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Broadening Participation: 21st Century Opportunities for Amateurs in Biology Research

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Synopsis The modern field of biology has its roots in the curiosity and skill of amateur researchers and has never been purely the domain of professionals. Today, professionals and amateurs contribute to biology research, working both together and independently. Well-targeted and holistic investment in amateur biology research could bring a range of benefits that, in addition to positive societal benefits, may help to address the considerable challenges facing our planet in the 21st century. We highlight how recent advances in amateur biology have been facilitated by innovations in digital infrastructure as well as the development of community biology laboratories, launched over the last decade, and we provide recommendations for how individuals can support the integration of amateurs into biology research. The benefits of investment in amateur biology research could be many-fold, however, without a clear consideration of equity, efforts to promote amateur biology could exacerbate structural inequalities around access to and benefits from STEM. The future of the field of biology relies on integrating a diversity of perspectives and approaches—amateur biology researchers have an important role to play.

Introduction

Over the last century, research in the field of biology has become increasingly professionalized and siloed, largely in the name of scientific advancement. The resulting disconnection between publics and professional scientific communities and between the growing number of specialized scientific fields hampers our ability to tackle the pressing global challenges of today (Casadevall and Fang 2014; Professionalism and Science n.d.; So Long to the Silos 2016). Technological and sociological innovations in the last few decades offer new ways to reintegrate amateurs into biology research, reforming science and technology as accessible and responsive to the needs of a far broader range of stakeholders and incorporating more diverse perspectives and expertise.

People across time and regions have endeavored to understand, benefit from and reshape the living world. These efforts date back millenia, with biotechnologi-

cal milestones such as the development of fermentation and staple crop domestication, and were pursued in the absence of salaried biologists or research institutes. In 18th century Europe, biology as a modern professional discipline began to take shape (Shelishch 1982), with this trend of professionalization accelerating globally in the 19th and 20th centuries. Today, biology research is as a substantial societal undertaking, with federal funding for departments that support biology research in excess of \$60 billion in 2021 in the USA alone (Science News staff 2020). The scale and prestige of the modern professional enterprise of biology dominates our understanding of what it means to do biology research. Nevertheless, amateurs, those who are not paid to conduct scientific research as a primary livelihood (Vetter 2011), have continued to make research contributions, often alongside and with the active encouragement of professionals (Johnston 2018).

Many famous figures in biology have been amateurs, even in the period after professional biology became widely recognized. Gregor Mendel, known as the “father of genetics” for his pioneering inheritance experiments in pea plants, had no advanced university training in biology and operated with limited resources away from established scientific institutions. Other notable amateur researchers include paleontologist Mary Anning (Noè et al. 2019), and discoverer of bacteriophage Felix d’Herelle (Summers 2016). Amateurs have also been biotechnology innovators, at times responding to necessity. Eva Saxl, for example, produced insulin in the Jewish ghetto of Shanghai, when supplies for this important commodity were limited during the Second World War. Luther Burbank, hailed in his day for his expertise in plant breeding, was largely self-taught and shunned by many in the scientific establishment (Smith 2009). While lacking recognized credentials, many amateurs, like Mendel (Dunn 1968), have considerable expertise gained through a mixture of formal study and personal experience and devote themselves for decades to their work. In some cases amateurs have greater expertise than any professional, particularly if this expertise is based on specific geographic location or activities that have never received professional attention (McLain et al. 1998; Elbroch et al. 2011).

Both the nature and degree of involvement of amateurs in biology research has varied across time and across sub-disciplines. Amateurs have played key roles in the collection of observational data on natural phenomena, such as flowering dates of plants and insect outbreaks, dating back thousands of years (Tian et al. 2011; Miller-Rushing et al. 2012). This model is put into practice today, with large-scale projects such as the North American Breeding Bird Survey, which relies on thousands of volunteers to collect data on bird abundances each year (Bystrak 1981). In other cases, amateur researchers are active in the development and design of a project, which might be referred to as a “co-created” or “collaborative” model rather than the “contributory” approach exemplified by the outsourcing of data collection (Bonney et al. 2009). These different models are often collectively referred to as “citizen science” (Miller-Rushing et al. 2012; Bonney et al. 2014) or “community science” (Dosemagen and Parker 2018). Recently, the term “community science” has come to be used frequently for all forms of research that are not solely conducted by professionals, in order to avoid the unintentional exclusionary connotation of “citizen.” However, particularly in the US, the term “community science” has traditionally been reserved for research fully driven by the interests of those directly affected by the matter at hand (Cooper et al. 2021).

We believe that the current norms and practices of professional biology research, particularly the requirement for highly-specialized fields that often struggle to communicate and collaborate with each other, are a hindrance to tackling the great challenges facing people and the planet in the 21st century. Recent calls have been made to “reintegrate biology research,” including the National Science Foundation-funded initiative (Award number 1940791) that inspired this paper. We feel that embracing and facilitating amateur involvement should be an important element of the reintegration of biology research. While amateurs have long played a role in science, recent advances have opened up new opportunities for amateur involvement in the 21st century, which has important implications for the advancement of the field and for society as a whole.

The case for amateur integration

The overall value of amateur research being integrated alongside professional research draws from a number of different factors, some of which have been explored elsewhere (McKinley et al. 2017).. Here, we present several arguments within the broader case for integration of amateurs into biology research.

Amateur driven research is socially relevant and culturally responsive

Compared to professional researchers, who may be driven by career accolades or financial incentives, amateur researchers are more likely to be directing biology research towards issues or questions of immediate personal and/or community relevance. Research studies that engage relevant community stakeholders in the design, execution, evaluation, and dissemination of results, have been shown to benefit from the improved “rigor, relevance and reach” (Balazs and Morello-Frosch 2013) that this approach may provide. In the right circumstances, the unique perspectives of amateur researchers can drive systemic change across biology research. For example, inspired by the rare disease diagnosis of her own children and the closed and inefficient biomedical research practices she encountered (Terry 2003), amateur scientist Sharon Terry organized and contributed to novel biomedical research into the condition (Saux et al. 1999) and became a pioneer and advocate for open, participatory biomedical research practices (Terry et al. 2007; Lambertson et al. 2015).

As technologies have developed in the new millennium, people increasingly have the means to easily alter natural environments, with practices such as the introduction of genetically-modified organisms, with many ecologically, socially, and economically compelling cases for doing so (Popkin 2018). In this con-

text, it is imperative that professional biotechnologists work with the communities that have a stake in a given intervention, to avoid pitfalls that may result from lack of community- or ecosystem-specific knowledge and to develop effective solutions to the problems at hand. Building meaningful collaborations with community partners, where communities are undertaking research of their own, at the conception of a project, such as in the recent “Mice Against Ticks” project (Buchthal et al. 2019), will lead to better outcomes, and avoid the reality or perception of technologies imposed on communities by remote professionals without a real understanding of or stake in the long term health of impacted ecosystems.

Amateur driven research is expansive

When biology is pursued outside of the structures and accompanying norms of academia or industry, there are opportunities for alternative ways of knowing and doing beyond common professional biology practices, such as systematic data collection, hypothesis testing, and design-test-build-learn cycles. A striking expression of this is the way that art and science practices can blend seamlessly in the context of amateur biology research (Wilbanks 2017). Art can be a powerful tool for critical reassessment of the present direction of science and technology, often by offering visions of possible futures (Dixon 2008). Alternative scientific practices that predate the western scientific traditions, such as Traditional Ecological Knowledge have an important role to play in advancing the state of the field as well (Snively and Corsiglia 2001; Kimmerer 2002), but are not commonly integrated into professional practice. We envision a future in which greater collaboration between professionals and amateurs in biology research leads to a fruitful sharing and expansion of research practices providing both amateurs and professionals with more ways to know, work with and communicate about the living world.

Amateur biology research has a broader reach

Professional biology today is facilitated by substantial infrastructure, purpose built facilities, expensive equipment, and administrative staff. Amateur research stands largely in contrast to this model, utilizing innovative approaches that minimize costs to projects and participants. Because of this, amateur research can be effectively conducted across a wide range of settings, not just in areas with large universities or research institutions. This is particularly important in bringing research to underserved urban or rural communities and developing areas of the world that may have a substantial need to address a host of questions in biology research, from conservation to public health (Fauci 2001; Lenzen et al.

2012), but have only modest research infrastructure in place. In a study of applied conservation research in the Philippines, the integration of amateurs into biodiversity monitoring efforts was found to be both more efficacious and more cost effective than approaches relying only on professionals (Danielsen et al. 2007).

This increased reach of amateur-enabled science also applies to the scope of research that can be conducted. For instance, the crowd-sourcing model, frequently seen in large-scale studies, makes use of amateur participation to collect data on spatial and temporal scales that would otherwise be cost prohibitive. Data can be collected at times or in places where professional researchers may not otherwise typically be present, such as in the winter months in the Arctic (Solli et al. 2013).

Amateur biology research builds trust and understanding

Amateur biology research can build trust and understanding between stakeholders. Greater amateur participation in biology research should create publics with a higher degree of interest in and understanding of science, facilitating productive debate around science-led policy, and greater recognition of some of the pressing global challenges that professional scientists have been seeking to highlight for decades, including environmental degradation, climate change, and effective public health interventions. While many initiatives attract publics with high existing scientific engagement levels (Martin 2017), limiting the breadth of impact on public discourse and action, even this limited demographic reach can lead to longer term, beneficial behavioral changes that might otherwise not have occurred (Groulx et al. 2019). Providing an increasing number and variety of means in which amateurs can engage with biology research will consequently extend the beneficial social consequences of scientifically engaged publics.

New opportunities for amateur participation in the 21st century

We believe that it is not only desirable to increase the involvement and activity of amateurs in biology research but that it has also never been easier to do so. We highlight two major advances that have facilitated amateur participation in recent years. First, is the advancement of digital infrastructure that has enhanced connectivity and enabled data sharing, collection, and storage on a scale and in ways not previously possible. Second, is the emergence of community spaces for laboratory biology over the last decade. These developments have opened access for many individuals that would otherwise not

be able to participate in field-, computation-, and lab-based biology research, and have helped to democratize participation in the sciences.

Advances in digital infrastructure are expanding the range and scale of amateur participation

The development of the internet and its integration into everyday life has had a profound effect on access to information and on connectivity among individuals. These advances mean that potential amateur researchers can more easily find ways to get involved in research efforts, in person or virtually, independently or as part of a larger project. Increased digital infrastructure has also facilitated new funding models for research through crowdfunding platforms such as Experiment.com (Marcus 2015), where even small donations to support research can result in substantial sums of money in aggregate. Increased connectivity also means easier access to training and background information that might be necessary to participate in research, and more ways to broadly advertise existing projects seeking to recruit more researchers.

Advancements in digital infrastructure have had a particularly significant impact on the scale at which research can be effectively conducted, making it possible to “crowdsource” a number of aspects of research, such as data collection, classification, and analysis (Bonney et al. 2014, Franzoni and Sauermann 2014). In many cases, amateur researchers need only an internet capable device to contribute. Interfaces designed with accessibility in mind could be developed to engage individuals who may be otherwise unable to participate due to literacy levels (Krisp 2013). Some of the most prominent examples of amateur participation in research are those in which amateur researchers collect data as a part of a larger project. Online interactive platforms make it easier for users from around the world to contribute. For example, projects such as eBird (Sullivan et al. 2014; ebird.org) and iNaturalist (inaturalist.org) have millions of users collecting information at a global scale on a variety of animals, plants, and fungi. These efforts may leverage existing hobbies of users (i.e., birding, naturalism and mycology) while also engaging new individuals to participate in these activities.

In addition to data collection, large numbers of amateur researchers participate through data classification and analysis. Online platforms such as Zooniverse (Smith et al. 2013) provide a mechanism for individuals to engage with research projects on a wholly online basis. Projects on the Zooniverse platform might ask users to identify penguins in images as a part of the Penguin Watch project (Jones et al. 2018), or help to dig-

itize herbarium records as part of the Notes from Nature project. Projects such as Fold-it (Cooper et al. 2010) ask users to rearrange proteins through a web interface to find more optimal arrangements, advancing understanding of structural biology. In some cases, projects encourage continued participation through “gamification,” where game-like elements are incorporated with rewards and achievements given based on project participation (Bowser et al. 2013). Web-based projects such as these rely on the ability to store large datasets online, providing a user-friendly front-end interface for user interaction (Silvertown 2009). The reach of projects such as these can be substantial, with Zooniverse projects involving over 1.8 million volunteers working on over 100 projects across multiple disciplines (Trouille et al. 2020).

Amateur biologists can also apply their expertise to help solve biological problems via data analysis. Data science competitions, via platforms such as Driven Data (drivendata.org), ask users to develop predictive models to address a specified problem. Would-be participants might be professional data analysts, though amateurs in the field of biology. Code is made available through collaborative tools, such as Jupyter notebooks and Github, which facilitate the sharing of data analysis techniques that might be applied to a number of problems in biology (e.g., Humphries et al. 2018).

Amateur biologists are engaging in collaborative knowledge dissemination outside of any institution, using social media technologies, such as Facebook, Twitter, Instagram and YouTube (Irga et al. 2020). Amateur mycologists share newly discovered mushroom species, best practices for cultivating edible mushrooms, and new cultivation technologies. Some mycologists got their start as self-described amateurs, such as the notable mycologist Paul Stamets. Twitter can also be a means for amateurs to engage professional biologists, soliciting advice and guidance as well as offering their own valuable expertise.

While projects involving large-scale amateur participation, such as the North American Bird Phenology Program, have existed for many decades, the increased connectivity, low-cost computing power, and digital storage capacity facilitated by advances in digital infrastructure have brought the scale of these research efforts to another level and made wholly novel approaches possible (e.g., Youngflesh et al. 2021). Importantly, these frameworks also allow for a large degree of flexibility in the commitment from amateur researchers—an individual can choose when and how much to participate (which may vary substantially among individuals (Wood et al. 2011)). Overall, these advances have not only created more opportunities and broadened access for amateur participation in biology research within the

framework of existing projects, but also provided individuals with access to critical information and training that might allow them to conduct research on a more independent basis. While more “contributory” (Bonney et al. 2009) research efforts are often the focus of discussions of amateur participation, the diversity of ways in which amateurs contribute extends well beyond this.

Community biolabs afford new opportunities for amateur participation in biology research

Laboratory biology has flourished over the last century, as have the number and diversity of specialist instruments involved. Unfortunately the requirement for a dedicated space and specialist equipment creates financial and training barriers for amateur participation as well as logistical barriers around controlled access to research spaces, even with the proliferation of used and low-cost lab equipment available *via* e-commerce sites. However, in the last decade an increasing number of laboratory spaces supporting amateur work have opened that are accessible to amateurs and designed to support their participation in biology work (Landrain et al. 2013; Talbot 2020) (Fig. 1).

DIYbio as a term was first brought to prominence in 2008, with the explicit intent of helping to organize interest and action around the dissemination and use of low-cost biotechnology (Tocchetti 2014). DIYbio has since become an umbrella term used to refer to a broad range of non-traditional bioscience and technology practices and spaces as well as a broader social movement (Delgado 2013; Landrain et al. 2013; Seyfried et al. 2014; Kuznetsov et al. 2015; Ferretti 2019). The broader DIYbio movement includes community biolabs, defined here as not-for-profit laboratory spaces supporting life science activities that can include research, technology development, art, design, education, and outreach. Even this narrow definition encompasses many independent organizations, with different missions, resources, norms, and practices. Community biolabs are distributed across the US and worldwide, each with their own history, norms and supported activities. In the US, early examples include GenSpace (<http://www.genspace.org/>) in Brooklyn, New York (Kean 2011), and BioCurious in Santa Clara, California (<https://biocurious.org/>). To our knowledge, DIYbio sphere (<https://sphere.diybio.org/>) currently provides the most comprehensive online database of community biolabs and associated projects.

Community biolabs have been compared to makerspaces and hackerspaces (Landrain et al. 2013), which similarly provide space, equipment and training for exploration and innovation (Peppler and Bender 2013; Davies 2017; Sang and Simpson 2019). Community biolabs seem to similarly align with a “civic techno-

science” model that has been proposed to understand the activities and goals of makerspaces and related activities (Dickel et al. 2019). Some studies have even included community biolabs as a subcategory of makerspace (Menichinelli and Schmidt 2020). Nevertheless community biolabs have a distinct social history as well as a distinct focus on laboratory biology, meaning in practice different equipment and different supported activities.

Concerns have been raised about whether biosafety, biosecurity and bioethics can be upheld outside of professional environments (Engells and MacIntyre 2016), but amateur research labs have, in general, worked proactively with relevant authorities. They provide lab users with training to facilitate a culture of safety (Scheifele and Burkett 2016) and typically adopt codes of ethics (Keulartz and van den Belt 2016) to encourage responsible working practices. In 2020, a community-developed biosafety manual for amateur research spaces was launched to provide a common reference for biosafety and security practices in community biolabs (<https://www.genspace.org/community-biology-biosafety-handbook>).

Projects conducted at community biolabs are diverse and no central database exists, though platforms such as DIYBio sphere offer a platform to share information on projects (<https://sphere.diybio.org/>) while other platforms such as Just One Giant Lab (jogl.io) facilitate geographically distributed collaborative projects. The Open Insulin project (<https://openinsulin.org/>) is an example of a collaborative effort with participation from amateur research teams at multiple community biolabs with the goal of developing biotechnological solutions to low-cost, open-source insulin production (Gallegos et al. 2018). Community biolabs can also be involved in professional-amateur partnerships. Under the banner of “Barcoding the Harbor,” community researchers at the Baltimore Underground Science Space (<http://bugssonline.org/>) have been working together with professional scientists at the The Institute of Marine and Environmental Technology and conservationists from the National Aquarium to sample the biodiversity of the Baltimore Inner Harbor using DNA barcoding. Employing a similar collaborative approach, researchers at University College London worked with amateur researchers affiliated with the London Biohackspace to characterize *Roseobacter* bacteria as novel chassis organisms for synthetic biology (Borg et al. 2016). In describing the research and how it was conducted, they also describe how undergraduate biology students and professionals from non-biology disciplines were integrated into the project alongside amateurs with no professional scientific research qualifications (Borg et al. 2016). Community biolabs not only support project work within their own labs and among their own mem-

bers but can serve as partners in developing research projects that invite expertise from across disciplines and that blend training opportunities and public outreach with impactful original research.

Some community biolabs also support technology development projects and host biotech start-up businesses. Life science technology innovations are already arising from work at community biolabs, with examples thus far centered on providing lower cost, or simpler, versions of existing technologies. For example, OpenTrons (May 2019) develop, and distribute a low-cost, open-source liquid-handling robot and was started as a project at GenSpace, a community biolab in New York. Low-cost real-time PCR machines now distributed through the company ChaiBio (<https://www.chai.bio.com/>), can be traced back to early work carried out as part of the OpenPCR project initiated at BioCurious in Santa Clara, California. Materials and reagents are also significant cost areas and are being addressed with open, DIY initiatives being pursued at or promoted by community biolabs. The Free Genes project developed by the BioBricks Foundation and Stanford University researchers (<https://biobricks.org/freegenes/https://stanford.freegenes.org/>) has teamed up with the Open Bioeconomy Lab and others to get open biomaterials to practitioners across the globe (<https://openbioeconomy.org/>).

The foundation of the DIYbio organization in 2008 is often cited as an important milestone within the amateur research landscape in the United States (Landrain et al. 2013). In the last decade, a number of meetings, conferences and related activities have been facilitated to further creation of community as well as to establish norms and practices for amateur research labs. Ongoing regular summits that support amateur research labs and associated practices include the Global Community biosummit (biosummit.org), Biohack the planet (biohacktheplanet.com), and the Gathering for Open Science Hardware ([http://openhardware.science](https://openhardware.science)). The international Genetically Engineered Machine (iGEM) student bioengineering competition began in 2004 with five US-based undergraduate teams, in 2019 reaching 353 teams across a range of age levels and geographic regions. iGEM has been identified as a central source of education and inspiration as well as a nucleating activity for many community biolab users (Landrain et al. 2013). Other bioengineering and biodesign competitions have developed in recent years such as the Biodesign challenge (<https://biodesignchallenge.org/>) and the Biomimicry global biodesign challenge (<https://biomimicry.org/design-challenges/>). This small ecosystem of community platforms, including conferences and competitions, is supporting the further growth and spread of amateur research laboratories.

Beyond the scientific research projects carried out at community biolabs, we see their potential to serve as a platform for stakeholder engagement, contributing to the collective strength and resilience of communities. Their accessibility can facilitate intersectional collaboration in biology initiatives, including those that address emergent and/or unique community needs. For example, initiatives such as The Essential Ag Worker PPE Initiative by Xinampa (<https://xinampa.bio/ppe>), which coordinated local distributed manufacturing and large-scale distribution of personal protective equipment to essential farm workers during the COVID-19 pandemic, demonstrate the power of community-centered coordination. Another example is Xinampa's public interest technology partnership with the Tech Interactive, Bio + Food + Tech (<https://bioplusfoodplustech.weebly.com>) to co-create an asynchronous forum to explore community feedback and thoughts on how to better design and develop culturally relevant and inclusive youth engagement around the topics of agtech, biotech, and food systems. Community biolabs also act as learning hubs and generators of STEM outreach initiatives and education programming. For example, in partnership with Stanford University student groups, Xinampa co-facilitates BioJam (<https://biojamcamp.weebly.com>), a free academic program that "engages high school students in biology, art, and engineering through their own culture and creativity." Amateur research labs can serve as points of nucleation for new types of community initiatives based around science and technology, bringing together sets of individuals and groups that might not otherwise meet to form meaningful connections.

How you can support amateur participation in biology research

Investments can be made by a range of stakeholders to help amateur biology research thrive. While amateur biology research is a cost-effective approach to address research questions, it still requires time and money to function in a meaningful way (McKinley et al. 2017). While financial investment is essential, time and expertise are equally valuable. The following illustrative examples are provided for current professional biology researchers and administrators, particularly those working within academia, and should not be seen as an exhaustive list.

- (i) Initiate an amateur research project. Professional biology researchers have a critical role to play in the facilitation of amateur research. Even projects that are co-designed with amateur researchers will necessarily be shaped by professional support with

which they are provided. This support can come in the form of professionals designing or helping to design projects that integrate amateurs into the research process (Rudko et al. 2020). Leveraging existing expertise and knowledge of amateurs, engaging in community priorities (issues that matter to would-be amateur researchers), and involving participants throughout the scientific process can help to facilitate continued engagement of a diverse set of communities and provide participants with a sense of ownership of the project (Pandya 2012). Those in a relevant position of influence can also seek to leverage institutional resources for greater return (see the Cornell Lab of Ornithology's eBird program (Sullivan et al. 2014) as a template for how this might be accomplished).

- (ii) Reach out to existing amateur science initiatives. Professionals might also facilitate amateur research by getting involved within existing frameworks, providing training, mentorship, expertise, and field-specific knowledge. Community biolabs in particular offer the chance for professionals to act as strong partners and collaborators without having to invest in the research infrastructure, or recruit participants. Other science-focused institutions that engage with the community, such as museums and nature centers, may also have opportunities for professional researchers based outside of those institutions to engage with amateur researchers or those interested in making an impact on the development of the next generation of STEM talent, supporting young people carrying out their first research projects in community biolabs could be a particularly rewarding activity (Grobler 2018; Thiagarajan 2018). Additionally, professionals can help by disseminating and publicizing results from amateur research projects more widely, which can help build momentum behind a project and illustrate the value of the work that participants are undertaking (Pandya 2012).
- (iii) Support amateur biology through your research. Much research has been published on the practices and benefits of amateur biology research as well as concerns and risks in areas of biosafety and biosecurity. An important but less explored opportunity is in systems design research to support laboratory biology work outside of institutions (Kuznetsov et al. 2012; Fernando 2019). Numerous design guidelines and tools have been developed to support large online citizen or community science projects (Charlene Jennett 2014; Tinati et al. 2015), but there is little similar work focused on supporting research work in community biolabs or similar settings. In addition, since educational interventions can and should be optimized to the delivery setting (Wang et al. 2006; Delaney et al. 2008; Penuel and Fishman 2012), we believe that research on the effective design of STEM education interventions delivered in or including community biolabs is another important area for future research.
- (iv) Support the development of standards and best practices. Professional biology researchers can also support amateur research by helping to develop a set of best practices either by communicating their own experiences working within amateur research settings, or through participation in deliberative processes. In the USA, community biology lab spaces fall outside the bounds of bodies that traditionally regulate biological research (Fuisz 2017). Due to these holes in regulatory structure, non-institutional biolab spaces are currently monitored by the Federal Bureau of Investigation (Sara and Sara 2015; Wolinsky 2016). New ways of doing research will require new ways of ensuring that this research is done safely and ethically. Institutional actors have a key role to play by engaging with those operating outside of institutions to help to establish a "trust architecture" of systems, mechanisms and standards that will allow amateur research to flourish according to mutually respected ethical standards (Rasmussen et al. 2020). As part of this process, community biolabs could be more formally integrated into institutional bodies that regulate standards and best practices.
- (v) Become an amateur researcher. The overabundance of PhD graduates relative to the availability of long-term academic research positions (Powell 2015), can lead to personal frustration and a diminished return on the societal investment in extensive specialist training. Research pursued outside of academic or established industrial laboratory settings has been suggested as a productive and exciting opportunity for academically trained biologists (Baker 2015). Indeed, people with current or past professional STEM experience were the core of the early DIYbio movement (Tocchetti 2014), with 15% of participants having PhD-level training in biology, according to a 2013 survey (Millet 2013). Conducting research as a professional in one sub-field also does not preclude one from participating in research as an amateur in the same or another field. Indeed, many professional ecologists contribute observations to platforms such as eBird and iNaturalist, even if their own research does not make use of these data.

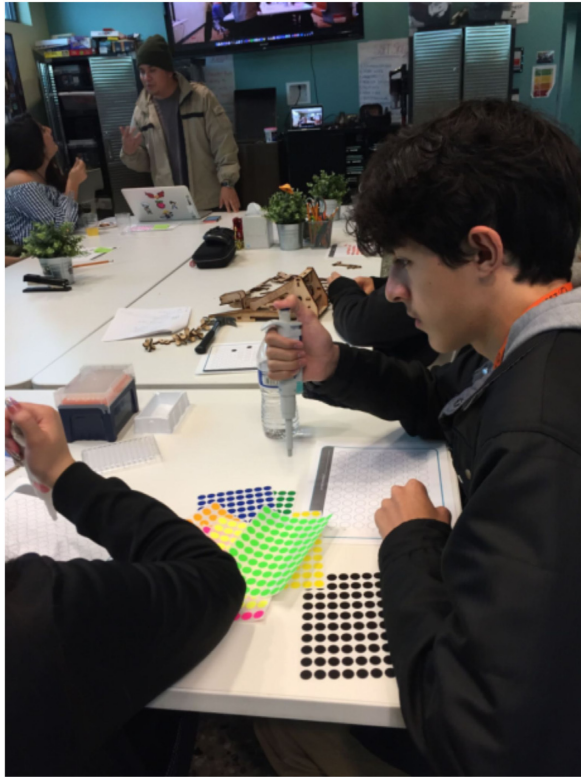


Fig. 1 Amateur biology research and STEM education activities facilitated by Xinampa, community biolab in Salinas, California, whose leadership includes several of the authors of this paper.

- (vi) Increase funding for amateur research initiatives. Individual researchers might accomplish this through existing funding opportunities. For example, amateur research efforts might be funded as a part of the “Broader Impacts” components of National Science Foundation grants, or through funding calls specifically supporting work in this area (e.g., NASA’s Citizen Science for Earth Systems Program). Researchers can also advocate for greater governmental and philanthropic financial investment, which could support, among many options, the establishment of community biolabs, expansion of high-speed broadband as part of improved data infrastructure for amateur research, as well as continuing to support individual citizen or community science projects.
- (vii) Value work that supports amateur research. Government and academic institutions must incentivize professional researchers to get involved with and support amateur research. For example, hiring, promotion, and tenure committees must encourage and reward these efforts. Even those without high levels of institutional influence can provide incentive structures to graduate or undergraduate students that reward involvement with amateur research.

With concerted action amateur biology can drive equity in Science

Exclusion and under-representation in science based on race, gender and economic privilege is a persistent problem in the USA (Riegle-Crumb et al. 2019; NSF 2019) and elsewhere. Starting at an early age, systemic barriers give rise to disparities in STEM motivation and engagement (Betancur et al. 2018) leading to long term disparities in opportunities and employment. While a number of recommendations have been made to address inequity among the ranks of professional science (e.g., (Choo et al. 2019; Schell et al. 2020)), investment in and cultivation of amateur research can also help to provide a platform for more individuals to engage in science (Fig. 1).

However, investments must be approached with equity in mind. Many citizen or community science platforms have suffered from many of the same issues as professional science, with initiatives not reaching historically underrepresented groups (Pandya 2012).

Since amateur research is not a full-time paid activity, there is a persistent risk of access being restricted to those with the financial means to volunteer their time and labor. This echoes issues seen in fields such as conservation biology, which rely on an abundance of unpaid volunteers, perpetuating inequality in the discipline (Vercammen et al. 2020). Participation at

most community biolabs not only comes with a lack of financial compensation but instead requires paying fees. As noted above, community biolabs are frequently used by people with professional biology training, potentially creating situations where these sites facilitate financially well-resourced individuals gaining direct access to professional expertise, exacerbating, rather than diminishing, structural inequalities with regard to access to STEM careers and resources. For many amateur research projects, funding even basic overhead remains a consistent concern, forcing some amateur research labs to choose between making their spaces truly accessible and charging fees high enough to cover the considerable operational costs inherent in running even a low-cost community biolab (Scheifele and Burkett 2016). We advocate that through external support and setting of internal priorities, amateur research initiatives, including but not limited to community biolabs, should offer financial support to ensure broad access as a first step to participation.

Broadening access is not just a matter of removing cost barriers. People must know about the existence of a space or program, feel motivated to engage with it and feel comfortable continuing to participate. It seems reasonable to expect that non-institutional settings, such as community labs, might be inherently more welcoming and inclusive spaces and consequently more conducive to diverse participation. However, the opposite can also arise if amateur communities, with little to no external oversight, develop intimidating and exclusionary cultures (Reagle 2013; Lam et al. 2019). Those engaged in amateur research initiatives should pursue concerted action to address inequities that might be programmed into or unintentionally arise from the design of a particular initiative (Ahmadi et al. 2019; Cooper et al. 2021; Davishahl 2021).

With proper investment, broadening access to biology research and science literacy that is grounded in culturally relevant pedagogies (Brown 2021), could give amateur researchers who have varying degrees of expertise, the opportunity to be enfranchised and to use science as a medium to learn, explore, and develop technologies for the public interest. Spaces such as community biolabs are already meeting points for scientists, entrepreneurs, and enthusiasts. Funding programs that engage a broader, diverse community could be a pathway to achieve equitable opportunities that can lead to more robust solutions for projected challenges in the 21st Century.

Conclusion

Amateur researchers have played a central role in the field of biology since its inception. While that role has

changed over the last several centuries, thanks to new technologies and practices developed in recent decades there has never been a better time to invest in amateur participation in biology research in terms of avenues for investment and returns on investment for both science and society. Amateur involvement in research can help to broaden participation in the field, reach more people with science, incorporate more perspectives, and ultimately help to reintegrate the field of biology. Addressing the grand challenges of our field will take a diversity of perspectives and approaches, and amateur researchers can help to make these efforts a success that benefits everyone. We envision a future where biology research is, by default, collaborative and interdisciplinary, and we believe that a key step in achieving this goal is making greater investments of diverse resources into the integration of amateurs into biology research.

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Data availability statement

No new data were generated or analyzed in support of this research.

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