (SOM)	19 (+)	3 (+)	14 (+)	6 (+)	23 (+)
CEC and ECEC	17 (+)	12 (+)	9 (+)	10 (+)	15 (+)
Soil reaction (pH)	14 (+)	12 (+)	11 (+)	10 (-)	21 (+)
Calcium carbonate ($CaCO_3$)	13 (+)	5 (-)	11 (+)	14 (-)	16 (+)
Base saturation (BS)	15 (+)	22 (-)	7 (+)	6 (-)	22 (+)
List one or more SDGs that are the most relevant to each laboratory exercise.					
Soil texture	12 (+)	8 (+)	15 (+)	6 (-)	37 (+)
Bulk density and compaction	14 (+)	15 (+)	24 (+)	6 (-)	19 (+)
Soil organic matter (SOM)	19 (+)	6 (+)	19 (+)	12 (+)	29 (+)
CEC and ECEC	14 (+)	12 (+)	16 (+)	16 (+)	17 (+)
Soil nutrient analysis and liming	37 (+)	11 (+)	31 (+)	7 (+)	28 (+)
Field interpretation	14 (+)	15 (+)	21 (+)	16 (-)	21 (+)

Note: SDG 2. Zero Hunger, SDG 6. Clean Water and Sanitation, SDG 7. Responsible Consumption and Production, SDG 13. Climate Action, and SDG 15. Life on Land. CEC = cation exchange capacity, ECEC = effective cation exchange capacity for soils with soil reaction (pH) less or equal 5.5. A positive sign (+) indicates a strong relation to an SDG, while a negative sign (-) indicates less relation to an SDG.

Table 5 shows the number of students' selections associating soil properties and laboratory exercises with a particular SDG, which can result in multiple selections. Many of these selections demonstrate students' understanding of linkages between soil properties/laboratory exercises and SDGs. For example, saturated hydraulic conductivity is mostly linked to SDG 6: Clean Water and Sanitation. Laboratory on "Soil nutrient analysis and liming" is linked to SDG 2: Zero Hunger. However, students' selections can also demonstrate a lack of understanding of soil property and its linkage to SDG (e.g., AWC), which needs to be further explained and clarified to help students understand the meaning of the soil property (AWC) and help to identify the source of the confusion. Comparison of Table 3 to Table 5 identifies discrepancies between expert knowledge and student answers which provides feedback to an instructor to improve subject matter content explanation when there is a mismatch. The SDG framework is a useful teaching tool to improve subject matter instruction.

In addition to having the students pair SDGs with soil properties or exercises, students were asked to write one or more paragraphs where they used their critical thinking skills to discuss the relation of SDGs to at least one field or laboratory activity, while also describing how the skills learned in that activity could be used to support sustainable development (Table 6).

Table 6. Selected students' comments in response to an assignment asking students to relate a United Nations (UN) Sustainable Development Goal (SDG) to at least one field or laboratory activity and also detail how the skills or knowledge learned in that activity could help them contribute to sustainable development in a professional or personal manner.

Students' Comments
SDG 2. Zero Hunger
"Soil Nutrient Analysis and Liming" laboratory relates to Zero Hunger—In order to grow food, the soil needs to have suitable amounts of nutrients. If plants have the correct amounts of nutrients, they will be more successful at growing food.
The lab using the penetrometer to test for soil compaction relates to several sustainable development goals. Soil compaction knowledge is important for SDG 2 because porous soils are better for plant growth and SDG 6 because non-compact soils store water resources.
Learning about soil pH and making slides for our soil series project relates to zero hunger as soil pH determines what crops can be grown. Creating visuals allows me to share my knowledge with others.
SDG 6. Clean Water and Sanitation
Learning about hydraulic conductivity (Ksat) relates to clean water and sanitation because it is used for the "perc" test and septic suitability in the field.
The soil texture lab relates to the clean water and sanitation SDG in that different soil textures pertain to the drainage of water and the quality of groundwater. One skill I learned was the ability to identify these textures which could help me to know which soils are best for infiltration. "Soil Nutrient Analysis and Liming" laboratory relates to Clean Water and Sanitation—You have to use the correct amount of nutrients because if you put too much, there can be runoff into bodies of water which can harm the ecosystem (like phosphorous and algae blooms).
SDG 7. Responsible Consumption and Production
Field soil interpretation where we analyzed soil layers, slope and scoring soil relates to life on land and responsible consumption and production. Through field soil interpretation we can determine if the soil floods often or very dry.
Bulk density and compaction are important because they determine how well water and nutrients can move through the soil. I learned how to determine different compaction levels and what they meant for the soil. We measured this using a penetrometer and learned how to read it. This is related to sustainable development goals in many ways. Zero hunger and responsible consumption and production relate to this because bulk density and compaction determine how well plants can grow.
SDG 13. Climate Action
The lab that we did on the soil organic matter relates to SDG 13 Climate action because when stuff breaks down in the soil it can cause gasses to be released.
SDG 15. Life on Land
Soil organic matter lab activity heavily relates to life on land because soil organisms are strongly influential in keeping a balanced food chain. These hands-on activities have shown me that the SDG life on land is much more than just the organisms you see, but also all land organisms below ground as well.
The field soil interpretation activity, I think directly relates to life on land SDG. Preserving life on land is directly related because learning and understanding our soil can help to preserve life on land.

4. Discussion

4.1. Significance of a Matrix Approach in Integrating UN SDGs with STEM Education

The matrix approach was successfully used in integrating sustainability into business education [11] and the current study explored its use in integrating SDGs into a STEM course. The results of this study demonstrate that the matrix approach is highly useful in integrating SDGs into STEM education since SDGs are closely related to sustainability and its three pillars: social, economic, and environmental [23]. The educational system at various levels including HEI plays an important role in increasing the awareness of the SDGs among instructors and students [23]. Higher education institutes (e.g., universities, colleges) are particularly relevant since they educate future decision-makers and leaders [24–26]. Figure 2 demonstrates examples of the adaptation of the options matrix with various "structural options" (e.g., existing, new) for integrating the SDGs into STEM education, which can have a narrow (discipline-specific) or broad focus (cross-disciplinary). This matrix provides a framework for discussion (e.g., advantages, disadvantages, recommendations of each option) of the current options as well as future planning.

Delivery

Focus	**Existing Structures**	**New Structures**
Narrow Focus (discipline-specific)	**Option 1.** Integration of SDGs into an existing STEM course for one major.	**Option 2.** Create a new course activity focused on one or two SDGs for one major.
Broad Focus (cross-disciplinary)	**Option 3.** Integration of SDGs into an existing STEM course, which is a core requirement for multiple majors.	**Option 4.** Develop a new STEM course focused on multiple SDGs, which is a core requirement for multiple majors.

Figure 2. Option matrix for the United Nations (UN) Sustainable Development Goals (SDGs) integration in Science, Technology, Engineering, and Mathematics (STEM) disciplines (adapted from Rusinko (2010) [11].

Table 7 describes the advantages, disadvantages, and applications of each option in Figure 2. It is important to consider various scenarios for integrating SDGs into STEM education. For Option 1, the SDG integration is limited to a course that is limited to a specific major, which could integrate multiple SDGs, this has the advantage of not requiring changes in curriculum but has limited impact in an academic unit (e.g., department, school, or college). Option 2, where a new course activity is added requires changes in the structure of the course, which may limit the focus to one or two SDGs and is also limited to one major. Option 4 involves both course creation and curricular changes, which could be impactful, but takes the most resources and time to implement.

Our study used "Option 3" (Figure 2), where UN SDGs were integrated into an existing STEM course (soil science), which is a core requirement for multiple STEM majors (forestry; wildlife; and environmental science) in the department. This provides a cross-disciplinary integration of SDGs using existing structures with minimal instructional changes and no new course or curricular development. Also, the soil science course appears to be well suited because it integrates several scientific concepts, areas, and practical skills that are directly relevant to other STEM disciplines and the SDGs. We have expanded the use of the matrix approach to include identifying the alignment of specific soil science subject matter areas with specific SDGs (Table 1).

Table 7. Major advantages, disadvantages, and applications for matrix options to integrate United Nations (UN) Sustainable Development Goals (SDGs) in Science, Technology, Engineering, and Mathematics (STEM) education (adapted from Rusinko (2010 [11])).

Option	Advantages	Disadvantages	Applications
1.	Ability to integrate multiple SDGs.	No cross-disciplinary impact.	Limited resources are available, and no course is available that serves students across majors.
2.	Least effort to integrate and implement.	Limited impact because of narrow focus.	Limited resources are available and no course that could integrate multiple SDGs.
3.	High potential impact and cross-disciplinary.	----	Limited resources available.
4.	High potential impact using multiple SDGs and cross-disciplinary.	Major effort and may need changes in curricula.	Significant resources are available with an identified need for an additional course for SDGs.

4.2. The Role of Different Teaching Methods in Helping Students to Relate STEM Subject Matter to UN SDGs

Although the concept of sustainability has been widely incorporated in HEI, the newer concept of SDGs is only recently being used in HEI. While the concept of sustainability is broad and often general in nature, the SDGs give specific goals, targets, indicators, and deadlines that can provide a more detailed and actionable educational context to sustainability [27]. To achieve effective results in educating about sustainability and SDGs, all pedagogical methods should be utilized synergistically so that students have the necessary background knowledge and can apply it to sustainability through the SDGs. Our study demonstrates that it is important to utilize both more traditional passive (e.g., lecture) and active (e.g., hands-on laboratory activities) learning techniques to help students gain an understanding of concepts that can support specific SDGs. The key to integrating SDGs with existing course content within the study was to follow these lectures and laboratory exercises with quizzes that asked the students to relate the existing course concepts with the SDGs that had been explained in the lecture material. The students had to use critical thinking to describe how they believed the course material was related to different SDGs, which identified both comprehensions of the course material and the SDGs themselves. This process also revealed gaps in understanding of course material that were addressed through subsequent explanations. The course topics related to SDGs provide examples of how existing course content can be used to help students understand SDGs, by highlighting the importance of the specific soil science concepts in this study. Below are examples of how our study integrated different teaching methods.

Soil texture contributes to provisioning ecosystem services (ES) [9] and many of the SDGs (e.g., SDG 2, SDG 6, SDG 7, and SDG 15), because it impacts agricultural and engineering land use [28]. During the lecture, students learned about the definition of soil texture and its importance for agriculture and water regulation [9]. A laboratory exercise provided hands-on activities including texture determination using a texture triangle, and "texture-by-feel" analysis [29], which enabled students to relate soil texture to various uses (e.g., agriculture, water holding capacity, etc.) [19].

Bulk density, soil compaction, and porosity play a critical role in many ES and the SDGs (e.g. SDG 2, SDG 6, SDG 7, and SDG 15), because soil compaction impacts plant growth, and porosity facilitates water and greenhouse gas (GHG) transmission [9]. During the lecture, students learned the definitions of these soil physical properties, the ES they provide, and field methods used to measure soil penetration resistance (SPR). Laboratory exercise involved field determination of SPR using penetrometers at three locations (forest, mulch, grass) on the university campus, as well as bulk density analysis, where students used tables of soil physical properties from Web Soil Survey [21] to graph bulk density values for each soil horizon and then analyzing a trend in bulk density distribution with depth [19].

Saturated hydraulic conductivity (Ksat) contributes to regulating ES and SDG 6, and SDG 7, because it is used for septic tank suitability determination [9], which is important for responsible land consumption. During the lecture, students learned about the definition of Ksat, the ES it provides, and the field methods used to measure it. Field exercise on Ksat and septic tank absorption field suitability involved using field soil profile descriptions and soil property measurements (e.g., soil texture, structure, redoximorphic features, etc.) included in the soil judging scorecard [19].

Available water capacity (AWC) contributes to provisioning and regulating ES and the SDGs (e.g. SDG 2, SDG 7, and SDG 15), because AWC is one of the most important soil characteristics for plant growth, influencing photosynthesis rates, carbon allocation, and nutrient cycling [30]. During the lecture, students learned about the definition and function of AWC using a sponge demonstration, its importance in plant growth, and the ES it provides. Students also had an opportunity for field determination of AWC as part of a soil judging exercise by using soil horizon depth and corresponding soil texture class coefficients [19].

Soil organic matter (SOM) plays a critical role in many ES and the SDGs with particular importance for SDG 2, SDG 13, and SDG 15, because it is a supercolloid necessary for food production and greenhouse gas (GHG) regulation [9]. During the lecture, students learned about the definition of SOM, the ES it provides, composting, and laboratory methods used to measure it. Laboratory exercise on SOM involved the calculation of regulating ES using the concept of "avoided" and "realized" social costs of carbon (SC-CO_2) [31], where students used tables of soil physical properties from Web Soil Survey [21] (horizon depth, bulk density, and SOM) to calculate C storage and SC-CO_2 values for each soil horizon and then total for the whole soil profile [32]. Future teaching improvements can include more problem-solving activities.

Cation exchange capacity (CEC) and effective cation exchange capacity (ECEC) contribute to provisioning ES and the SDGs (e.g. SDG 2, SDG 6, SDG 7, SDG 13, and SDG 15), because CEC is important for soil fertility and nutrient retention capacity for plant growth [33]. During the lecture, students learned about the definition of CEC and ECEC, and the ES they provide. Hands-on laboratory exercise involved the comparison of different soils in two states of the country (Kansas, and South Carolina) by mapping CEC and ECEC and providing an explanation for the differences [19].

Soil reaction (pH) and calcium carbonate ($CaCO_3$) contribute to provisioning ES and the SDGs (e.g. SDG 2, SDG 6, SDG 7, SDG 13, and SDG 15), because soil pH impacts plant growth and indicates the need for liming (e.g., $CaCO_3$, etc.) which promotes soil fertility [33]. During the lecture, students learned about the definition of soil pH and $CaCO_3$ (also referred to as soil inorganic carbon, SIC), and the ES they provide. Laboratory exercises involved analysis of pH distribution with depth using Web Soil Survey [21] data, calculating provisioning (using the concept of liming replacement cost) and regulating ES (based on the concept of SC-CO_2) values provided by $CaCO_3$, [32], calculating exchangeable acidity using "active" pH and "buffer" pH from soil analysis reports provided by soil nutrient analysis laboratory and use of liming tables for different target pH [19].

Base saturation (BS) contributes to provisioning ES and the SDGs (e.g. SDG 2, SDG 7, and SDG 15), because BS is directly related to soil fertility regarding the number of base cations (Mg^{2+}, Ca^{2+}, Na^+, K^+) present in soil [34]. During the lecture, students learned the definition and applications of BS for soil fertility. Hands-on soil judging field exercise involved using BS values for soil epipedons classification (e.g., mollic, umbric, etc.) [19].

These specific soil science concepts are part of the foundational knowledge necessary for students to be able to use an understanding of soils in their future studies and careers. By integrating SDG content with soil concepts, students gained knowledge of the sustainability implications of these soil chemical and physical properties. This method of weaving SDGs into existing course materials served to give students a range of passive and active learning opportunities to understand sustainability. Students' successes and challenges in using critical thinking to relate SDGs to this course content and identified knowledge gaps can be used to improve the existing lecture and laboratory material for future student cohorts.

4.3. Challenges and Opportunities in Integrating UN SDGs with STEM Education

Initially, sustainability education was a broad concept that mirrors the definition of sustainability itself which can be understood as a balance between the natural and human-made world over time, where environmental, social, and economic concepts remain in harmony [27]. Sustainable development, which serves to further refine the concept of sustainability, is focused on attaining cultural and social progress, while also having growth of the economy and maintaining an environmental equilibrium [27]. Furthermore, these three concepts (environmental, social, and economic) are often seen as the three pillars of sustainability (Figure 3) [27]. A more recent refinement, which served to further focus actions that can support sustainability, is the adoption of the UN SDGs, which listed specific goals and targets to help countries track and monitor sustainability [1]. These SDGs also served as topics and measures that could be used to improve sustainability education, because they more clearly define actionable areas for teaching, research, and community outreach (Figure 3).

Figure 3. Interrelation between sustainability, sustainable development (SD), United Nations (UN) Sustainable Development Goals (SDGs), the three pillars of sustainable development (society, economy, and environment), and the three pillars of education for sustainable development (teaching, research, community).

While SDGs provide a useful learning structure, the related SD targets and goals are somewhat general, which can limit the opportunity to develop quantitative hands-on learning activities to help the students better understand how societal decisions impact sustainability. For example, soils are rarely mentioned as part of SDGs despite the obvious interrelationship between soil science and SDGs.

The ecosystem services framework can be also integrated with SDGs to provide a more meaningful and synergistic teaching experience. In our study, regulating ES (climate regulation) provided by SOM was linked to SDG 13 (Climate Action) in a laboratory exercise which required students to calculate the social costs of carbon (SC-CO_2) using the concept of "avoided" and "realized" social cost [32]. During another laboratory exercise, provisioning ES (food) provided by soil pH and $CaCO_3$ was calculated based on the concept of liming replacement cost provided by $CaCO_3$ [32]. The ecosystem services-based approach toward achieving the SDGs is identified as one of many implementation strategies by experts on sustainability and ES [35–37].

Successful integration of SDGs and ES into STEM education is also dependent on students' interests, which can be a powerful motivation in learning about SDGs. Despite a common assumption that students do not have interests in required STEM courses (outside their majors), Mikhailova et al. (2022) [38] reported that most students had "personal" and "utility value" types of interests before taking a required STEM soil science course [38]. Students were also interested in ecosystems and provisioning ES provided by soils [38]. Based on this prior analysis of student interest, the best-suited interest intervention types were selected: problem-based learning and utility value [38]. For future STEM activities involving SDGs, surveys of student interest can be used to design effective course activities.

Regulating and supporting ES also lend themselves to measurements and monitoring using new technologies. For example, satellite or unmanned aerial vehicle (UAV) based remote sensing could be used by students to study primary production, flood or erosion regulation. Sensor-based studies could be used by students to evaluate the air and water purification ES. Tying measurements and analysis to ES can be linked back to SDGs and sustainability education, by providing several hands-on active learning opportunities to have students evaluate the status of environmental systems.

5. Conclusions

Improving education on sustainability is possible by integration of the United Nations (UN) Sustainable Development Goals (SDGs) into existing course content for various disciplines, including Science, Technology, Engineering, and Mathematics (STEM). Soil science is a STEM discipline with course content that can be directly related to multiple SDGs. The objectives of this study were to use a matrix approach to integrate SDGs into existing introductory soil science course in a way that helped students improve their understanding of sustainability. The course was enriched with a lecture on SDGs which helped students understand the importance and content of relevant SDGs. A series of quizzes were used after students completed passive and active learning activities around core soil concepts, asking the students to relate SDGs to this course material using critical thinking. The results of this study were successful based on the post-assessment survey, which revealed an increase in familiarity with SDGs, their relevance to soil properties, and course activities. Most students agreed and strongly agreed that the course activities were an effective way to learn about SDGs with examples from soil science. The advantage of this approach is that it seamlessly integrates SDGs with existing course materials while relying on students' critical thinking skills to effectively analyze soil science information and form a judgment on how it relates to SDGs. Comprehensive changes to curricula could improve sustainability education by adding courses and updating multiple courses with SDG content, but in many cases, these wholesale changes within a major would be difficult to impossible. The approach of targeting core knowledge courses that serve multiple majors can serve as a first step to improving sustainability education.

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Glossary

ESD	Education for sustainable development
ENR	Environmental and natural resources
EPA	Environmental Protection Agency
ES	Ecosystem services
FOR	Forestry
HEI	Higher education institution
NRCS	Natural Resources Conservation Service
RLO	Reusable learning object
SC	South Carolina
SC-CO_2	Social cost of carbon emissions
SD	Sustainable development
SDGs	Sustainable Development Goals
SOC	Soil organic carbon
SIC	Soil inorganic carbon
STEM	Science, Technology, Engineering, and Mathematics
UAV	Unmanned aerial vehicle
USA	United States of America
USDA	United States Department of Agriculture
UN	United Nations
WFB	Wildlife and Fisheries Biology

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