

Integrating Parasitoid-Microbe Research into Middle School Curriculum: Development and Assessment of the *Symbiosis and Other Relationships* Module

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ABSTRACT: This study describes the collaborative development and assessment of middle school curriculum materials that translate parasitoid wasp research into classroom activities. Through a three-way partnership among university researchers, curriculum specialists, and teachers, the *Symbiosis and Other Relationships* module integrates authentic experimental data from parasitoid-virus-host interactions into standards-aligned learning experiences.

The curriculum uses parasitoid wasps—insects whose larvae develop inside host caterpillars with assistance from symbiotic viruses—as an anchoring phenomenon for exploring ecological relationships. Students analyze authentic research data showing growth differences between parasitized and non-parasitized caterpillars, then investigate complex three-way relationships among wasps, viruses, and hosts through online and paper-based activities.

A two-phase, quasi-experimental study involving 680 middle school students across diverse geographic regions found statistically significant learning gains. Overall effect size was large ($d = 0.72$); objective-specific gains ranged from small to moderate ($d = 0.24$ – 0.60). Students demonstrated the strongest improvements in understanding species interdependence and relationship classification, while gains in multi-organism dynamics were smaller but remained statistically significant.

Findings provide empirical support for integrating authentic research phenomena into middle school science instruction while maintaining developmental appropriateness. The curriculum development process demonstrates how intermediary organizations can facilitate effective research-to-practice translation, offering a replicable model for university-K12 partnerships. The curriculum is freely accessible at <https://teach.genetics.utah.edu/content/symbiosis/>.

INTRODUCTION

The study of insects has long fascinated students and academics alike, as insects represent breathtaking diversity in growth and reproductive strategies among Earth's most abundant animals. Insect-based classroom tasks can effectively engage multiple student populations by leveraging existing knowledge of their everyday world (Bouillion & Gomez, 2001; Matthews et al., 1997; Moje et al., 2001; Warren et al., 2001). Educational research demonstrates that student interest plays a critical role in learning quality (Alexander et al., 1994; Hidi, 2001; Renninger et al., 2002; Schiefele, 1996, 1999).

Parasitoid-microbe relationships provide excellent anchoring phenomena for integrating current research into classroom instruction. Parasitoids lay eggs inside other insects, where larvae develop by consuming living hosts

(Burke & Sharanowski, 2024). Host immune defenses can be overcome when parasitoids gain microbial partners that suppress the host's immune response (Coffman et al., 2022; Drezen et al., 2022). Learning about microbial interactions connects to everyday experiences, while symbiosis concepts tap into fundamental questions about biological relationships that have long captured human imagination. Species interactions involving parasitism can be particularly engaging, inspiring science fiction and horror media (Glassy, 2015).

The National Research Council (NRC) defines science as “both a body of knowledge that represents current understanding of natural systems and the process whereby that body of knowledge has been established and is being continually extended, refined, and revised” (NRC, 2007, p.26). Recent recommendations encourage decreased emphasis on

memorizing facts and increased focus on developing evidence-based explanations and reasoning (NRC, 2015). Experiential learning provides an effective educational model using concrete experiences, reflective observation, abstract conceptualization, and active experimentation (Kolb, 2015). The National Science Foundation's (NSF) Faculty Early Career Development Program (CAREER) supports early-career faculty by requiring them to combine educational activities with their research initiatives (NSF, 2022). This program requirement creates opportunities for faculty at research institutions to develop experiential learning based on their research while enhancing student understanding of scientific content and processes aligned with NRC recommendations.

However, translating university-level parasitoid research into materials accessible for middle school students presents significant challenges. Researchers often lack formal teaching training and benefit from collaboration with curriculum design professionals when translating research into classroom materials (Donovan et al., 2015; Ko et al., 2022). These partnerships enable researchers to access pedagogical expertise while shifting from transmission-focused to student-centered approaches (Donovan et al., 2015).

To translate complex parasitoid-microbe research into effective classroom materials, we established collaboration between a University of Georgia (UGA) parasitoid wasp researcher, middle school teachers, and curriculum specialists and educational researchers at the Genetic Science Learning Center (GSLC) at the University of Utah. This interdisciplinary team developed middle school lessons centered on the parasitoid wasp *Microplitis demolitor*, its soybean looper caterpillar host (*Chrysodeixis includens*), and *Microplitis demolitor* bracovirus.

We designed the *Symbiosis and Other Relationships* module using Kolb's experiential learning framework, which guides learners through concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 2015). This approach ensures that students encounter authentic ecological phenomena, analyze observable patterns, construct conceptual understanding, and apply their knowledge to novel scenarios in developmentally appropriate ways. The framework informed our curriculum sequencing decisions and shaped realistic expectations for learning outcomes achievable within a brief, phenomenon-anchored module under typical middle school constraints.

The curriculum aligns with three dimensions of the Next Generation Science Standards integrating disciplinary core ideas, science and engineering practices, and crosscutting concepts (NGSS Lead States, 2013). Materials include paper-based simulated experiments, videos, interactive diagrams, and classification activities, all freely accessible through Learn.Genetics.utah.edu (GSLCa,b, 2026). This study addresses the following research question: To what

extent does implementation of the *Symbiosis and Other Relationships* curriculum improve middle school students' understanding of ecological relationships, as measured by pre- to post-instruction gains in content knowledge? Here we describe the collaborative development process, classroom implementation, and learning outcomes.

METHODS

Team Composition and Collaborative Approach. Our interdisciplinary team consisted of a University of Georgia research scientist specializing in parasitoid wasp research, middle school teachers (Georgia and Utah), and curriculum specialists and educational researchers from the Genetic Science Learning Center (GSLC) at the University of Utah. This collaboration ensured scientific accuracy, pedagogical appropriateness, and alignment with Kolb's (2015) experiential learning framework.

Timeline. Curriculum development occurred from 2018 to 2021. Classroom implementation was delayed until 2023 due to the COVID-19 pandemic. Phase 1 pilot testing was conducted during the 2023-2024 school year, and Phase 2 field testing occurred during the 2024-2025 school year.

Anchoring Phenomenon Selection. Following NGSS guidance to anchor modules with phenomena and guiding questions, our team selected the three-way relationship among the parasitoid wasp *Microplitis demolitor*, the soybean looper caterpillar *Chrysodeixis includens*, and the *Microplitis demolitor* bracovirus as the anchoring phenomenon.

The guiding question "How can wasps develop inside insect hosts by using host resources?" focuses student attention on resource redirection in parasitized caterpillars—a striking biological effect manifesting as reduced growth. To make the anchoring phenomenon accessible and engaging for diverse classroom settings, we developed paper-based and multimedia activities using biologically accurate illustrations, photos, and videos that bring the parasitoid-host system to life.

Curriculum Module Development Process. Development began with structured planning meetings between the scientist (Burke, a research professor specializing in insect-microbe interactions), a GSLC scientific content manager, and an experienced Georgia middle school teacher. These meetings established the anchoring phenomenon, defined the guiding question, and identified target NGSS standards: MS-LS2 (Ecosystems: Interactions, Energy, and Dynamics); LS2.A (Interdependent Relationships in Ecosystems); Cross-cutting Concepts of Patterns, and Cause and Effect; and Science and Engineering Practices of Analyzing and Interpreting Data (NGSS Lead States, 2013).

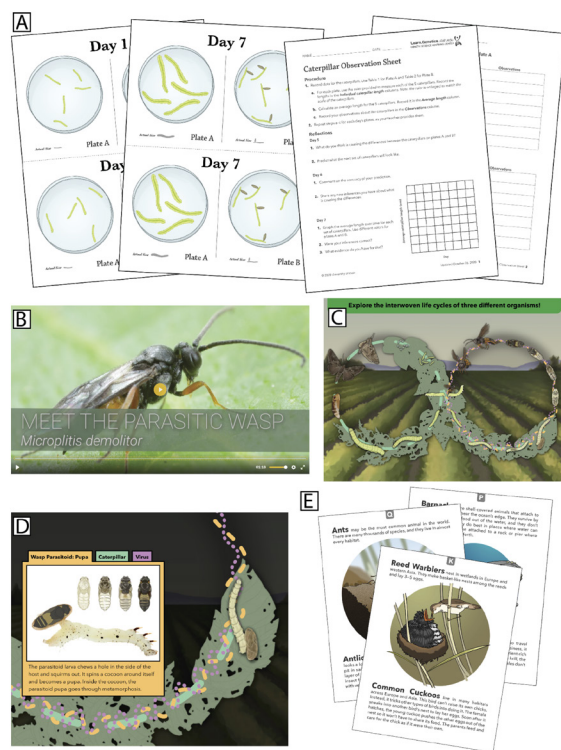


Figure 1. Elements of the *Symbiosis and Other Relationships* curriculum module. **a)** Data images from a paper-based simulated experiment in which students measure caterpillars each day and observe their development. Petri dishes containing caterpillars are named “Plate A” and “Plate B”, corresponding to the presence or absence of parasitism. Students are unaware of the differences between the two groups of caterpillars and make observations, predictions, and analyze differences in caterpillar growth over a 7-day period. **b)** A short video introduces the parasitoid wasp *Microplitis demolitor*, focusing on its developmental stages and relationship with host caterpillars. **c)** An online multimedia interactive depicts the interwoven life cycles of caterpillars, *M. demolitor* wasps, and viruses that are produced by wasps and injected into caterpillars during parasitism. **d)** Students can zoom into the interwoven life cycles and learn about the relationships and functions of the wasp, caterpillar, and virus at each stage. **e)** “EcoDuo” cards are a flexible, paper-based resource describing two organisms that interact, exemplifying a variety of different ecological relationships that students can characterize, compare, and classify by type.

The team designed a paper-based simulated experiment in which students measure and compare two caterpillar groups without knowing one is parasitized (Figure 1a). We used results from primary literature and trial experiments performed with undergraduate students at the University of Georgia to guide the simulated experiment design and determine data ranges (Pruijssers et al., 2008).

Additional materials contextualizing the anchoring phenomenon included: videos introducing the soybean looper and parasitoid wasp; an online interactive diagram detailing interwoven life cycles; and card-based activities demonstrating diverse ecological relationships and complex three-way symbioses (Figure 1b-e). A UGA-based macrophotographer

provided scientifically accurate images and videos of parasitoid and caterpillar life stages.

The GSLC scientific content manager and research professor developed text and video scripts, while the GSLC art team created illustrations and multimedia components. The team then produced the Module Overview and Suggested Lesson Sequence posted on Teach.Genetics.utah.edu (GSL-Cb, 2026) with detailed implementation instructions.

Alignment with Experiential Learning Framework (Kolb, 2015). Each curriculum component addresses Kolb’s (2015) experiential learning framework elements (Figure 2). The paper-based simulated experiment provides concrete experience as students collect caterpillar growth data over seven days. Videos and interactive life cycle diagrams facilitate reflective observation, helping students make sense of the growth differences they observed and understand the parasitoid-host-virus relationships. The curriculum supports abstract conceptualization as students develop explanations for observed growth differences, formulating concepts about ecological relationships and symbiosis. Card-based classification activities encourage active experimentation as students apply conceptual understanding to categorize novel ecological relationships. This systematic alignment with all four learning cycle stages ensures students engage with scientific concepts through multiple modalities, strengthening both content knowledge and scientific practice understanding.

Curriculum Development and Structure.

Learning Objectives. The *Symbiosis and Other Relationships* curriculum module addresses specific, NGSS-aligned (NGSS Lead States, 2013) learning objectives for middle school science (Table 1).

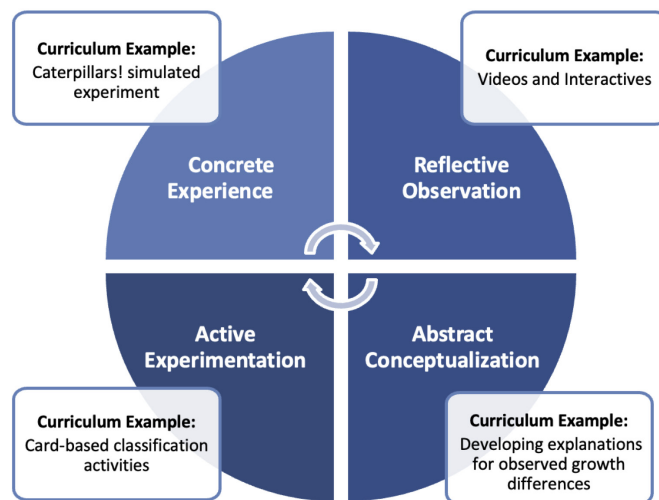


Figure 2. Alignment with Kolb’s Experiential Learning Framework.

Table 1. Learning objectives for the Symbiosis and Other Relationships curriculum module.

Learning Objective	Description
LO1	Recognize that within ecosystems, organisms of different species depend on one another
LO2	Identify and describe predatory interactions involving two or more species, including the roles and relationships among all participating organisms
LO3	Identify and differentiate among ecological relationships—including competition, predation, parasitism, commensalism, and mutualism—by analyzing the effects of these interactions on two or more species, and determining whether they are beneficial, harmful, or neutral for each participant
LO4	Evaluate how organisms engage in behaviors that increase their odds of survival and reproduction
LO5	Understand that some species completely depend on others for survival
LO6	Describe how each species is helped, harmed, or not affected in ecological relationships that involve three or more species
LO7	Apply understanding of ecological relationships to novel scenarios by determining how each species is affected—beneficially, harmfully, or neutrally—and explaining how organisms use different strategies to survive

Module Overview and Structure. The materials were designed for flexible use: components may be implemented independently, in any order, or integrated with other lessons. However, they are intended to function as a coherent sequence that interweaves the parasitoid case study with broader ecological concepts. In this study, teachers implemented the suggested sequence with only minimal supplementary additions.

The module consists of the following components:

1. “Meet the Soybean Looper” (Video, 5 minutes): Introduces the soybean looper caterpillar’s physical characteristics, feeding behaviors, and ecosystem role.
2. “Caterpillars!” (Simulated Experiment, 90 minutes over 7 days): Students measure growth patterns in two caterpillar groups without knowing one is parasitized, using authentic data from Pruijssers et al. (2008) that reveals reduced growth in parasitized caterpillars by Day 5.
3. “Meet the Parasitic Wasp” (Video, 10 minutes): Reveals how the parasitoid wasp *Microplitis demolitor* causes observed growth patterns, introducing parasitism as an ecological relationship.
4. “What’s the Relationship?” (Classification Activity, 60 minutes): Using “EcoDuo” cards showing organism pairs, students analyze interactions by

determining whether each organism is helped, harmed, or unaffected.

5. “Interwoven Life Cycles” (Interactive Diagram, 40 minutes): This online interactive introduces the bracovirus, demonstrating how caterpillar, wasp, and virus life cycles interconnect.
6. “Examples of Symbiosis” (Optional Video, 20 minutes): Describes symbiotic relationship examples, bridging basic ecological relationships and complex three-way interactions.
7. “EcoTrios & Symbiotic Strategies” (Classification Activity, 40 minutes): Students explore complex three-way relationships using “EcoTrio” and “Symbiotic Strategy” cards.

The entire module can be implemented over 1-2 weeks, providing approximately 4-5 hours of instructional time. All materials are freely available through Learn.Genetics.utah.edu and Teach.Genetics.utah.edu (GSLC, 2026a,b), ensuring broad accessibility for educators.

Classroom Implementation and Module Testing.

Research Design. This study employed a two-phase, quasi-experimental, pre-post design to evaluate curriculum effectiveness (Shadish et al., 2002). This design accommodated educational setting constraints while enabling rigorous assessment of learning impacts across urban, suburban, and rural schools in multiple states.

The Phase 1 pilot study validated and refined the measurement instruments and instructional module by evaluating assessment item functioning and collecting teacher feedback on curriculum usability. The Phase 2 field study implemented the revised instrument and curriculum across multiple middle school classrooms.

Research Question. The central research question was: To what extent does implementation of the *Symbiosis and Other Relationships* curriculum improve middle school students’ understanding of ecological relationships, as measured by pre- to post-instruction gains in content knowledge?

Classroom Implementation Procedures.

Participant Recruitment and Ethics. Participating teachers and schools were recruited through educational conferences, the GSLC email list (20,000+ subscribers), and the GSLC website. All procedures were approved by the University of Utah Institutional Review Board (IRB 00085654), with district and school administrative permissions, teacher and parent informed consent, and student assent obtained. Students received anonymous ID numbers for confidentiality while enabling pre-post data matching.

Teacher Preparation and Implementation. Teachers attended structured GSLC training sessions covering lesson sequence, the implementation protocol, and data collection procedures. They implemented materials in a prescribed sequence with minimal supplementation, allowing only essential clarifications to preserve intervention integrity. The module was implemented over 1-2 weeks according to school schedules, averaging 4-5 hours total instructional time.

This module replaced teachers' typical symbiosis instruction, representing students' first formal exposure to symbiotic relationship vocabulary and categorization. Based on NGSS learning progressions, middle school represents the introduction point for systematic instruction on symbiosis concepts, following elementary-level exposure to basic organism interactions (NGSS Lead States, 2013).

Data Collection Procedures. Students completed the content assessment immediately before and after module implementation via a secure Qualtrics platform during regular class periods (approximately 30 minutes per administration). Assessments were presented to students as low-stakes activities intended to inform curriculum improvement rather than as graded tests. Teachers completed implementation surveys after instruction concluded.

Participants and Settings. The study involved middle school students (grades 6-8) from 12 classrooms across the United States. Phase 1 (instrument development and pilot testing) included 5 teachers across five regions; Phase 2 (implementation with refined assessment instruments) included 7 teachers across three regions. Schools represented rural, urban, and suburban settings (Table 2).

Data were collected from 154 students in Phase 1 and 526

Table 2. Participating teachers and students by geographic region and school setting.

Teacher	Geographic Region	School Geographic Area	Number of Students
Phase 1 (Pilot Study: Instrument Validation & Curriculum Feedback)			
Teacher 1	Northeast	Suburban	26
Teacher 2	Mid-Atlantic	Urban	42
Teacher 3	Mid-West	Rural	35
Teacher 4	Pacific Northwest	Suburban	30
Teacher 5	Mountain West	Urban	21
Phase 2 (Field Study: Data Collection to Answer Research Question)			
Teacher 6	Northeast	Rural	56
Teacher 7	Mid-West	Suburban	91
Teacher 8	Mid-West	Urban	101
Teacher 9	Northeast	Suburban	90
Teacher 10	Southeast	Urban	60
Teacher 11	Northeast	Urban	100
Teacher 12	Northeast	Rural	28

Table 3. Participant eligibility and instrument completion by study phase.

Data Collection Parameter	Phase 1	Phase 2
Number of student participants	154	526
Pre-assessment completed ($\geq 80\%$ items)	123	427
Post-assessment completed ($\geq 80\%$ items)	132	429
Matched pairs for analysis	101	330

Note: Phase 1 focused on instrument validation. Students missing $>20\%$ of assessment items were excluded from content assessment analysis. Differences between pre-assessment, post-assessment, and matched pair sample sizes reflect normal patterns of student availability across testing sessions.

students in Phase 2; analytic sample sizes reflect assessment completion and matched pre-post availability (Table 3).

Instrument Development and Validation Process. The study utilized two measurement instruments: a content knowledge assessment and a teacher implementation survey. Both were administered via a secure Qualtrics platform; student responses were anonymous.

Content Knowledge Assessment. The assessment was developed through collaboration among content experts, curriculum designers, and assessment specialists to evaluate students' understanding of seven targeted learning objectives (Table 1). Items assessed achievement at an appropriate depth of knowledge (Webb, 2002), emphasizing analyzing and classifying ecological relationships and applying conceptual understanding to novel scenarios, plus three prerequisite knowledge areas. The assessment underwent a two-phase validation.

Phase 1 Assessment Validation Procedures. The initial 23-item multiple-choice assessment was piloted with 154 students from five schools. Item analysis examined difficulty, discrimination, distractor patterns, item-to-item correlations, and reliability. Paired-samples *t*-tests assessed pre-post learning gains with Cohen's *d* effect sizes, revealing areas for improvement and informing targeted revisions.

Based on item analysis, distractor revisions improved two problematic items. Twelve "sister items" were created to assess identical constructs with reduced linguistic complexity while preserving conceptual demands. Conceptual equivalence was operationalized by targeting the same Depth of Knowledge level (Webb, 2002) as the original items, with revisions focused on linguistic accessibility rather than the cognitive processes required for response.

Phase 2 Assessment Validation Procedures. The Phase 2 assessment included 23 original items (with modifications) plus 12 sister items, totaling 35 items administered to 526 students. Post-field study validation analyses were conducted to evaluate the effectiveness of modifications and determine final item selection. Items were evaluated using

the same statistical criteria as Phase 1, with particular attention to discrimination indices, reliability coefficients, and alignment with learning objectives. One item exhibiting negative item-total correlation was removed based on psychometric criteria, yielding the final 34-item assessment used for all analyses (see Appendix, *Symbiosis and Other Relationships*: Student Assessment).

Teacher Implementation Survey. The End-of-Implementation Survey gathered feedback on implementation experiences, student engagement, and perceived outcomes using a multi-block structure examining engagement across seven activities, scientific practices comparisons, overall impressions, and practical implementation data (see Appendix, *Symbiosis and Other Relationships*: Teacher End-of-Implementation Survey). All participating teachers completed surveys (100% response rates: five in Phase 1, seven in Phase 2), with quantitative responses analyzed using descriptive statistics and qualitative responses analyzed thematically.

Data Analysis. To assess curriculum effectiveness, analyses were conducted on content knowledge assessments and teacher implementation surveys. Statistical analyses were conducted primarily using SPSS Version 30 (IBM Corp., 2024), with some supplementary analyses conducted using R (R Core Team, 2024), and significance level set at $p < .05$.

Content Knowledge Assessment. Students were included in analyses only if they answered at least 80% of assessment items (that is, missing no more than 20%). For included students, any remaining unanswered items were scored as incorrect because item skipping could not be distinguished from lack of knowledge. After applying these criteria, Phase 1 yielded 123 students with sufficient pre-assessment data, 132 with sufficient post-assessment data, and 101 matched pairs; Phase 2 yielded 427 with sufficient pre-assessment data, 429 with sufficient post-assessment data, and 330 matched pairs.

Student responses were scored as correct or incorrect, with each item mapped to its corresponding learning objective. Scores were calculated as percentage correct both overall and by learning objective. Pre-post changes in content knowledge were analyzed using paired-samples t tests on matched pairs to determine statistical significance of overall gains. Learning objective-specific gains were similarly analyzed to identify areas of curriculum strength and potential improvement. Cohen's d for paired samples was calculated for each measure to assess the magnitude of score change from pre- to post-test.

Teacher Implementation Survey. Teacher survey responses were analyzed using descriptive statistics and frequency distributions for quantitative items. Qualitative responses were analyzed using thematic analysis to identify implementa-

tion patterns, challenges, and perceived student outcomes. Response patterns were examined for consistency across implementation phases, with all 12 participating teachers (100% response rate) providing complete implementation feedback.

This analytical approach balanced methodological rigor with practical considerations of classroom-based research, ensuring data quality while maximizing the use of available information across different measurement approaches.

RESULTS

This study examined the development and effectiveness of the *Symbiosis and Other Relationships* curriculum module through a two-phase design. Phase 1 focused on instrument validation and initial curriculum implementation, while Phase 2 examined the curriculum's effectiveness in addressing the study's primary research question.

Phase 1 Validation Study Results.

Content Knowledge Assessment. Validation analysis using the 101 matched student pairs was conducted on the initial 23-item content assessment. Item analysis revealed that the assessment was challenging for students, with average overall difficulty of $M = 40.7\%$ ($SD = 16.7$) on the pretest. Individual item difficulties on the pretest ranged from 13% to 81% correct, with 15 items (65.2% of the 23-item assessment) answered correctly by fewer than half of students. The most challenging items included those addressing three-way ecological relationships (13% correct) and complex species dependency scenarios (14% correct), while basic measurement and fundamental relationship identification showed higher success rates (up to 81% correct).

Posttest performance showed meaningful improvement, with average overall difficulty increasing to $M = 48.4\%$ ($SD = 18.3$). Individual item difficulties on the posttest ranged from 15% to 84% correct. The number of items below 50% difficulty decreased to 13 items (56.5%), representing improvement from the pretest's 15 items below this threshold.

Students demonstrated statistically significant improvement from pretest to posttest, $t(100) = -4.484$, $p < .001$, with a moderate effect size (Cohen's $d = 0.45$) despite the challenging nature of the assessment. Students' mean assessment scores increased from 40.7% ($SD = 16.7$) on the pre-assessment to 48.4% ($SD = 18.3$) on the post-assessment, representing a mean gain of 7.7 percentage points, 95% CI [4.3, 11.1].

The assessment demonstrated below-acceptable internal consistency reliability on the pretest ($\alpha = .605$) but improved to acceptable levels on the posttest ($\alpha = .765$). Average item discrimination improved modestly from 0.35 on the pretest to 0.38 on the posttest but remained relatively low. The combination of high item difficulty and low discrimination indicated that many items were not effectively differentiating

Table 4. Learning Objective-specific results for Phase 1 Pilot Study.

Learning Objective	Pretest Mean (SD)	Posttest Mean (SD)	Gain Mean	t-value (df)	p-value	Cohen's d
Overall	.407 (16.7)	.484 (18.3)	.077	-4.484 (100)	<.001	0.45
LO1: Species Interdependence	0.60 (0.31)	0.76 (0.29)	0.16	-5.029 (100)	<.001	0.50
LO2: Predatory Interactions	0.45 (0.35)	0.49 (0.36)	0.04	-1.193 (100)	=.236	0.12
LO3: Relationship Classification	0.44 (0.30)	0.51 (0.31)	0.07	-2.353 (100)	=.021	0.23
LO4: Adaptive Behaviors	0.47 (0.44)	0.58 (0.44)	0.11	-2.422 (99)	=.017	0.24
LO5: Species Dependency	0.35 (0.34)	0.38 (0.34)	0.03	-0.777 (99)	=.439	0.08
LO6: Three-way Relationships	0.26 (0.33)	0.29 (0.33)	0.03	-0.973 (96)	=.333	0.10
LO7: Novel Applications	0.27 (0.31)	0.38 (0.31)	0.11	-3.439 (96)	<.001	0.35

between students of varying ability levels.

Analysis by learning objective revealed differential performance patterns across content areas (Table 4). Given the below-acceptable reliability ($\alpha = .605$ to $\alpha = .765$) and high item difficulty observed in Phase 1, these results should be interpreted cautiously as validation data rather than definitive evidence of curriculum effectiveness. The primary value of Phase 1 learning objective analysis was identifying content areas requiring assessment refinement rather than drawing conclusions about student learning.

Learning Objectives (LOs) 1, 3, 4, and 7 showed significant gains (Cohen's $d = 0.23$ - 0.50), while LOs 2, 5, and 6 showed minimal improvement, indicating assessment refinement needs for complex dependency and multi-organism concepts.

Based on distractor analysis and item statistics, alterations were made to the distractors for two items that showed problematic response patterns. Additionally, twelve sister items were systematically created for the most challenging items from Phase 1, specifically targeting items with difficulty levels below 30% correct and focusing on LOs 5, 6, and 7, which addressed complex multi-organism relationships and dependency scenarios.

This approach allowed us to test whether linguistic complexity rather than conceptual difficulty was contributing to poor item performance, particularly for advanced ecological concepts that showed persistent challenges during the pilot phase.

Teacher Implementation Survey. All five Phase 1 participants completed implementation surveys (100% response rate), teaching 7th grade students (80%) and 8th grade students (20%) across several geographic regions.

Implementation fidelity was high, with participants completing 6.75 of 7 activities on average. Most activities achieved 100% completion rates, except the optional “Examples of Symbiosis” video (75% completion due to scheduling constraints). Implementation times aligned closely with recommendations, averaging 4.6 hours versus the recommended 4-5 hours (Table 5).

Student engagement received high ratings ($M = 3.79$ on 5-point scale, range 3.0-4.2). The “Meet the Parasitic Wasp” video received the highest ratings ($M = 4.2$), while “Interwoven Life Cycles” showed the most variability. All participants (a) rated materials as better than other similar resources, (b) planned future use of the materials, (c) felt well-prepared to implement the module, and (d) found implementation information “very easy” to locate. All rated actual lab data as “generally important” for instruction, with 75% reporting the module supported student science interest.

Teacher feedback emphasized the value of hands-on activities and research connections, with one participant noting, “I feel students are more engaged when they are learning about the current research about a topic.” Implementation challenges included lower engagement with the Interwoven Life Cycles interactive, vocabulary barriers in classification

Table 5. Activity implementation times and completion rates (Phase 1, $n=5$). The Likert scale for Engagement Rating ranged from (1 = least engaging to 5 = most engaging).

Activity	Recommended Time	Actual Time Mean (Range)	Completion Rate	Engagement Rating Mean
Meet the Soybean Looper	5 min	7.0 (3-10)	100%	4.00
Caterpillars!	90 min*	66.3 (45-110)	100%	4.00
Meet the Parasitic Wasp	10 min	12.0 (3-30)	100%	4.20
What's the Relationship?	60 min	72.5 (45-110)	100%	3.60
Interwoven Life Cycles	40 min	36.3 (10-45)	100%	3.00
Examples of Symbiosis	20 min	21.0 (3-50)	75%	3.75
EcoTrios & Symbiotic Strategies	40 min	62.5 (45-90)	100%	4.00
Overall	265 min (4.4 hrs)	277.6 min (4.6 hrs)	96.4%	3.79

*Distributed over 7 days.

Table 6. Learning Objective-specific results for Phase 2 Field Study.

Learning Objective	Pretest Mean (SD)	Posttest Mean (SD)	Gain Mean	<i>t</i> -value (df)	<i>p</i> -value	Cohen's <i>d</i>
Overall	.437 (.189)	.549 (.215)	.113	-13.069 (329)	<.001	0.72
LO1: Species Interdependence	.559 (.308)	.748 (.296)	.189	-10.863 (329)	<.001	0.60
LO2: Predatory Interactions	.517 (.303)	.619 (.283)	.102	-6.172 (329)	<.001	0.34
LO3: Relationship Classification	.430 (.282)	.575 (.298)	.145	-7.938 (329)	<.001	0.44
LO4: Adaptive Behaviors	.469 (.326)	.562 (.337)	.093	-4.292 (329)	<.001	0.24
LO5: Species Dependency	.330 (.249)	.430 (.296)	.100	-6.364 (329)	<.001	0.35
LO6: Three-way Relationships	.470 (.316)	.556 (.319)	.086	-4.746 (329)	<.001	0.26
LO7: Novel Applications	.330 (.221)	.444 (.261)	.114	-7.910 (326)	<.001	0.44

activities, and students struggling with the cognitive demands of conceptualizing three-way relationships.

Phase 2: Field Study Results.

Content Knowledge Assessment. Data analysis was conducted on 330 matched pairs of students. The Phase 2 assessment demonstrated substantially improved psychometric properties compared to the Phase 1 assessment. One item (LO6.1) exhibited a negative item-total correlation ($r = -.262$) and was removed from analysis. This removal improved internal consistency reliability from $\alpha = .830$ to $\alpha = .842$ for the pretest and from $\alpha = .886$ to $\alpha = .891$ for the posttest, yielding the final 34-item assessment used for all results. For this assessment, average item discrimination was 0.388 on the pretest and 0.463 on the posttest, indicating that items effectively differentiated between high and low performers.

Item difficulty improved from $M = 0.437$ (pretest) to $M = 0.549$ (posttest), with challenging items below 50% difficulty decreasing from 22 (pretest) to 12 items (posttest), demonstrating meaningful improvement across the assessment. The most challenging items on both administrations included those addressing complex species dependency scenarios (LO5.3: 17.7% to 25.7%) and multi-organism strategic relationships (LO7.3: 23.2% to 30.6%), while basic ecological interdependence concepts showed higher success rates (LO1.4: 45.0% to 75.0%).

Despite items ranging from 3rd to 11th grade reading level ($M = 7.8$), Flesch-Kincaid grade level (DuBay, 2004) showed no significant correlation with item difficulty ($r = -.017$, $p = .923$) and explained negligible variance in performance ($R^2 < .001$). Sister items demonstrated improved psychometric properties compared to original counterparts, with more appropriate difficulty levels ($M = .59$ vs. $M = .44$) and stronger discrimination indices ($M = .41$ vs. $M = .35$). This pattern suggests that the linguistic revisions addressed processing demands not captured by standardized grade level readability metrics.

Implementation of the curriculum resulted in statistically significant improvements in students' overall ability to un-

derstand and categorize ecological relationships. Students' mean assessment scores increased from 43.7% ($SD = 18.9$) on the pre-assessment to 54.9% ($SD = 21.5$) on the post-assessment, representing a mean gain of 11.3 percentage points, 95% CI [10.0, 12.5]. Pretest scores in both phases (Phase 1: $M = 40.7\%$; Phase 2: $M = 43.7\%$) were consistent with students having a basic understanding of organism interactions but minimal prior formal instruction on symbiosis concepts, as expected, given that this was students' first systematic exposure to symbiotic relationship categorization. The pre-post improvement was statistically significant, $t(329) = -13.069$, $p < .001$, with a moderate to large effect size (Cohen's $d = 0.72$), demonstrating educationally meaningful learning gains.

Analysis by learning objective revealed significant improvements across all targeted content areas (Table 6), representing a substantial advancement over Phase 1 findings where only four of seven learning objectives showed significant gains.

The Phase 2 field study demonstrated substantial improvements over Phase 1 across multiple dimensions. The Phase 2 matched sample size increased more than threefold ($N = 330$) compared to Phase 1 ($N = 101$), the overall effect size improved from moderate in Phase 1 ($d = 0.45$) to large in Phase 2 ($d = 0.72$), and most notably, all seven learning objectives achieved statistical significance in Phase 2 compared to only four in Phase 1. Thus, the assessment revisions successfully addressed limitations identified in Phase 1.

Teacher Implementation Survey. All seven Phase 2 participants completed implementation surveys (100% response rate). Teachers primarily taught 7th grade students (71%), with additional representation from 8th grade (14%) and sixth grade (14%) across several geographic regions.

Implementation fidelity was strong, with participants completing an average of 6.6 out of 7 activities. The first five activities achieved 100% completion rates, while the "Examples of Symbiosis" video was completed by 86% and the final "EcoTrios & Symbiotic Strategies" activity by 71%. End-of-year timing pressures contributed to declining

Table 7. *Teacher Implementation Survey results (Phase 2, n=7).*

Activity	Recommended Time	Actual Time Mean (Range)	Completion Rate	Engagement Rating Mean
Meet the Soybean Looper	5 min	4.0 (2-10)	100%	4.43
Caterpillars!	90 min*	66.4 (45-90)	100%	3.71
Meet the Parasitic Wasp	10 min	7.4 (5-15)	100%	4.71
What's the Relationship?	60 min	53.6 (30-90)	100%	4.43
Interwoven Life Cycles	40 min	41.4 (20-90)	100%	3.14
Examples of Symbiosis	20 min	15.7 (5-30)	85.7%	3.57
EcoTrios & Symbiotic Strategies	40 min	58.6 (30-90)	71.4%	4.14
Overall	265 min (4.4 hrs)	247.1 min (4.1 hrs)	93.9%	4.02

*Distributed over 7 days.

completion rates for later activities. Implementation times closely aligned with curriculum recommendations, averaging 4.1 hours total compared to the recommended 4-5 hours (Table 7).

Student engagement received high ratings across all activities, with mean ratings ranging from 3.14 to 4.71 on a 5-point scale (overall $M = 4.02$). The “Meet the Parasitic Wasp” video received the highest engagement ratings ($M = 4.71$), while the “Interwoven Life Cycles” interactive showed the lowest ratings ($M = 3.14$). Consistent with Phase 1, teachers reported that complex activities, particularly “Interwoven Life Cycles” and “EcoTrios & Symbiotic Strategies,” continued to present challenges for students despite high overall engagement.

All teachers (100%) planned to use the resources in the future, with 86% recommending the module to colleagues. Preparation levels were high, with 86% feeling “very prepared” or “somewhat prepared” to implement the curriculum. All participants rated actual lab data as “generally important” or “extremely important” for science instruction, and 86% reported the module supported students’ interest in science.

Teacher feedback emphasized the value of hands-on activities and research connections, noting high levels of student engagement with the curriculum materials. While this study lacks a comparison group using the same assessment with traditional symbiosis instruction, teacher surveys provide insight into perceived value. Teachers reported the module supported scientific practices more than their typical instruction, particularly practices involving analysis to make sense of data (typical practice $M = 2.9$; this module $M = 3.7$), mathematical and computational models to make and test predictions ($M = 2.7$ vs. 3.6), and engaging in critiquing scientific arguments based on evidence ($M = 2.8$ vs. 3.3). These patterns suggest the curriculum provided valued opportunities for authentic scientific practices, though the absence of a control group limits conclusions about comparative effectiveness. Overall, teachers perceived the curriculum as feasible for classroom implementation while effectively engaging students with current scientific research.

Summary of Findings. Implementation of the *Symbiosis and Other Relationships* curriculum produced significant learning gains across all targeted ecological concepts. Students achieved particularly strong improvements in understanding species interdependence and relationship categorization, with smaller but significant gains in multi-organism dynamics. The pattern of effect sizes suggests that ecological concepts fall along a continuum of difficulty rather than distinct categories, highlighting the varying levels of challenge that different concepts present for middle school learners and demonstrating the educational potential of this curriculum approach.

DISCUSSION

Key Findings and Educational Impact. The Phase 2 field study demonstrated significant learning gains across all targeted learning objectives, with strongest improvements in ecological interdependence, relationship classification, and novel applications. These findings represent substantial improvement over Phase 1, where only four of seven learning objectives achieved significance. These changes in findings between study phases highlight the importance of pilot testing assessment items with students and refining them before conducting efficacy research.

Assessment refinements, particularly sister items designed to reduce linguistic complexity while preserving Depth of Knowledge demands (Webb, 2002), successfully addressed measurement limitations and enabled detection of learning gains across all objectives. The absence of a relationship between Flesch-Kincaid grade level (DuBay, 2004) and item difficulty suggests that standardized grade level readability metrics may not adequately capture the cognitive demands students encountered when processing assessment items. Rather, targeted reductions in sentence length and terminology complexity, while preserving cognitive expectations, appeared to have contributed to improved item performance, though the possibility that unmeasured student, teacher, or school factors influenced these outcomes cannot be ruled out.

The effect size pattern suggests ecological concepts fall along a difficulty continuum rather than distinct categories reflecting developmental constraints in middle school students' ecological reasoning. Students at this age are transitioning from concrete to formal operational thinking with substantial individual variation (Piaget, 1970), and systems thinking develops gradually through hierarchical progression (Ben-Zvi Assaraf & Orion, 2010). Students' reasoning about interdependent relationships progresses from linear, one-way causal thinking toward understanding complex multi-organism dynamics (Dozier et al., 2023), with system-specific features, particularly indirect effects and relationship types, determining difficulty levels (Mambrey et al., 2020).

Strong gains in species interdependence and relationship categorization indicate middle school students readily grasp fundamental organismal dependencies and transfer categorical thinking to new scenarios. Smaller effect sizes for complex concepts may reflect cognitive threshold concepts requiring different instructional approaches.

The anchoring phenomenon, which demonstrated a concrete, observable biological interaction, created conceptual foundations supporting symbiotic relationship learning. This suggests that authentic scientific phenomena may serve as crucial cognitive anchors that help students organize and connect new information. The findings also indicate that categorization skills and systems thinking skills may be differentially affected by developmental stage, implying that ecological literacy involves multiple, semi-independent cognitive competencies rather than a single, unified understanding.

Research-to-Practice Collaboration Insights.

The Critical Role of Intermediary Organizations. This study demonstrates how specialized intermediary organizations can facilitate effective research-to-practice translation. The Genetic Science Learning Center provided capabilities that neither researchers nor teachers could contribute individually: expertise in translating complex scientific concepts into age-appropriate language, multimedia production skills for creating engaging educational materials, knowledge of educational standards alignment, and experience in curriculum sequencing and assessment design.

The GSLC team understood both the scientific content and the pedagogical challenges of making it accessible to middle school students. This dual expertise was important for maintaining scientific accuracy while ensuring developmental appropriateness, a balance difficult to achieve through direct researcher-teacher collaboration alone. The intermediary organization facilitated communication between research expertise and educational practice, enabling materials that preserved the intellectual excitement of authentic scientific discovery while providing appropriate scaffolding for student success.

Authentic Research Integration: Opportunities and Challenges. The successful integration of genuine experimental data demonstrates that middle school students can engage meaningfully with real scientific findings rather than simplified textbook examples. Students worked with actual growth measurements, analyzed authentic patterns from research studies, and grappled with the types of observational puzzles that drive scientific inquiry.

However, this authenticity required careful pedagogical translation. The research team identified which aspects of the complex parasitoid-virus-host system could be meaningfully adapted for middle school cognitive levels while preserving accuracy. The anchoring phenomenon approach—using concrete, observable biological interactions as foundations for exploring broader concepts—proved effective, suggesting research translation efforts should identify compelling, observable phenomena serving as cognitive anchors for abstract concepts.

Collaborative Development Process: Evidence and Outcomes. The systematic development process demonstrated the value of sustained teacher input throughout curriculum creation, beginning with early involvement during initial planning meetings. One teacher contributed to establishing the anchoring phenomenon, defining the guiding question, and identifying NGSS standards, ensuring the curriculum design was grounded in classroom realities. Another teacher on the GSLC team participated in designing activities and the teacher materials.

Teachers continued active roles throughout development and implementation, participating in orientation sessions and providing feedback that informed assessment refinement. This collaborative approach, where teachers served as active contributors rather than passive recipients, proved essential for creating materials that functioned effectively across diverse contexts.

The substantial improvement from the Phase 1 to Phase 2 studies occurred through assessment refinements that better captured student learning rather than through changes to the curriculum itself, which remained consistent across both phases. This highlights that initial implementations may underestimate effectiveness due to measurement limitations rather than instructional challenges. The successful implementation across rural, urban, and suburban settings in multiple U.S. regions demonstrates that carefully designed research-integrated curricula can function across varied educational contexts, although teachers necessarily adapted activities to fit local constraints.

Limitations and Methodological Considerations. The quasi-experimental design without control groups raises questions about whether learning gains resulted from curriculum design, content novelty, or unmeasured factors. Pre-

post design captures only immediate gains without addressing retention or transfer. Assessment improvements from Phase 1 to Phase 2 highlight how linguistic complexity can obscure understanding rather than reflect curriculum effectiveness.

Despite teacher preparation and explicit protocols, teachers necessarily adapted the module to local contexts and student needs, most commonly through supplemental vocabulary materials. These adaptations were minimal across classrooms (e.g., graphic organizers to support vocabulary acquisition). However, the impact of these additions was not a focus of this study. This reflects a fundamental tension in educational research: rigid adherence to protocols may yield more interpretable results but at the cost of practical applicability, while flexible implementation better represents real-world conditions but complicates identification of effective elements. Future research examining the specific contributions of teacher-developed supplemental materials would strengthen understanding of how the curriculum performs across diverse classroom contexts.

The relatively small number of participating teachers ($N=12$) may not adequately capture the full range of teaching styles and classroom contexts present in typical middle school instruction. Schools and teachers who volunteered may differ systematically from typical educational settings in motivation, resources, or administrative support. The study lacks detailed demographic information about participating students, limiting understanding of curriculum performance across different student populations.

The brief implementation period (1-2 weeks) may not have provided sufficient time for deep conceptual understanding to develop. Additionally, the cognitive demands of completing two 30-minute assessments on challenging material within a two-week period may have influenced student performance, complicating interpretation of learning gains.

Further, the focused scope on ecological relationships limits conclusions about broader applicability of research-integrated curricula across other scientific domains.

Implications for STEM Outreach Professionals. Our experiences in developing and assessing this curriculum module provide practical insights and recommendations for STEM outreach professionals who are considering research-to-practice translation.

Partnership Model Considerations. A three-way partnership model enables specialized curriculum development intermediaries to facilitate effective communication between research expertise and educational practice.

STEM outreach professionals should consider how similar intermediary partnerships could support their translation efforts, recognizing that effectiveness depends on participating organizations' expertise, resources, and institutional

commitment. Early teacher involvement in curriculum planning proved essential, illustrating how meaningful translation benefits from sustained educator input rather than brief consultations.

Engaging experienced teachers during initial conceptual planning rather than only during implementation phases is beneficial. Early input on learning objective alignment, cognitive appropriateness, and practical constraints proved essential for creating viable classroom materials, grounding curriculum design in classroom realities from the outset.

Research Selection and Anchoring Phenomena. When selecting research for educational translation, STEM outreach professionals should consider prioritizing phenomena that are directly observable or easily visualized, producing measurable outcomes that students can analyze, and generating cognitive puzzles that mirror authentic scientific inquiry. The parasitoid-host system succeeded because students could measure concrete changes (caterpillar growth) without initially knowing the cause, creating genuine investigative engagement rather than passive content consumption.

The anchoring phenomenon approach proved useful for maintaining student interest while building conceptual understanding. Research topics that contain elements of biological "strangeness" or unexpected relationships may be especially effective for capturing student attention and sustaining engagement throughout extended learning sequences.

Assessment Development Strategy. STEM outreach professionals are advised to plan for iterative assessment development alongside curriculum creation. Initial assessments may obscure learning gains if item wording introduces processing demands beyond the targeted conceptual challenge. The substantial improvement from Phase 1 to Phase 2 occurred primarily through assessment refinements that better captured student understanding, highlighting that initial measurements may underestimate program effectiveness.

Creating alternative items that reduce linguistic processing demands while maintaining Depth of Knowledge requirements can help distinguish conceptual understanding from item accessibility. Notably, standardized readability metrics may not identify problematic items; in this study, Flesch-Kincaid grade level showed no relationship with item difficulty, yet linguistically revised items still outperformed originals. This approach may be particularly valuable for diverse student populations.

Implementation Support and Evaluation. STEM outreach professionals should provide structured, pre-implementation teacher orientations that include hands-on experience with all activities, explicit discussion of implementation flexibility boundaries, and clear protocols for data collection. The

100% teacher completion rate for implementation surveys suggests that well-supported teachers can provide valuable feedback for program improvement and sustained implementation success.

The differential effectiveness across learning objectives suggests that evaluation frameworks should anticipate variable outcomes rather than assuming uniform impact across all targeted objectives. Evaluation tools should be matched to program goals, duration, and realistic implementation constraints.

Scalability and Sustainability Considerations. Testing curriculum implementation across multiple geographic and demographic contexts early in development is recommended, rather than scaling from single successful sites. The curriculum's effectiveness across rural, urban, and suburban settings in multiple regions suggests that well-designed materials can transcend local contexts, but this requires intentional testing rather than assumption.

Plan for ongoing material hosting and teacher support beyond initial development. The curriculum's continued availability through Learn.Genetics.utah.edu suggests that sustainable access requires institutional commitment to long-term hosting and maintenance, not just development funding. Consider partnership agreements that specify ongoing support responsibilities and resource allocation for sustained impact.

The geographic diversity of successful implementation demonstrates that research-integrated curricula can function across varied educational contexts when properly designed, but teachers will necessarily adapt materials to local constraints. Building flexibility into curriculum design while maintaining core learning objectives appears essential for broad implementation success.

Future Research Directions.

Learning Progressions in Ecological Reasoning. The success in basic relationship categorization coupled with persistent difficulties in complex multi-organism dynamics suggests cognitive thresholds in ecological thinking warranting systematic investigation. Future research should examine whether this boundary represents developmental limitations, conceptual prerequisite gaps, or instructional design challenges, specifically testing whether understanding strategic symbiotic relationships requires abstract reasoning abilities that develop later than middle school.

Partnership Model Optimization. Research examining cost-effectiveness and scalability of intermediary partnership models compared to direct researcher-teacher collaborations could inform institutional investment decisions. Studies should investigate which curriculum development

expertise aspects are most critical for successful translation and whether similar functions could be distributed among existing organizations. Comparative research across intermediary organization types (science museums, educational nonprofits, university centers) could reveal optimal partnership structures for different contexts.

Anchoring Phenomena and Authenticity. Questions remain about which research phenomena characteristics best support educational translation. Research systematically comparing student responses to different biological phenomena types (observable vs. microscopic, familiar vs. exotic, simple vs. complex) could inform strategic topic selection. Investigating whether “strange” phenomena like parasitoid manipulation consistently generate higher engagement than familiar relationships could guide researchers in identifying educational potential. Studies examining how research data authenticity levels (real experimental data vs. simulations vs. idealized examples) affect engagement, and understanding would inform authenticity-accessibility balance decisions.

Long-term Impact Assessment. Research examining whether students engaging with authentic research data show different patterns of scientific interest, course-taking behavior, or reasoning skills in subsequent years could demonstrate impacts beyond immediate gains. Studies investigating knowledge retention and transfer sustainability would address critical questions about the relationship between short-term assessment performance and meaningful conceptual understanding.

CONCLUSION

Project Impact Summary. This study demonstrates that university researchers can successfully translate cutting-edge scientific research into educationally effective middle school curricula through strategic partnerships with curriculum development specialists and classroom teachers. The *Symbiosis and Other Relationships* module demonstrated significant learning gains (Cohen's $d = 0.72$), with learning objective-specific effect sizes ranging from $d = 0.24$ to 0.60 , providing empirical evidence that authentic research phenomena can enhance science education while maintaining both scientific rigor and developmental appropriateness.

The differential effectiveness pattern—with strongest gains in ecological interdependence ($d = 0.60$) and more modest but significant improvements in complex multi-organism concepts—reveals important insights about science literacy development. This suggests that ecological reasoning involves a progression of cognitive demands rather than uniform difficulty, with implications extending beyond ecological content to science education broadly.

Contributions to Research-Practice Translation. This research advances understanding of effective models for bridging university research and K-12 education. The three-way partnership involving research expertise, specialized curriculum development capabilities, and classroom teaching experience proved essential for creating materials that preserved scientific authenticity while ensuring educational accessibility. The Genetic Science Learning Center’s intermediary role—providing expertise in educational design, multimedia development, and pedagogical translation—addressed critical gaps that neither researchers nor teachers could fill independently.

The systematic development process, incorporating early teacher input and iterative refinement, enabled successful integration of parasitoid research into middle school instruction. Students engaged with authentic scientific data showing observable effects of parasitism, then explored the underlying mechanisms through interactive materials depicting the complex three-way relationship among wasps, viruses, and hosts. By working with genuine research phenomena rather than simplified textbook examples, students demonstrated that the perceived gap between “real science” and “school science” may be smaller than typically assumed when appropriate translation expertise facilitates the process.

Implications for STEM Education Policy and Practice. The moderate effect sizes achieved through this focused intervention suggest that systematic scaling of research-integrated curricula could yield substantial educational benefits across large student populations. The successful integration of NSF CAREER program research into educational practice provides a concrete model for maximizing research impact while maintaining scientific productivity, directly addressing funding agencies’ goals for broader societal benefits.

For research institutions, this work demonstrates that effective research-to-practice translation requires sustained collaboration and specialized support structures rather than individual faculty initiative alone. The replicable framework developed here—encompassing anchoring phenomenon selection, learning objective alignment, and iterative assessment development—offers a roadmap adaptable across scientific disciplines and educational contexts.

Future Directions and Sustained Impact. The identification of learning progressions in ecological reasoning provides a foundation for future research on science literacy development and curriculum sequencing decisions. The curriculum’s continued availability through Learn.Genetics.utah.edu ensures ongoing educational impact beyond this research study, while the documented partnership model offers guidance for other institutions seeking to enhance their educational contributions.

As expectations for research accountability and broader

impacts continue to evolve, this study demonstrates how rigorous scientific investigation can be transformed into measurable educational benefits through thoughtful collaboration, appropriate institutional support, and recognition that effective translation requires specialized expertise in both scientific content and educational practice. The work establishes a foundation for sustained university-community partnerships that advance both scientific understanding and educational excellence.

ASSOCIATED CONTENT

Supplemental material mentioned in this manuscript can be found uploaded to the same webpage as this manuscript.

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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ABBREVIATIONS

CAREER: Faculty Early Career Development Program; GSLC: Genetic Science Learning Center; NRC: National Research Council; NSF: National Science Foundation; UGA: University of Georgia

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