
PRACTICE BRIDGE

Building student capacity to lead sustainability transitions in the food system through farm-based authentic research modules in sustainability sciences (FARMS)

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Undergraduate courses provide valuable opportunities to train and empower students with the knowledge, skills, and motivation to advance society in more sustainable directions. This article emphasizes the value of bridging primary scientific research with undergraduate education through the presentation of an integrated experiential learning and primary research model called Farm-based Authentic Research Modules in Sustainability Sciences (FARMS). FARMS are collaboratively designed with agricultural stakeholders through a community needs assessment on pressing food system issues and opportunities with the objective for faculty and students to jointly identify evidence-based management solutions. We illustrate the implementation of FARMS in an undergraduate course in Ecological Agriculture at Dartmouth College, NH where students assessed various agroecological solutions for managing plant vitality, weeds, soil quality, pests, pollinators, and biodiversity at the Dartmouth Organic Farm. Student reflections indicate that the FARMS course component was beneficial for understanding agroecological theories and concepts while also motivating involvement in sustainability sciences despite the challenges of primary research. Educator reflections noted that the FARMS pedagogical approach facilitated achieving course objectives to develop students' ability for systems thinking, critical thinking, and interdisciplinarity while fostering students' collaboration skills and overall motivation for creating change. Adopting the FARMS model should enable faculty in the sustainability sciences to serve as bridges between the learning, practicing, and scientific communities while supporting educational programming at student and community farms. Ultimately, it is expected that the implementation of FARMS will increase student capacity and prepare the next generation of leaders to address complex challenges of the food system using an evidence-based approach.

Keywords: sustainable food systems; agroecology; experiential learning; undergraduate primary research; student farms; scholarship of teaching

1. Introduction

1.1 Need and opportunity

Efforts to promote agroecology and sustainable food systems have developed in the past few decades with the goal to address the environmental externalities, public health concerns, and socio-economic issues associated with the modern food system. Agroecology and sustainable food systems pro-actively support environmental and human wellbeing. From an environmental perspective, it is

widely recognized that the modern food system produces air and water pollution, soil depletion, loss of biodiversity, pressures on limited fossil fuels, and emissions of greenhouse gases (Francis et al., 2008; Gliessman, 2015; Gomiero et al., 2011; Mazurkewicz et al., 2012). From a public health perspective, the modern food system is associated with the supply of foods linked to diet-related chronic diseases including cardiovascular disease, diabetes, and cancers (Horrigan et al., 2002). Interacting political, market, population, and other societal factors further perpetuate a food system characterized by unsustainable modes of production, heightened consumption of resources, social equity issues, and food insecurity (Breggin and Myers, 2013; de Wit and Iles, 2016; Gomiero et al., 2011).

Institutes of higher education have a crucial role to play in the development of professionals whose work will directly shape the food system towards advancing

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sustainability (Valley et al., 2017). However, researchers and educators tend to conceptualize and address diverse food system challenges as separate, disconnected issues rather than interdisciplinary ones (Valley et al., 2017). This lack of an interdisciplinary approach represents a key barrier to reforming the food system (Valley et al., 2017). Most agricultural science at the university level in the United States remains discipline-oriented from the founding days of agricultural programs at land grant universities (Francis et al., 2008; Parr et al., 2007). Such a strictly disciplinary approach to higher education risks leaving students underprepared to address the complexities of modern food systems (Coops et al., 2015; Wiek et al., 2011). Several institutions across the country have developed agroecology and sustainable food systems degree programs, certificates, and courses to train students to address the multifaceted, interdisciplinary, and transdisciplinary nature of food systems issues (Grossman et al., 2010; Jacobsen et al., 2012; Malone et al., 2014; Mazurkewicz et al., 2012; Parr and Van Horn, 2006; Reeve et al., 2014; Jordan et al., 2014; Valley et al., 2017).

Agroecology has evolved from a science focused on applying ecological concepts for assessing crop production systems (Bensin, 1925) to a science and practice that emphasizes ecological, economic, and social dimensions of agricultural systems (Altieri, 1995) as well as the entire food system (Francis et al., 2003; Gliessman, 2007; Wezel et al., 2009). This involves not only examining ecological processes within agricultural systems, but also designing evidence-based production systems that emphasize complex ecological interactions capable of providing ecosystem services for the management of soil fertility, productivity, pollination, and pest and disease control (Altieri, 1995).

More recently, the study of food systems has developed as a distinct transdisciplinary field that unifies knowledge from food production and distribution through consumption and waste (Basarab, 2002; Francis et al., 2008; Francis et al., 2011; Chase and Grubinger, 2014). The study of food systems requires a socio-ecological systems approach that examines ecological, economic, cultural, and human health dynamics of food. For example, the study of food systems ranges from examining the effects of production on ecosystem services to issues of social equity, food access, nutrition, power dynamics, and value chain complexity (Francis et al., 2011: 229; Hilimire, 2016). Educators have identified common pedagogical themes evident in sustainable food systems programs that comprise a signature pedagogy, or a conceptual model by which professional education in a specific field is designed, structured, and implemented (Valley et al., 2017). Central components within a signature pedagogy for sustainable food systems education are: (1) systems thinking, (2) multi-, inter- and trans-disciplinarity, (3) experiential learning approaches, and (4) collective action projects.

1.2 Bridging scientific knowledge with undergraduate education towards fostering sustainability transitions

With an urgent need to reform the current dominant food system, it is vital to strategize *how* sustainability transitions will be implemented and realized, including

how educators will train able leaders to tackle societal problems with innovative solutions. One way to train future leaders of sustainability transitions is to build capacity in the undergraduate classroom through experiences that empower students with the knowledge, skills, and motivation to ultimately address complex food system challenges. This necessitates that educators critically examine and reconceptualize learning in the undergraduate classroom. Not only must educators analyze the ways in which knowledge is produced, but they must also critically analyze the ways in which they prepare students to ask questions, think across disciplines, test possible solutions, collaborate with a diverse range of stakeholders, facilitate community engagement, and implement potential solutions. Ultimately, educators must ask: *How can the undergraduate classroom best equip students to initiate and lead sustainability transitions in the food system?* This question points to the need to bridge sustainability science research with pedagogy and learning.

Researchers have long been forefront thinkers who work with existing knowledge, theory, and practice to produce new knowledge. However, there is often a disconnect between faculty research and student learning. This article emphasizes the value of bridging primary scientific research with undergraduate education focused on identifying and implementing sustainability solutions through an evidence-based approach. We present a type of integrative experiential learning and primary research model for undergraduate food systems curricula that can be implemented at student university-based farms, which we refer to as Farm-based Authentic Research Modules in Sustainability Sciences (FARMS). If a learning institution does not have a student university-based farm, FARMS can be implemented in other local farms or gardens such as community gardens.

In the FARMS model (**Figure 1**), educators in the sustainability sciences bridge the learning, practicing, and scientific communities to facilitate a deeper understanding of the nature of science and its potential for transforming the food system through research and community engagement. The FARMS model supports educators, students, and other stakeholders to “co-construct knowledge” (Parr et al., 2007) through primary research on locally relevant food system challenges. Moreover, the FARMS model bridges science and practice by identifying research topics that are locally relevant through a community needs assessment. Educators expect that the tangible, place-based inquiries of the FARMS model will aid students’ understanding of course content and the process of scientific research while developing skills and motivation for facilitating change through an evidence-based approach.

The FARMS model not only bridges course-based faculty-student research opportunities, but has the potential to bridge student university-based farms with academic departments through educational and research programming focused on experiential learning. As of 2016, there were 57 student farms or gardens at colleges and universities in the United States (Parr, 2016). In many instances, student farms developed largely out of student efforts before the creation of most formal sustainable agriculture and food systems programs (Parr and

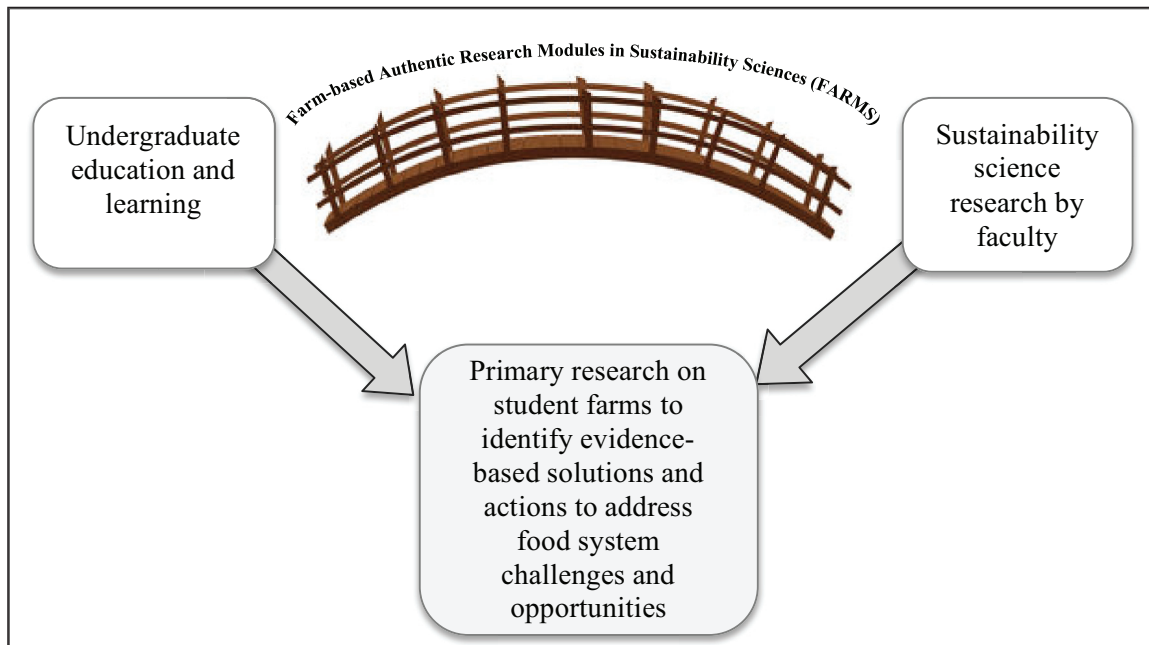


Figure 1: Bridging education and research through farm-based authentic research modules in sustainability sciences (FARMS). Farm-based Authentic Research Modules in Sustainability Sciences (FARMS) present opportunities to bridge faculty research focused on identifying sustainability solutions with undergraduate learning through course-based primary research implemented at student university-based farms. Ultimately, this bridge seeks to build student capacity to lead sustainability transitions using an evidence-based approach. Note: This image was created using an open source stock image from Fotosearch. DOI: <https://doi.org/10.1525/elementa.239.f1>

Trexler, 2011). Student farms have been shown to be important spaces for learning as they provide concrete real-world agricultural experiences linked to more abstract academic content (Parr and Trexler, 2011). Given the notable number of existing student farms as well as those that are increasingly being created, there is both a need and opportunity for course-based learning and research to take place on student farms. The adoption of FARMS at student farms helps rationalize support of these spaces while enhancing the rigor of agroecology and food systems curricula through place-based experiential learning.

In this Practice Bridge article, we first summarize experiential learning models in agroecology and sustainable food systems curricula at the undergraduate level in order to better situate the FARMS model. We then describe the pedagogical approach of FARMS followed by an illustration of the implementation of FARMS carried out as part of an Ecological Agriculture undergraduate-level course at Dartmouth College. Student, educator, and other stakeholder reflections contextualize the challenges and opportunities involved in the implementation of FARMS towards meeting various learning objectives. This paper contributes to the growing body of research-based literature on agroecology and sustainable food systems education. It further contributes to the scholarship of teaching linked to experiential learning on student farms.

2. Experiential learning models in agroecology and sustainable food systems curricula

Experiential learning has been identified as a key pedagogical approach in agroecology and sustainable food systems curricula to meet learning objectives for

students to develop the knowledge, skills, and dispositions to effectively address complex food system challenges (Bawden, 1996; Valley et al., 2017; Andreasen, 2004; Grossman et al., 2010; Hilimire, 2016; Jordan et al., 2005; Sipos et al., 2008). By focusing on active hands-on learning through experience and reflection, experiential learning models bring students outside of the traditional classroom lecture setting (Garkovich et al., 1992; Kolb, 2014; Moncure and Francis, 2011). Kolb's seminal model of experiential learning is based on a framework that links education, work, and personal development with the goal to foster both academic and personal development in ways that are learning centered through the process of constructing knowledge through experience (Kolb, 2014). Experiential learning approaches provide inquiry-based learning experiences in real-world settings where the learner actively makes firsthand discoveries. Compared to rote or didactic learning such as 'cookbook' laboratory exercises, experiential models may motivate students to retain and pursue further knowledge (Handelsman et al., 2004; Bentley, 2012; Sobel, 2004; Dewey, 1938).

Numerous educators in the areas of agroecology and sustainable food systems have highlighted the benefits of experiential learning for enhancing student understanding of course material while increasing vital skills related to systems thinking, deep reflection, problem solving, research, professionalism, communication, collaboration, community engagement, agency, and ability to design solutions for transforming the food system (Andreasen, 2004; Galt et al., 2013b; Grossman et al., 2010; Helms, 2014; Hilimire, 2016; Jordan et al., 2005; Jordan et al., 2014; Reeve et al., 2014; Coops et al., 2015;

Jordan et al., 2014; Schroeder et al., 2006; Sipos et al., 2008). Experiential learning has also been described as an effective way for students to understand underlying phenomena, effectively apply skills, discover meaning in the world, and work towards greater social justice (Andreasen, 2004; Garkovich et al., 1992; Freire, 1973; Kolb, 2014; Kolb and Kolb, 2012; Moncure and Francis, 2011). Furthermore, experiential learning helps students become autonomous learners and generates capacity to link theories and scientific knowledge with practice (Lieblein et al., 2007).

Table 1 provides a brief overview of various experiential learning models implemented in several sustainable food systems programs including the following: action-based learning, community service-learning, implementation of a values-based approach, reflection, on-farm research, field trips, and open-ended cases. These various pedagogical models all focus on building student knowledge and academic skills as well as on preparing well-informed citizens, leaders, and reflective *human beings* armed with the capacity to lead change. Multiple alternative methods for evaluating student performance in experiential learning activities have been used in sustainable food systems

education, including reflective essays (Andreasen, 2004; Battisti et al., 2008; Sipos et al., 2008; Francis et al., 2009; Mazurkewicz et al., 2012; Galt et al., 2013b; Reeve et al., 2014; Coops et al., 2015), peer evaluations (Jordan et al., 2014), personal portfolios to track student exploration, team projects (Coops et al., 2015), and participation in out-of-class and in-class activities (Jordan et al., 2005).

Action-based learning, service-learning, and primary research are three prominent experiential learning models implemented in agroecology and sustainable food systems curricula. Specifically, action-based learning involves some type of activity on the part of learners either in an individualized context or in a collaborative group-based setting (Lieblein et al., 2004; Lieblein et al., 2012; Naidu and Bedgood, 2012). This type of experiential learning can take many forms in sustainable food systems curricula, including inquiry-based approaches to problem solving (Francis et al., 2009), service learning (Grossman et al., 2010), eliciting systems-thinking perspectives in order to facilitate holistic understanding of complex food systems issues (Creamer et al., 2009; Coops et al., 2015; Jordan et al., 2005; Jordan et al., 2014; Schroeder

Table 1: Summary of experiential learning models in undergraduate food systems curricula. DOI: <https://doi.org/10.1525/elementa.239.t1>

Source	Institution	Learning Model(s)	Learning Objectives and Curricula Activities
Andreasen (2004)	New Mexico State University	Experiential learning in capstone courses	Students are guided in a culminating capstone experience to “receive, relate, reflect, and reconstruct” an integrated knowledge base.
Coops et al. (2015); Sipos et al. (2008)	University of British Columbia, Vancouver	“Head, heart, and hands”	The curriculum objectives are to instill knowledge, skill and practice, and values and passion in a holistic manner.
Francis et al. (2009)	Iowa State University	Open-ended cases	The learning model emphasizes co-learning by students and instructor through a case study approach; evaluations are based on group and individual written findings and reflections.
Galt et al. (2013a, b)	University of California, Davis	Learner-centered inquiry	Learning goals are to develop student competency in areas including inquiry, analysis and interpersonal skills.
Grossman et al. (2010)	Cornell University ^d	On-farm research; field trips; service learning	Curricula activities include farm visits to increase relevance of lab work and student reflective essays to assess impact of the program.
Helms (2014)	Virginia Polytechnic Institute and State University	Civic engagement/ service learning	Students are trained to complete a community action project related to food systems and reflect on their professional development.
Hilimire (2016)	Fort Lewis College	Integration of experience-theory-skills ^e	To encourage professional development and civic engagement as well as to apply the ecosystem concept to agriculture and study organic farming methods.
Jordan et al. (2005)	University of Minnesota	Service learning	Collaborative efforts to address human <i>and</i> ecological problems through community partnerships.
Reeve et al. (2014)	Utah State University	On-farm research; service learning	Emphasis on detail and depth of student research analyses, reflections, and communication with peers and community.
Creamer et al. (2009); Schroeder et al. (2006)	North Carolina State University	Multilevel approach and on-farm activities	Students carry out agroecology research in experimental plots; Emphasis is placed on oral and written communication as well as collaboration.

et al., 2006), course-based research (Reeve et al., 2014), implementing an explicit values-based approach (Jordan et al., 2005), and motivating individual or societal change (Battisti et al., 2008). For example, Utah State University's hands-on Student Farm Practicum course offers action-based learning in which students design and implement agroecological research projects, such as determining the most suitable potting soil mixture for greenhouse seedling production (Reeve et al., 2014).

Service learning is a type of experiential learning that integrates course learning objectives with community service by introducing students to opportunities for social change through curriculum activities. Grossman et al. (2010) introduce service learning as "the act of linking students to community partners to address public needs while developing disciplinary competency..." as a proven way to engage students in real-world learning. Drawing from the land grant mission of incorporating research, education, and extension into the work one does (Jacobsen et al., 2012; Niewolny et al., 2012; Schroeder et al., 2006; Trexler et al., 2006), multiple sustainable food system programs and courses emphasize learning through community service and civic engagement (Jordan et al., 2005; Grossman et al., 2010; Niewolny et al., 2012; Reeve et al., 2014). Examples of service learning projects in sustainable food systems curricula include engagement with community gardens, food pantries, and non-profit organizations. Students in an agroecology program who worked with non-profit organizations to address agroecological issues in their local communities noted that service learning helped them connect their coursework to real-world problems; educators of this program reflected that these experiences were powerful stimulants for learning concepts that can otherwise seem abstract and arcane (Jordan et al., 2005).

Primary research in the undergraduate classroom, also known as Course-based Undergraduate Research Experiences (CURE; Auchincloss et al., 2014), is a type of experiential learning that develops students' ability for systems thinking and critical thinking (Linn et al., 2015; Derting and Ebert-May 2010; Hunter et al., 2007; Brownell et al., 2015) and fosters intellectual and professional development (Staub et al., 2016; Brownell et al., 2015; Derting and Ebert-May, 2010; Hunter et al., 2007). Through primary research in the undergraduate classroom, students develop scientific literacy skills related to inquiry, data collection, and analysis that facilitate problem solving and critical thinking (Ritchie and Rigano, 1996). For example, qualitative survey findings from an inquiry-based biology research course for first-year college and high school students indicated academic and personal development, including 'career and interest,' 'thinking and working like a scientist,' 'skill development' and 'self-confidence' (Staub et al., 2016).

3. Farm-based Authentic Research Modules in Sustainability Sciences (FARMS)

3.1 Farm-based Authentic Research Modules in Sustainability Sciences

Farm-based Authentic Research Modules in Sustainability Sciences (FARMS) follow an experiential learning model that incorporates primary research into course curricula.

The overall objectives of FARMS are as follows: (1) to provide opportunities for students to apply agroecology and sustainable food systems course concepts in a real-world agricultural setting, (2) to facilitate educators, students, and other stakeholders to co-construct knowledge in the process of identifying sustainability solutions for food system challenges, (3) to develop students' field and laboratory research skills, critical thinking, collaborative ability, and motivation in leading sustainability transitions, and (4) to motivate students to engage in designing evidence-based solutions and lead sustainability transitions. The underlying pedagogy for FARMS rests within the principles of the sustainable food systems signature pedagogy (Valley et al., 2017) including interdisciplinarity, experiential learning (Andreasen, 2004; Cory-Watson, 2013; Earley, 2014; Parr et al., 2007; Reeve et al., 2014), systems-thinking (Hilimire, 2016; Jordan et al., 2014), and collective action projects. The type of experiential learning that FARMS focuses on is primary research in the undergraduate classroom (Auchincloss et al., 2014).

The FARMS experiential learning model further draws from the Authentic Research Modules in Sciences (ARMS) model that was implemented through the NSF Graduate Teaching Fellows in K-12 Education Program (NSF GK-12) at the City University of New York. The NSF GK-12 ARMS pedagogical strategy was originally designed to facilitate graduate students to develop their skills as educators while bringing primary research into the high school classroom. The program also helped to create research resources for public schools in New York City. Science education at the high school and undergraduate level often emphasizes rote memorization of a changing body of knowledge supplemented by formulaic and pre-prepared laboratory experiments. Such an educational approach may result in cognitive and experiential gaps between the content of science textbooks and students' everyday lives and discourage students from pursuing an education and career in the sciences. ARMS seeks to overcome this cognitive and experiential gap between content and students' daily lives through place-based research projects in students' neighborhoods on locally relevant topics to which students can more easily connect.

FARMS builds on the integrated experiential learning and primary research model of ARMS. Each FARMS model is developed as a hands-on, place-based, investigative science course carried out on locally relevant food system topics designed to enable students to think and work like scientists. The FARMS pedagogical model seeks to reconceive science education as a creative, active, and open-ended pursuit in order to stimulate student interest in the sustainability sciences and develop motivation for creating food system change. FARMS differs from conventional science experiments in the undergraduate classroom in that they are not formulaic pre-prepared laboratory experiments. Rather, FARMS tests real sustainability solutions in place-based research projects intended to better inform management of agricultural systems. Educators design and implement FARMS by adapting the theoretical, methodological, and experiential frameworks of their own

research coupled with community engagement with local food system stakeholders.

FARMS-based courses position students at the center of the learning process. FARMS engage students at multiple dimensions through field research activities that allow students to make meaning of their surroundings through direct experience in a structured learning environment. This aspect of FARMS reflects a heuristic approach to education in which each learner individually and socially constructs systems of meanings based on contextual experiences (Dewey, 1938; Driver et al., 1994). In contrast to focusing on the delivery of isolated facts and theories, the design and implementation of FARMS focus on the experiences of students and the changing food system contexts in which they live. Course instructors take the role of learning facilitators and research mentors by sharing in tasks of problem solving with students rather than presenting material from the position of an expert. We expect that the FARMS approach will address the challenge highlighted by Lieblein et al. (2007) regarding designing agroecological courses that provide students with “relevant educational experiences that will strengthen their motivations and prepare them for a complex future.”

3.2 Methods for FARMS Development and Implementation

Courses developed using the FARMS model integrate content, methods, and experiences to identify evidence-based sustainability solutions. These courses build upon student learning experiences and skills, and map out thematic units and associated learning goals through instructional scaffolding (Beed and Hawkins, 1991). Instructional scaffolding is a process designed to promote a deeper level of learning to help students become autonomous learners (Beed and Hawkins, 1991) and develop cognitive maturation. Research activities, materials, and assignments are then developed based on these thematic units and learning goals. The course syllabus and other course materials such as guidelines for individual assignments and lab reports emphasize different course objectives.

Once course themes and learning goals are determined, the instructor works with local and regional agricultural producers and other instructional stakeholders to design research activities that comprise the key FARMS course components. The design of FARMS takes place before the course and proceeds through a community needs assessment carried out during focus group workshops with local and regional agricultural producers. These focus group meetings can be carried out during existing meetings such as producer conferences and agricultural extension workshops or can be arranged by bringing producers together in meetings specifically for this purpose. If in-person focus groups are not possible, instructors can carry out a community needs assessment through an online or paper survey. When the FARMS model is being implemented in a course that is part of a sequenced agroecology or sustainable food systems program, the community needs assessment can be included in a course that students take leading up to the FARMS course. Alternatively, instructors

can lead a community needs assessment towards the end of a FARMS course to identify research projects for following course iterations.

After sharing course learning objectives and the goals of FARMS with focus group participants, the course instructor facilitates focus group dialogue through a series of prompts to identify local food system issues and opportunities. Next, the course instructor leads the focus group through a ranking exercise to prioritize the different challenges and opportunities that they perceive should be addressed through research projects. The group then brainstorms potential sustainability solutions and/or actions to address the most highly prioritized food system challenges and/or opportunities. If the FARMS model has been previously implemented in a course, the instructor can also draw on student research suggestions from previous course experiences. The course instructor then works with the farm manager(s) to design research projects based on the outcomes of the focus group workshop, the instructor's research, and the context of the farm. Course themes and learning objectives are revisited to refine and finalize the research questions and experimental design of the FARMS.

FARMS-based courses are designed to allow students to spend at least 25% of their time engaged in primary research activities. Each course is structured around a key group research project that can be comprised of smaller projects. Once research questions and experimental design are determined, the instructor maps and divides the projects into labs over the course of the term. The instructor identifies the associated skills and content areas that students will need to successfully complete the FARMS research activities. Each weekly experiment is designed to build on the content and skills of the previous activity in terms of complexity and student independence in the learning process through instructional scaffolding. Depending on the research question(s), the experimental setup may be implemented prior to the start of the course or, when possible, at the start of the class with the help of students.

In addition to research, students in FARMS-based courses are led through course content through interactive lectures, hands-on activities, reflections, and peer-led team teaching in order to engage student learning in multiple ways. Following the initial curriculum design, FARMS are pilot-tested in the classroom setting and adapted based on outcomes and feedback. Teaching experiences and student evaluations are integrated in the refinement, compilation, and dissemination of syllabi and lesson plans for other educators to adapt.

4. Illustration of FARMS at the Dartmouth Organic Farm

Here, we illustrate the development and implementation of FARMS through the example of an Ecological Agriculture course (hereafter referred to as ENVS 25) taught at Dartmouth College in Hanover, New Hampshire during summer 2016. In brief, ENVS 25 is a 10-week summer course that teaches undergraduate students how

to apply concepts from ecology to the study of agriculture and the design of sustainable production systems. ENVS 25 has been taught at Dartmouth College for the past 20 years. This course serves as a core course in the environmental studies major at Dartmouth College and is generally taken by students at the end of their sophomore year. The pre-requisite to register for ENVS 25 is completion of either Introduction to Environmental Science or Ecology. This course is generally capped at 30 to 40 students.

ENVS 25 includes lecture, laboratory, and recitation (X-hour) components. The lecture component meets three times a week for 65 minutes during each meeting. The laboratory component is divided into two lab sections that each meet once per week for three hours at the Dartmouth Organic Farm (**Figure 2**), located approximately three miles from the Dartmouth College campus. The lab component for ENVS 25 is taught in the focal agricultural production area of the Dartmouth Organic Farm, a 0.5 acre USDA certified organic crop



Figure 2: Study Site at Dartmouth Organic Farm. The FARMS model was implemented at the Dartmouth Organic Farm of Dartmouth College in New Hampshire. The study site is located in USDA plant hardiness zone 5A. The production field is located on a flood plain adjacent to the Connecticut River with open grass fields in the immediate surroundings and nestled within a diverse temperate forest. The primary agroecological management practice of the organic-certified production field is annual crop rotation comprising of five botanical families. The tomato cropping experiment presented here was carried out in this annual crop rotation field. DOI: <https://doi.org/10.1525/elementa.239.f2>

field on the flood plain of the Connecticut River amongst diversified temperate forest. The recitation section meets for one hour once per week during select weeks either in the classroom or at the Dartmouth Organic Farm.

During the 2016 iteration of this course (taught by this article's corresponding author), the curriculum was adapted to integrate the FARMS model to link agricultural systems with the broader food system. While the 2016 iteration of ENVS 25 was grounded in the fundamentals of agroecology, the course utilized a sustainability framework to evaluate cultural, socio-economic, and policy dimensions associated with agricultural systems, including challenges and opportunities for adopting ecological agriculture more broadly. The FARMS model was implemented along with other conventional classroom activities (lectures and exams) and experiential learning components including a farm practicum (comprising of service learning on crop production and other farming tasks), field observations, stakeholder engagement, inquiry-based case studies, student reflections, critical systems-thinking perspectives, and peer-led team teaching. **Figure 3** illustrates the multidimensional

pedagogical strategies of ENVS 25 and situates the FARMS component within the broader course structure and interactions with other course components and learning outcomes.

The learning objectives for the FARMS-based version of ENVS 25 during the 2016 iteration were as follows:

- A. *Systems Thinking*: Demonstrate an understanding of agriculture and the ability for systems thinking based on agroecological and food systems perspectives.
- B. *Research Skills*: Gain natural and social science research skills to examine processes within food systems using an evidence-based approach.
- C. *Experiential Learning and Development of Agency*: Develop practical experience and agency regarding challenges and opportunities associated with ecological agriculture through practical on-farm crop cultivation experience, research in experimental plots, and interactions with stakeholders during field trips. Agency is defined as the reflexive product of action, which allows

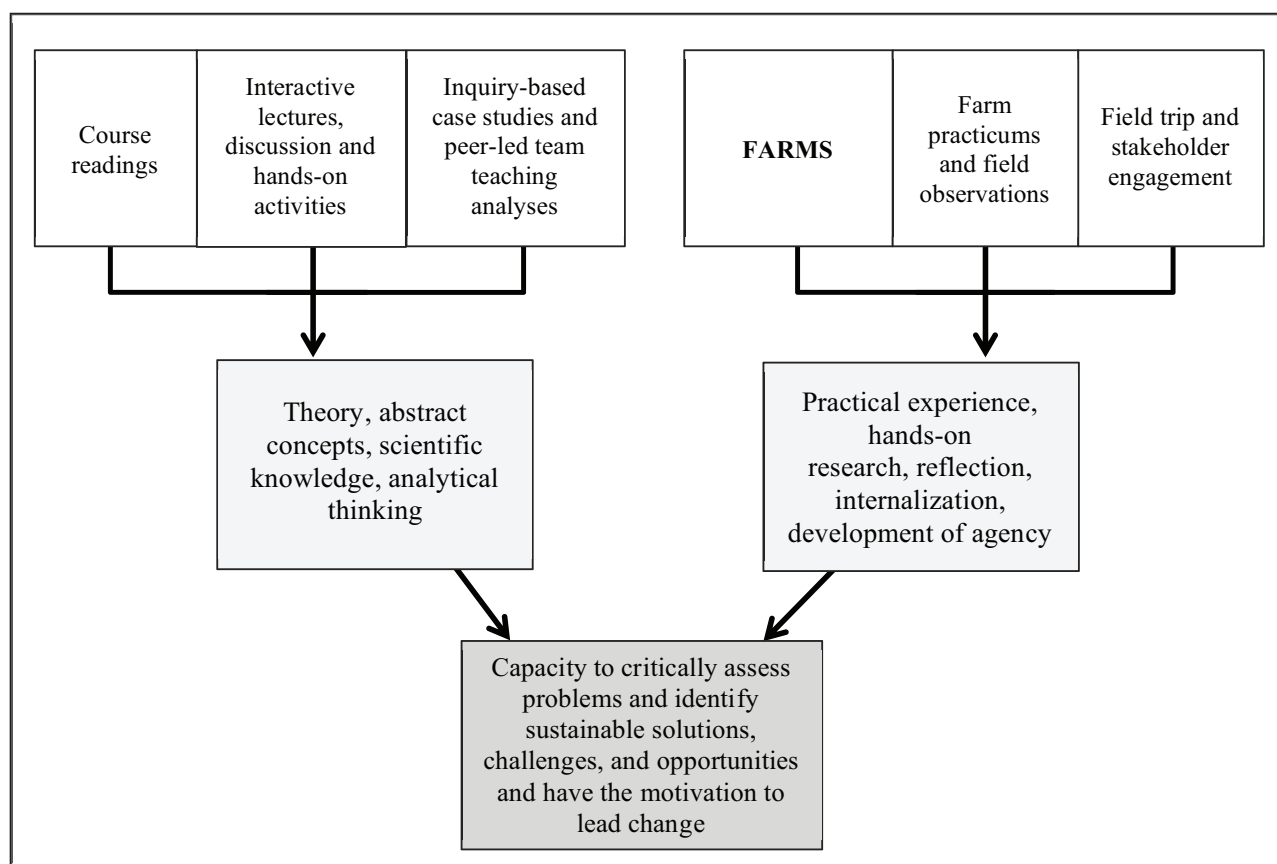


Figure 3: Integrated learning model of Ecological Agriculture course at Dartmouth College. During Summer 2016, the Ecological Agriculture course at Dartmouth College was designed to integrate the agroecology and sustainable food systems theory, content, and scientific knowledge of with the experience, participation, reflection, and internalization of experiential learning opportunities. A key aspect of the course was conducting primary research through farm-based authentic research modules in sustainability sciences (FARMS) at the Dartmouth Organic Farm. Together, these course components interact to address the overarching goal of the course: to increase student capacity to critically identify challenges and opportunities in transforming our food system through agroecological management practices. DOI: <https://doi.org/10.1525/elementa.239.f3>

- individuals to understand who they are, what they are doing, and why (Gubrium and Holstein, 1995).
- D. *Interdisciplinarity and Critical Thinking*: Apply a sustainability framework to evaluate the environmental, cultural, socio-economic, and human health dimensions of variably managed agricultural systems
 - E. *Communication and Collaboration Skills/Civic Engagement*: Develop collaboration and outreach skills to work with peers and food system stakeholders on the dissemination of research findings and other material.

The FARMS component of ENVS 25 was designed through collaboration between the course instructor and Farm Program Manager of the Dartmouth Organic Farm with input from other key stakeholders including regional farmers, students, and instructional specialists. The course instructor identified sustainability challenges and opportunities in agriculture from the course readings and broader literature, her own research, and focus group interviews with regional farmers during a community needs assessment. The main community needs assessment was carried out during an existing regional smallholder producer conference (5th Annual Soil and Nutrition Conference of the Bionutrient Association in MA). The instructor then collaborated with the Farm Program Manager to identify key challenges and opportunities faced at the Dartmouth Organic Farm in the context of the overall challenges and opportunities in the food system as well as to identify potential agroecological solutions that could be implemented at the Dartmouth Organic Farm. Along with other instructional stakeholders, a total of five research projects were designed as part of the FARMS-based ENVS 25 course that focused on the following agroecological management practices: (1) cover cropping, (2) crop rotations, (3) compost amendments, (4) trap crops, and (5) maintenance of biodiversity. These five projects focused on the following overarching research question: What are the effects of agroecological management on pests, pollinators, weeds, soil quality, plant vitality, biodiversity, and other ecosystem services?

The five research projects identified for ENVS 25 during the 2016 course iteration were mapped and divided into labs over the course of the term. Each weekly experiment was designed to correspond to the course readings and content that scaffold on content and skills from previous weeks. Given the parameters of crop development, research design, and the timing of the course, the Dartmouth Organic Farm Program Manager assisted with part of the experimental setup prior to the start of the course. Students helped carry out other parts of the experimental setup when possible.

Before each investigation, students formed hypotheses on the basis of course content and understanding of agroecological systems. Course instructors, the Farm Program Manager, and other stakeholders were unaware of the research outcomes unlike in conventional laboratory exercises. Thus, instructional stakeholders participated

in the process of scientific inquiry with the students in a process of co-constructing knowledge. Data collection was divided among several student teams in the two lab sections of the ENVS 25 course to develop collaboration and coordination skills during data collection and input. Each student group entered data into an aggregate spreadsheet for statistical analysis and wrote-up findings in research reports that were structured following the format of a scientific research article. Student discussion of research findings focused on implications of implementing specific agroecological management practices as sustainability solutions at the Dartmouth Organic Farm and in smallholder farms regionally. Further, the instructor emphasized that students reflect on the feasibility for scaling up these practices for mid to large-scale agriculture more broadly, contributing to a food systems perspective. Students were guided to apply a sustainability framework to evaluate the environmental, cultural, socio-economic, and human health dimensions of implementing the examined agroecological management practices. For example, student discussions included consideration of social justice dimensions of food systems, including issues of farm workers and food access disparities of consumers based on location. In addition, students were encouraged to reflect on their positionality as students in the research process. Thus, while the FARMS experiments focused on the production aspects of the food system, discussions and reports focused more holistically on interdisciplinary food system issues. Students were further guided to recommend future research at the Dartmouth Organic Farm based on their experiences and findings.

At the end of the course, students synthesized and disseminated findings from the FARMS for both an academic audience and for agri-food system stakeholders. Findings were disseminated during the final lab meeting time through an outreach booth set up at the Hanover Farmers Market in Hanover, NH. The Hanover Farmers Market was identified as a suitable outreach site because of its broad range of participants including local producers, community members, students, and faculty. The goals for the outreach activities allowed students to communicate research findings in an engaging manner to various audiences. After course completion, two students volunteered to further disseminate findings and evidence-based solutions through an oral presentation at a smallholder producer conference (the 6th Annual Soil and Nutrition Conference of the Bionutrient Association in MA).

Supplementary Text S1 summarizes one of the five FARMS experiments that were implemented in ENVS 25 during the summer of 2016; specifically, we present the experiment of cover cropping and other weed management practices on the tomato cropping system. S1 demonstrates the function of FARMS as both a tool in natural science curricula and a pedagogy for interdisciplinary food systems research. Next, we provide insight into student and educator experiences in ENVS 25 FARMS implementation to analyze the unique challenges and opportunities for integrating FARMS into course curricula.

5. Reflections on opportunities and challenges for implementing FARMS

5.1 Student reflections

Two of the student authors (AS and SK) of this manuscript prepared and administered a survey of open-ended and multiple choice questions (Creswell 2013; Fowler 2013) to gauge student perceptions regarding the implementation of FARMS as part of their Ecological Agriculture course. Students implementing and analyzing the survey completed human subjects training and submitted an application to the Institutional Review Board for the protection of human subjects for exempt status for administration of the survey tool; the application was approved with exempt status (SA08231-EX). The survey tool consisted of a total of 17 questions (Text S2) and was administered online via the Qualtrics program as an optional survey during the final week of ENVS 25. The multiple-choice responses were analyzed for frequency of specific responses and the open-ended responses were coded for prevalent themes.

A total of 18 of the 32 students in the course completed the survey for a 56.25% response rate. Respondents included 11 Environmental Studies majors and four Environmental Studies minors with the remaining students having majors in the fields of Geography, Earth Sciences, and Economics. Students responded that the primary reasons for taking the course were their overall interest in the areas of ecological agriculture or food systems (72.22%) as well to fulfill requirements for the completion of their Environmental Studies major or minor (38.89%).

Overall, student feedback revealed that the majority of students (72.33%) identified the FARMS-based component of research activities to be the most valuable course component contributing to their understanding of ecological agriculture, followed by classroom activities (55.56%) which involved interactive lecture, discussion, and hands-on activities. In comparison, readings, hands-on farm practicums, case-study inquiry, and peer-led team teaching received mixed student evaluation. Some students reported that primary research at the Dartmouth Organic Farm allowed them to think critically about research design, data collection, and findings as well as about implications of findings for sustainable food systems and sustainability more broadly. All student respondents agreed that ENVS 25 should continue to adopt a FARMS approach with new experiments that inform agro-ecological management at the Dartmouth Organic Farm. Collaborating on research activities was widely recognized among students to be a positive aspect of the course with 83.33% of respondents reporting that working together on research positively influenced their course experience.

Students were asked to compare ENVS 25 and its associated laboratory component to other lab courses that they have taken at Dartmouth College. A majority of students (72.22%) responded they have previously taken a college-level lab class at Dartmouth College. Of the students who had previously taken a college-level lab course, 61.54% responded that in comparison to the original research component of ENVS 25, other lab courses had predictable

and/or “correct” outcomes. Several students shared positive comments regarding the genuine form of inquiry carried out in ENVS 25 in their open-ended responses. One student expressed the following: “This [conventional lab model with expected outcomes] takes the genuine experimentation out of the scientific method and I think that having labs without an expected outcome and letting the data speak for itself allows students to think critically and really analyze the data in their own ways, instead of trying to conform to the expected outcomes.”

The FARMS outreach component of disseminating research results to the general audience and farming community at the Hanover Farmer’s Market was met with positive student response. One survey respondent stated, “Students are never typically encouraged to make their findings and research applicable and comprehensible to the general public; however, this is highly important to make a real difference in our food system. It helps students gain skills to connect with people outside of academia, such as legislators and consumers.”

Along with benefits of FARMS, students also noted the challenges associated with carrying out authentic research. A total 33.33% of the respondents noted that the inconclusive nature of interpreting the meaning of research findings for sustainability solutions was a major challenge. Other challenges include working in groups, writing research reports, and engaging in physical labor to carry out on-farm experiments.

While it is impossible to assess how FARMS may ultimately influence students in the long-term, most students responded that ENVS 25 either strongly increased their interest (61.11%) or moderately increased their interest (33.33%) in learning more about and being involved in creating a more sustainable food system. However, few students identified concrete ways in which they could influence change in the food system beyond personal food choices. When asked to reflect on actions that they can take to influence the food system during or after college, most students indicated effecting change through personal food choices (44.44%). Only 11.11% students referenced action through policy change. This suggests that students may reflexively turn to market-based solutions in an effort to consume their ways to sustainability. Galt et al. (2013b) examine this type of “neoliberal consciousness” (Read, 2009) as just one of multiple possible understandings by students for food citizenship and sustainability transitions in the food system. It is important to make students aware of the diversity of actions that can be taken toward more socially just and ecologically based agriculture and food systems. Effective routes of action do not exist in isolation, but rather in cooperation with one another (Galt et al., 2013b).

While motivating, these student responses highlight the need for courses such as ENVS 25 and sustainable food systems curricula to take the next step and present students with concrete and diversified avenues to identify opportunities in their present and future lives for influencing the food system. For example, by integrating more opportunities for students to serve as sustainability transition leaders through classroom activities such as the

outreach activity at the Hanover Farmers Market in ENVS 25, students can learn to work with different stakeholders.

5.2 Educator reflections

One of the student authors (EA) of this manuscript prepared and administered a survey of open-ended questions (Creswell 2013; Fowler 2013) regarding FARMS that was administered online following the completion of the course via the Qualtrics program (Text S3). This survey was included in the application to work with human subjects along with the student survey that received exempt status from the Institutional Review Board (SA08231-EX). The survey was distributed to ten instructional stakeholders that contributed to and/or observed ENVS 25 during the summer of 2016. Nine instructional stakeholders (90%) completed the survey. Open-ended responses were assessed for prevalent themes.

A majority of the instructional stakeholders (90%) agreed that ENVS 25 should continue to adopt a FARMS approach for labs in future years while one stakeholder was unsure because of the space occupied in the production field for these experiments. Multiple benefits of the FARMS approach were noted by instructional stakeholders including: (1) applying science for the service of society through informing agroecological management decisions, (2) creating a stronger sense of student ownership over the experiments with research findings that have the potential to inform farm practices, (3) increasing student engagement in labs and sustainability sciences through testing of solutions that address sustainability challenges and opportunities and, (4) helping facilitate experiential learning. Instructional stakeholders expressed that the FARMS approach was beneficial compared to standard field labs in offering greater student engagement, stronger emphasis on student ownership of their learning, and greater reflection through more diversified experiments that were integrated into the production system. Carrying out research in the same study site each week stood out to one instructional stakeholder because it allowed students to get a more holistic picture of the farm landscape. Some instructional stakeholders noted that the FARMS model allowed the class to evolve with changing farm conditions. If instructors continue to adopt FARMS models in ENVS curricula, students will have the opportunity to incorporate data from previous years for long term monitoring and evaluation of agroecological management.

Overall, instructional stakeholders saw the FARMS model as a more impactful way for the student university-based farm to serve students as well as university research. One instructional stakeholder who has been involved in ENVS 25 labs in previous years shared the following observation, “[In previous years] we set up and collected data on a nutrient input experiment with corn and varying nitrogen and carbon input levels. They [the students] collected data on the corn each week and would then go on to learn about another aspect of the setting- soil, insects, aquaponics, etc. This has been the structure of the labs for this class for many years. This experiment felt a little bit out of context with the rest of the food production that happens

at the farm, and also did not connect cohesively with the other aspects of the lab experience. While the corn plot is a visually impactful experiment, I enjoyed the way we integrated experiments into the production field this year. By conducting several different experiments to examine the effectiveness of various organic cultivation methods (weed suppression, pest control, companion planting, and soil amendments), the students were able to get a more holistic view of what organic farming entails and how various methods could be used effectively. The data they gathered is real and can be used by the farm to inform our future growing methods. It was exciting to watch the class progress over the course of the term and start to grasp how the ideas put forward by the field experiments can connect to a larger context of farming, food systems, and current challenges facing agriculture today. Overall, I felt that the structure of the labs this year were organized and well prepared. The labs were designed thoughtfully to effectively teach basic lab skills and scientific principles, while connecting the experimental process and results to a larger social, political, and cultural context. This hopefully created a meaningful experience that students will be able to draw on and apply to a variety of disciplines.”

Instructional stakeholders observed a steep learning curve for students in all aspects of the research process. However, instructional stakeholders noted that students became more comfortable with the research process and farm landscape over the course term. Instructional stakeholders further observed that a few students occasionally seemed frustrated or bored with repetitive data collection required an adequate sample size while other students enjoyed this process and took the opportunity to bond with their peers during on-farm data collection. From an educator’s perspective, it can prove advantageous to provide students with such educational challenges that bring them outside of their perceived comfort zones. This is especially pertinent for courses in the sustainability sciences, which seek to address complex, multifaceted challenges and reinforce innovative thinking across disciplines. By the end of the term, instructional stakeholders found that students became more independent learners and were more motivated to create change in the food system.

While instructional stakeholders agree that the FARMS model should continue to be adopted by ENVS 25 in future years, they noted several challenges in implementing FARMS, including: (1) limits of time, (2) limits of space, and (3) variability of student experience with research and ability. Instructional stakeholders stated that the FARMS model is more time-consuming to plan and prepare compared to a conventional lab model because it requires the development of new research that reflects the local context and needs. We expect that implementing FARMS in the course in future years will be less time consuming based on lessons learned during the first year of the implementation. Regarding the greater space in the production system occupied at the study site farm, we hope that the FARMS experiments will positively influence production in the long-term because one of the goals of this pedagogical approach is to offer sustainability

solutions for future farm management. Instructional stakeholders noted that the variability in engagement and research skills amongst the students was a challenge, particularly in the beginning of the course. Instructional stakeholders made several valuable suggestions for designing experiments in future courses including the following: (1) fewer experiments with greater breadth, (2) more experiments reflecting additional ecological agriculture concepts, (3) designing experiments that focus on greater complexity of the agroecosystem including predator prey relationships, multiple trophic levels, and interactions with the broader ecosystem, (4) providing enhanced guidance to students for reflecting on their positionality as students and researchers in the FARMS process, and (5) providing students with additional guidance and concrete examples on how they can actively influence food system change through their actions and career path.

6. Discussion

The undergraduate classroom provides a valuable space in which to train and empower students with the capacity to lead sustainability transitions. Just as university faculty and other scientists may seek to transition the food system to achieve sustainability goals, they must also transition the educational system in a manner that supports these goals. At the same time, while researchers are forefront thinkers in advancing sustainability practices, there is often a disconnect between faculty research and student learning. In response to this gap, this article emphasizes the value of bridging primary scientific research with undergraduate education focused on identifying and implementing sustainability solutions. Specifically, we present an integrated experiential learning and primary research model known as Farm-based Authentic Research Modules in Sustainability Sciences (FARMS) in which faculty in the sustainability sciences bridge the learning, practicing, and scientific communities. The FARMS model was designed to align with the principles of the sustainable food system signature pedagogy that includes interdisciplinarity, systems thinking, experiential learning, and collaborative action projects (Valley et al., 2017).

Our illustration of FARMS in an undergraduate course in Ecological Agriculture at Dartmouth College indicated that this experiential learning component of the course was beneficial for understanding agroecological theories and concepts while also motivating involvement in sustainability sciences despite the perceived challenges of primary research. Students noted challenges regarding data interpretation, working in groups, writing research reports, and engaging in physical labor to carry out on-farm experiments. From educators' perspectives, the FARMS pedagogical approach facilitated achieving course outcomes to develop students' ability for systems thinking, critical thinking, and interdisciplinary work while fostering students' collaboration skills and overall motivation for initiating change in the agri-food system. Overall, our findings highlight the following benefits of the FARMS approach: (1) brings to life agroecology and food systems concepts through experiential learning and

primary research; (2) helps foster systems thinking, critical thinking, and interdisciplinarity; (3) hones students' analytical skills; (4) emphasizes the importance of using an evidence-based approach to identify and assess sustainability solutions; (5) develops student motivation regarding creating food system changes; and (6) refines student collaboration and outreach skills to work with peers and community stakeholders.

Challenges that exist in implementing FARMS include limits of time, limits of space in production systems, and variability of student experience with research and ability. These findings on the benefits of FARMS align with previous studies demonstrating the benefits of experiential learning in agroecology and sustainable food systems curricula to meet learning objectives for students to develop the knowledge, skills, and dispositions to address complex food system challenges (Bawden, 1996; Valley et al., 2017; Andreasen, 2004; Grossman et al., 2010; Hilimire, 2016; Jordan et al., 2005; Sipos et al., 2008).

It is impossible at this stage to identify the long-term effectiveness of the FARMS approach on both students and the food system. Previous course-based research experiences for undergraduates have been associated with higher retention rates (Kerr and Yen, 2016) as well as with higher graduation rates and completion of science, engineering, and mathematics degrees (Rodenbusch et al., 2016) compared to conventional learning models. Levy and Petrulis (2012) suggest that there is a spectrum of independence within inquiry-based learning, and therefore, educators should guide undergraduate students through novel, course-based inquiries before students pursue their own original research questions. Linn et al. (2015) support that course-based undergraduate research may be more effective than isolated research assistantships to better enable students to integrate material from lectures into original investigations. In addition to standard measures of retention and graduation rates, it is important for educational research to consider the capacity-building for student research. That is, course-based learner inquiries effectively introduce and guide students through the scientific research process. Therefore, considering a diversity of educational outcomes allows educators to more holistically assess the outcomes of inquiry-based learning.

We hope that the FARMS experiments will ultimately have a positive influence on the goals of environmental and social sustainability for future farm management and production. To best achieve the objectives of FARMS in preparing the next generation of sustainability leaders, we suggest additional opportunities for students to bridge science and practice through community involvement. This change would be best implemented through a whole-program curriculum approach (Jordan et al., 2014) in which courses in a specific major or curriculum are designed to build on skills and opportunities developed in previous courses through instructional scaffolding. These opportunities help students navigate challenges and opportunities associated with community-based agri-food system issues, while also providing important resources to communities located near universities.

The FARMS model has the potential to bridge student university-based farms with academic departments through educational and research programming. There is both a need and opportunity for course-based learning and research to take place on student university-based farms (Parr and Trexler, 2011). The adoption of FARMS at student university-based farms, or community farms, helps rationalize university support of these spaces while enhancing the rigor of academic programs through place-based experiential learning.

As noted by both students and instructional stakeholders, the FARMS model has taken some students outside of their comfort zones during farm activities, data collection and analysis, and outreach. Anthropologist M. David Napier (2003) contends that experiences with otherness provide new paradigms for living and for science. It is hoped that students participating in FARMS-based courses have been provided with such new paradigms. The pedagogical tenets of Paulo Freire (2000) in promoting student awareness, responsibility, self-empowerment, and agency resonates well with the design and implementation of FARMS.

7. Conclusions

Undergraduate students are the future leaders who will address the challenges and opportunities of the food system and advance society in more sustainable directions. The ways in which educators prepare students through development of curricula ultimately influence their future capacity to develop and implement innovative and effective solutions to address food system challenges as well as to proactively take action to support environmental and human wellbeing. This article emphasizes the value of bridging primary scientific research with undergraduate education focused on identifying and implementing sustainability solutions through an integrated experiential learning and primary research model known as Farm-based Authentic Research Modules in Sustainability Sciences (FARMS).

Key benefits of the FARMS approach identified in this study include enhanced understanding of course concepts and motivation for future involvement in sustainability sciences. From an educator perspective, the FARMS approach facilitated achieving course learning objectives including developing students' abilities for systems thinking, critical thinking, and interdisciplinary work while fostering students' collaboration skills and overall motivation for initiating change in the food system. Student challenges to be overcome with the implementation of the FARMS approach are those associated with the primary field research and collaborative work including challenges regarding data interpretation, working in groups, writing research reports, and engaging in physical labor to carry out on-farm experiments. In addition, while the FARMS approach encourages motivation to lead food system change, course instructors need to provide tangible ways and next steps to support students to actively engage in food system change. From an educator perspective, limits of time, acquiring experimental space in production systems, and variability of student experience with research need to be overcome for more effective implementation of the

FARMS model. Ultimately, it is expected that adoption of the FARMS model will enable faculty in the sustainability sciences to bridge the learning, practicing, and scientific communities in order to increase student capacity and motivation to serve as future leaders in transforming the food system towards enhanced sustainability.

Supplemental Files

The supplemental files for this article can be found as follows:

- **Figure S1.** Effect of Weed Suppression Management Practices on Plant Performance and Plant Vitality Measures in a Tomato Cropping System. DOI: <https://doi.org/10.1525/elementa.239.s1>
- **Figure S2.** Effect of Weed Suppression Management Practices on Total Weed Biomass in a Tomato Cropping System. DOI: <https://doi.org/10.1525/elementa.239.s2>
- **Figure S3.** Abundance of Weed Type in a Tomato Cropping System on the Basis of Weed Suppression Treatment. DOI: <https://doi.org/10.1525/elementa.239.s3>
- **Figure S4.** Effect of Weed Suppression Management Practices on Sensory Attributes of Tomatoes. DOI: <https://doi.org/10.1525/elementa.239.s4>
- **Figure S5.** Effect of Weed Suppression Management Practices on Total Phenolic Concentrations of Tomatoes. DOI: <https://doi.org/10.1525/elementa.239.s5>
- **Figure S6.** Agroecological Management Practices to Foster Biodiversity. DOI: <https://doi.org/10.1525/elementa.239.s6>
- **Text S1.** Summary of FARMS methodology and findings on weed suppression strategies for a tomato cropping system. DOI: <https://doi.org/10.1525/elementa.239.s7>
- **Text S2.** Plant vitality survey. DOI: <https://doi.org/10.1525/elementa.239.s8>
- **Text S3.** Student survey questions. DOI: <https://doi.org/10.1525/elementa.239.s9>
- **Text S4.** Educator survey questions. DOI: <https://doi.org/10.1525/elementa.239.s10>

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The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: SA
- Contributed to acquisition and interpretation of FARMS data: LB, JE, EA, SK, AS, SA
- Contributed to acquisition and interpretation of student data: AS, SK, EA
- Contributed to acquisition and/or analysis and interpretation of educator data: EA, SA
- Drafted the article: SA, AS, EA, SK, LB, JE
- Approved the submitted version for publication: SA, AS, EA, SK, LB, JE

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Knowledge Domain: Sustainability Transitions

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