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Article

Interdisciplinary Training in Mathematical Biology through Team-based Undergraduate Research and Courses

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Inspired by *BIO2010* and leveraging institutional and external funding, Truman State University built an undergraduate program in mathematical biology with high-quality, faculty-mentored interdisciplinary research experiences at its core. These experiences taught faculty and students to bridge the epistemological gap between the mathematical and life sciences. Together they created the infrastructure that currently supports several interdisciplinary courses, an innovative minor degree, and long-term interdepartmental research collaborations. This article describes how the program was built with support from the National Science Foundation's Interdisciplinary Training for Undergraduates in Biology and Mathematics program, and it shares lessons learned that will help other undergraduate institutions build their own program.

INTRODUCTION

In 2002, a group of faculty and students from the mathematical and life sciences at Truman State University began working together in a way that would transform them, many of their colleagues and classmates, and the university. With support from the National Science Foundation's (NSF) Interdisciplinary Training for Undergraduates in Biology and Mathematics (UBM) program, their collaborative work has broadened to include 24 faculty from mathematics, biology, statistics, and computer science and more than 60 undergraduate research collaborators. Even more students were affected through new interdisciplinary courses that bridged the mathematical and life sciences and were designed to support what would become Missouri's only genuine undergraduate degree-granting program in mathematical biology. This successful program is an expression of a passion for the ideas articulated in *BIO2010* (National Research Council [NRC], 2003) and for the desire to supply the nation with scientists and mathematicians trained to work in the twenty-first century. This article describes our program and its strategies in ways the authors hope suggest how other colleges and universities can strengthen their efforts to prepare undergraduates to learn and work in an interdisciplinary manner.

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PROGRAM DEVELOPMENT

Truman is a medium-sized (approx. 5800 students) university in rural Kirksville, MO. As a primarily undergraduate institution, its commitment to be affordable attracts many first-generation college students as well as many students who qualify for need-based financial aid. As Missouri's only highly-selective public, liberal arts, and sciences university, Truman draws creative and ambitious students to the school. Its combination of talented students, a liberal arts culture that values interdisciplinary thinking and learning, and a long institutional history of providing high-quality, faculty-mentored undergraduate research experiences make for fertile soil in which to grow the undergraduate mathematical biology initiative described below.

Before 2000, there was little interaction between the Biology Department and the Mathematics and Computer Science Department. One or two mathematics faculty had collaborated at some point with one or two biology faculty, but it was not something that was talked about or celebrated. The mathematics degree and the computer science degree both required students to take at least one science course, but neither major allowed any biology courses to fulfill that requirement. If there was any lab science that the mathematical scientists cared about it was physics. The biology degree required students to take a traditional five-credit engineering calculus course and a basic statistics course, but the biology curriculum made few connections to mathematics. Like their curriculum, the biology faculty had little interest in the mathematics beyond statistics. Aside from the ecologists, many biology faculty avoided mathematics when possible and felt unprepared to talk about it with students in research or in the classroom. In many ways, this situation was typical of biology and mathematics departments at other colleges and universities in America.

In 2001, one author (J.E.M) joined a mammalogist's research group to assist in his effort to determine how ultrasonic recordings of a bat's call might be used to identify the species of the bat. The team included undergraduates majoring in biology and others majoring in mathematics. The biology students acquired recordings of calls through field work and the mathematics students worked in the computer lab, filtering the recordings with wavelets and looking for patterns. Periodically, the entire team would discuss what we were learning and ask questions. Those conversations challenged everyone. Through them, we were each learning a new disciplinary language and teaching our disciplinary language to our teammates.

This experience prepared J.E.M, his collaborator, and some other close colleagues to understand the importance of the message of the NRC report *BIO2010* (2003). In 2003, the NSF solicited proposals for a trial of its UBM program. In response, Truman assembled a group of faculty to submit a proposal to build infrastructure for a long-term interdisciplinary program in mathematical biology using year-long interdisciplinary undergraduate research projects mentored by cross-disciplinary pairs of faculty. Funding from the NSF UBM program has led to the program we describe below.

PROGRAM DESCRIPTION

At the heart of Truman's mathematical biology program are our undergraduate research projects that are locally and grant-funded. Projects sponsored by our program each year concern a range of mathematical concepts and biological scales. In addition to the project already mentioned, our program sponsored projects that:

- Used image analytical tools and algebraic graph theory to measure features in vascular networks of endothelial cells;
- Created a Glazier-Granier-Hogeweg model of the four-cell stage of *Caenorhabditis elegans* to understand how intercellular forces cause changes in the embryo shape and how shape relates to genetic factors;
- Developed a metapopulation model for dispersion of the Missouri bladderpod that uses geographical information system data acquired through field work and relies on a Leslie matrix model on a graph that represents patches in the field site;
- Used field data and the scientific literature to design agent-based models of snake metabolism and foraging behavior;
- Designed a computational method, based on measurements of fossil specimens and experimentation with extant species, for predicting flight dynamics of extinct species of pollen;
- Investigated mechanisms of plastron respiration in ticks using mathematical inference, electron microscopy, and the Advanced Proton Source at Argonne National Labs;
- Studied the effects on the population structure of predatory beetles of burning habitat using field work and spatial modeling;
- Investigated gravitropic sensitivity in seedling roots using lab experiments, digital image analysis, and image processing;
- Through field work and statistical analysis, developed new statistics for phylogenetic community ecology that takes into account the local and regional abundance of species in the phylogeny;
- Studied data on and simulations of mutations of the HIV virus to refine the Tajima D statistic (which measures evolutionary trends of genetic data) into a related statistic that is sensitive to the source of evolutionary change; and
- Created a system for both visualizing functionality in the genome of maize's shoot apical meristem and for automatic gene annotation from microarray data using Bayesian statistics and neural networks.

Each supported project grew out of the active research program of one of Truman's biologists, and this continues to be the way we choose research projects for our interdisciplinary training program.

Each participating biologist leads an interdisciplinary team to leverage mathematical and computational skills against one of their own research questions. Their project team is an interdisciplinary quartet of two faculty, the biologist and a mathematical scientist (a mathematician, statistician, or computer scientist), and a similar pair of undergraduates. They work together to craft new research approaches that integrate as much time modeling and theorizing as in the field or at the bench. Together, the team prepares a research plan that includes the students in the overall design of the investigation. This planning results in a written research proposal that includes a literature review, detailed description of experiments, and a discussion of the work's importance.

Undergraduate researchers are selected for the program through a competitive application process. All available projects for a program year are described on the program's Web portal for students to read. After visiting with some or all of the project mentors, students submit an online application that includes their preference ranking of the available projects. The mentors then convene to select the students for their teams. By honoring each student's rank-ordering of projects, selection is usually easy. However, recruiting qualified students to apply to the program is sometimes a challenge. It is the mentors' responsibility to advertise their projects to students they feel could be qualified collaborators. The grant principal investigator (PI) team also make efforts to more widely publicize the program when applications are being taken. They use the program's Web portal, a program e-mail listserv, departmental listservs, posters, and in-class announcements. Since 2004, approximately 135 students have applied to participate in the program and 60 have been accepted into the program.

The program targets high-ability rising juniors, and it has developed a reputation for being very highly selective. The strongest candidates for the program already have prior research experience. Prerequisites for participation vary by student major. A biology major should have completed a course in calculus and at least a basic statistics course. A mathematics major should have completed at least one college-level biology course. In addition to these program expectations, the online application lists project-specific prerequisite skills. Student attitude is weighed heavily in the selection process. A student with weak academic credentials but a strong work ethic and an eagerness for immersion in an interdisciplinary experience will often be a much stronger candidate than a student with a high grade point average and a simmering sense of entitlement.

The official program engages students and their mentors for a calendar year, from January to December. Students begin the experience in the Spring semester, reading relevant scientific literature with their team to understand the central question to be investigated, planning experiments and data analysis, and writing up a research proposal. The program structure puts each person's research team at the center of his/her experience, emphasizing the importance of producing and sharing results. To create a sense of community for the program cohort, a biweekly Mathematical Biology seminar brings all participants together for a colloquium lecture and a chance to interact over refreshments. By the end of the semester, each team has completed its formal research proposal, which it submits to the program, and each individual has developed a connection to the other participants and the program's goals.

Students and mentors return to campus in the summer for a 10-wk immersive experience. During this time, they live together in a campus residence hall. This living arrangement fosters social interaction, allows students to immerse themselves in their project, and leads to a shared enthusiasm for and intensity toward their research projects. Weekly program meetings for mentors and students give students a venue for informal updates on progress and challenges. Over time attending these meetings, one can watch student growth—from being frustrated by research and by working across disciplinary boundaries—to being confident in their expertise and their interdisciplinary abilities.

At the end of the summer, all students and mentors travel to an external venue to give an end-of-summer symposium. In the past two years, team presentations were given at the University of Missouri's Christopher S. Bond Life Science Center and the Donald Danforth Plant Science Center in St. Louis, MO. Public presentations motivate students to do their best work and give the program managers a chance to make connections with external stakeholders. Invitations to the presentations are sent to participants' families, past participants, graduate program directors, and other faculty from regional universities (e.g., University of Missouri, Washington University), and professionals from important industries (e.g., Monsanto, Pfizer). Their presence at our presentation raises Truman's regional profile, creates demand for our program's graduates, and helps us gather programmatic feedback.

During their last semester, each team carries out follow-up activities such as data analysis, follow-up experiments, model analysis, and prepares a manuscript for peer-reviewed publication. The Mathematical Biology seminar continues to be a gathering time for participants, and some teams use it to give presentations of their work to the Truman community. This serves to advertise the program to new students and potential mentors. Each year, many of the undergraduates continue follow-up work through the following spring as new undergraduates are brought on to their mentors' project. By overlapping new and veteran students, the faculty mentors can take advantage of the veterans as peer mentors to start training the new students. Some students will actually apply to participate in the program for a second year. Allowing this has the disadvantage of limiting the overall number of students who benefit from the training program, but allowing extended involvement in a project boosts a team's research productivity significantly. This benefits the students, the faculty mentors, the program, and the university.

DISCUSSION

Our mathematical biology program is atypical. We tell program participants (faculty and students) that our program is not designed to turn mathematics majors into biology majors or to turn biology majors into mathematics majors; rather, our program leads to a deep appreciation and understanding of what the complementary field brings to the table and how to communicate with individuals in that field in research and work. In this way, preparation for interdisciplinary graduate study and a career at the intersection of the life and mathematical sciences is a goal that we articulate to all participants in the program. We build on solid and deep content-area expertise to train students to work at the intersection of the mathematical and life sciences. Our aim is to prepare undergraduates (and faculty members) to be scientists and mathematicians for the twenty-first century.

This appears to be working based on the remarkable productivity of the program. At last count, faculty and students have published eight papers in peer-reviewed journals (Schwendemann *et al*., 2007; Beck *et al*., 2007; Buckner *et al*., 2007; Zhang *et al*., 2007; Ohtsu *et al*., 2007; Adams, 2008; Vollmer and Adams, 2008; Young *et al*., 2008;) with several others having been recently submitted; undergraduates have given 34 poster presentations and 41 oral presentations at regional, national, and international professional conferences; faculty have given presentations at nine national and international conferences; and three teams have secured additional external funding for projects that were piloted in our program.

Undergraduate participants have gone in a variety of directions after graduating from Truman. At last count, of the 25 program participants who have graduated, 12 are pursuing Ph.D.s in the life or mathematical sciences, one is in medical school, three have become secondary science teachers, and five went directly to industry. Five of the Ph.D. students are in highly interdisciplinary programs, and several of the others are pursuing topics that take advantage of their undergraduate training. Several of these students report that their interdisciplinary research experience played an important role in their being selected for their graduate program. They also say it has put them at an advantage as a graduate student. Three of the students who went directly to industry are working in the biotechnology sector where they (and their supervisors) report that their training has a direct and positive impact on their work.

Selecting students for the program in a way that accounts for their attitude also serves Truman's commitment to broadening participation in science and mathematics. Through prior and continuing efforts to recruit to and retain more women in computer science, we have learned that for computer science to become an attractive major to women, it helps if it is presented less like a field for 'code monkeys' and more like the field that it is: one that has great potential to effect social change, solve problems, and lead to careers that have significant social interaction (AAUW Educational Foundation, 2000; Carter, 2006). We have also learned that the same lessons can be applied to recruiting and retaining individuals from historically underrepresented groups in science, technology, engineering, and mathematics (STEM) to biology and mathematics (Beck *et al*., 2007). High-quality, faculty-mentored undergraduate research, with its one-on-one interactions, is an ideal tool for increasing diversity in these fields (Beck *et al*., 2007; Nagda *et al*., 1998; Seymour *et al*., 2003). Mathematical biology is a wonderful vehicle for making mathematics relevant for all students in our program and for making them feel like they are contributing to the search for solutions to capacious social issues. For example, years ago we had an applicant for the program whose grades were plummeting as he was visualizing himself bound for a career as the manager of the local Taco Bell. However, something about a bioinformatics project caught his interest. The project's mentors knew him from a past course and took a chance on him. He excelled in research with us, and his course work improved in parallel. When he applied for graduate programs, several schools were highly interested in him, and he is now pursuing a Ph.D. in computational biology at Carnegie Mellon University. Other students in our program can tell similar stories of finally finding a passion for science and/or mathematics through the program. Through an NSF STEP (STEM Talent Expansion Program)-funded project at Truman, we have also leveraged our interdisciplinary projects to create research opportunities to help younger students experience the exciting and rewarding nature of science and mathematics even earlier in their career. Students are attracted to integrative, team-oriented research projects that have clear connections to the real world.

Putting research experiences at the core of our program gave the original project some strategic advantages. First, because undergraduate research activity is a core value of our institution, it had broad support of faculty and administration. By attracting the best and brightest undergraduate students to our program, we also attracted faculty who wanted these students as their undergraduate researchers. Second, a traditional course-based program in mathematical biology would have faced bureaucratic obstacles (e.g., faculty governance approval of new courses), philosophical obstacles (e.g., debates over topics to be covered in courses and programs), and financial obstacles (e.g., the cost of offering courses with the required frequency). The ability of such obstacles to kill faculty enthusiasm for an innovative idea cannot be overestimated, so we chose to work outside the curricular system. By establishing a reputation for high quality and productivity, faculty alliances, and earning administrative support, these obstacles have been significantly reduced.

Initially, the biologists generally view the added collaborators as something of a training burden, but most have a good attitude about it and are motivated by working with talented students and the prospect of gaining new insights into questions that are deeply interesting to them. The experiences tend to cause a paradigm shift for many traditionally trained experimentalists who now declare that the interdisciplinary experience transformed the way they plan and carry out research that occurs independently of our UBM program.

The effect on mathematicians is more subtle. Early on, our program was able to attract several mathematicians who were in the early stages of their career. They were drawn by the combined forces of the value placed by Truman on undergraduate research, the grant-funded opportunity to do interdisciplinary work in an area of great national interest, and the desire to become part of a scholarly community with some shared interests. Many of the mathematics faculty learned new mathematics to support the work of their biology colleagues, while others gravitated toward projects to which they could apply their highly specialized knowledge. All of them learned that biology is a 'messy' and beautiful science with an abundance of mathematical opportunities. All are more active in scholarship and research. Some even discovered interesting mathematical questions from the biology.

There certainly are challenges as individuals from each discipline start learning the language of the other. For example, a "cell" in a biological system can mean a very different thing than a "cell" in a mathematical model. Regular team meetings to discuss the progress and direction of the project helped clarify many of these challenges. At least one team has used concept mapping (Novak and Canas, 2008) to overcome the challenge of epistemological and language differences between teammates. By having teammates from each discipline make a map of the concepts germane to the research project, and then by working together to unite those into a single map, the teams develop a common language for their collaboration. At a larger scale, the program requires all participants from all teams to participate in weekly program meetings at which participants share their solutions to research- and training-related challenges.

Our plan for sustaining the program relies on developing connections to the curriculum. Our original proposal to the NSF included the development of four new interdisciplinary courses, which allowed us to broaden the impact of our interdisciplinary work. We developed sophomore-level courses in Bioinformatics, Mathematical Biology, Biostatistics, and Scientific Computing. The latter two courses were created and offered twice each, after which the biology and computer science faculty, respectively, modified existing courses in ways that made these two new courses unnecessary. The two other courses, Bioinformatics and Mathematical Biology, fill nearly to capacity when offered and receive overwhelmingly positive feedback from students. Two faculty, one from computer science and one from biology, alternate the responsibility to teach bioinformatics each year. The Mathematical Biology course is a module-based course that is team-taught by a cross-disciplinary pair of faculty. The instructors model each discipline's mode of inquiry and help students learn to work as part of an interdisciplinary team.

Both courses are taught in ways that require students to collaborate across disciplines. Early in the semester, biology students are concerned because they feel deficient in computer programming as compared with their mathematics peers, and mathematics students often feel overwhelmed by the degree of biological information that is presented. However, by the end of the semester, most students learn how to work as part of an interdisciplinary team that builds on the strengths of each team member.

We have taken the curricular aspect of our program beyond simply offering courses by creating an interdisciplinary minor in mathematical biology. The minor differs from a typical minor. Instead of being course-based, our minor is based on outcomes and uses a portfolio-based system that requires students to provide evidence of their proficiency in each of the following areas:

- Data acquisition: acquiring data on biological phenomena in a lab, in the field, or both;
- Modeling: developing or applying mathematical models in a biological context;
- Computation: developing or applying computational tools in a biological context;
- Statistical analysis: applying statistical testing of biological hypotheses; and
- Research: investigating an open-ended question by conducting research at the intersection of the life and mathematical sciences.

Successful completion of certain courses are also recognized ways of meeting some proficiency requirements. A student earns the minor after taking our introduction to mathematical biology course plus 15 credits of course work that will generate material for his/her minor portfolio. This minor allows us to certify on students' transcripts that they are prepared to be a scientist or mathematician in the twenty-first century. This certification, in turn, motivates students to seek and take our interdisciplinary courses. In its first year three students earned the minor, and two more are currently on track to earn it.

It has taken a while, but efforts to move the science and mathematics communities at Truman in the direction pointed by *BIO2010* (NRC, 2003) appear to be working. Our mathematical biology program has changed the way faculty look at the relationship between the mathematical and life sciences on our campus. The computer science degree now allows a majors-level biology course to count toward its science requirement. While the mathematics department has not yet made the analogous change, it has modified its degree requirements to allow students to count credit earned through our new courses and mathematical biology research toward their degree. Biology faculty have pursued ways to highlight mathematical contributions to biological study, especially in core major-level courses. Last year, 114 of 394 students in the major-level introductory biology course (BIOL 107) created and analyzed a mathematical model on enzymatic activity before conducting a wet-lab experiment examining enzymatic function. The mathematical biology program has also changed the way faculty conduct research. In the Mathematics and Computer Science Department, the mathematical biology program has helped more faculty engage in scholarship and made their work more visible to colleagues, students, and administration. Several senior biology faculty members have proclaimed that their involvement in this program has fundamentally changed the type of research questions they ask, and they recognize computation and modeling as instrumental to their research. The biology department promotes this program to job candidates, and several new hires have pointed to the program as one of the reasons they chose to join the Truman faculty and now have active research projects in the program, including author T.W. Once on campus, these faculty members sought out the directors of the program to discuss possible applications of their research to the program.

Program faculty members have used their interest in mathematical biology (and interdisciplinary STEM) education to make connections with colleagues at other institutions through regional and national workshops. Mathematicians, biologists, statisticians, and computer scientists have participated in workshops on interdisciplinary teaching and learning like those provided through the BioQuest Curriculum Consortium, Park City Mathematics Institute, the Mathematical Association of America's (MAA) Professional Enhancement Program, the Institute for Mathematical Biology Education and Resources, the Mathematical Biosciences Institute, the National Institute for Mathematical and Biological Synthesis, and the Howard Hughes Medical Institute (HHMI). These professional connections are a source of curricular and research ideas that enriched our work. The connections also allow us to participate in the national effort to transform undergraduate science education to be more integrative. Several program faculty (including the authors), through involvement in professional organizations such as the MAA's Special Interest Group for Mathematical and Computational Biology and the Society for Mathematical Biology's Education Committee, have taken an active role in helping to broaden institutional participation in efforts to connect their mathematics and biology curricula at the early-undergraduate level.

In conclusion, we outline several steps that we believe were instrumental in the development of the Mathematical Biology Program at Truman. While the grassroots of the program involved the joint efforts of few faculty members, it has now grown to have broad support of the faculty of the departments involved and the administration of the university. By building on the undergraduate research resources that were already in place in the university, the program developed a reputation as a venue for some of the best students to pursue research opportunities. It also provided a means to develop interdisciplinary teams of researchers, created opportunities for curricular and scholarly conversations between faculty in the two departments, and supported faculty development using topics of greatest interest to faculty (i.e., their own research interests). Developing a cadre of faculty and administrators who were supportive of the research efforts reduced potential barriers to further development of the program, including interdisciplinary courses and the portfolio-based minor in mathematical biology. Having external funding gave faculty and students the time and resources that were necessary for professional and curricular retooling. Our experience affirms *BIO2010*'s (NRC, 2003) assertion that curriculum redesign requires time and human resources. The successes of our mathematical biology program have drawn serious interest from faculty in other STEM disciplines, so we are optimistic that we will have the opportunity to put into place broader interdisciplinary changes as called for in *BIO2010*.

We still have a tremendous amount of work before us if we really hope to integrate the mathematical and life sciences in the undergraduate curriculum. As our undergraduate minor program grows, we anticipate being able to attract more highly qualified students to the research projects. And if we hope to truly affect change in the undergraduate training of scientists and mathematicians, we will do for entry-level majors' courses in biology and mathematics what we've been able to do for research experiences. A recent NSF Proactive Recruitment in Introductory Science and Mathematics (PRISM) grant will support this effort, as will a curriculum development facet of our recent UBM award. Those resources, along with the dedication of a large group of faculty and interested students, will allow us to continue to build our undergraduate program in mathematical biology and extend that model to other integrative STEM efforts.

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More information about Truman State University's Mathematical Biology Program can be found at http://mathbio.truman.edu. Information about the portfolio-based minor can be found at http://mathbio.truman.edu/minor.

REFERENCES

AAUW Educational Foundation: Commission on Technology, Gender, and Teacher Education. (2000). Tech-savvy: educating girls in the new computer age. www.aauw.org/research/girls_education/techsavvy.cfm (accessed 20 November 2006).

Adams, M. J. (2008). Graph decompositions for demographic loop analysis. J. Math. Biol. *57*, 209–221.

Beck, J., Buckner, B., Nikolova, O., and Janick-Buckner, D. (2007). Using interdisciplinary bioinformatics undergraduate research to recruit and retain computer science students." ACM SIGCSE Bull. *39*, 358–361.

Buckner, B., Beck, J., Browning, K., Fritz, A., Grantham, L., Hoxha, E., Kamvar, Z., Lough, A., Nikolova, O., Schnable, P. S., Scanlon, M. J., and Janick-Buckner, D. (2007). Involving undergraduates in the annotation and analysis of global gene expression studies: creation of a maize shoot apical meristem expression database. Genetics *176*, 741–747.

Carter, L. (2006). Why students with an apparent aptitude for computer science don't choose to major in computer science. ACM SIGCSE Bull. *38*, 27–31.

Nagda, B. A., Gregerman, S. R., Jonides, J., von Hippel, W., and Lerner, J. S. (1998). Undergraduate student-faculty research partnerships affect student retention. Rev. Higher Educ. *22*, 55–72.

National Research Council (2003). BIO 2010: Transforming Undergraduate Education for Future Research Biologists, Washington, DC: National Academies Press.

Novak, J. D., and Canas, A. J. (2008). The Theory Underlying Concept Maps and How to Construct Them. Pensacola, FL: Florida Institute for Human and Machine Cognition. Technical report #2006-01 Rev 01-2008.

Ohtsu, K., Smith, M., Emrich, S., Borsuk, L. A., Zhou, R., Chen, T., Zhang, X., Timmermans, M. C. P., Beck, J., Buckner, B., Janick-Buckner, D., Nettleton, D., Scanlon, M. J., and Schnable, P. S. (2007). Global gene expression analysis of the shoot apical meristem of maize (*Zea mays* L.). Plant J. *52*, 391–404.

Schwendemann, A. B., Wang, G., Mertz, M. L., McWilliams, R. T., Thatcher, S. L., and Osborn, J. M. (2007). Aerodynamics of saccate pollen and its implications for wind pollination. Am. J. Botany *94*, 1371–1381.

Seymour, E., Hunter, A., Laursen, S., and DeAntoni, T. (2003). Establishing the benefits of research experiences for undergraduates: first findings from a three-year study. Sci. Educ. *88*, 493–534.

Vollmer, J., and Adams, M. J. (2008). DLA.GUI code for Matlab. www2.truman.edu/~mjadams/loopanalysis.htm (accessed 20 March 2010).

Young, C., Morrison, L., Kelrick, M., and DeBacker, M. (2008). Monitoring *Lesquerella filitormis Rollings* (Missouri bladderpod): application and evaluation of a grid-based survey approach. Natural Areas J. *24*, 370–378.

Zhang, X., Medi, S., Borsuk, L., Nettleton, D., Buckner, B., Janick-Buckner, D., Beck, J., and Scanlon, M. (2007). Laser microdissection of narrow sheath mutant maize uncovers novel gene expression in the shoot apical meristem. PLoS Genet. *3*, e101.