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Integrating authentic geoscience research into K–12 education via measurement of microbial extracellular enzymes in natural waters: A case report of two initiatives

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ABSTRACT

Participation in authentic scientific research has been shown to greatly benefit undergraduate students, both in terms of perception of science and knowledge of scientific concepts. We define authentic scientific research as projects in which results

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are unknown prior to performing experiments and are appropriate for presentation in peer-reviewed scientific journals and/or scientific conferences. Kindergarten through grade 12 (K–12) students have less frequent opportunities to participate in authentic research than university students, and the effects of research participation on such students are less well understood. From 2013 to the present, we organized two collaborations with different groups of K–12 students and teachers, each aimed at engaging K–12 students in authentic geoscience research, with a focus on K–12 students from excluded backgrounds who may have had restricted access to resources. First, the Malcolm X Shabazz Aquatic Geochemistry Team was an initiative to involve high school students at Malcolm X Shabazz High School in Newark, New Jersey, USA, in research focused on the activities of microbial communities inhabiting streams and rivers in New Jersey and eastern Pennsylvania. Second, the Integrating Continuous Experiential Activities for Geoscience Education (ICE-AGE) project is a Pathways into the Earth, Ocean, Polar and Atmospheric & Geospace Sciences (GEOPAths) project funded by the National Science Foundation that involves K–12 students in experiential learning through diverse means, including involving middle school students taking part in a summer program pseudonymously referred to as the Liberation Literacy Program (LLP) in geoscience research on a number of topics. Here, we report qualitative observations of the successes and challenges of these programs, as well as lessons learned, which may be useful for other researchers seeking to involve groups of K–12 students in authentic geoscience research education.

INTRODUCTION: VALUE OF AUTHENTIC SCIENTIFIC RESEARCH FOR K–12 STUDENTS

Authentic Science Research for K–12 Students

The early engagement of kindergarten through grade 12 (K–12) students from populations that have historically been excluded, e.g., due to race, gender, or disability, in geoscience programs has been identified as a priority by the National Science Foundation (NSF). This priority is clearly stated in the mission of NSF's Directorate for Geosciences, which includes training a diverse and inclusive geosciences workforce as one of three areas of focus (U.S. National Science Foundation, 2024). Such early engagement in authentic research experiences would help to increase the number of students pursuing geoscience degrees. Currently, Virginia, Kentucky, Kansas, and Nebraska are the only U.S. states that require an earth and space science course for high school graduation; in other locations, students may receive little explicit instruction in geoscience (Petcovic et al., 2021). To reach the goal of increasing recruitment and retention of diverse student populations in geoscience programs, especially in states where exposure to geoscience prior to college is minimal, novel and innovative approaches must be developed that simultaneously generate initial interest in the geosciences and retain students through college. Such approaches include significant practical experiences such as performing original research and demonstrating novelty relative to published literature that are both authentic and relevant to a career in the geosciences, and that have been demonstrated to improve recruitment and retention (Dahlberg et al., 2008; Thiry et al., 2012).

Black, Indigenous, and people of color (BIPOC) scientists are underrepresented in the geosciences relative to the U.S. population, the extent of this underrepresentation is among the most severe of all scientific disciplines (Dutt, 2020), and there has been no progress on this over the past 40 years (Bernard and Cooperdock, 2018). The fundamental reasons are much broader than a failure to recruit (Marín-Spiotta et al., 2020; Morris, 2021; Ali et al., 2021). Racism in science fields has also aided in maintaining racial disparities in science, technology, engineering, and mathematics (STEM) fields (Carter et al., 2019). This is due to a host of reasons, including the exclusionary culture of STEM disciplines, which tend to be competitive and individualistic (Hurtado et al., 2012). Critical race theory scholars have argued that racism is institutionalized and, thus, embedded in schools from K–12 and beyond (Ladson-Billings, 2021). Both institutionalized and interpersonal encounters with racism make matriculation through STEM courses and programs a challenge for BIPOC students. However, culturally affirming learning environments, like Historically Black Colleges and Universities, have significant success educating minoritized students in geoscience (Archer et al., 2019; Bililign, 2019; Aluka, 2023). Providing K–12 students with opportunities to positively interact with geoscience can lead to more positive views of geoscience and increase the number of students who choose geoscience majors at the undergraduate level (Stokes et al., 2015; Sherman-Morris and McNeal, 2016; Carpi et al., 2017). We thus view providing early, positive geoscience experiences as a necessary but insufficient step toward diversifying geoscience. Here, we describe two programs that attempted to familiarize K–12 students with geoscience via participation in authentic geoscience research. An authentic student research experience is a type of experiential education that enhances learning through purposeful educator-learner engagement and focused reflection on experiences to enhance future learning. Because the research outcomes are unknown, the students engage in real-world discoveries. Environmentally focused experiential learning programs have been shown to increase awareness of students' local environment (Ali Tabidian, 2007). Research by DeFelice et al. (2014) suggests that underrepresented high school students who engage in authentic research experiences situated in their local environment develop positive science identities and gain awareness of what scientists do. Positive impacts on science identities of underrepresented high school students also result from engagement in field experiences alongside undergraduate STEM majors who serve as near-peer mentors (Kuchynka et al., 2022). Similarly, elementary students who engage in culturally relevant experiential learning opportunities show increased interest in science (Djonko-Moore et al., 2018). Science education experiences centered on phenomena that relate to students' interests and address relevant community issues can illustrate to students that science is an inclusive culture of building knowledge (Penuel, 2020).

Culturally Relevant Pedagogy as a Lens for Authentic Scientific Research Experiences

According to Ladson-Billings (1995a, 1995b), culturally relevant pedagogy (CRP) focuses on three specific tenets: (1) students experiencing academic success; (2) students maintaining cultural competence; and (3) students developing critical consciousness to help identify and challenge inequities. CRP is a "theoretical model that addresses student achievement but also helps students to accept and affirm their cultural identity while developing critical perspectives that challenge inequities that schools (and other institutions) perpetuate" (Ladson-Billings, 1995b, p. 469). CRP acknowledges the home-community culture of students and works to create culturally congruent learning experiences that incite student curiosity and engagement (Brown-Jeffy and Cooper, 2011).

Culturally relevant educators work to design learning experiences that connect to students' backgrounds. CRP acknowledges how communities engage in science in their daily lives as well as how scientific exploration is relevant to addressing inequities. Torres-Velasquez and Lobo (2005) suggest that students perform better academically when their cultures and values are supported in the learning process. Students develop their confidence as learners of subjects like math and science where there has been historical underrepresentation and exclusion. However, despite rich evidence demonstrating the benefits of CRP, few educational spaces draw upon CRP; in fact, some states have made moves to ban CRP from classrooms (Majewska and Feeder, 2022; Willever, 2022).

In addition to CRP, education scholars have also looked to experiential learning, which is learning by doing, where students engage in hands-on experiences and reflection as a tool for helping students to develop an interest in and internalize new content (Kolb and Kolb, 2009). Experiential learning can include the use of concrete materials as well as authentic scenarios that reflect everyday problems and daily life (Burns and Hamm, 2011). Experiential learning can be used to engage learners in direct experiences to develop skills, clarify values, improve knowledge, and increase students' capacity to create a more socially just world (Djonko-Moore et al., 2018). These goals of CRP and experiential learning work well in concert with one another by placing students' interests at the core of learning activities and objectives.

Two Programs to Involve K–12 Students in Authentic Science Research

The Malcolm X Shabazz High School Aquatic Geochemistry Team

In 2013, Mr. Patrick Murray, a teacher at Malcolm X Shabazz High School (MXSHS), approached Drs. Karen Lloyd and Andrew Steen, faculty at the University of Tennessee, and family friends of his, with a request to engage his high school students in authentic environmental science research. MXSHS at the time was marked as a "failing" school. In the 2012–2013 school year, the school ranked in the 5th percentile in New Jersey for academic achievement, in the 29th percentile for college and career readiness, and in the 8th percentile for graduation and postsecondary success (State of New Jersey, 2013). Of the 645 students enrolled that year, 99.8% identified as Black or Hispanic. Nearly 100% of students spoke English as a first language. These numbers stayed roughly constant between 2012–2013 and 2018–2019, with the exception of enrollment, which decreased to 446 by 2018–2019 (State of New Jersey, 2019).

Initially, Mr. Murray was interested in involving his students in research related to environmental deoxyribonucleic acid (DNA). However, it was quickly determined that this was impractical for his students: The amount of background knowledge students would need to learn to perform useful research would be difficult to acquire in the time constraints of the semester. Instead, a different facet of Dr. Steen's research at that time proved to be more accessible. Dr. Steen's research focused on measuring activities of microbial extracellular enzymes in environmental samples. These measurements can easily be taught to high school students in an afternoon, benefit from the participation of many students, and do not involve prohibitively expensive equipment or consumables (Box 1).

Each year between 2012–2013 and 2018–2019, Mr. Murray worked with students to teach them about environmental microbiology, enzymes, and biogeochemistry. Students in some years used Google Scholar to search for literature related to extracellular enzymes in the environment. Dr. Steen periodically used Skype to discuss enzyme science with students and answer their questions for additional clarification on the project. Near the end of the school year (in June, after end-of-year tests but before the school year ended), students, MXSHS faculty, and in some cases

Box 1: Microbial Extracellular Enzymes in the Environment and Their Measurement

Heterotrophic microbes, i.e., those that gain energy from metabolizing organic carbon, cannot typically assimilate large organic molecules directly (Benz and Bauer, 1988). Many therefore secrete extracellular enzymes to break down large molecules outside of the cell, prior to taking up resulting small molecules. Thus, measuring the activities of extracellular enzymes in environmental materials can be a powerful way to assess microbial community demand for specific elements or molecules and therefore to gain insight into the microbial role in Earth's biogeochemical cycles (Arnosti et al., 2014).

The most common approach to measure extracellular enzymes, and the one used here, is to add substrate proxies to an environmental sample (German et al., 2011). These analogs for an enzyme's natural substrate contain a fluorophore (or chromophore), which only becomes fluorescent (or colored) when it is cleaved from the substrate proxy by an enzyme (Fig. 1). Enzyme activity is measured by monitoring fluorescence (or optical absorbance) in a sample to which the substrate proxy has been added, often in the presence of a pH buffer.

There are therefore two steps to measuring enzyme activities with fluorogenic substrate proxies (e.g., Steen et al., 2015c). First, a fluorogenic substrate proxy is added to an ~1 mL sample, which is kept in a plastic cuvette (Fig. 2). Next, the fluorescence of the sample is measured over time, typically ~1–4 h. Enzymatic activity produces a linear increase in fluorescence over time. The slope of fluorescence versus time indicates the enzyme activity, and it has units of RFU (relative fluorescence units) per unit time. Relative fluorescent units do not indicate a specific quantity of fluorescent chemical, so these slopes must be calibrated to units of concentration of fluorophore (or bonds broken) per unit time.

To do this, we prepare environmental samples identically to the way in which the samples were prepared for enzyme assays. However, instead of adding fluorogenic substrate proxies and measuring fluorescence over time, we add known quantities of the fluorophore that is released from fluorogenic substrate proxies. We calculate the slope of this relationship, in units RFU per micromole fluorophore. Enzyme activity is calculated by dividing the slope of fluorescence versus time by the slope of fluorescence versus fluorophore concentration to yield a value with units of fluorophore concentration per unit time:

$$activity = \frac{\textit{slope of fluorescence vs time}}{\textit{slope of fluorescence vs standard concentration}}. \qquad (1)$$

This corresponds to the quantity of reactions catalyzed by enzymes in the sample per unit volume per unit time (Fig. 3). Uncalibrated enzyme activities (Figs. 3A and 3C) are combined with a calibration curve (Fig. 3B) to yield calibrated enzyme activities, which have units of concentration (usually nanomoles per liter) of fluorophore or chromophore per unit time (usually per hour).

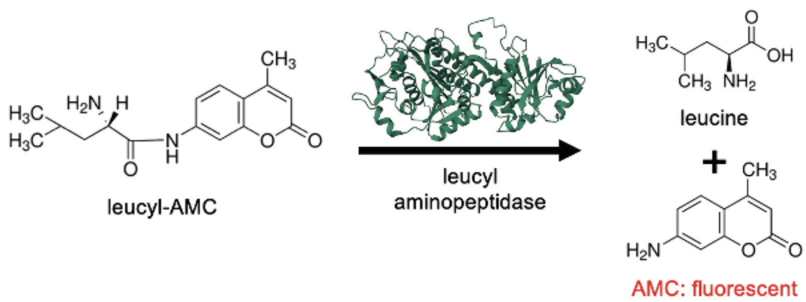

Figure 1. Enzyme-catalyzed hydrolysis of substrate proxies releases a fluorescent or colored product. In this example, the enzyme leucyl aminopeptidase catalyzes the hydrolysis of L-leucyl-7-amido-4-methylcoumarin (leu-AMC) to l-leucine and 7-amido-4-methylcoumarin, which is fluorescent. Chromogenic substrate proxies release a colored rather than fluorescent product, but they work along the same principle.

other University of Tennessee faculty and/or students traveled to the Pocono Environmental Education Center (PEEC), in Dingmans Ferry, Pennsylvania, a residential environmental education facility, for an ~3–4 day stay (Rosalsky, 2013). Students spent about half of their time at PEEC working with Dr. Steen to collect water samples, assay extracellular enzyme activities, analyze data, and discuss the practicalities of a scientific career. During the other half of the time, they participated in environmental education and team-building activities coordinated by PEEC, which regularly hosts school groups. These trips were initially funded by MXSHS, and later by grants from the Foundation for Newark's Future, the Geraldine R. Dodge Foundation, and small-scale fundraising.

The project was successful from a geomicrobiology standpoint. Students produced useful data, which Dr. Steen began incorporating into talks and presentations as early as 2014 (Steen et al., 2014, 2015b; Steen, 2015, 2018). The data were also combined with data collected by graduate students at the University of Tennessee and published in the peer-reviewed geoscience literature (Mullen et al., 2018). Ultimately, a total of ~60 MXSHS students presented research at six different conferences, including three student-led presentations at the fall meeting of the American Geophysical Union, which is the largest meeting of geoscientists in the world (Anyeji Boerrigter et al., 2016; Igiebor et al., 2017; Ajuwon et al., 2018). In addition, Mr. Murray presented perspectives on the program at two international meetings (Steen et al., 2015a; Murray et al., 2016). The involvement of teachers directly in science is a benefit in and of itself (Jarrett and Burnley, 2003).

ICE-AGE: Authentic Science for Middle School Students in East Tennessee

In 2019, NSF Pathways into the Earth, Ocean, Polar and Atmospheric & Geospace Sciences (GEOPAths) grant 1911565, titled "ICE-AGE: Integrating Continuous Experiential Activities for Geoscience Education," funded a program based on the MXSHS Aquatic Geochemistry Team, based in east Tennessee. We identified a summer education program that serves primarily Black and Hispanic elementary and middle

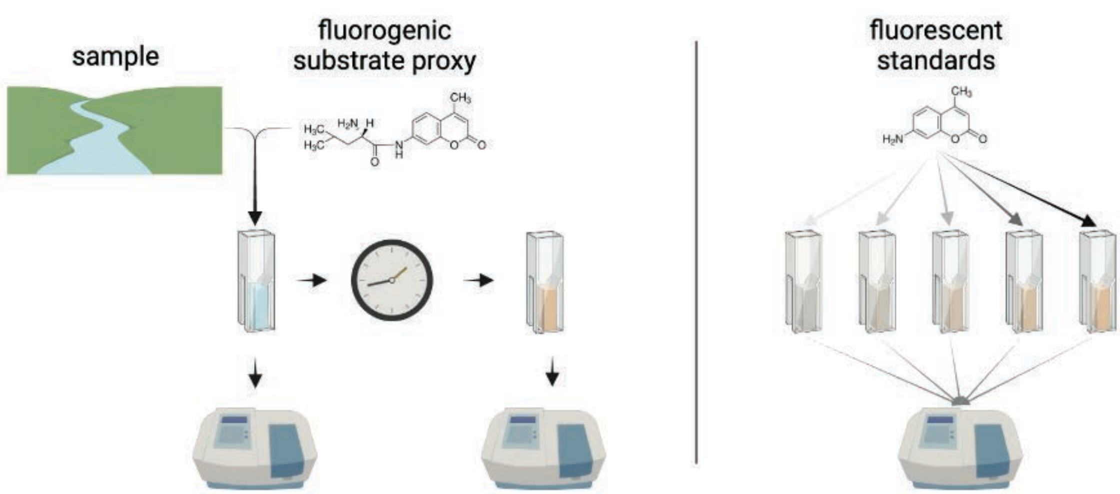

Figure 2. Enzyme activity is measured in two steps. First, a sample (e.g., water from a stream) is mixed with a substrate proxy (and in some cases a buffer, not shown). Fluorescence (or optical absorbance, in the case of chromogenic proxies) is monitored over time. The incubation time will depend on the activity of the sample, but usually 30 min to 4 h is appropriate. The slope of a plot of fluorescence or optical absorbance versus time yields an uncalibrated enzyme activity. This is calibrated by measuring the slope of fluorescence or absorbance versus standard concentrations.

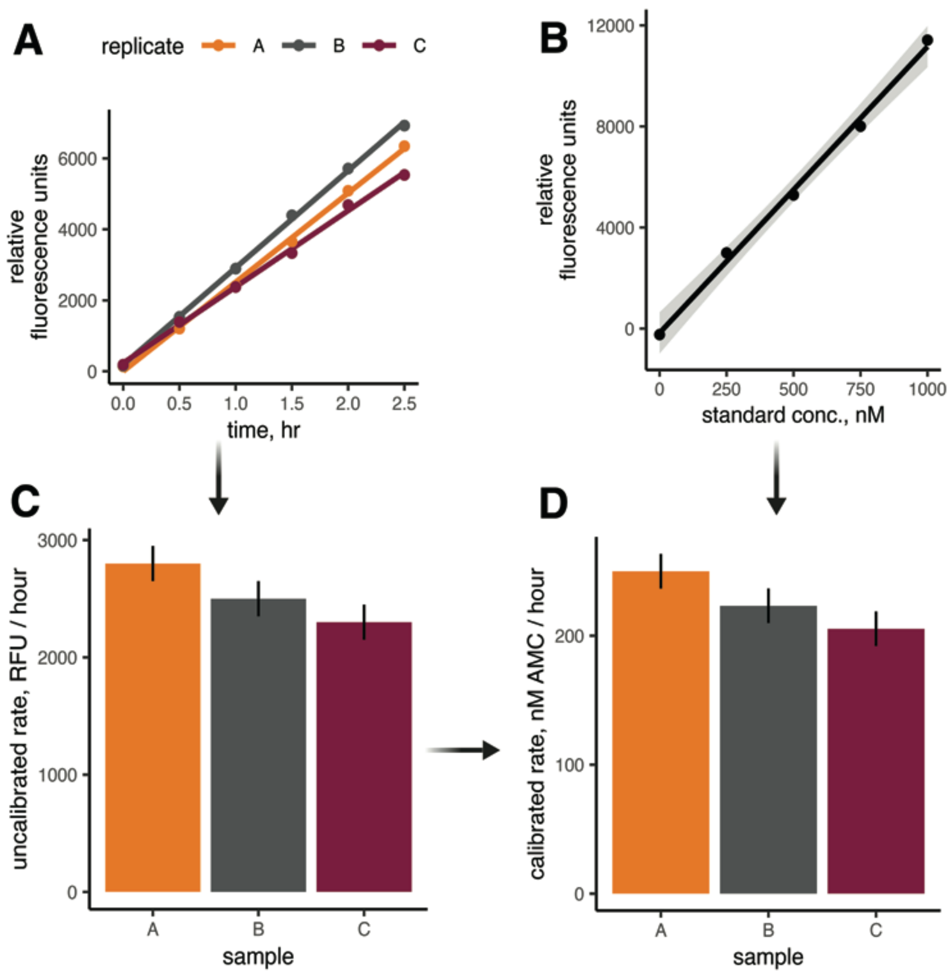

Figure 3. Idealized data showing the two primary measurements required to calculate enzyme activities. (A) Fluorescence of a sample + substrate mixture is measured over time. The resulting curves should be linear and increasing. (B) Separately, a calibration curve is conducted using the same samples but with standards rather than fluorogenic substrates. Unlike in A, this is a one-time measurement. (C) Uncalibrated enzyme activities are calculated as the slope of lines fit to the data in A. Finally, the uncalibrated activities (D) are calibrated by dividing the slope of fluorescence versus time data (A) by the slope of the calibration curve (B).

school students, here pseudonymously referred to as Liberation Literacy Program (LLP). LLP meets for ~6 hours per day, 5 days per week, for 6 weeks during the summer. We met with one LLP class, which consisted mostly of middle school students with a small number of high school students, for 2 hours per day, 3 days per week.

During that time, we sought to lead students to design a research project on a predetermined theme, to execute that research project, and to create a presentation of results. This involved discussing general scientific concepts, such as how to create a scientific question, how to create a research hypothesis, and how to test that hypothesis, as well as find domain-specific information on the chosen scientific theme. We then worked with students to collect samples, carry out research, and present findings at the summer's-end finale.

Extracellular Enzyme Assays as an Entry Point into Authentic Geoscience Research

For the MXSHS Aquatic Geochemistry Team and for the first year of the ICE-AGE project, we focused on measuring microbial extracellular enzyme activities in local freshwater bodies. This included streams, ponds, and a river near the PEEC campus for the MXSHS Aquatic Geochemistry Team and a small stream in east Tennessee for the ICE-AGE work. Briefly, microbes produce extracellular enzymes as a way to access large molecules in the environment, similar to how humans produce digestive enzymes in the gut to break down large molecules (Arnosti et al., 2014). Thus, extracellular enzymes catalyze a key step in the microbially driven part of Earth's carbon cycle. We selected extracellular enzyme assays (see Box 1) as an entry point into authentic research for the following main reasons:

(1) The method is central to one author's (Steen's) field, so we could easily identify gaps in existing research that student-driven experiments could fill.
(2) The method is easy to teach, so K–12 students can start collecting usable data after an afternoon or so of instruction.
(3) The method is relatively inexpensive (Box 1).
(4) There is enough work required to perform these experiments such that all students can stay busy and engaged, and the amount of work can easily be scaled to the

number of students participating by changing the number of samples analyzed.

(5) Use of the method involves key math and science concepts, such as calculating the slope of a line, that are consistent with widespread state standards for middle school and high school math and science curricula.

(6) Relatively few measurements have been published from many natural waters, allowing students to engage in novel research.

OUTCOMES AND LESSONS LEARNED

Lack of funding for the MXSHS work and complications from the coronavirus 2019 (COVID-19) pandemic, not only for the first year of ICE-AGE work in summer 2020, but also with lingering impacts over subsequent years, prevented formal educational research on the effects of these projects on the students and teachers involved. Despite the lack of formal outcomes research, however, we are able to share several qualitative lessons learned.

Extracellular Enzyme Assays as an Avenue for Authentic Geoscience Research

We found that students in grades 9–12 were able to collect publication-quality extracellular enzyme data after an ~4 h training period, with relatively little supervision. In that sense, this method was a success. Students quickly became proficient with transferable skills such as pipetting, data entry, and evaluating the linearity of data versus time. Students also generally understood that enzyme activity was indicated by the rate of increase of fluorescence, rather than the level of fluorescence, which implied an understanding of the rate of change as a metric. Finally, students qualitatively appeared to increase their understanding of the concept of biogeochemistry, the role of microbes in ecosystems, and the concept of enzymes as proteins that catalyze reactions. This was particularly true for the subset of MXSHS students who participated in the field experience and then presented work at a conference.

Although extracellular enzyme assays provided an avenue for authentic geoscience research, certain outcomes of the research process and of students' perspectives toward future careers in geoscience were not what we had initially anticipated. First, enzyme activities are calculated as the ratio of two slopes: an uncalibrated activity measurement (fluorescence vs. time) and a calibration curve (fluorescence vs. concentration of an added standard). While students typically understood that uncalibrated activity is indicated by the rate of increase in fluorescence over time in a sample, calibrating the enzyme activity by dividing the slope of fluorescence versus time by the slope of the calibration curve proved conceptually challenging. This was perhaps exacerbated by the fact that activity measurements are made in a single cuvette, repeatedly measured over time, whereas calibration curves are calculated by adding different concentrations of standard to different cuvettes, each of which is measured only once. Second, informal discussions with students after the program suggested that it did little to increase students' interest in geoscience and/or environmental science per se. Rather, the students who participated most intensely in the program seemed to be motivated by a desire to build their résumés for a career track they had already chosen. Given the push to select career paths earlier in students' educations, in the form of job training within the K–12 level (e.g., Tennessee Department of Education, 2018), and a growing pressure to declare majors upon initial admission at the college level, future recruiting and outreach efforts among these age groups may face an uphill battle if the geosciences are not presented as a viable option even earlier in students' schooling.

Thus, while we found that high school students were able to quickly learn to perform extracellular enzyme assays for environmental samples and that performing these assays was the focal point of a program that achieved several educational goals, we also observed that extracellular enzyme assays as an educational tool were limited in that comprehension of the full assay, including calibration, was challenging for students. We also learned that although authentic science research using extracellular enzymes did not appear to drive a broader interest in environmental science, it taught many useful transferable skills and helped some students move toward career goals in general.

Comparing the Two Authentic Scientific Research Experiences in the Context of CRP

The use of extracellular enzyme activity assays in the ICE-AGE project was considerably more challenging than in the MXSHS context. There were three major differences between the ICE-AGE collaboration and the MXSHS collaboration. First, the MXSHS Aquatic Geochemistry Team consisted entirely of high school students, whereas the ICE-AGE students were almost entirely middle school students. From both a cognitive and experiential perspective, the two populations were very different, requiring different CRPs. Jansen and Kiefer (2020) listed multiple research-based neurological changes in young adolescents, including the development of executive functioning and cognitive flexibility, while also cautioning that their ability to regulate emotions is limited. Throughout adolescence, they will progress in their ability to apply learning to new situations and apply prior experiences to current tasks (Murty et al., 2016). Second, we met with students in the ICE-AGE for 2 hours per day over the course of 6 weeks, whereas we met with the MXSHS group occasionally over the course of a year as well as three full days at an environmental education center that was hours away from their homes in a forested, rather than urban, setting. Removing them from their daily lives made them more open to new concepts. Finally, and perhaps most importantly, the MXSHS project was led at MXSHS by a high school teacher, Mr. Patrick Murray, who enthusiastically promoted the project to students. Contributing to scientific presentations at international conferences also helped keep students engaged in the MXSHS project, since it exposed them to a wide range of real-world scientists, including many from universities and governmental agencies such as the National Aeronautics and Space Administration, whom the students already respected.

Of the three biggest differences between the two projects, we propose that this enthusiasm from a teacher was integral to the students' enthusiasm for the project and resulted in a higher level of student impact. This was particularly important due to the esoteric nature of the scientific question: What set of extracellular enzymes is produced by microbes in freshwaters? While interesting from a scientific point of view, this question does not connect directly to students' lives. From the standpoint of CRP, the project did little to help affirm students' identities.

This lack of connection to students' everyday experience became evident in the ICE-AGE collaboration. With the MXSHS Aquatic Geochemistry Program, students' lack of connection to the scientific material was less relevant because students were less motivated by the science per se and more motivated by the career opportunities they felt the program could create. This motivation was informally encouraged by teacher Mr. Murray: Although participation in the project was not tied to grades, his enthusiasm for the project and its potential to serve as a résumé builder was apparently an effective motivator. An explicit goal of the experience was to provide students with a résumé-building activity in order to strengthen college applications and to encourage them to undertake similar extracurricular work in college.

By contrast, the ICE-AGE project initially did not explicitly include teachers as team members. Rather, the academics who were principal investigators of the ICE-AGE program worked directly with students in the LLP program, with assistance from graduate and undergraduate students. Additionally, LLP "servant leader interns" (SLIs, akin to teachers or counselors) were present, but they were mainly responsible for managing students rather than scientific instruction. This lack of a teacher as intermediary between the academic leaders and the students exposed the fact that students were not fundamentally interested in the scientific subject matter. In retrospect, the MXSHS program met the goals of CRP, to some extent at least, not because students were able to connect the science to their lives, but because they saw contributing to the program as a way to fulfill their career goals (e.g., through success in college). The short-term, more tangible promise of trips to professional science conferences was probably an important bridge to these longer-term goals. The first year of the ICE-AGE program was less successful because students neither connected the scientific project itself to their experiences, nor were most students able to connect the program to personal or professional goals. Working with middle school students who were still at least four years away from postsecondary career opportunities presented more challenges with making connections to longer-term career goals as compared to working with high school students, particularly when they did not have a known advocate such as their classroom teacher who was enthusiastically encouraging their participation.

We note that it might be possible to present environmental enzyme assays in a way that would be more directly appealing to students. For instance, enzyme assays have been used to infer water pollution by excessive nutrients (Pamer et al., 2011). In our experience, both ICE-AGE and MXSHS Aquatic Geochemistry Team students were keenly interested in issues of pollution.

FUTURE PATHS AND ADVICE TO GEOSCIENTISTS

The ICE-AGE program was funded for three total years, and funding has been extended as broader impacts of a separate grant. For the second and third years of the program, we have chosen geoscience topics that are more connected to students' lives. In 2022, LLP students used low-cost portable air-quality and temperature sensors to assess temperature differences in their city as a function of historical patterns of redlining (i.e., systematic denial of mortgages or other loans in order to encourage racial segregation). Noisy data prevented clear conclusions from these data, but students appeared to be much more engaged in this project and took more direct ownership of the experimental design and data interpretation. In the future, we intend to study the distribution of lead in soils around the same city, since this is a socially relevant geoscience question that can be addressed with relatively low-cost lead analysis kits. We also acquired funds to hire a K–12 trained teacher to lead day-to-day activities and keep the students engaged and inspired.

Based on these experiences, we offer the following opinions to geoscience researchers who are interested in collaborating with K–12 students on authentic scientific research:

(1) Collaborations with K–12 students can yield authentic, publishable science, which can be professionally valuable to geoscience leaders as research output as well as outreach.

(2) The framework of CRP is a valuable tool to design authentic science projects that are engaging for students.

(3) Environmental enzyme assays have some advantages as a focus for authentic science projects for K–12 students. However, some aspects of activity calculations were challenging for high school students to grasp.

(4) In our experience, students were not excited about extracellular enzyme assays per se. It might have been possible to increase interest by focusing the research project on use of extracellular enzymes as a proxy for water quality (e.g., Pamer et al., 2011).

(5) MXSHS Aquatic Geochemistry Team students were excited about the career/life opportunities and the more concrete benefits (travel to other cities; networking with scientists at well-known universities and governmental agencies) that the program provided.

(6) The presence of an enthusiastic teacher who is close to students and well integrated into the research side of the project can positively impact students' perceptions of the value of engaging in the research (Mahler et al., 2018).

As an authentic research experience, measurement of environmental enzyme activities has a few unique advantages and disadvantages with respect to these constraints. As described herein, this type of authentic research activity is useful because it is accessible, it is easily scalable, and it can easily be made scientifically novel. However, care must be taken to ensure the scientific inquiry is relevant to the students' cultural and lived experiences. This effort is greatly aided by teachers who help to bridge the gap between researchers and students, providing important context to help students see the relevance in their lives. By achieving the right balance of feasibility, scientific value, and personal relevance, simple experiments such as extracellular enzyme assays, or air-quality test kits, can provide effective avenues for student engagement that create culturally meaningful and personally enriching experiences. Such engagement in authentic research at an early age may expand participation from historically excluded groups in STEM fields in the long term.

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