Environmental Science and Climate Studies

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Why Environmental Science and Climate Studies?

Global climate change is real [1]. It is incumbent upon us all to address numerous questions at local, regional and global levels, such as these:

- Who and what will be significantly affected?
- When and where will we see major changes?
- How can we prepare?

When put in context of specific situations, these problems require knowledge in one or more disciplinary fields, including natural and/or social sciences, to obtain a quantitative result. Mathematics plays an important role in the investigation of environmental science and climate studies (ESCS) issues.

As evidenced by the participation of over 100 institutions and organizations in the Mathematics of Planet Earth 2013 thematic year, mathematicians are well aware of the need to apply mathematical knowledge to better understand our dynamic planet. Many academic institutions are adding courses and degree programs in sustainability and environmental studies to meet the student interest and demand, and a growing job market in the area [2,3,4].

Outside of environmental engineering programs (see [5] for many examples), however, undergraduate ESCS-related programs seldom require upper-level mathematics. This is so despite broad awareness of mathematical needs of students who continue in ESCS at the graduate level. For example, *Applied Math for Environmental Studies*, a graduate course in the Yale School of Forestry & Environmental Studies, aims to "help students refresh or acquire new math skills and succeed in content and 'toolbox' graduate-level courses … the course assumes that, at a minimum, students took college algebra and perhaps a semester of calculus (but might not really remember it)" [6].

The need for mathematically-focused ESCS programs at the undergraduate level is clear. Finding viable approaches to implementation is the focus of this report.

ESCS in the undergraduate mathematics curriculum

"Our populace is becoming less able to evaluate or assess the trade-offs between

> alternatives. It would be exceptionally useful if the environmental courses would be able to open the eyes of the non-mathematics major to the evaluation of alternatives."
>
> Lee Seitelman, 1992

The examination of ESCS in the undergraduate mathematics curriculum is not new. The 1992 CUPM report, *Environmental Mathematics* [7], discussed the value of exploring environmental themes over 20 years ago, yet Seitelman's observation from that report is perhaps even more appropriate today. As a population we have access to and search for more and more data, but we seldom trouble to analyze the information or its underlying tools and techniques.

The mathematics needed to address ESCS issues spans the undergraduate mathematics curriculum, from basic algebra (applied in linking higher CO_2 levels to temperature increase) to partial differential equations (applied in tracking weather patterns). The 1992 report recommended the development of environmentally-focused introductory mathematics courses and materials to incorporate environmental themes into courses in the major.

This Program Area Study Group (PASG) recommends that these efforts continue, not least to increase awareness of the need for sound mathematics in ESCS. Connections across disciplines should also be identified and strengthened to better prepare students for future study and careers in the many ESCS subdisciplines.

Designing an ESCS-focused mathematics program

Scientific study of the environment and the planet's climate is inherently multidisciplinary. This same breadth and applicability to many areas, including chemistry, biology, sociology, and others, allows departments flexibility to design ESCS-focused math programs that suit institutional needs by leveraging pre-existing resources.

To appropriately address issues in ESCS and properly prepare a student for further academic study in a related field, a program should focus on standard applied mathematics and incorporate significant coursework in an ESCS field of interest. We recommend that ESCS-focused math programs include, along with standard beginning mathematics major material, at least four applied courses such as mathematical modeling, numerical analysis, operations research, ordinary differential equations, partial differential equations, statistics, and probability.

Foundational courses

In this section we discuss several courses that are taught at many institutions and support the study of ESCS topics.

Mathematical Modeling

Mathematical modeling is the process of building a mathematical representation of reality to answer open-ended questions, make predictions, or simulate real-world phenomena. Modeling is the foundation of any applied mathematics program and a critical link between mathematics and ESCS. This PASG recommends a modeling course that allows students both to explore (i.e., understand and apply) existing ESCS models and to build new models to investigate relevant questions.

A modeling course should both build sufficient technical breadth and explore real-world problems motivated by ESCS issues. Air quality, for instance, is a broad topic that can be addressed differently depending on a university's location and nearby resources. Obtaining actual samples or previously logged information (often publicly available) is one feasible method of incorporating real data. This single application can involve simple exponential decay models, systems of differential equations, and numerical methods. Studying roles of invasive species in population dynamics involves similar mathematical depth and breadth, and allows students to learn more about their own region. Modeling courses in general offer great opportunities to compare and contrast different approaches and to introduce students to new (or new uses for) mathematical tools. Some common investigations include linear vs. nonlinear functions, time dependent vs. steady state differential equations, analytic vs. data-driven solutions, deterministic vs. random searches, and exponential vs. polynomial behavior.

Modeling courses should offer a full "start to finish" modeling experience: students should develop a model from "scratch", incorporate real-world data, validate and analyze results, and then refine the model. There is no shortage of ESCS issues to study. Predicting the movement of a contaminant in a stream or aquifer, analyzing and fitting data to predict species evolution (e.g., algae in a lake), and optimizing farming practices under uncertain weather conditions are just a few examples. Regardless of the subject, students should submit a modeling project as a written or oral report.

Data Analysis, Statistics, and Probability

Students seeking careers in ESCS will need to make sound decisions using available data. A basic course in statistics, including introductory probability theory, is essential; ESCS data sets can range from the immense (collections from sensors, satellites, or social media) to the tiny (biological sampling from remote field locations). A second course in statistics that includes exploratory statistics, non-parametric statistics, and ANOVA is strongly recommended. With an emerging emphasis on big data and uncertainty quantification, exposure to data visualization, data management, advanced inference tools, and a range of software tools (SAS, R, …) would be beneficial. Where a mathematics department lacks resources to offer these courses, business schools or engineering programs may do so.

Numerical Analysis and Operations Research

Motivated by the notion that current models used in the field of ESCS may not be solvable analytically or the fact that they are data-driven (thus emphasizing the need for the previously listed courses), a course in numerical analysis or operations research can be a powerful tool for students to seek solutions to a broad range of ESCS problems.

A course in numerical analysis offers students a theoretical understanding of numerical methods, experience using software to implement numerical methods, and the ability to choose numerical methods appropriate to particular applications. For example, groundwater flow through unsaturated porous media can be modeled with the so-called Richards equation. For some realistic soil parameters this parabolic partial differential equation can be highly nonlinear and non-smooth, requiring smoothing splines, nonlinear solvers, and implicit time stepping—all techniques that might appear in a numerical analysis course and used beyond the classroom to tackle environmental modeling problems.

Operations research (OR) is another subject that can introduce students to a variety of decision-making methods for studying complex systems encountered in ESCS. For example, companies planning investment in cleaner energy production need to consider resource limitations, energy needs, and EPA regulations in order to choose cost-effective technologies. Constrained optimization problems like this one can be studied using linear and nonlinear programming techniques. A focus on resource management highlighting ESCS-related problems can fit smoothly into common beginning OR courses, which often emphasize linear programming. Including multicriteria decision analysis methods in OR courses gives students powerful tools "to evaluate or assess the trade-offs between alternatives" in ESCS topics, as Seitelman recommends in [7]. Stochastic processes such as Markov chains can also be introduced in OR courses and applied to population biology. Doing so can extend the scope of OR courses beyond traditional applications to business management.

Computational needs of students in either course, even those with minimal programming background, can be supported through user-friendly computational software such as MATLAB, *Mathematica*, Maple, or SAGE.

Computer programming

Although most of the courses listed above will have strong programming components, the special value of courses that focus on programming-based problem solving is worth noting. Regardless of the programming language chosen, introductory programming courses provide a basic understanding of fundamental programming ideas. More advanced applied mathematics courses that require programming in MATLAB, Maple, *Mathematica*, etc., can build on students' prior programming experience, focusing instead on learning new syntax and advanced applications.

Programs in ESCS

Course offerings and degree programs in ESCS vary greatly at institutions across the country. The range of options for students is limited only by resources available at a given institution. Ideally, a student will pursue an area of interest by taking courses on the scale of a minor in an ESCS subdiscipline. For example, a student might choose among geology, hydrology, and atmospheric science tracks. We outline a general course plan in what follows.

- *Introductory course.* As soon as a mathematics student becomes interested in an ESCS field, he or she should take an introductory course, which may also satisfy general education requirements.

- *ESCS subdiscipline focus.* In ESCS programs that identify a subdiscipline, students may need to plan a sequence of courses with the help of an advisor from the affiliated department in order to gain appropriate depth.

- *Field course experience.* It is valuable to learn where “real-world” data comes from and the methods required to obtain it. Doing so can guide appropriate uses of data and speak to the reliability of results.

- *Quantitative course outside the mathematics department.* Many ESCS programs offer “in-house” quantitative courses that focus on methods, techniques, and even software specific to a certain discipline. It is valuable to experience first-hand how practitioners use and perceive mathematical and statistical methods. Possible courses include Geographic Information Systems, Applied Geostatistics, and Ecology.

- *Technical communication experience.* As a multidisciplinary field, ESCS requires people with strong communication skills. Mathematics specialists must communicate their work clearly and concisely, to audiences both with and without ESCS expertise. Technical communication experience is often an essential component of a course or a requirement for completion of a degree program. At some institutions technical communication courses satisfy a general education requirement.

- *Internship.* Internships, common within science, technology, and engineering fields, offer students real work experience in their areas of specialization, and sometimes lead to job offers. Internship opportunities are less common for advanced mathematics majors, but should be pursued if possible, particularly for students interested in non-academic careers in ESCS fields. Many colleges and universities have internship offices or coordinators. Because internships for math majors with ECSC specialization are less common, mathematics departments interested in arranging local internships will need to work both with internship offices and with prospective internship sites to identify specific skills and background employers seek and to discuss mutually beneficial job opportunities.

- *Capstone/senior project.* These projects, required for graduation at many institutions, allow students to collaborate on research across disciplines.   Doing so should be encouraged.

Overview of academic program

Undergraduates earning a math degree with an ESCS specialization should obtain the content knowledge and experience necessary to develop environmental intuition that supports meaningful real-world problem solving. Mathematical knowledge is crucial, but so are depth in an outside area and communication skills. Students who complete study in an ESCS specialization will be well positioned to begin graduate work in applied mathematics programs, environmental engineering programs, and in ESCS programs related to their chosen subdisciplines. A student with such a degree should also be equipped to enter the job market in various entry- to intermediate-level ESCS-related fields. The specific nature of future employment will depend, of course, on the structure and depth of the student's specific program.

Implementation

The first step towards development of an ESCS specialization in a department is to identify courses and resources available at the institution. A department that offers a good variety of applied math courses will likely be able to meet the ESCS needs and interests of students on its campus.

Creating a new program specialization requires more than designing a plan of study. Following are some ideas and suggestions.

- *Introduce ESCS themes to your department.* One way to highlight the applicability and practicality of ESCS to students and colleagues is to invite a practitioner to speak at a department seminar.

- *Incorporate ESCS topics into existing courses.* Many ideas and resources are available. For example, the November 2013 issue of *College Mathematics Journal* focused on the Mathematics of Planet Earth. Recent JMM sessions, such as Undergraduate Sustainability Experiences in Mathematics at JMM 2015, have been devoted to ESCS.

- *Identify related departments and start a discussion.* In addition to inviting colleagues to help developing your program, consider asking questions like these: How do you incorporate mathematics into your degree programs? What constitutes a minor in your discipline? What courses can non-majors take?

- *Engage administrators.* Developing a specialization may require additional resources to fully develop your specialization; support from your college or university school can help.

References

1. National Aeronautics and Space Administration. "Global Climate Change: Vital Signs of the Planet".
2. Vincent, S., S. Bunn and S. Stevenson, "Sustainability Education: Results from 2012 Census of U.S. Four Year College and Universities", National Council for Science and the Environment, January 2013.
3. Lepisto, M., "Growth field: Environmental studies a 'college major with a future'", September, 2012.
4. Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook, 2014-15 Edition, Environmental Scientists and Specialists .
5. "Schools Offering Degree Programs in Environmental Engineering".
6. Fenichel, E., "[F&ES 762a] Applied Math for Environmental Studies", Yale School of Forestry & Environmental Studies website.
7. Fusaro, B. et al. (1992) "Environmental Mathematics". In Steen, L. A. (Ed.), "Heeding the Call for Change: Suggestions for Curricular Action", (pp. 83-92) MAA.

Resources

Books and textbooks

Drake, J. B., *Climate Modeling for Scientists and Engineers*, SIAM 2014.

Fusaro, B.A., *Environmental Mathematics via the Visual, Qualitative & Computational*, Online textbook.

Fusaro, B. A. and P. C. Kenschaft (eds.), *Environmental Mathematics in the Classroom*, MAA 2003.

Hadlock, C. R., *Mathematical Modeling in the Environment*, MAA 1998.

Hadlock, C. R., *Six Sources of Collapse*, MAA 2012.

Kaper, H. G. and H. Engler, *Mathematics and Climate*, SIAM 2013.

Kaper, H. G. and C. Rousseau, *Mathematics of Planet Earth*, SIAM 2015.

MacKay, D. JC., *Sustainable Energy – without the hot air*, UIT Cambridge 2009. Full text is available online for download.

Slingerland, R. and L. Kump, *Mathematical Modeling of Earth's Dynamical Systems: A Primer*, Princeton University Press 2011.

Walter, M., *Mathematics for the Environment*, CRC Press 2011.

Reports

Levin, S. A., and W. C. Clark, (eds.), *Toward a Science of Sustainability: Report from the NSF toward a Science of Sustainability Conference*, 2009.

Rehmeyer, J. *Mathematical and Statistical Challenges for Sustainability*, 2011.

Other resources

The listed websites contain links to ESCS-focused mathematics resources including data, articles, and information about relevant activities and events. Some websites contain links to developed ESCS curricular materials.

MAA Special Interest Group on Environmental Mathematics (SIGMAA EM)

Mathematics and Climate Research Network (MCRN)

Mathematics of Planet Earth (MPE)

Maths of Planet Earth (Australia)

NASA's Sustainability Portal

National Renewable Energy Laboratory (NREL)

The Science Education Resource Center (SERC) at Carleton College (SERC Sustainability Site Guide)

SIAM Activity Group on Mathematics of Planet Earth (SIAG/MPE)

Sample degree programs

Examples of existing Mathematics and Environmental Science and Climate Studies related B.S. degree programs

Lancaster University (England) Environmental Mathematics, program website.

St. Lawrence University, Environmental Studies – Mathematics Combined Major, program website.

University of California at Los Angeles, Mathematics/Atmospheric & Oceanic Sciences, program website.

University of Exeter (England), Mathematics and the Environment (B.S.), program website.