Fig. 1. IRES Pollinators in Changing Climates: the 2021 cohort of students and mentors from the United States, Colombia, and Peru.

Creating a Virtual International Research Experience

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In the era of globalized science, it is increasingly important that undergraduate students are not only exposed to local research environments, but also have the opportunity to interact with a broader international research community. Despite the benefits of such experiences, international research programs are generally offered to undergraduates of R1 universities (that is, academic programs that offer doctoral degrees and have a very high research activity based on the Carnegie Classification of Institutions of Higher Education) through costly courses that are inaccessible to most students. Inequity related to who has access to international research experiences is frequently amplified for students from underrepresented groups, who often have responsibilities outside of their academic activities (e.g., jobs; caregiving) that prevent them from international travel. To address these issues, the National Science Foundation (NSF) funds projects that offer international research opportunities to undergraduates through the program International Research Experiences for Students (IRES; https://tinyurl.com/6t7x8c2t). Due to the

COVID-19 pandemic, these programs faced sudden and unforeseen challenges as the pandemic impacted the education system worldwide (Gonzalez et al. 2020). Many programs shut down or postponed their activities because of restrictions on international travel. Similarly, universities and other research institutions closed their doors, which translated into reduced opportunities for undergraduate students to engage in research activities.

In 2021, we organized an eight-week summer IRES program on research topics related to pollinators and climate change that involved travel to Colombia and Peru with undergraduate students and six faculty mentors from Penn State University. Because we were unable to travel to the international locations, we altered the course and offered the program entirely online with the participation of faculty from four institutions (Penn State University, University of Kansas, Universidad Militar Nueva Granada, and Pontificia Universidad Católica del Peru). Here, we describe our efforts to adjust this program to a virtual environment and demonstrate that despite limitations during these unprecedented times, we were able to provide an alternative, effective, and transformative research experience for undergraduate students.

What We Had Planned: Integrating Fundamental Concepts, Hands-On Research Experiences, and Cultural Immersion

The research goal of our NSF-funded IRES project, Pollinators in Changing Climates, is to characterize behavioral and physiological responses of pollinators to climatic changes in tropical areas. Insects in the tropics are predicted to be more severely impacted by rising environmental temperatures than insects in temperate regions, yet we know little about how these organisms are responding to thermal stress. Some of the specific research topics of this program included (1) predicting bee foraging patterns and the trajectories of pollinators under different ambient temperatures; (2) understanding mechanistic effects of drought and flooding events on crop–pollinator interactions; (3) an assessment of the variation of pollinator thermal tolerance in tropical ecosystems; and (4) the development of regional climate downscaling to relevant microclimatic scales for pollinators. After the selection process of undergraduate student applications based on relevant coursework, grades, and reference letters, we had planned to invite five students to participate in the program to engage in the following activities:

- An in-person visit to the Penn State University Park campus for one week to receive initial training on core concepts in climate science, plant–pollinator interactions, data visualization, and technologies available to study insect movements. Additionally, all project leaders would give short presentations about the proposed research projects, and students would visit the laboratories of PIs to meet groups of graduate students and postdocs.
- After arriving at our international destination, we would then continue the discussion about projects with the local mentors and students who were interested in participating in the program to finalize the groups leading each project.
- Students would perform research for their projects from week 3 to week 8 of the program, working on data collection, data analysis and visualization, and communication of their results through written reports and oral presentations. All of these activities will take place while constantly interacting with local students and mentors and learning from how they approach scientific questions.
- During the last week, we planned a one-day symposium to share the results of all research projects with other members of the student body at the host institution. Students would develop a short video about their results in English and Spanish to further facilitate scientific outreach and impact of the project.

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How the Course Was Implemented: Adaptation Process to the Virtual Platform

In 2021, the international research program was offered virtually due to COVID-19 international travel restrictions. For student recruitment, we were particularly interested in attracting students from underrepresented groups in STEM, so we heavily advertised the program through colleagues from minority-serving institutions. From the 32 applications we received, we selected seven undergraduate students from institutions all across the United States. Additionally, five students and four mentors from Colombia and Peru participated in the program (Fig. 1). The planned activities for the in-person program were modified as follows:

- The first week of the program consisted of virtual lectures, discussions, and readings of scientific literature, as originally planned. The virtual platform (Zoom Video Communications, Inc., San Jose, CA, USA) allowed the participation of mentors from all participating institutions in the United States, Colombia, and Peru in these activities.
- During the following seven weeks, all research activities and group discussions took place through the virtual platform, allowing students and mentors from all institutions to engage in scientific discussions and research activities on a weekly basis. Students worked mostly within four smaller cohorts, each led by mentors from the United States and South American institutions.
- Students and mentors from all groups also met once a week (Fig. 1). These meetings were informal and were used to allow each group to share updates of the weekly

Fig. 2. Quantifying the effect of thermal tolerance on pollinator foraging behavior. Students collected bee and fly visitors of plants near their homes and either used their kitchens or desks to operate the water baths used as devices to quantify critical thermal maxima in pollinators. Photo credit: Alonso Delgado

activities, challenges, and progress on research.

- The projects had to be slightly modified to adjust to the virtual platform and limitations to the collection of empirical data (see the section on research themes).
- During the last week of the program, we hosted a mini-symposium in which students gave 15-minute presentations about their projects. The virtual setting for this symposium allowed the attendance of mentors, faculty, and peers from the students' undergraduate institutions. Talks followed the format of conference presentations, and emulated the setup of scientific conferences. Each student also wrote a report in the format of a scientific paper.
- As the outreach component of the project, students developed short group videos to disseminate the results of each project to the general public. Videos are publicly available through a blog post (https://tinyurl.com/5cj2nk97).

Research Themes of the International Virtual Program

Impact of thermal tolerance on pollinator foraging behavior. Students collected data to test hypotheses related to the association between pollinator thermal tolerance and patterns in foraging behavior. We sent supplies to each of the participating students to set up devices to estimate critical thermal maxima from insects (as per Garcia-Robledo et al. 2020). Students collected empirical data in their backyards or in natural areas located near their homes (Fig. 2), and used their kitchens or desks as temporary laboratories throughout the duration of these experiments. In some cases, family members helped students collect data. One of the key findings of the study was that adult bee and fly pollinators often have different peaks of activity at flowers, with bees foraging during hotter parts of the day than flies. We found a similar pattern in critical thermal maxima, with bees showing greater tolerance to high temperatures than flies.

How air pollutants affect pollinator foraging patterns. Using air quality data sets and information on floral scents, students investigated how ambient oxidants, such as ozone, can modify the specificity and informational composition of floral scent mixtures used by insect pollinators to locate flowers. We found that in elevated concentrations, air pollutants dramatically modify the quantity and the quality of floral scents, and can reduce the distance that floral compounds travel by 33% compared to unpolluted conditions. The degradation of floral cues can directly impact the length of time that pollinators must spend trying to identify odor plumes to locate flowers. These findings indicate that air pollution is yet another abiotic stressor that pollinators face in an era of rapid regional and global environmental change.

Tracking complex foraging patterns of bees with radar. Novel radar technologies are currently under development at Penn State to better describe complex foraging patterns of insects. Due to the COVID-19 pandemic, outdoor measurements with the radar were not possible, but students were able to use synthesized radar data (SRD) of the trajectories of insects. Students in this project used Python to analyze, process, and display detailed foraging patterns of honey bees throughout the day from the SRD. Despite the limitations of this approach, one very important outcome of the project was the development of a geo-referencing feature using GPS to accurately locate the radar system position and produce airborne insect flying trajectories in an interactive map. This accomplishment is important to

construct long-term data storage and management tools to study insect trajectories.

Pollination footprint of cities. Students used publicly available data from the USDA National Agricultural Statistics Service, crop pollination dependence coefficients based on published literature, and ArcGIS analytical tools to quantify and map the indirect flow of pollination services from crop production regions to 70 major cities in the United States under the scenario of future rising temperatures (i.e., heat stress/heat waves). The goal was to determine how these regions would be impacted by a shortage of pollination-dependent crops under scenarios of high environmental temperatures. One interesting outcome was that pollination footprint for both consumption and production decreased when temperatures rose. Our results imply that the pollination footprint will decline in cities as temperature increases, decreasing the supply of pollinator-dependent commodities, while demand for these crops will increase due to increasing population pressure. These findings identified another potential impact of climate change on food supply chains involving pollinator-dependent crops.

Accomplishments and Lessons Learned

Despite the unforeseen and difficult circumstances of running a virtual international program in 2021, we successfully brought together a group of students and mentors from three countries to complete a virtual international undergraduate research program and accomplished important goals for the research training and professional development of the participating students. Towards the end of the program, most students indicated that they plan to attend graduate school. Students reported increasing their knowledge of the disciplines represented by their projects and their research skills. The virtual platform was generally considered a positive aspect of this program because it gave students more flexibility in time to work on their projects and other activities. In addition, the Zoom platform allowed more "equal" participation among students and mentors, regardless of their academic status (Javeri 2021).

Another important aspect of this project was the recruitment of students from underrepresented groups in STEM, who were advised by mentors with similar cultural backgrounds. It has been recognized that mentors' cultural diversity and competence can positively influence student academic success (Atkins et al. 2020). Students of the IRES 2021 program commented on the positive impact of having mentors who have similar life stories and backgrounds as they do (e.g., Latinx, international, etc.), and the unique opportunity that the program offered by having an international research experience without traveling.

STUDENTS COLLECTED EMPIRICAL DATA IN THEIR BACKYARDS OR IN NATURAL AREAS LOCATED NEAR THEIR HOMES.

The virtual international research experience proved to be a successful platform for biologists, climate scientists, and engineers to synergistically work in a group setting to advance our understanding of pollinator responses to abiotic stressors while training undergraduate students on diverse research skills. Our 2021 summer program serves as proof of concept for the potential that virtual programs have as catalyzers of mentoring and research opportunities with international collaborators. This type of environment, in which people with diverse perspectives work together to find solutions to problems, fosters the creative team-building that is necessary for scientific, technological, and economic competitiveness (Hoever et al. 2012). While a virtual research experience cannot replace the sensory and cultural experiences of an in-person program in an international setting, our IRES program demonstrates that effective and meaningful online research training and mentoring for undergraduate students are possible. Without a doubt, it has the potential to be used as a complementary approach during regular IRES projects.

Acknowledgments

We thank the National Science Foundation (Award No. 1952470) for the support for this program. We would also like to thank the students who participated in the program and made it a true success, including Maren Appert, Abigail Jiménez, Alonso Delgado, Renata Proano, Alonso Zevallos, Rocio Beneito, Tatiana Terranova, Andrés Herrera, Ruben Martín, Yannet Quispes, Luis Ocupa, and Juan Tello.

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DOI: https://doi.org/10.1093/ae/tmac017