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Biological Impact and Ethical Implications of Pesticide Use: A Short Module for Upper-Division-Undergraduate Biochemistry Courses

Lisa M. Ryno*[,†,§] and Cheryl Cottine[‡,§]

[†]Department of Chemistry and Biochemistry, Oberlin College, 119 Woodland Street A263, Oberlin, Ohio 44074, United States
[‡]Department of Religion, Oberlin College, 10 North Professor Street, Oberlin, Ohio 44074, United States

Supporting Information

ABSTRACT: In the Fall of 2015 and in the 2016−2017 academic year, we conducted a two-week, team-taught, interdisciplinary module concurrently in an advanced biochemistry course, offered in the Chemistry and Biochemistry Department, and a sophomore-level environmental-ethics course, offered in the Religion Department, at Oberlin College. The focus of the unit was the mechanism of pesticides and the ethics of their use domestically and in agriculture, using *Silent Spring* by Rachel Carson as a primary text. The general question our students explored was: How does understanding the chemistry of various pesticides impact biological systems and larger preservation and conversation practices? Posing the question in this manner signaled to students that to adequately grapple with pressing environmental concerns, we must utilize an integrated approach and response. Students in both classes were exposed to chemical and biological mechanisms of different types of pesticides at their level of assumed knowledge and learned about several ethical theories that they then applied to real-world case studies. The two instructors (a biochemist and an ethicist) visited each other's classrooms and taught lectures relevant to their specialties (e.g., the biochemist taught a lecture on pesticide mechanisms of action). Students completed a reflection assignment about the unit as well as a research paper about a pesticide of their choice, which demonstrated their knowledge about the pesticide's mechanism of action and explored the ethics of that pesticide's use. We believe this module is easily adaptable to any biochemistry or environmental chemistry course. We provide a detailed description of the module and our assessment of its impact on students' ability to apply general ethical theories to complex societal issues.

KEYWORDS: *Ethics, Biochemistry, Upper-Division Undergraduate, Interdisciplinary/Multidisciplinary, Problem Solving/Decision Making*

INTRODUCTION

Here we describe the implementation and qualitative assessment of an interdisciplinary, team-taught module on the biochemical mechanisms of pesticides and the ethics of their use in agriculture. We encouraged our students to augment their knowledge of a pesticide's biochemical influence on an ecosystem by asking broader questions of ethical responsibility. We reminded students that one cannot ignore the science behind certain preservation and conservation mechanisms, nor is it acceptable to ignore the larger ethical implications of proposed interventions. This module served a three-fold purpose: (1) to introduce and demonstrate the application of different ethical doctrines to scientific problems, (2) to explore the molecular and physiological mechanisms of action of commonly used pesticides, and (3) to create an interdisciplinary and active discussion about the responsible use of chemicals and their impact on humans and the environment.

Technological advances have the potential to mediate societal problems, though these advances can raise complicated moral questions that need to be evaluated and explained carefully to the public. Therefore, the incorporation of ethics in undergraduate chemistry courses is critical for the development of the next generation of scientists and citizens of the world.[1] The American Chemical Society dictates that "[e]thics should be an intentional part of the instruction in a chemistry program" for accredited departments,[2] though how ethics is incorporated in the curriculum can vary widely across different institutions.[3−6] Explicit discussions of research ethics occurs for all students participating in NIH- and NSF-funded research and is often also incorporated into classroom laboratory experiments.[7,8] Limiting students' exposure to moral dilemmas centered solely around the execution of scientific research, however, is a disadvantage to their development as critical thinkers. Coppola and Smith noted that ethics permeates the average responsibilities of a scientist, from the design of experiments and data collection to collaboration with and evaluation of colleagues.[9] Our approach, which teaches students fundamental ethical theories that can be applied to any type of problem, encourages students to start considering additional, deeper questions, particularly those associated with social responsibility, when undertaking or analyzing a project. Students began to ask scientific questions within a humanitarian framework and discovered that ethical reflection rehumanizes the scientific endeavor. Adopting this mindset helped students think broadly about the implications of a particular scientific research project or experiment and consider the often-numerous stakeholders involved in and impacted by a particular project outcome or action. McArthur and Smith (colleagues from the Philosophy and Chemistry

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departments of Colby College, respectively, who advocated for ethics to be taught in science courses in the early 1980s), note that "[t]he goals of an ethics course are to learn how to give reasons for one's views and what sorts of reasons are in the final analysis acceptable."[10] With respect to pesticide use and development, students not only considered the effectiveness of a particular chemical compound on its intended target but also the impact the pesticide had on different ecosystems as well as on those who actually produce the product, both physically and financially. When students considered both the wider implications of pesticide use as well as its means of production, they naturally began asking different questions than the ones they would have asked if addressing the issue from a purely scientific framework.

We chose Rachel Carson's book *Silent Spring* as the primary text for the module.[11] A common text for environment-focused chemistry and humanities courses, *Silent Spring* offered students a snapshot into the mid-20th century taken by an individual who was both perceptive about the influence of chemicals on the environment and eloquent in her ability to convey science to the average person. Importantly, we dissected the *Silent Spring* text both as concerned citizens and as scientists, critiquing the effectiveness and scientific accuracy of Carson's arguments. We used case studies throughout the module in order to introduce ethical theories and apply them in practical situations, a technique that has been employed previously in chemistry classrooms with success.[12,13] An example case study discussed in this report examined the use of the pesticide 1,2-dibromo-3-chloropropane (DBCP, Nemagon) on Costa Rican banana plantations in the second half of the 20th century as a way to expose students to the use of pesticides banned in the United States since the reception of *Silent Spring* and the ethical dilemmas that arise when U.S. companies use foreign labor and goods.[14]

The two-week module (four 75 min class periods) we describe herein was offered in the Fall 2015 and 2016 semesters in an upper-division biochemistry course and in the Fall 2015 and Spring 2017 semesters in an environmental-ethics course hosted in the Religion Department at Oberlin College, a small liberal-arts institution. This interdisciplinary unit was taught to two different populations of students, approximately half of whom were entrenched in the humanities, and the other half focused on the natural sciences. *Silent Spring*, alongside other historical excerpts, case studies, textbooks, scientific research articles, and even pesticide advertisements, served several purposes. The combination of primary and secondary literature and peer-reviewed scientific evidence (1) exposed students to the mechanisms of small-molecule pesticides in biological systems, (2) provided students with the opportunity to explore and discuss the ethical implications and broader societal and ethical questions posed by the use of these pesticides, and (3) helped students foster awareness and curiosity about humanity's impact on the natural world. We assessed students' knowledge about pesticides and ethical theories in several ways. First, students in both courses were required to write a substantial research paper on a pesticide that was utilized in the United States after the reception of *Silent Spring* (e.g., used after 1962), describing the mechanism of action and applying an ethical theory to justify the use of the pesticide. Second, students in the biochemistry course were given short answer and essay questions on a midterm and final exam that tested their knowledge about molecular mechanisms of pesticides and an ethical theory discussed in class. The instructors utilized a short reflection assignment, due shortly after the completion of the module, and end-of-semester evaluations to assess the success of the module as a whole.

Although many chemistry courses incorporate discussions and examples that have ethical and environmental content, this is the first description, to our knowledge, of a brief module that operates as an interdisciplinary, team-taught, and discussion-based unit focusing on the mechanisms of action and ethical implications of pesticides in the environment. Although the success of this module is not necessarily dependent on having two instructors, one an expert in ethics (C.C.) and the other an expert in biochemistry (L.M.R), we believe that this interdisciplinary pairing added additional depth to the module and demonstrated the fruitful nature of collaboration between a humanist and scientist. We demonstrated to students that a question, in this case, whether the use of pesticides is safe and justified, can be examined from multiple viewpoints, and by working together, we are able to generate a comprehensive and informed assessment of that problem. We believe this module, described below, can be easily adopted and adapted by any instructor interested in adding an ethical and environmental component to their current chemistry courses.

■ MODULE DESCRIPTION

We taught this module to two separate groups of students: (1) upper-division biochemistry students with a considerable foundation of chemical and biological knowledge and (2) students taking an environmental-ethics course in the Religion Department, many of whom had no undergraduate science background. Although we taught a majority of the module identically to both student groups, we differentially emphasized the level of detail of the chemical and biological mechanisms depending on the audience, allowing for more relevant discussion and evaluation for each class. An upper-division biochemistry course is well suited to incorporate a module of this nature, as the content of the course is more flexible than introductory chemistry courses, and there can be considerable overlap with conventionally discussed topics. For example, an instructor can introduce gated ion channels by discussing the mechanism of action of dichlorodiphenyltrichloroethane (DDT), which binds to the membrane-bound portions of voltage-gated sodium channels, disrupting their normal function by keeping them open and constantly propagating a neuromuscular signal.[15] Below we describe the timeline of topics discussed in the module.

We used *Silent Spring* to guide the topics discussed within this module (Table 1). We began the module with a brief history of pesticide use throughout the world and, in particular, the United States since World War II, taking approximately half of the class period (35 min of a 75 min class) to introduce students to the material via a PowerPoint presentation.

Table 1. Course Schedule with Assigned Readings

Day	Topic Covered	*Silent Spring* Assigned Reading
1	History of Pesticides	Chapters 1−6
2	Mechanisms of Action of Pesticides	Chapters 12−14
3	Exploring the Ethics of Pesticide Use	Chapters 8−9, skim chapters 7−11
4	Pesticides: Looking Forward	Chapter 17

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We utilized secondary texts, such as Frederick Rowe Davis's *Banned*[16] and *The Excellent Powder: DDT's Political and Scientific History* by Richard Tren and Donald Roberts,[17] to help provide context to the use of pesticides in the second half of the 20th century. Students learned about five classes of pesticides: heavy metals, chlorinated hydrocarbons, organophosphates, synthetic and extracted pyrethroids, and neonicotinoids. Students spent the second half of the class period in group discussion of Carson's text and questions that introduced new terminology and concepts with which students may not have been familiar (Box 1). From the outset, we encouraged students to examine the impact a pesticide has on both human and nonhuman entities by considering pesticide solubility and introduced students to concepts like bioaccumulation (the accumulation of a substance in an organism over time) and biomagnification (the increasing concentration of a substance in the tissues of organisms at successively higher levels of the food chain). We have included selected discussion questions from each day in Supporting Document 1 to facilitate the adoption this module.

Box 1. Selected Student Discussion Questions

Example Discussion Questions:

Why do we need insecticides?

What is different about synthetic (as compared to previous) pesticides?

What does it mean for chemicals to concentrate in the food chain? Why does Carson raise this issue as being important?

What is the intended target of the pesticide 2,4-D? What makes it different than the other compounds Carson discusses?

Students spent the second day of the module exploring the mechanism of action of several types of pesticides, including chlorinated hydrocarbons (specifically DDT, a primary focus in *Silent Spring*), organophosphates, and neonicotinoids. The biochemist (L.M.R.) taught this portion of the module to both classes and tailored the lecture to the background of the class. Both classes learned the basics of neuronal function by learning how an impulse is conducted and what occurs in the synaptic cleft, the space between two neighboring neurons.[15] We focused on how pesticides can disrupt typical neuronal function in different ways depending on their chemical structure. For example, DDT, which is a fairly hydrophobic molecule, binds to a sodium channel at a location deep in the lipid bilayer, stabilizing the channel's open conformation and allowing sodium ions to continue to enter the cell, potentiating the impulse.[15] In the upper-division biochemistry course, the instructor was able to assume the class had knowledge about acyl-substitution reactions and serine proteases when discussing the mechanism of action of organophosphate pesticides and how they inhibit acetylcholinesterase enzymes (Figure 1A).[18] In the environmental-ethics course, the same topic was introduced using a simple schematic to demonstrate how the pesticide physically interacts with the enzyme and blocks the area of the enzyme that needs to be accessible for its function (Figure 1B).

This portion of the module also used *Silent Spring* as a primary reference, and students engaged in small-group discussions to dissect Carson's explanation of how DDT was killing mammalian life. Students learned that Carson emphasized the disruption of the energy-production process, namely, the synthesis of adenosine triphosphate (ATP) by oxidative phosphorylation. The instructor introduced recent research on how DDT and other pesticides impact mammals and other wildlife, including evidence of endocrine-system disruption in humans.[19−22]

Additionally, students had the opportunity to critically examine some of the material presented in *Silent Spring*. We took time to emphasize that although this book has been in publication for over 50 years, it was never peer-reviewed like scientific manuscripts, and although Carson did cite many peer-reviewed publications in *Silent Spring*, the book has factual errors and now out-of-date explanations. An example of a factual error that we discuss in class is Carson's explanation of the mechanism of action of the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D) on mammalian life. Although Carson correctly discusses the impact of 2,4-D on the production of both sugars and nitrates in certain plant life, her discussion of how those nitrates, which turn into nitrites in mammalian systems, impact oxygen transport by hemoglobin is incorrect. Carson explains: "nitrites act on the blood pigment to form a chocolate-brown substance in which oxygen is so firmly held that it cannot take part in respiration [...]."[11] Carson is referring to the impact of nitrite on hemoglobin, the protein that is responsible for the transport and release of oxygen. Nitrite certainly binds to hemoglobin and interferes with oxygen transport, but it does so in a way that stabilizes *deoxygenated* hemoglobin, which is observed as the "chocolate-brown" color, not by stabilizing the oxygenated form, as Carson suggests.[23,24] The *Science* paper Carson cites does correctly explain the mechanism by which nitrites stabilize the methemoglobin (deoxygenated) form of hemoglobin; however, this is not relayed in the text of *Silent Spring*.[25] The biochemistry students had already learned about hemoglobin earlier in the semester, and immediately identified the error when the section on 2,4-D was discussed. The environmental-ethics students were given more background and context about why Carson's description about how nitrates were impacting hemoglobin was incorrect. Although it seems like a small point, this example highlights that *Silent Spring* is a fact-filled book different from a textbook or peer-reviewed manuscript. This serves to remind students to be critical, especially when the message of a book resonates with their own ideas and opinions.

The third day of the module was devoted to considering the ethics of pesticide use, and both classes received lectures from an ethicist (C.C.). As with the biochemistry lecture, the ethics lecture was tailored to the specific knowledge base of the students involved. For the lecture delivered to the biochemistry class, no background knowledge in ethics was assumed. The lecture began by asking the students to define ethics and to discuss the question: What is the aim of science? This broad opening discussion encouraged students to reflect on some of the values they brought to their study as well as on the larger motivating factors driving their various inquiries. Broader questions focusing on issues of motivation can understandably be overshadowed as students focus on the complexities of learning a scientific discipline, but these questions are imperative to the overall health and well-being of humans and the environment alike, as Carson's book reminds them.

The majority of the ethics lecture was devoted to introducing students to four major ethical theories: deontology, consequentialism, virtue ethics, and the rule of double effect.[26] Students then had the opportunity to see how each of the theories applied to a case study. We asked students to

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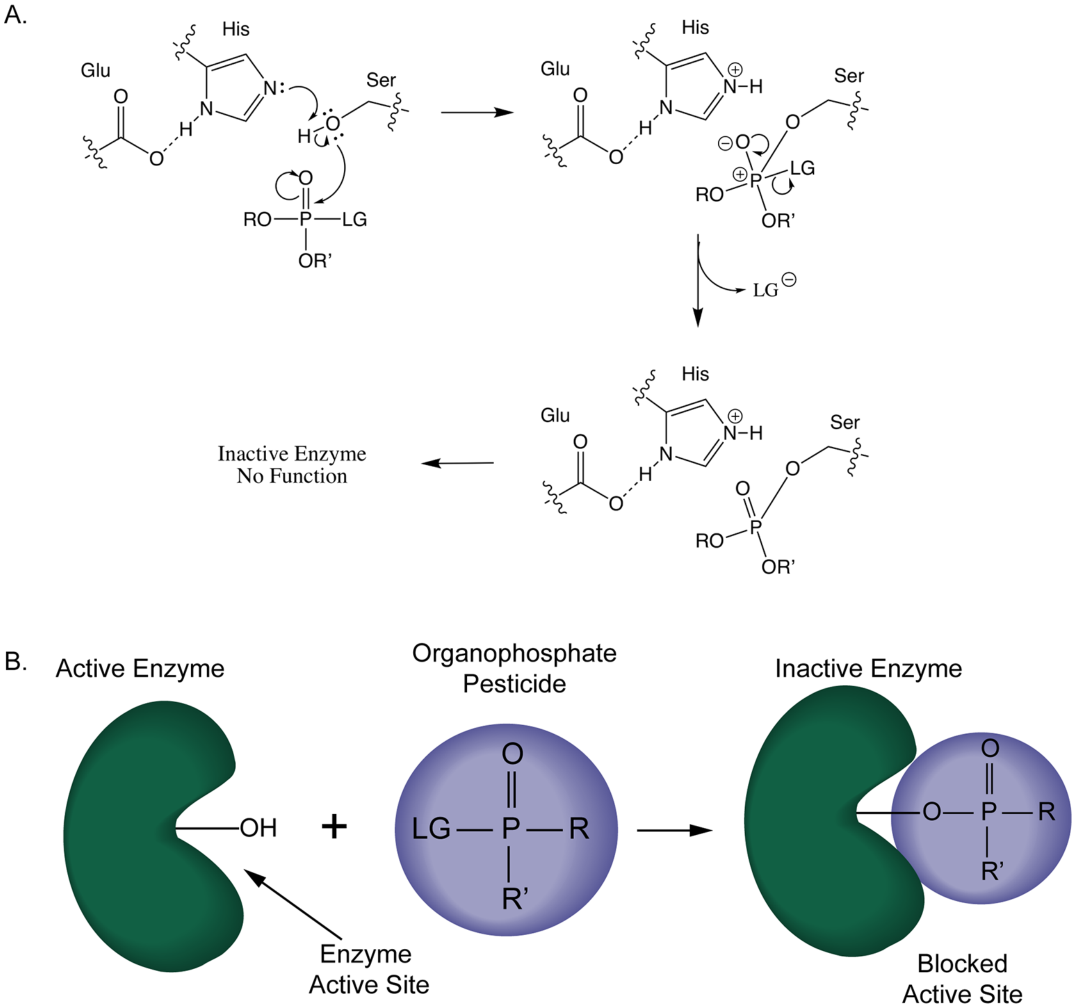

Figure 1. Acetylcholinesterase inhibition by organophosphate pesticides. (A) Mechanism of inhibition of active serine residue by organophosphate. (B) Scheme of enzyme inhibition. LG, leaving group.

identify the stakeholders, the values at play for each, and what each party had at stake in the case. Then, students applied each ethical theory to the case, identifying the facts and questions each ethical framework would deem most relevant for determining the ethical course of action. Applying different ethical frameworks to a case highlighted the complexity that arises when different sets of values and questions lead to dramatically different conclusions for an ethical course of action.

The final day of the module focused on alternatives to the chemical control of insects and a critical examination of the reception of *Silent Spring* and ended with a case study, worked on in groups, which tied the module together. In the lecture portion of the class, students learned about sterile-insect techniques, including methods of irradiation and genetic modification. In the Fall 2016 class, there was a timeliness to the recent outbreak of Zika virus being attributed to mosquitos, and we had the opportunity to discuss how scientists were working to genetically modify mosquitos to curb the transmission of the virus, and how that was being received by the communities most affected by the Zika virus outbreak.[27,28]

We also spent time discussing the reactions of people, from average citizens to academic and industrial scientists, to *Silent Spring* and Rachel Carson, and how some of those responses shaped the formation of the Environmental Protection Agency. We used an article in the *New York Times* that was published during the 50th anniversary of the publication of *Silent Spring* to give a historical perspective of Carson's interactions with the public, politicians, and even the chemical industry.[29] We also used a book review published in Chemical and Engineering News in 1962 titled "Silence, Miss Carson", authored by Professor William Darby, an esteemed biochemist and member of the National Academy of Sciences, which was especially critical of Carson's use of literary devices and charged language to "aggravate unjustifiably [the reader's] own neurotic anxiety," and ultimately said "this book should be ignored."[30] Despite criticism, some founded and some baseless, Carson testified before a U.S. Senate subcommittee in the summer of 1963, less than a year before her death, to argue against aerial spraying and for the rights of the private citizen and their knowledge of what chemicals were being used on their property. As we studied *Silent Spring*, we had the luxury of over 50 years of analysis, additional experimentation, and implemented policy to evaluate the importance of the book and Carson's legacy. Students reported in evaluations that they appreciated a holistic view of how the book was received at the time and made note of the parallels they see currently with the fossil-fuel industry and climate change.

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The module ended with a case study about the use of the pesticide 1,2-dichloro-3-bromopropane (DCBP, Nemagon) in Costa Rica.[14] DCBP is a nematicide that was used on fruit plantations in Central America until the mid-1980s and is known to cause organ damage and male infertility.[31] Students worked in groups of three or four to learn about DCBP, its use in the 1970s and 1980s in Costa Rica and Central America, and in particular the role of U.S. chemical and fruit companies in the distribution and use of DCBP on Costa Rican banana plantations. Students put themselves in the shoes of each one of the stakeholders (e.g., Dow Chemical Company, plantation workers, the Costa Rican government, the environment, etc.) and discussed whether or not the use of the pesticide was ethical, and whether or not workers should receive compensation from the chemical and fruit companies for any maladies they might have as a result of their exposure to the pesticide. We asked students to think about the ethical implications of transnational chemical corporations continuing to produce and export DCBP to countries with fewer environmental and occupational regulations.[31] Although many Oberlin students are environmentally conscious, only a few had heard about DCBP prior to this case study. The shock and dismay that many students felt when learning about the use of this pesticide on fruit (bananas in particular) was palpable. A case like this that draws a visceral reaction provided a valuable teaching moment, as we encouraged students to note their discomfort with the practice described and then provide ethical and scientific justifications for why the practice seemed morally abhorrent, even if it was legally and economically sound. Although many students found that making ethical arguments against the use of DCBP came naturally, we also implored students to make an argument, using both the science and ethical theory, for how it could be morally permissible for a company to use the pesticide on its produce operations. Although harder to do, we found that this exercise encouraged students to deeply consider the issue from a different angle, thus ultimately, in many instances, enabling them to more thoroughly defend their conclusions about why the practice was morally questionable.

During the Fall of 2015, the first iteration of the module, both classes met during the same semester, which provided a unique opportunity for the students in each class to engage one another. We required students to attend either a lunch meeting or an evening seminar given by a scholar of environmental ethics and strongly encouraged students to attend both. At these events we provided food, discussion questions, as well as time and space for students to mingle. During the lunchtime meeting, we requested students form small groups with students represented from both classes wherein they discussed *Silent Spring*, the DCBP case study, and the use of pesticides in agriculture internationally and domestically. Instructors moved around the room and joined conversations with each group and, during the last 10 min of the period, brought the group back together as a whole to discuss some of the broader questions about *Silent Spring*. During this semester, the instructors also invited Professor Lisa Sideris from Indiana University to campus, a prominent scholar of environmental ethics and a Rachel Carson specialist. Sideris attended one of the biochemistry classes, participated in the conversation surrounding the DCBP case study, and delivered a lively lecture that broadly discussed the intersection of science and religion. Although we recognize that bringing in outside speakers is funding-dependent, we found the seminar greatly enhanced the conversation between the two classes.

Students who took our classes during the 2016–2017 academic year met during different semesters and therefore did not have the ability to meet together in groups outside of class. Interestingly, in the reflection assignment, discussed below, students mentioned that they had heard about the mixed-group discussions of the previous year, noted that they would have enjoyed having more opportunities for interdisciplinary interactions, and suggested the addition of outside discussion opportunities in future iterations of the module.

■ STUDENT ASSESSMENT

The primary mechanism of the student assessment for this unit was a 1500–2000-word research paper exploring a pesticide used since the reception of *Silent Spring*. For the biochemistry course, this research paper was worth approximately 10% of their final grade. The students had the freedom to choose a pesticide to study that was of interest to them. Although some students chose common pesticides used in the United States like glyphosate (Round Up) and imidacloprid (a neonicotinoid), others chose to explore genetically modified crops (Bt toxin); pesticides used in countries other than the United States, like the use of dieldrin in Brazil; and pesticides that are marketed as "less toxic", like neem oil. Students explored the mechanism of the pesticide; how, where and when it is used; the impact of the pesticide on unintended targets (flora and fauna); and the ethical implications of using the pesticide (Supporting Document 2). Students chose an ethical theory to frame their analysis of whether or not they thought using the pesticide was justified. Not surprisingly, many students argued that their pesticide should no longer be used or should be used sparingly under tightly controlled conditions, ensuring workers all had appropriate personal-protective equipment.

In the biochemistry course, students also had a portion of a midterm exam and final exam (approximately 7% of their final grade) dedicated to answering questions about this unit. These questions included explaining the mechanisms of action of different classes of pesticides, specific questions about the DCBP case study, and questions with an ethics component. An example ethics question gave information about the use of DDT in South Africa, which banned DDT temporarily in 1996 and saw a 600% increase in malaria,[32] and asked students to decide whether the use of DDT in South Africa was ethical using the rule of double effect, which has four rules to guide decision making.[26] This question required students to draw on their knowledge of how DDT impacts humans and the environment, a subject that was thoroughly covered in class, and also required them to remember and appropriately apply the tenets of the rule of double effect. Several additional exam questions can be found in Supporting Document 3.

We required students to submit a reflection assignment at the end of the module, which was graded on the basis of completion only. In this assignment, we asked students to consider how the material covered in the module connected to their experiences outside of the classroom as well as their overall assessment of the unit: what worked and what could use improvement. The responses received reflected the importance of interdisciplinary units and the inclusion and consideration of ethics when teaching science courses. The students in the biochemistry course found the humanist perspective enriching, as evidenced by selected responses below:

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"Rarely has the question of—well we can now synthesize all of these compounds, but should we?—been posed in my classes. This unit has really helped me to think critically about my role as a future scientist."

"Furthermore, our nuanced discussion of environmental ethics was an important reminder that science does not exist in a vacuum and we must interrogate how the knowledge we are learning is inherently political."

Students in the environmental-ethics class discussed the importance of learning the science behind broad ethical problems in the reflection assignments. A few excerpts from their responses are highlighted below:

"I've found learning about pesticide mechanisms and their ethical implications enriching to my learning experience [...] by gaining specific understanding of the dynamics and mechanisms at work in an environmental system, actors can offer informed opinions about what ethical action might look like, in concrete terms."

"I always knew pesticides were harmful, but never knew the specific extent of damage, contamination and about bioaccumulation they caused. Bioaccumulation in particular was unknown to me before. Taking this class really expanded and strengthened my understanding of pesticides, and the different ethical views to approaching and viewing pesticides."

Suggested improvements include expanding the unit beyond two weeks, having more time dedicated to learning about ethics, and introduction and explanation of the mechanisms of a greater number of currently used pesticides in the United States. In the second iteration of the module, during the academic year of 2016−2017, we incorporated the mechanisms for a few more pesticides and discussed in greater depth newer technologies, including using the genetic-modification sterile-insect technique through the creation of repressible, dominant lethal mutations (RIDL), where the insects are not actually sterile but carry a genetic mutation that causes lethality to wild insects of that particular species.[33]

CONCLUSIONS AND FUTURE DIRECTIONS

This module provided students with the tools to analyze complicated biochemical mechanisms of synthetic pesticides and their impact on the environment through the lens of both the scientist and the ethicist. The interdisciplinary theme of the module, which combined detailed chemical mechanisms with expansive questions about moral philosophy, enriched the experience of the students and instructors alike. Our goal is to eventually expand this module into a semester-long course on the ethical use of chemicals, which would include a much longer unit on pesticides as well as a unit on pharmaceuticals. We also believe this interdisciplinary working relationship was fruitful and are eager to jointly teach similarly structured units on other topics, including medical ethics and biomedical-research ethics. By teaching ethical theories in the context of popular environmental and societal issues, we believe our students will be better equipped to extrapolate their knowledge of ethics to other scientific and cultural issues that they will undoubtedly face as engaged citizens of the world.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.8b00379.

Supporting Document 1: Discussion questions (PDF, DOCX)

Supporting Document 2: Pesticide assignment (PDF, DOCX)

Supporting Document 3: Example exam questions (PDF, DOCX)

AUTHOR INFORMATION

Corresponding Author

*E-mail: lryno@oberlin.edu.

ORCID

Lisa M. Ryno: 0000-0002-9211-8297

Author Contributions

§L.M.R. and C.C. contributed equally to this work.

Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Coppola, B. P. Targeting Entry Points for Ethics in Chemistry Teaching and Learning. *J. Chem. Educ.* **2000**, *77* (11), 1506−1511.

(2) ACS Committee on Professional Training. *Undergraduate Professional Education in Chemistry: ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs*; American Chemical Society: Washington, DC, 2015. Available at https://www.acs.org/content/dam/acsorg/about/governance/committees/training/2015-acs-guidelines-for-bachelors-degree-programs.pdf.

(3) Moody, A. E.; Freeman, R. G. Chemical Safety and Scientific Ethics in a Sophomore Chemistry Seminar. *J. Chem. Educ.* **1999**, *76* (9), 1224−1225.

(4) Singiser, R. H.; Clower, C. E.; Burnett, S. C. Preparing Ethical Chemists through a Second-Year Seminar Course. *J. Chem. Educ.* **2012**, *89*, 1144−1147.

(5) Caspers, M. L.; Roberts-Kirchhoff, E. S. Incorporation of ethical and societal issues in biochemistry into a senior seminar course. *Biochem. Mol. Biol. Educ.* **2003**, *31* (5), 298−302.

(6) Hanson, M. J. Introducing ethics to chemistry students in a "Research Experiences for Undergraduates" (REU) program. *Biochem. Mol. Biol. Educ.* **2015**, *43* (2), 76−80.

(7) Plimpton, S. H. NSF's Implementation of Section 7009 of the America COMPETES Act. *Fed. Regist.* **2009**, *74* (160), 42126−42128.

(8) National Institutes of Health Office of Intramural Research. Responsible Conduct of Research Training. https://oir.nih.gov/sourcebook/ethical-conduct/responsible-conduct-research-training (accessed July 2018).

(9) Smith, D. H.; Coppola, B. P. A Case for Ethics. *J. Chem. Educ.* **1996**, *73* (1), 33−24.

(10) McArthur, R. P.; Smith, W. L. Ethics in science: Recombinant problems. *J. Chem. Educ.* **1982**, *59* (10), 839−841.

(11) Carson, R. *Silent Spring*; Houghton Mifflin: New York, 1962.

(12) Fisher, E. R.; Levinger, N. E. A Directed Framework for Integrating Ethics into Chemistry Curricula and Programs Using Real and Fictional Case Studies. *J. Chem. Educ.* **2008**, *85* (6), 796−801.

(13) Kulak, V.; Newton, G. A guide to using case-based learning in biochemistry education. *Biochem. Mol. Biol. Educ.* **2014**, *42* (6), 457−473.

(14) Saito, J.; Odenyo, O. Costa Rica Pesticides, Worker Health and Agricultural Exports. *TED Case Studies.* **1995**, *4* (1).

DOI: 10.1021/acs.jchemed.8b00379
J. Chem. Educ. XXXX, XXX, XXX−XXX

(15) Yu, S. J. *The Toxicology and Biochemistry of Insecticides*, 2nd ed; CRC Press: Boca Raton, FL, 2014.
(16) Rowe Davis, F. *Banned*; Yale University Press: New Haven, 2014.
(17) Roberts, D.; Tren, R.; Bate, R.; Zambone, J. *The Excellent Powder*; Dog Ear Publishing: Indianapolis, 2016.
(18) Nelson, D. L.; Cox, M. M. *Lehninger Principles of Biochemistry*, 7th ed.; W. H. Freeman: New York, 2017.
(19) Mrema, E. J.; Rubino, F. M.; Brambilla, G.; Moretto, A.; Tsatsakis, A. M.; Colosio, C. Persistent organochlorinated pesticides and mechanisms of their toxicity. *Toxicology* **2013**, *307*, 74−88.
(20) Eskenazi, B.; Chevrier, J.; Rosas, L. G.; Anderson, H. A.; Bornman, M. S.; Bouwman, H.; Chen, A.; Cohn, B. A.; de Jager, C.; Henshel, D. S.; Leipzig, F.; Leipzig, J. S.; Lorenz, E. C.; Snedeker, S. M.; Stapleton, D. The Pine River statement: human health consequences of DDT use. *Environmental Health Perspectives.* **2009**, *117* (9), 1359−1367.
(21) Campagna, M.; Satta, G.; Fadda, D.; Pili, S.; Cocco, P. Male fertility following occupational exposure to dichlorodiphenyltrichloroethane (DDT). *Environ. Int.* **2015**, *77*, 42−47.
(22) Berg, C.; Blomqvist, A.; Holm, L.; Brandt, I.; Brunström, B.; Ridderstråle, Y. Embryonic exposure to oestrogen causes eggshell thinning and altered shell gland carbonic anhydrase expression in the domestic hen. *Reproduction* **2004**, *128* (4), 455−461.
(23) Huang, K. T.; Keszler, A.; Patel, N.; Patel, R. P.; Gladwin, M. T.; Kim-Shapiro, D. B.; Hogg, N. The reaction between nitrite and deoxyhemoglobin. Reassessment of reaction kinetics and stoichiometry. *J. Biol. Chem.* **2005**, *280* (35), 31126−31131.
(24) Kosaka, H.; Imaizumi, K.; Imai, K.; Tyuma, I. Stoichiometry of the reaction of oxyhemoglobin with nitrite. *Biochim. Biophys. Acta, Protein Struct.* **1979**, *581* (1), 184−188.
(25) Stahler, L. M.; Whitehead, E. I. The effect of 2,4-D on potassium nitrate levels in leaves of sugar beets. *Science* **1950**, *112* (2921), 749−751.
(26) Rachels, J.; Rachels, S. *The Elements of Moral Philosophy*, 7th ed; McGraw Hill: New York, 2012.
(27) Allen, G. Florida Keys Approves Trial Of Genetically Modified Mosquitoes To Fight Zika. *NPR*, Nov 20, 2016. Available at https://www.npr.org/sections/health-shots/2016/11/20/502717253/florida-keys-approves-trial-of-genetically-modified-mosquitoes-to-fight-zika.
(28) Servick, K. Brazil will release billions of lab-grown mosquitoes to combat infectious disease. Will it work? *Science*, Oct 13, 2016. Available at http://www.sciencemag.org/news/2016/10/brazil-will-release-billions-lab-grown-mosquitoes-combat-infectious-disease-will-it.
(29) Griswold, E. How 'Silent Spring' Ignited the Environmental Movement. *New York Times*, Sept 21, 2012. Available at https://www.nytimes.com/2012/09/23/magazine/how-silent-spring-ignited-the-environmental-movement.html.
(30) Darby, W. J. Silence, Miss Carson. *Chem. Eng. News* **1962**, *40* (40), 60−63.
(31) Thrupp, L. A. Sterilization of Workers from Pesticide Exposure: The Causes and Consequences of DBCP-Induced Damage in Costa Rica and Beyond. *Int. J. Health Serv.* **1991**, *21* (4), 731−57.
(32) Ovuorie, T. African countries adopt controversial deadly chemical, DDT, for malaria treatment. *Premium Times*, July 17, 2013. Available at https://www.premiumtimesng.com/news/141150-african-countries-adopt-controversial-deadly-chemical-ddt-for-malaria-treatment.html.
(33) Alphey, L.; Koukidou, M.; Morrison, N. I. *Transgenic insects: techniques and applications*; Benedict, M. Q., Ed.; CABI: Wallingford, Oxfordshire, U.K., 2014.

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