



Cultivating Bioliteracy, Biodiscovery, Data Literacy, and Ecological Monitoring in Undergraduate Courses with iNaturalist

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CASE STUDIES

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ABSTRACT

iNaturalist is a large and growing open-source online platform connecting a global community of users to the natural world and to each other. iNaturalist makes it simple for anyone to share observations, get identifications, and make identifications of any species. We demonstrate how iNaturalist can connect students to nature in undergraduate courses, simultaneously contributing to biodiversity knowledge. Our three case studies use iNaturalist to improve student bioliteracy (awareness and knowledge of biodiversity), to engage them in biodiscovery (discovering undocumented biodiversity occurrences, behaviors, and interactions), to introduce students to systematic ecological sampling (documenting biodiversity patterns and trends), and to improve their data literacy (by depositing and accessing open biodiversity data and by performing analyses). Included are examples from a variety of contexts—a required general science course, introductory courses for science majors, and more specialized electives. We discuss the rationale for iNaturalist inclusion, how iNaturalist inspires students and complements courses, and outputs of our students' iNaturalist use. Introducing students to tools such as iNaturalist helps build the next generation of bioliterate and biocurious citizens and scientists, fluent in open collaborative research and learning. With wider uptake and coordination, iNaturalist has potential to connect undergraduate ecology courses to form a distributed virtual global biodiversity observatory.

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INTRODUCTION

The biodiversity crisis looms large (IPBES 2019), with numerous and varied causes behind species declines and extinctions (Rosenberg et al. 2019; Wagner et al. 2021). In addition to conserving and preserving the wild (and not so wild) spaces where species exist, the moment is now for widespread participatory action. Together with our students, we need to act, using available technology and tools. For most taxa, in most places, we do not know what is increasing or declining (Dirzo et al. 2014), and there are many impediments to understanding the changes happening in the natural world. Educators have a unique responsibility, and opportunity, to engage with students to advance knowledge of species and to collectively discover, monitor, and celebrate biodiversity. We need more biodiversity data, and we need it to be open and use international data standards (Morrison et al. 2017).

Enter iNaturalist, a global social platform where anyone can make, share, identify, discuss, and download observations of organisms (iNaturalist 2021). iNaturalist is not a traditional citizen science project with prescribed methodologies, nor is it primarily a data repository, but it can be those things; what iNaturalist is, is flexible. This

flexibility makes it useful in undergraduate courses; as we demonstrate here, it is a tool for improving bioliteracy, biodiscovery, and data literacy (**Figure 1**).

iNaturalist is freely accessible as a website and as a mobile application, and is a joint initiative of the California Academy of Sciences and the National Geographic Society. Its primary goal is to “connect people to nature,” with the secondary goal to “generate scientifically valuable biodiversity data from these personal encounters” (iNaturalist 2021). Using iNaturalist is as simple as uploading a photo or sound recording and letting the community and/or computer vision suggest identifications. “Projects” on iNaturalist can aggregate and curate observations for particular purposes. Collection Projects automatically aggregate observations using a set of rules. Umbrella Projects group projects for comparison. Traditional Projects require users to manually add observations, with options for custom **observation fields**. Although collecting structured monitoring data is not the platform’s focus, students can make consistent observations using Traditional Projects with observation fields in a way suitable for simple ecological monitoring.

Undergraduate courses can make valuable contributions to biodiversity knowledge by using iNaturalist. We can train students who are open to learning from all sources

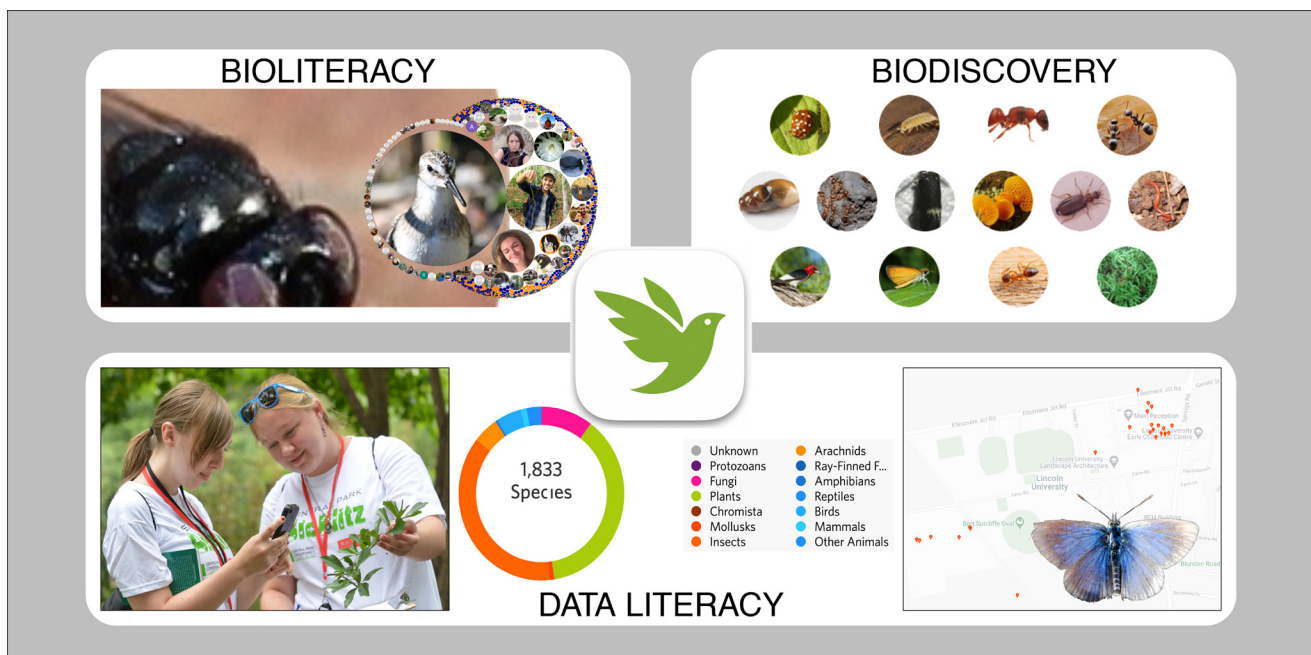


Figure 1 iNaturalist has many uses in undergraduate teaching. It can increase bioliteracy, providing students experiences finding, identifying, and learning about biodiversity. The circles and iNaturalist profile pictures are our students, scaled by their total number of iNaturalist observations. The massive fly icon in the background is @edanko, a user with 29,235 observations. Among these observations are biodiscoveries, including species observed by our students not otherwise recorded on iNaturalist from our project areas. See the text for details of the species profiled with icons. By creating, exploring, and mapping open data, students gain skills in data literacy. Data literacy is illustrated by a photo of a student observing with the iNaturalist app, an iNaturalist display of the species observed in the Brandeis University biodiversity project, and an iNaturalist map of students’ observations of the New Zealand (NZ) blue butterfly, *Zizina oxleyi*, from Lincoln University. See Figures 2 and 3 for examples of simple ecological monitoring.

of expertise, and who share their biological knowledge (building bioliteracy) in their communities. Bioliteracy can take many forms, from being aware of the ecosystem services biodiversity provides, to being able to identify local species by name and learning about their natural history (Janzen 2001). As students use iNaturalist, they can also contribute to biodiscovery (Gazdic and Groom 2019; Putman et al. 2021) and ecological monitoring (Forister et al. 2021). We define biodiscovery as the discovery of new species, interactions, and behaviors not previously recorded in a place and time period. Students learn and discover by contributing open, public, standards-compliant biodiversity knowledge and ecological data.

The study of natural history and the collection and curation of biological specimens is declining across higher education institutions (Tewksbury et al. 2014). For many students, learning about natural history is relegated to accessing off-campus networks, like natural history societies, where it is still celebrated. The decline of natural history in academia is not just concerning on its own, but is potentially limiting the ecological advances that might be made by our students (Able 2016; Barrows, Murphy-Mariscal, and Hernandez 2016). An action we can take now is advocating for students to discover natural history through tools like iNaturalist.

iNaturalist also provides an opportunity to focus on data literacy. Data literacy in biology is defined broadly to include basic numeracy, graphical interpretation, knowing which analytical tools to use, using data to answer questions, and clearly communicating results (Gibson and Mourad 2018). These skills were emphasized in *Vision and Change* (AAAS 2011), which included quantitative reasoning and modeling and simulation as core competencies. Student learning can be part of data collection, and science outcomes can be part of their learning. iNaturalist's data are open and straightforward to access and download, and students can contribute to the data as they practice data literacy skills.

iNaturalist is useful in data literacy training because it is open, flexible, and authentic. Students gain skills collecting, managing, analyzing, and visualizing data. By querying iNaturalist, students develop skills related to identifying data appropriate to a question. The global species occurrence data allows students to make broad comparisons of different areas and to think about issues across scales, whereas customizable observation fields facilitate collection of more structured ecological data. iNaturalist data are authentic because they are real data vetted by a large community that can be used to answer real and novel questions (Moore et al. 2019), instead of demonstration datasets or simulated classroom datasets. There is also value to handling “messy” data; students' data literacy can benefit from learning how to deal with

missing values, non-significant results, or mis-identified outliers (Kjelvik and Schultheis 2019).

CASE STUDIES: INATURALIST IN UNDERGRADUATE COURSES

We share our experiences with iNaturalist here, not as a how-to guide, but to illustrate the ways it can complement courses and to inspire other faculty to find a place for iNaturalist in their teaching. We bring the perspectives of a small United States (USA) liberal arts university (Brandeis University: Hitchcock), a small public New Zealand (NZ) university (Lincoln University: Sullivan), and a large USA multi-campus public university (Macaulay Honors College at the City University of New York: O'Donnell). Supplemental Table 1 provides greater detail about our institutions and courses, along with project and course/assignment details (with links).

WHY INATURALIST

There are many advantages, and some potential challenges, to using iNaturalist in our courses. iNaturalist connects students to a wider range of taxonomic expertise than we could provide, allowing students to identify a wider diversity of taxa to species level, and connects them to an enthusiastic and knowledgeable community to support their learning. iNaturalist use in courses has the flexibility to encourage a habit of observation, creates opportunity for discovery, and builds a sense of community among the students, while building species lists for study locations. It facilitates the generation of student-built course datasets, and collects and stores data in a systematic, robust way that supports inquiry. [Table 1](#) outlines how we meet learning goals around bioliteracy, biodiscovery, and data literacy, and Supplemental Table 2 shares accommodations made to address student accessibility issues when using iNaturalist.

HOW WE USED INATURALIST

Brandeis University

iNaturalist use began in 2016 as a single assignment in a biology elective (Conservation Biology) and has evolved into a semester-long bioliteracy project. In 2017, iNaturalist was integrated as a companion for a summer non-major online course (Biodiversity Connections). In addition, we host the place-defined *Brandeis University Biodiversity* Collection Project which is used to visualize data across years and to engage our campus community.

In Conservation Biology, engagement begins in January and culminates with the global *City Nature Challenge* (CNC) in April. Although students in this large lecture course are uniform in their concern for nature, few can identify species, have used field guides, or are familiar with natural history.

LEARNING OBJECTIVE	HOW ACHIEVED WITH INATURALIST
Biocuriousity & bioliteracy	
Inspire curiosity about the natural world	iNaturalist facilitates students finding and identifying species that are beyond the expertise of the course instructors. Students can be motivated by the enthusiasm expressed by the iNaturalist community.
Increase student proficiency in recognizing and identifying species and higher taxa	iNaturalist's Computer Vision and crowdsourced identifications provide students with prompt and reliable identifications for a broad diversity of taxa. iNaturalist taxon pages provide reliable information on taxa. Instructor feedback both inside and outside of the platform helps ensure success, and the iNaturalist connection to R also allows us to automate some student feedback by automatically detecting mistakes and omissions in student observations.
Familiarize students with a modern tool for identifying biodiversity	Students install the iNaturalist app on their devices, which allows them to identify any species at any time, outside the classroom and into their careers.
Biodiscovery & ecological monitoring	
Demonstrate how data collection and science research can be the byproduct of their learning	Class observations on iNaturalist can be amassed in Projects, either automatically in Collection Projects or by students adding manually to Traditional Projects. Both make it quick to highlight commonly and rarely observed species and map species distributions. When their observations become Research Grade and are uploaded to the Global Biodiversity Information Facility (GBIF), the students are potentially contributing to research projects at other institutions.
Participate in biodiscovery	iNaturalist allows instructors to encourage their students to observe a wide range of taxa. This eventually (often quite quickly) results in student discoveries of new species in an area, or rediscoveries of species not observed in an area for decades, or previously undocumented species interactions (iNaturalist's observations with interactions become part of Global Biotic Interactions [GloBI]).
Learn to collect consistent data with standard methods for use in ecological monitoring	Simple monitoring can be done on iNaturalist using Traditional Projects. These can be set up to require students to enter survey details into iNaturalist's observation fields. This, when combined with iNaturalist's powerful species-identification capabilities, make it a useful tool for ecological monitoring by students.
Data literacy	
Learn to observe carefully and record data precisely and accurately.	Students observation entry into iNaturalist allows their observations to be scrutinized and, if necessary, corrected, on iNaturalist by instructors, by other students, and by other iNaturalist users. Such iterative feedback helps to improve students' observation skills while increasing their bioliteracy and confidence using iNaturalist. Note that it is important to focus students on observation quality, not quantity, to reduce any incentive to upload fake observations or identifications.
Introduce students to open science practices	All iNaturalist observations are publicly visible (although the locations can optionally be made private or obscured on public maps). Students are introduced to the importance of open licenses for data. All students' open Research Grade data on iNaturalist is shared with the GBIF for global research use. We reserve time in class to collectively view and discuss student observations and identifications as a group. We use time together to learn from our mistakes, to discuss best practices, and to celebrate our successes.
Learn how to process and analyze real data to answer novel questions	iNaturalist's flexible mapping search tools and the CSV export option provide students and instructors with a convenient way to map, display, and begin to analyze data. The iNaturalist API and its integration with R allows higher-level undergraduates direct access to all iNaturalist data for analysis and graphing. Students can pose, and answer, novel ecological questions using real data.

Table 1 How undergraduate learning objectives around biocuriousity and bioliteracy, biodiscovery and ecological monitoring, and data literacy, can all be met by incorporating iNaturalist into undergraduate courses. The three case studies detailed in the text differ in their emphasis on each objective.

Annually, we create a date-defined Collection Project to observe within the iNaturalist place "*Brandeis University & Surrounding Area*."

A series of scaffolded assignments, aimed at improving students' bioliteracy, guides the observation process. First, students make a few observations and receive detailed

feedback (inside and outside of the platform) on both the quality of observations and recommendations for field guides to support identifications. Next, students improve their observations following instructor feedback and iNaturalist community interactions. Then, observations resume with either a taxonomic or location focus. Each assignment has explicit directions on how, when, what (loosely defined), and where to observe.

Throughout the semester, students learn about natural history collections, the biodiversity crisis, and the application of publicly generated data, thus reinforcing how their observations complement course content. CNC participation is the last assignment, which shifts the focus of student learning from their own bioliteracy to collective public participatory action to document biodiversity. Work culminates in a writing assignment reflecting on how their bioliteracy has changed, and on their learning about the potential scientific value of their observations.

Biodiversity Connections, a small asynchronous non-major online summer course, introduces students to basic topics in ecology and evolution. Community is created through a user-defined iNaturalist project in which observations from our often globally distributed students are shared. Observations are made in response to prompts relating to that week's topics. Students simultaneously receive feedback (peer and instructor) about their observation skills and how their observations meet the prompts. Given the ephemeral nature of our community, the project is dissolved at the end of the semester (but see Supplemental Table 1). The project's dissolution does not affect the retention of its iNaturalist observations, which continue to inform collective biodiversity knowledge.

Lincoln University

In 2013, we started using iNaturalist in our second-year Biological Diversity course, replacing ecological monitoring data spreadsheet templates. Use has since expanded into other science courses. iNaturalist is used for the entry, storage, identification, and data visualization of students' species observations.

In the Invertebrate and Microbial Biology course, we use iNaturalist for bioliteracy and biodiscovery in two 3-hour pollinator labs to get students to explore the insect diversity on campus and at their homes, to think about these species' ecosystem services, and to identify insects. We focus on insects visiting flowers, and students upload each of their plant and insect observations (up to 10) to our *Bios110 Pollinator Project*, first identifying insects using our key and then identifying them to lower taxa using iNaturalist's Computer Vision and identifiers.

In our second-year Biological Diversity course, five 3-hour labs and a 3-day field trip are paired with student

iNaturalist activities focused on specific taxonomic groups. Students learn how to identify species in a particular taxonomic group, and then practice surveying that group using iNaturalist. We use simple consistent sampling methods (Supplemental Table 1), to enable students to compare what they find with the discoveries of other students past and present. Traditional Projects are used with required and recommended observation fields to collect standardized ecological data. This has been a more efficient and accurate way to create a class dataset than our earlier approach of using validated spreadsheet templates (which never proved validated enough for some students not to break).

We extend this approach the following semester in our Field Ecology Methods course, where we monitor biodiversity across campus along six permanent transects. After each week's field sampling, students analyze and graph the patterns and trends in the data. We use R to connect to the datasets via the iNaturalist API (Application Programming Interface, <https://api.inaturalist.org/>). While students are not expected to write their own R scripts, they learn how to run R scripts, modify them to select a species for analysis, and interpret the statistics results and graphs.

Macaulay Honors College

Since 2013, iNaturalist has been used during an experiential learning event associated with Macaulay's required science course, Science Forward (SF), taken by approximately 500 sophomores every fall across eight CUNY colleges and taught by about 30 faculty. The SF curriculum is interdisciplinary and skills-focused, and since it's a required course, designed for a mix of science majors and non-majors. The interdisciplinarity shows students there is a common set of Science Sense skills that all scientists have: Number Sense (basic numeracy, unit conversion, etc.), Data Sense (data literacy skills such as data collection, analysis, visualization, etc.), and Knowledge Sense (experimental design, ethics, developing questions/hypotheses, etc.).

SF was designed to be experiential; students should learn how science works and practice the skills through engaging in the scientific process. To do this, SF begins with a 24-hour species diversity survey (a BioBlitz) of a green space in New York City. Students from all campuses complete a three-hour shift on small teams led by taxonomic experts. Data are collected on paper and with iNaturalist. In 2020, the Remote Macaulay Honors College BioBlitz was completed using only iNaturalist.

For each BioBlitz, we use a date- and place-defined Collection Project and send both students and taxonomic team leaders guidance on using iNaturalist. Each small team designates a person to be the iNaturalist recorder (a role that can rotate). Because students do not usually have

taxonomic experience, iNaturalist allows team members to split up and still inventory species even if they are not able to immediately identify them. The project page can be projected at the BioBlitz basecamp, providing an exciting live stream of observations to students waiting for their shifts to start. As the event goes on, they can see their combined effort and celebrate what they have accomplished together.

SF faculty come from diverse disciplines and choose exactly how they use the data in class. BioBlitz data should be used to support the learning objectives of the course, particularly those related to data literacy skills. The *SF Open Educational Resource* (O'Donnell, Brundage, and Ugoretz 2014) provides faculty with recommendations for using the data and structuring a research poster project. Faculty are encouraged to have students use iNaturalist data for the required SF poster project because they can engage with the scientific process from question formulation to results presentation. Students have a sense of ownership over these data and can practice a whole host of Science Sense skills as they build their original research project. They must ask a scientific question, extract the data necessary to answer it, analyze and visualize data, then draw conclusions and communicate their findings. This poster project is scaffolded throughout the semester so students can take the time to practice skills. Students learn how to use tools to manage, organize, and manipulate a large dataset. They need to figure out the best way to visualize data to clearly communicate their results and to address any biases that may come from these publicly collected data.

COVID RESPONSE

At all three institutions, iNaturalist's flexibility allowed for a smooth transition to fully remote learning during the 2020 COVID-19 pandemic. Place-based projects were switched to user-based ones to allow students to observe from wherever they were, and instructional sessions to guide the students were conducted via Zoom. Courses that used formal ecological survey-based projects using university equipment transitioned to a package of at-home activities. If students were not comfortable leaving their homes, we suggested observations that could be made from home or assigned annotation tasks instead. Students were still able to work on a project together and interact with the iNaturalist community with the added bonus, in some cases, of now exploring peer observations on a global scale.

DATA METHODS FOR ASSESSING BIOLITERACY AND BIODISCOVERY

An important feature of iNaturalist is that all data are easily downloadable as CSV spreadsheets (and KML maps).

If needed, more observation details can be obtained via iNaturalist's API, which returns requests in JSON format. For example, the API can list who made identifications and comments for each observation, and when, while the CSV spreadsheet provides only the current best identification and the number of agreements and disagreements. We use the API here to make an assessment of activity on our class projects, while students in most of our courses use only the iNaturalist website or the CSV spreadsheets.

Note that the API is designed to aid developers in adding iNaturalist functionality to their apps. Although it can be used to extract rich data, it should not be used to scrape large amounts of data. For large datasets, iNaturalist provides a *downloadable archive*, updated weekly, of all Research Grade data (this is the dataset shared with the Global Biodiversity Information Facility [GBIF]). Non-captive/cultivated observations in iNaturalist become Research Grade when more than 2/3 of identifiers are in agreement at genus level or lower, and there are supporting photo(s) or audio (Ueda 2021).

We used the *jsonlite* (Ooms 2014) and *iNatTools* (Hanly 2019) packages for R (R Core Team 2021) to connect to the iNaturalist API and download relevant data (Ueda 2021). *iNatTools* was used to download each course project's data, and *jsonlite* was used to download the taxa and number of observations made on iNaturalist within the bounds of our place-based projects, using the *observations/species_counts* and *observations/histogram* API calls. We used the 2.5% and 97.5% quantiles of each project's observation latitudes and longitudes to define its boundaries, to exclude any distant outliers. We also repeated these calls for observations and taxa within a 50 km by 50 km square centered around each of our projects. This was done to assess how many students' observations were important biodiscoveries, both within the project bounds and at this larger scale. We did not do this for our widely dispersed projects when students participated remotely during COVID-19 lockdown.

We excluded all course project observations made by faculty, teaching assistants, and associated experts (145 users), and the results section below reports the remaining observations. We counted the numbers of observations, photos, taxa contributed by our students, and calculated metrics of observation quality (e.g., how precisely could they be identified by the iNaturalist community) and students' identification accuracy, to measure their gains in bioliteracy. We also compared how many observations each student made in our projects and made in total as a measure of bioliteracy change. Almost all students are new to iNaturalist when they join courses, and the observations they contributed to iNaturalist outside of our projects were (mostly) made after our courses began.

We compared students' observations with all observations made in the project areas, and listed taxa that were first observed in the area by students, or are among ten or less observations of a taxon in the area, or are still the only observations of a taxon in this area. For all observations of taxa only observed in the area by our students, we manually checked identifications, where necessary by contacting relevant taxonomic experts. One observation (a fish) was identified to the wrong species, and another (a wasp) was identified to a plausible species but could not be identified with certainty from the photo. We highlight only vetted taxa as examples in the Biodiscovery section below, but we did not manually vet the hundreds of student observations of taxa that were in the ≤ 10 observations of each taxon in the area.

RESULTS OF INATURALIST USE

As of March 2021, 2,691 students in our course projects had made 66,249 observations of 5,278 taxa, including 3,269 taxa identified to the species level or below (Supplemental Table 3). These observations were supported by the students' 103,235 photos and 68,604 identifications. Excluding the students, faculty, teaching assistants, and experts directly assisting with courses, 3,070 iNaturalist users made identifications on students' observations, and 149 iNaturalist users made comments. In total, the iNaturalist community made 88,800 identifications on the students' observations, and there were 6,783 comments discussing these observations.

BIOLITERACY

iNaturalist gave students an opportunity to identify a wide range of taxa, including taxa beyond the expertise of the staff in our courses (Supplemental Table 2). The first identification was provided by the student on 90% of their observations, often guided by suggestions from iNaturalist's machine learning, which is called Computer Vision. Of these first identifications, 22% were exactly correct at the species level, 24% were higher taxa of the correct species, and 36% of students' first identifications were wrong and were later corrected by other iNaturalist users, often with comments. The remaining 18% have only student IDs, and are mostly of birds and butterflies of which the students were unable to get a photo. Wrong IDs are not bad; being curious about nature and willing to make and learn from wrong identifications are important ways to gain bioliteracy, as is working with the community to correct them.

Many students continued to use iNaturalist beyond our courses (36% Brandeis, 60% Lincoln, 31% Macaulay). Although most continuing students made few other

observations (median 4 observations, mean 46, s.d. 698), some students became frequent iNaturalist users, with 43 students each making more than 100 observations outside of courses. Although not a focus in our courses or part of graded assignments, 11.7% of students also made identifications on other iNaturalist observations, together contributing 199,861 identifications (36 students made 100 or more identifications, including 166,760 made by Brandeis student @edanko).

BIODISCOVERY

By focusing observations in one location, most of our projects documented species occurrences in these areas that have otherwise not been made on iNaturalist (Supplemental Table 4), even with more than 69 million observations now on the platform, including more than 34 million observations of more than 85,000 species in the USA, and more than 1 million observations of almost 20,000 species in NZ (Ueda 2021). For example, the 2015 Macaulay BioBlitz in Freshkills Park, New York, included 36 Research Grade observations not otherwise observed in Freshkills Park, among 60 taxa observed ≤ 10 times in the area on iNaturalist.

Impressively, when we placed a 50 km by 50 km square around our place-based course projects, there were still some Research Grade student observations of taxa that have not otherwise been reported from these areas. The student activities on the Brandeis campus have made Research Grade observations of 48 taxa otherwise not yet observed on iNaturalist within a 50 km by 50 km square around the campus. These are among 225 taxa that were observed by students and recorded ≤ 10 times in this area.

Among the notable species biodiscoveries (**Figure 1**) made by Macaulay students are four from our 2017 Alley Pond Park BioBlitz: the red-headed woodpecker, *Melanerpes erythrocephalus*, observed by @wvitiello527 and @danielkruglyak; the least skipper, *Ancyloxypha numitor*, observed by @elyas; the yellow-footed ant, *Nylanderia flavipes*, observed by @meganjeanlouis; and Japanese stiltgrass, *Microstegium vimineum*, observed by @edecaudin, @leahriella98, and @jadyynnmarshall. All are currently the only iNaturalist observations from this 265-ha park. *Melanerpes erythrocephalus* has been observed only 67 times in all of the New York City area. Our observation of *Ancyloxypha numitor* was the fifth observation of this species in New York City, and it has been observed only 54 times. *Nylanderia flavipes* has been observed only 12 times in New York City, and only 130 times in all of iNaturalist globally. *Microstegium vimineum* is an invasive plant native to southeast Asia, and our Alley Park records were the second observation on iNaturalist of this species in New York City. Another notable find is the glossy pillar snail, *Cochlicopa lubrica*, observed

by @sheenachin in the New York Botanical Gardens, which is the only observation of this species at this site and one of only 32 observations of this species from New York City.

Notable species discoveries made by Lincoln students include the small brown bush ant, *Prolasius advenus*, found by @frank_zhao_1102333 in a garden pitfall trap. This is one of only four iNaturalist observations of this species from the Canterbury region and the only lowland observation. The moth, *Heliozela catoptrias*, by @ashishthakur1, which was visiting a flower on campus, is the only South Island observation. Student @akika made the only observation of the naturalized fungus, *Favolaschia calocera*, in the Lincoln area, and @flora_w made the only observation of the beetle *Dromius meridionalis* from our campus.

At Brandeis, @eskybar123 made what is currently the only observation of the centipede *Strigamia bothriopus*, and @metzbach made the only observation of the cream-spotted ladybird, *Calvia quatuordecimguttata*, in the wider Boston area. Dedicated entomology student @edanko found several insect species that provided the only observations from the wider Boston area, including an observation of the terrestrial cave isopod, *Haplophthalmus danicus*, and an observation of the myrmosid wasp, *Myrmosa unicolor*, which is one of two iNaturalist observations from Massachusetts and of only eight observations from the USA. @edanko's observation of the silvery field ant, *Formica argentea*, is the only iNaturalist observation of this species from Massachusetts, and one of 29 from the USA.

USE OF INATURALIST RESULTS ECOLOGICAL MONITORING

The Lincoln projects are examples of ecological monitoring in which students use our iNaturalist data (past and present) to graph species patterns and trends. Students use simple statistics to assess the significance of these trends. Although this workflow could be done using spreadsheets, iNaturalist has produced cleaner, more accurate, and more taxonomically diverse data.

The Lincoln campus is a combination of an area of campus buildings surrounded by research farms, and one question the students assess using iNaturalist is which species are most abundant in each of these habitats. **Figure 2** shows the results for four birds. The swamp harrier, *Circus approximans*, and Australian magpie, *Gymnorhina tibicen*, are more abundant on the farm campus, and the NZ fantail, *Rhipidura fuliginosa*, and house sparrow, *Passer domesticus*, are more abundant on the built campus. Students are asked to speculate on what mechanisms might be driving these patterns.

Lincoln students also assess trends in species over time. For example, **Figure 3** shows the trend in numbers of the

NZ blue butterfly, *Zizina oxleyi* (Lycaenidae), in the Lincoln area, as revealed by annual 20-minute butterfly counts entered into iNaturalist. This species was rarely sighted in Lincoln before the 2015 demolition of an earthquake-damaged building and a 2017 felling of the surrounding trees. This created a 2-hectare wild, gravel area where the butterflies thrived. Construction has now begun on the replacement building and butterfly numbers have declined. We use trends like this to encourage students to consider what landscape changes benefit different species.

DATA LITERACY

iNaturalist data use differs depending on course type (majors/non-majors) and instructors. In all cases, making observations engages students directly in data collection. While students may or may not be learning field-specific sampling methodologies, they all learn about the importance of consistency and focus in building a robust dataset by contributing observations to an iNaturalist project.

The other data skills students focus on depend on what tools they use to access and interact with data. Students can use iNaturalist's built-in tools to visualize and summarize results. Collection Projects provide a basic summary of all observations collected (totals for observations and species, percentage of Research Grade observations, etc.), and allow students to do filtered searches for specific results (e.g., displaying just the wild plant observations). Simple species lists can be created with focus on specific taxa, and the distribution of observations within any species can be easily mapped within iNaturalist. The URLs of iNaturalist's search pages can be customized to dig deeper into iNaturalist data, like annotations and observation fields (Iwane 2021). For example, in the *Garden Invertebrate Hunt* project, we use this link, https://www.inaturalist.org/observations?project_id=garden-invertebrate-hunt&verifiable=any&view=species&field:garden%20invertebrate%20sampling%20method=at%20night%20light, to show all species that were collected using the "at night light" method.

Data management and analysis skills are practiced when students download data for manipulation in other programs. First, students must decide which data are relevant for the question being asked and set up an observation query via the iNaturalist website. With non-majors, the data download can be taken into a spreadsheet app to produce basic visualizations of species diversity or observation density, to calculate biodiversity indices such as Jaccard or Shannon, or to calculate linear correlations of species or of observation counts. More complex analyses (e.g., using R or GIS) are better matched to those with backgrounds in statistics and ecology. After analysis, students communicate their results.

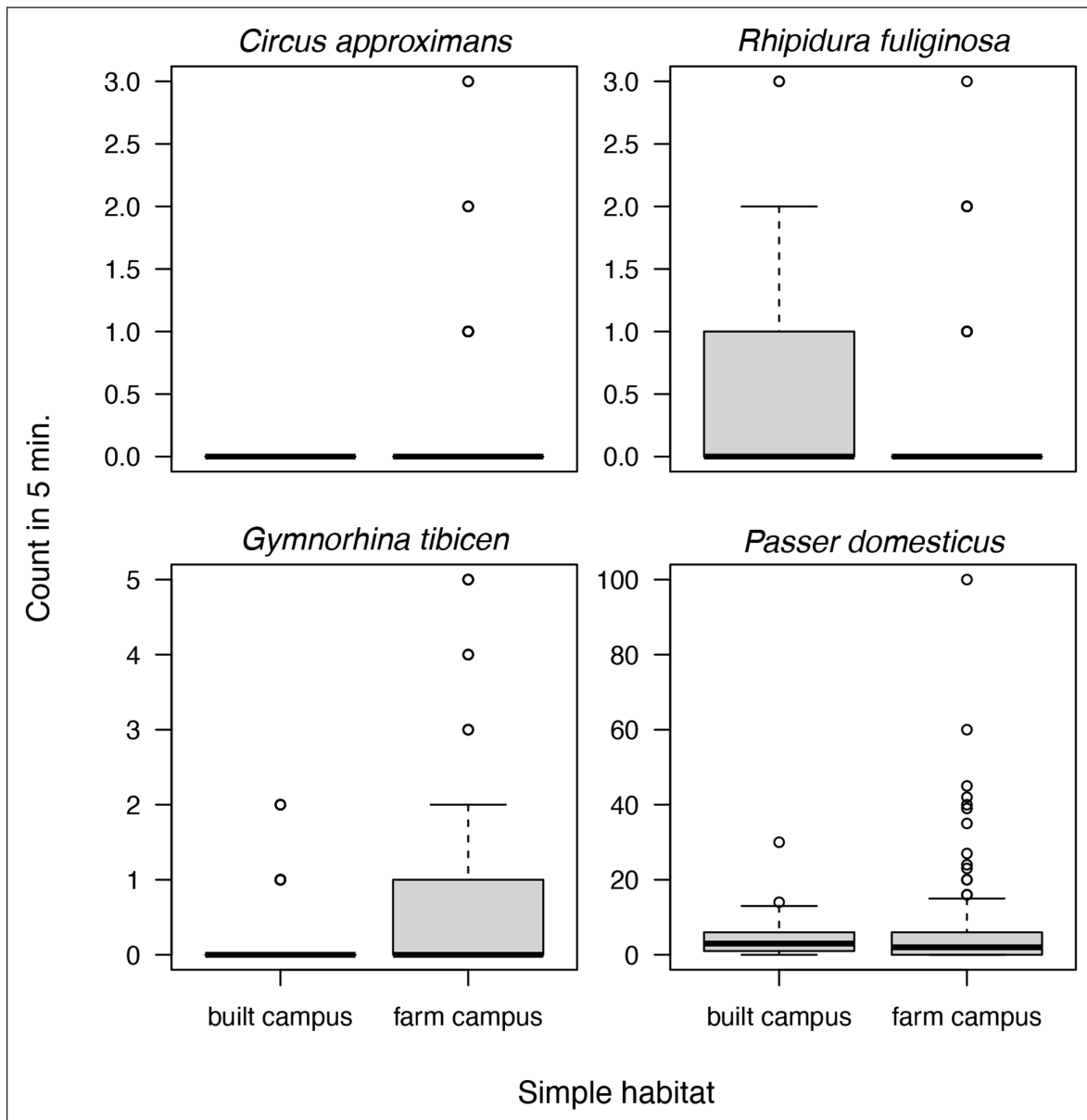


Figure 2 How the abundance of four bird species, as recorded with student five-minute bird counts entered into iNaturalist, differs in the built and farm areas of the campus of Lincoln University. Students enter counts of all the birds they see and hear in their five-minute surveys in observation fields on iNaturalist, which allows the birds not observed to be inferred. The swamp harrier (*Circus approximans*) and New Zealand (NZ) fantail (*Rhipidura fuliginosa*) are native birds, and the Australian magpie (*Gymnorhina tibicen*) and house sparrow (*Passer domesticus*) are introduced birds. Students create these graphs in a class lab.

DISCUSSION

As our case studies demonstrate, iNaturalist's flexibility is a strength for both students and faculty. Students engage differently depending on the course, the learning goals, and the interests, skills, and focus of the faculty. Yes, students may make mistakes in the process, but with a course-based introduction, scaffolded assignments and structured feedback, students learn from those mistakes and engage in practices to make observations that are scientifically relevant. Instructors need to take care that grading

practices, where implemented, do not create perverse incentives for students to behave poorly on iNaturalist (e.g., falsify observations, or purposefully misidentify observations). Key to success is the engagement of faculty alongside students coupled with consistent and detailed feedback to ensure that students contribute positively to the iNaturalist community. Feedback both within and outside of the platform, along with open discussions of both high- and low-quality observations, are practices that help support ethical behavior of students. We do not want our students to be creating inappropriate observations or

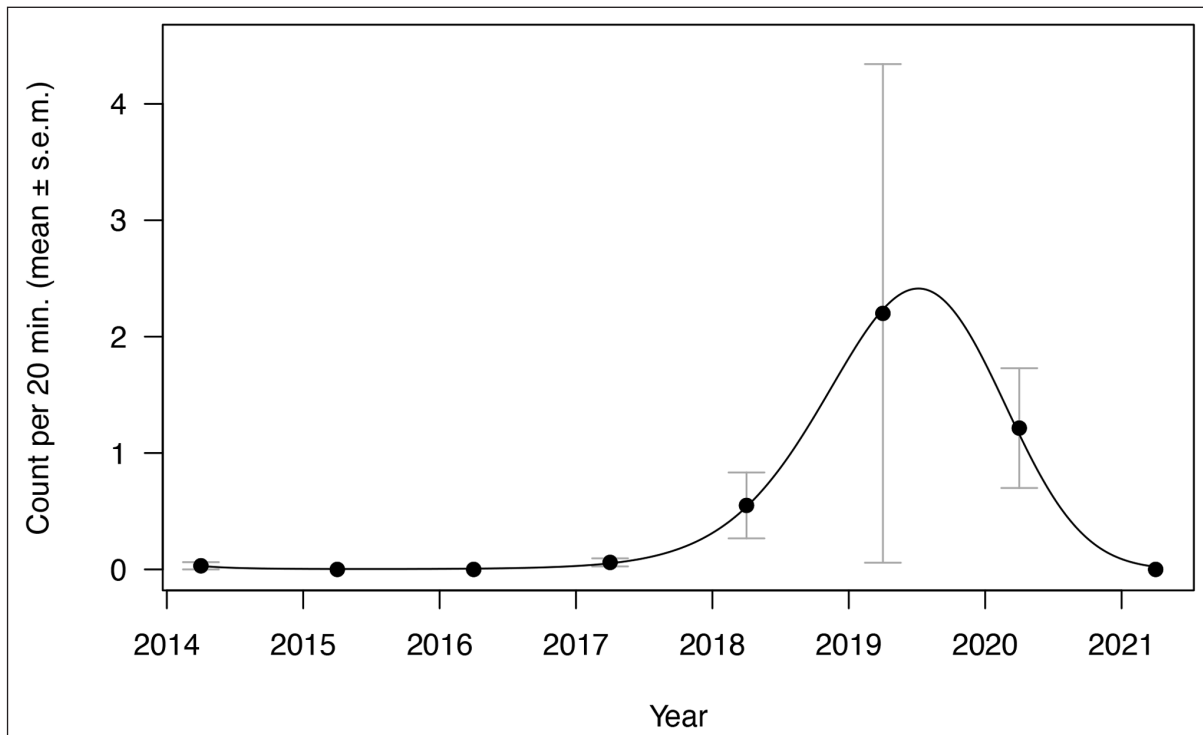


Figure 3 The abundance of the New Zealand (NZ) blue, *Zizina oxleyi*, on Lincoln University's campus since 2014, as revealed by student 20-minute butterfly counts. These were entered into an iNaturalist project that included observation fields for the maximum and minimum counts; the time surveying, in minutes; and whether or not the observer searched for all butterflies. The increase in butterflies corresponded with the clearance of a large building, which created a 2-hectare wild area from late 2017 to the end of 2020. The fitted line is from a quadratic quasipoisson generalized linear model.

identifications just for the sake of a grade. Assessments that focus on making verifiable, information-rich observations (e.g., taking good photos or having complete observation fields) versus those that focus on absolute numbers of observations or identifications help to limit bad behavior.

iNaturalist supports improvements in student bioliteracy through direct observation and students' use of the community's comments and identifications. In the past, these natural history skills would have developed as students created specimen collections. Although specimen collections are now rare in undergraduate biology courses, iNaturalist can facilitate this learning through the curation of a digital collection.

Our analysis of students' contributions via iNaturalist highlights only Research Grade observations, but it is important to note that *all* observations have the potential to be useful for research, with the right checks and caveats (Mugford et al. 2021). Just as there are plenty of non-Research Grade observations that are appropriate for use in research, Research Grade observations also should be checked before using them for research.

For each of us, finding the right fit for our students grew out of our own engagement on the platform, and here we've shared our collective 25 years of experience with students in iNaturalist. It is important for faculty to engage on the

platform, demonstrating how to provide feedback to others (giving as well as receiving), and discussing at frequent intervals what makes good observations. Students see us continuing to advance our own bioliteracy (making mistakes along the way) as a model of how to be curious and to engage in biodiscovery as professionals in an open and public way (e.g., [@hitchco](#), [@jon_sullivan](#), [@klodonnell](#)). The more we use iNaturalist, the more we learn as faculty about how it can support our students. Improvements to iNaturalist, such as the introduction of Collection Projects, more filters, observation fields, audio recording, annotations, and the API, have facilitated easier integration over the years.

The responses from students have been overwhelmingly positive. Students report iNaturalist "is great for mental health" because it gets them outdoors. They mention the benefits of community, noting it is "nice to see the class working together to learn about new species and help identify each other's observations." They also become aware of their growing appreciation of the natural world: "I did not think that the experience would affect me, but I discovered on the following Monday how false that was [...] While I was waiting for the train to come, I looked across from me and noticed for the first time that there were about 5 different types of trees in that one spot. Previously, I had just saw them all as uninteresting trees."

As our collective work demonstrates, students are making important contributions to biodiversity knowledge. Making discoveries on iNaturalist is exciting, from being the first to observe a species, to interacting with professional researchers who value these contributions, to celebrating discoveries with other enthusiasts. Anyone observing cannot help but be inspired by the knowledge that an observation made right here, right now, helps to form the foundation of ecological monitoring (Forister et al. 2021). In addition, strategic planning can create baseline species lists for green spaces and inspire professional research. For example, the 2015 Macaulay BioBlitz established an initial species list for the newly established Freshkills Park, formerly the world's largest landfill, and led to an additional survey of lichen diversity there (Allen and Howe 2016), and the 2013 Macaulay BioBlitz inspired the two-year survey of the spontaneous flora of Central Park (Atha et al. 2020).

There is a pressing need to document the state of biodiversity so that future historical ecologists have a baseline for comparison (Morrison et al. 2017). Ecology is built on knowledge of organisms and yet very little is documented about most of them (Greene 2005). The use of iNaturalist in undergraduate courses helps address these needs, through species occurrence records and (optionally) simple ecological monitoring. Just documenting where species are found allows future ecologists to ask how many of these species remain at these locations. We see great potential for much more widespread, and coordinated, use of iNaturalist in undergraduate courses globally.

CONCLUSIONS

Students benefit from iNaturalist use by becoming part of a public online community of nature enthusiasts. The openness of iNaturalist encourages students to do good work because their work is publicly visible and makes a real and permanent contribution to global biodiversity knowledge as they become citizen scientists. Students' iNaturalist use also provides them with a means to observe and identify species after their courses have ended. For students planning an environmental research career, their iNaturalist profile also provides a public demonstration of their biological skills.

iNaturalist has the flexibility to be a tool that students keep after they complete their degree. It is the tool that, as a professional, they can use to identify species and collect data, and it is the place where they can hang out to have fun observing the natural world.

Together we have the opportunity to collectively engage alongside our students on iNaturalist, increase our collective bioliteracy, and participate in biodiscovery and

ecological monitoring in an open and transparent way. We have the opportunity to inspire the next generation of bioliterate, biocurious, and data-literate citizens, and the next generation of scientists fluent in open collaborative research and learning. Most importantly, by using iNaturalist in our courses, we are taking action to help document and monitor biodiversity at this critical time, while making space for natural history exploration in higher education.

DATA ACCESSIBILITY STATEMENTS

All data are available via iNaturalist (Ueda 2021, *iNaturalist.org* data to 30 March 2021).

SUPPLEMENTARY FILES

The supplementary files for this article can be found as follows:

- **Supplemental Table 1.** Course details and iNaturalist Project Descriptions/Methods. DOI: <https://doi.org/10.5334/cstp.439.s1>
- **Supplemental Table 2.** Accessibility issues when using iNaturalist. DOI: <https://doi.org/10.5334/cstp.439.s2>
- **Supplemental Table 3.** Result summaries of student iNaturalist use in the course projects. DOI: <https://doi.org/10.5334/cstp.439.s3>
- **Supplemental Table 4.** Comparing students' observations with all observations made in the course project areas. DOI: <https://doi.org/10.5334/cstp.439.s4>

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

All authors contributed equally. JJS performed the data analysis.

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