# Harnessing foresters' engagement for climate change adaptation: the emerging tool of next-generation citizen science

**Marjorie Bison[a,1], Nicole Ponta[a,1], Daniella Maria Schweizer[a,1], and Katalin Csilléry[a,2]**

This manuscript was compiled on September 15, 2025

**Observations and experiments in ecology and evolutionary biology often suffer from context dependence, limiting the generality of findings, the development of theories, and the building of predictive models. Systematic reviews and meta-analyses, as well as data mining, are commonly used to find general patterns in nature; however, issues of data homogeneity often arise. Our thorough review of past and ongoing citizen science (CS) projects reveals that CS targeting the general public, equipped with smartphones, is increasingly used to amplify the spatial and temporal scale of data collection in biodiversity research. While this approach has provided an extraordinary boost to data collection, we propose that CS targeting members of the public with specialized knowledge, such as farmers, gardeners, foresters, birdwatchers, or divers, has high yet untapped potential to increase the scale of experiments and create generalizable knowledge. Here, we describe the recruitment strategy, experimental design, and lessons learned in such a "next-generation" CS project: MyGardenOfTrees. It involved recruiting over 300 foresters across Europe, each of whom agreed to set up and follow (for five years) a small unit of a continent-scale transplant experiment. This unprecedented experiment, run exclusively by foresters and for foresters, covers the whole species range of two ecologically and economically key temperate forest tree species. It aims to understand the spatial extent of local adaptation: a fundamental assumption of all assisted migration programs. We conclude by identifying other research areas in ecology and evolution where an experimental CS approach could help resolve context dependence in the context of global change.**

Assisted migration | Citizen science | Forest trees | Local adaptation | Participant recruitment

## Significance Statement

Citizen science (CS) is an increasingly common approach for obtaining large amounts of data over large spatial and temporal scales. Today, the majority of CS programs require completing smartphone-based tasks that take just a few minutes. Yet, a handful of CS projects demonstrate that citizens can also perform highly engaging tasks, including running experiments, similar to those expected from collaborating scientists. We highlight the untapped potential of CS to increase the scale of experiments through MyGardenOfTrees. This unprecedented continent-wide transplant experiment involves forester-citizens who dedicate their time and expertise to testing different seed origins in their forests over five years. Findings of the study will help foresters in choosing appropriate provenances for assisted migration decisions.

The quest for general patterns and predictable processes in nature has been a perpetual goal of ecologists and evolutionary biologists (1, 2). This quest has never been more relevant than it is today, given the ongoing biodiversity crisis. However, context dependency arising from interactions between biological processes and the environment often leads to findings that are not generalizable and therefore not transferable among sites or organisms (3, 4). While ecologists worldwide agree that there is an urgent need to increase the spatial and temporal scale of studies, fundamental challenges exist related to funding, project management, and academic barriers, such as the pressure to produce rapid results (5). To overcome the limitations of single-site and/or short-term studies, systematic reviews and meta-analyses have been proposed (6), and more recently, entire new research fields, such as macroecology (7) and macrogenetics (8), have been established to mine data for general patterns. Although these approaches have been fundamental in advancing the synthesis of case studies into generalizable knowledge (e.g. (9)), their power is often limited due to differences in design and methods across studies (10–12).

The scale of experiments can also be increased when collaborating research teams run experiments at multiple locations while following the same protocol: so-called coordinated distributed experiments (CDEs) (10, 13). Indeed, several CDEs (even though they have not always been named as such), such as long-term ecological networks (LTERs) or several international provenance trials in forestry (e.g. (14)), have led to considerable advances in our understanding of processes behind patterns (11–13), such as litter decomposition (15, 16), nutrient dynamics (17, 18), local adaptation and evolutionary potential of forest trees (19). Citizen science (CS), broadly defined as the partnering of scientists with volunteers to answer scientific questions (20), is also increasingly used to reach larger spatial and temporal scales of observational studies (21), particularly in monitoring the environment and biodiversity research (22–26). Yet, its mainstream use has not gone beyond observational research.

Author affiliations: [a]Evolutionary Genetics Group, Biodiversity and Conservation Biology Unit, Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland

K.C. obtained funding, designed the research, performed formal analysis, and wrote the first draft of the manuscript. M.B. performed formal analysis, contributed to the recruitment strategy of MyGardenOfTrees, and acted as local coordinator. N.P. contributed to the recruitment strategy of MyGardenOfTrees, coordinated the local coordinators' work, assembled the recruitment data, and conducted the semi-structured interviews. D.M.S. reviewed the CS literature, created the dataset of CS projects, and analyzed the semi-structured interviews. All co-authors contributed to the manuscript.

The authors declare no competing interests.

[1]M.B., N.P., and D.M.S. contributed equally to this work.

[2]To whom correspondence should be addressed. E-mail: katalin.csillery@wsl.ch

DRAFT

## A brief history of citizen science (CS)

A compilation of 639 CS projects related to the study of ecology and evolution, limited to those initiated by scientists to answer scientific questions (Materials and Methods; SI Appendix, Dataset S1), reveals that CS emerged independently in different places and times, with some flagship projects that are still running today (Fig. 1a). For example, the ladybird beetle observation network in Belgium started as early as 1800 (available from the Global Biodiversity Information Facility (GBIF); (27)), the phenology observation network in Austria (Vogelwarte) has been running since 1851 (though interrupted several times), and the Audubon Christmas Bird Count in the USA started in 1900 as a contest to discourage bird hunting. Intimately linked with the development of conservation biology, CS began to gain popularity in the 1980s, especially in economically developed countries in North America and Europe (Fig. 1b). In these early projects, participants were highly engaged based on our list of possible engagement types (Table 1): they were required to follow complex and demanding protocols, repeat observations at specific locations or at particular times, or manipulate specialized equipment (see SI Appendix, Dataset S1 for more examples). In contrast, the geographic scale of projects was relatively limited, reflecting the slow communication tools available, such as the post.

| Engagement type | Example |
|---|---|
| None | Citizens submit photographs of sharks taken anywhere and on any date[1] |
| Data collected in a specific place | Citizens use online forms to send observations of the environment around Lake Tahoe, USA[2] |
| Data collected in a specific time of the year/week/day | Citizens send night sky brightness observations[3] |
| Data collected in the same place at least twice | Citizens place cookies in their garden and then collect ants on them[4] |
| Commitment for more than one year/season | Citizens are assigned a specific place to monitor a rare species[5] |
| Presence of a written protocol | Citizens follow a protocol for monitoring dragonflies[6] |
| Collection of one data point takes at least 30 minutes | Citizens collect samples to assess water quality of a lake in Missouri[7] |
| Compulsory in-person training | Following in-person training, citizens monitor aquatic insects to assess water quality of a stream[8] |
| Manipulation of specialized equipment | With provided material, citizens build a multi-sensor system to monitor insects[9] |
| Samples are sent/brought to the researchers | Citizens capture and raise caterpillars of monarch butterflies and send a sample to the researchers[10] |
| Manipulation of the environment | Citizens implement a fenced open-field experiment and apply a fertilizer treatment[11] |

**Table 1. Definition of the engagement score of a citizen science (CS) project or a coordinated distributed experiment (CDE). Each line describes an aspect of engagement. Projects were assigned an engagement score of zero if they did not include these aspects. Each aspect increased the engagement score by one. [1]https://sharksofcalifornia.fieldscope.org/, [2]https://citizensciencetahoe.org/home, [3]https://globeatnight.org/, [4]https://scistarter.org/ant-picnic, [5]https://plantsofconcern.org/, [6]https://illinoisodes.org/, [7]https://www.lmvp.org/, [8]https://therouge.org/bug-hunts/, [9]https://kinsecta.org/citizen-science/, [10]https://monarchparasites.org, [11]https://nutnet.org/home**

As is often the case, the real breakthrough in CS happened at the moment of significant technological advances: the World Wide Web (2000) and, later, smartphones (early versions from the mid-2000s) revolutionized communication, and enabled CS projects to expand across countries and continents and to reach out to more citizens thanks to the eased data collection and sharing (Fig. 1a and c). In parallel, the creation of simpler numeric protocols, such as taking a photo of any individual plant or animal (e.g., in iNaturalist https://www.inaturalist.org/) or annotating an image from a camera trap (e.g., Snapshot Serengeti https://www.zooniverse.org/projects/zooniverse/snapshot-serengeti), has led to a decrease in the level of engagement required from participants (Fig. 1c). Indeed, in over 30% of projects in our dataset, none of the engagement types listed in Table 1 are relevant. Today, such mass-participation projects, targeting the general public across large spatial scales and requesting opportunistic data collection, are dominating the CS landscape (Fig. 1c). While they have well-recognized benefits, they also have shortcomings related to data quality (28–31). Indeed, oftentimes, data from such projects are not utilized in scientific publications (22).

Review of CS also highlights that some projects have resisted the current trend, recruiting a specific subset of the population to engage them in complex tasks. In fact, when

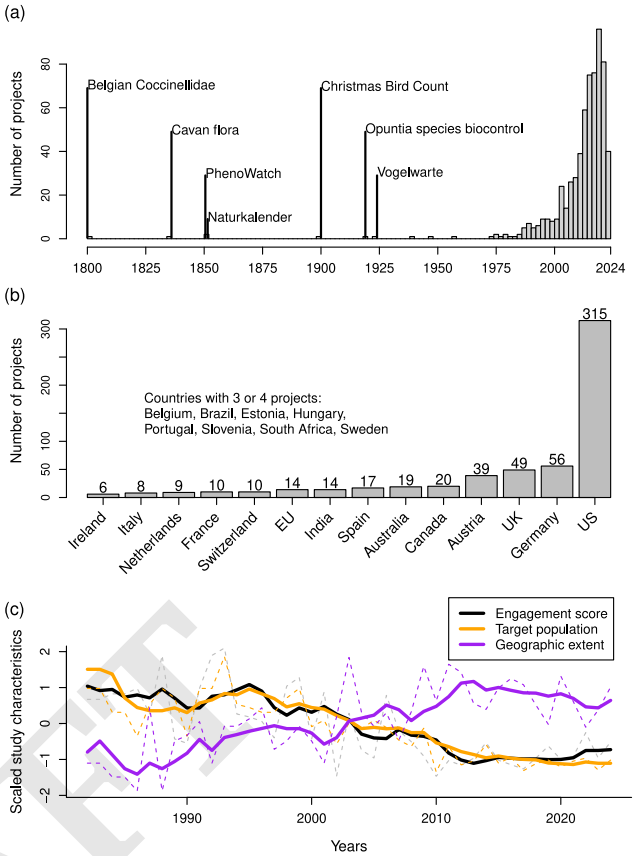


**Fig. 1.** The history of citizen science (CS) in biodiversity research, explored through a novel dataset compiled in this study (see Materials and Methods). (a) The timeline of CS projects, (b) the number of projects per country across the entire considered period, and (c) the trade-off between the geographic extent (ordinal scale: local, subnational, national, regional, continental, global), target population (ordinal scale: general public, public subset, public with affinity, public with specialized knowledge, fellow scientist), and the engagement score (see Table 1 for the definition) of CS projects through time, based on linear filtering with a moving average (see Materials and Methods).

DRAFT

comparing the engagement scores of CDEs and CSs, we notice that CS projects that work with citizens with specialized knowledge can have participant tasks that are just as engaging as those conducted by scientists participating in CDEs (Fig. 2). The most engaging CS projects involve bird ringing (e.g. https://odnature.naturalsciences.be/bebirds/), butterfly monitoring along transects available for volunteers with appropriate taxonomic skills (e.g. https://www.dagfjarilar.lu.se/), or bat monitoring, where volunteers are trained to use handheld ultrasonic detectors (e.g. http://wiatri.net/inventory/bats/). While most experimental projects rely on the participation of fellow scientists, a handful of CS projects have demonstrated that citizens can even manipulate the environment, i.e., conduct experiments, when the tasks align with their profession or special skills. For example, in SurfingForScience.org, citizen surfers manipulate microplastic trawl nets and take water samples. One of the most prominent examples, however, is participatory or collaborative plant breeding, where farmer-citizens test (32) or even breed (33, 34) agricultural varieties. Such experimental projects require targeted recruitment of a specific subset of the population, potentially those with special skills or knowledge, to conduct high-effort sampling, following a particular protocol (24, 35–37). We coined the term "next-generation citizen science" (NGCS) to refer to experimental approaches that involve collaboration with non-scientist professionals, using state-of-the-art communication and data handling technologies, to address scientific questions highly relevant to the participants' profession, skill set, or hobby.

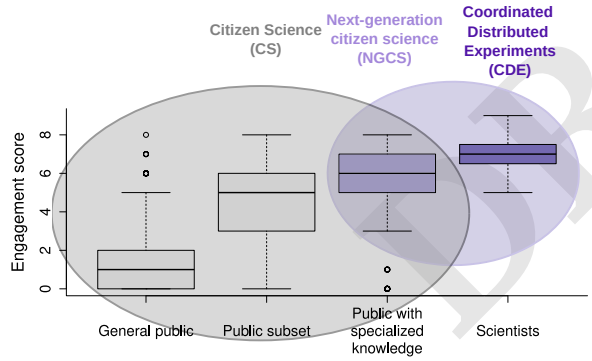


**Fig. 2.** Next generation citizen science (NGCS) at the intersection between citizen science (CS) and coordinated distributed experiments (CDEs). Engagement scores of CS projects in our dataset (see Materials and Methods), categorized by the target population and simplified into three categories. Public with specialized knowledge includes farmers and foresters, for example.

## Harnessing foresters' engagement for climate change adaptation

As climate change and global trends, such as deforestation and urbanization, expose tree populations to unprecedented conditions, many species are experiencing die-back (38–41). It remains unclear how commonly and rapidly local adaptation or plastic responses can arise to keep up with the unprecedented levels of climate change (42–44). Due to their long generation times, maladapted forest tree populations without natural regeneration could become common (45, 46). Assisted migration (AM), defined here as any climate-change-induced human-aided translocation of species within or outside of their range, is increasingly recognized as a necessary climate change adaptation and conservation strategy (47, 48), and it has been included in Europe in the New EU Forest Strategy 2030 (COM(2021)0572).

Several challenges related to context dependency hinder the development of effective AM programs. First, local adaptation may not be universal, particularly at the range margins, where inbreeding, gene swamping, or expansion load may lead to maladaptation (49–51). Second, existing studies often suffer from limited statistical power, due to inadequate representation of populations across species ranges (52, 53). Third, experimental environments, i.e., common garden trials, are frequently manipulated in ways that do not accurately reflect natural conditions in terms of soil, microclimate, and biotic interactions (53, 54), limiting our understanding of the relative roles of genetic, environmental factors, and phenotypic plasticity (55). Finally, our knowledge of adaptation is primarily based on production traits measured on young trees. Neglecting early life-history traits that are crucial for establishing future generations of locally adapted trees (56, 57). Considering the genetic correlations among traits is essential for anticipating species responses to environmental changes (58, 59), particularly in light of novel selection pressures that may affect production traits indirectly (60–62).

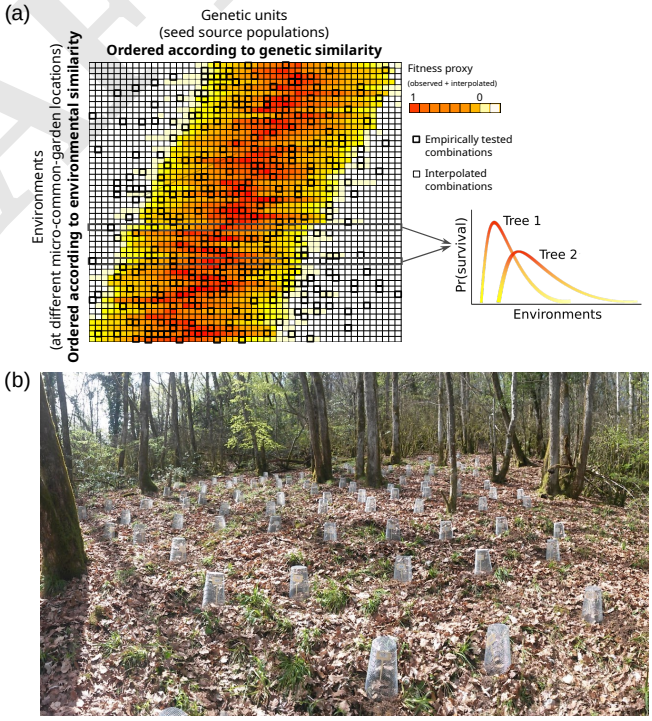


**Fig. 3.** The concept of distributed common garden experiments to obtain generalizable results. (a) Reaction norms of different genetic units vary across different environments. The panel illustrates an ideal case where gene–environment interactions are predictable. (b) Example of an experimental unit, a so-called micro-garden. Seeds are protected from seed predation and the forest site is protected from contamination by foreign seeds using custom-designed and custom-produced seed protectors.

To overcome some of the challenges mentioned above, MyGardenOfTrees (www.mygardenoftrees.eu), developed a range-wide transplant experiment, where experimental sites

DRAFT

are placed directly in the forest and seedlings are grown using direct seeding (63). The ambitious aim of MyGardenOfTrees is to understand gene–environment interactions and to estimate so-called reaction norms (64) for a large number of traits starting from germination until at least fifth-year growth. Similar objectives have previously only been set for simple organisms that can be raised in a laboratory across a wide range of environments (65). The difference is that here we could not explore the whole gene environment space experimentally, but set up a representative set of experiments that explore this space (Fig. 3, see details in "Design and implementation of a continent-wide transplant experiment"). For this, we selected provenances for seed collection that represented the entire genetic heritage of the species, and we recruited participants, aiming for representativeness in several factors that could potentially bias the observations.

MyGardenOfTrees is an NGCS project that recruited professionals, i.e., European foresters, to carry out an experiment that builds on their professional knowledge and experience (Fig. 1b). The project's engagement score is eight, and participants are required to follow the experiment over a period of five years. This involves dedicating a 100 $m^2$ forest area that they own or manage to the experiment and committing, on average, 35 hours of voluntary work in the first year, with a smaller amount of time in the following years as seedling mortality occurs (SI Appendix, Text S1 and S2). The project focuses on two major European tree species, European beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.), and their Mediterranean and Oriental sister species (*Fagus orientalis* Lipsky, *Abies nordmanniana* (Steven) Spach and *Abies borisii-regis*). Both species complexes have a high economic and ecological importance in Europe, and some are discussed as species resilient to climate change or as potential species for AM (66, 67). In the following section, we showcase the lessons learned from MyGardenOfTrees' recruitment strategy, and we describe how this continent-scale experiment was designed to minimize the pitfalls specific to CS (68).

## Participant recruitment across Europe

Participants in CS are not customers, yet there are parallels with customer-facing sectors, such as the need to market a product/project, enhance the customer/participant experience, and retain customers/participants (69). Initially, CS projects can benefit from recruiting strong participants, referred to as "champions" (70), who will serve as amplifiers of the project's goals. We employed this strategy during two sets of pilot trials, "2021 summer trials" and "2021–2023 trials" (see https://www.mygardenoftrees.eu/), where we recruited a handful of colleagues, foresters, environmental activists known to us through our network, and even family members. The implementation of these trials and the preliminary results obtained from them were crucial in launching the more ambitious main trials, where the aim was to recruit hundreds of forest owners and managers from across Europe. Notably, at that point, we could create the first outreach media items, such as the project website, magazine articles, videos, social media posts, and elaborate on the experimental protocol. In the main "2023–2028 trials", champions, hereafter referred to as "local coordinators", were actually hired for the project. They were in charge of recruitment in one or several countries, while often being a participant as well, which helped us to overcome the omnipresent linguistic and cultural barriers in Europe (SI Appendix, Table S1).

We utilized four main recruitment action types for the recruitment of voluntary foresters (Table 2; SI Appendix, Dataset S2). First, creating outreach materials was the initial essential step in the entire recruitment process, as we used and referred to these materials in other types of actions. The primary outreach materials were the project website, with 18 country-specific versions, outreach articles, and a project flyer. Second, directly contacting potential participants relied on prior knowledge of contacts, which were obtained from the countries' national forest service and private owner associations, and were extended through the networking activities of the local coordinators. Third, we attended the principal forestry fair in several countries, where we rented a stand. Finally, we utilized social media to amplify the impact of our outreach actions, such as posting news items on the website. During the recruitment period, we conducted a total of 273 recruitment actions, reaching approximately 16,000 people across 23 countries (SI Appendix, Dataset S2).

| Action type | Examples | Impact |
|---|---|---|
| Outreach | Website development (by country)<br>Article in magazine for professionals<br>Newspaper article by a journalist<br>Project videos | 100 (2781) |
| Direct contact | General email to a large target group<br>Personalized email to a person or a small target group<br>Phone call to a person<br>Online or personal meeting with a person or small group | 5.5 (250) |
| Events | Unplanned informal chat at events (conferences, fairs)<br>Formal participation at events (talk, stand, poster) | 25 (100) |
| Social media | FaceBook posts<br>LinkedIn posts | 5 (88) |

**Table 2. The four main types of recruitment actions used for MyGardenOfTrees by the local coordinators across the 20 participating European countries. Impact indicates the median (maximum) number of people reached by a single action of the type. For outreach, the maximum indicated the total number of visits to the project's website during the recruitment period. For social media, impact indicates the number of visits to the project's Facebook page in a single day.**

We used marketing mix modeling (MMM) to estimate the impact of each recruitment action type on the registrations, using the number of people reached by each action as a measure of impact (Fig. 4a; see Materials and Methods; SI Appendix, Datasets S2 and S3). Using the so-called adstock function, we could account for the diminishing effect of each action in time. Our analysis revealed that direct contact was overall the most effective tool for recruitment across all regions of Europe (Fig. 4b). For every 100 people reached, 1.2 participants registered on average ($t=5.730$, p-value$<0.001$). Each direct contact also required the presence of an outreach medium, and, in turn, outreach media required follow-up advertising. Yet our analysis suggests that the impact of outreach media was crucial on its own, as it reached an average of 4.6 registered participants for every 1000 people reached ($t=2.176$, p-value$=0.0319$). Outreach was particularly effective in Western Europe (Fig. 4b). Attending events such as forest fairs was also an efficient way of recruiting: contacts made

DRAFT

at events often led to registrations, particularly in Southern Europe (Fig. 4b; t=2.084, p-value=0.0397). Social media did not contribute to the recruitment (t=-0.958, p-value=0.3402) and even had an adverse effect in some regions (Fig. 4b). We hypothesize that this is because social media is based on the idea of regularly posting small amounts of information to keep followers, which is not suitable for advertising just once for an engaging project like MyGardenOfTrees.

The participants' answers to the marketing attribution question (Question 17: "where you heard about MyGardenOfTrees?", SI Appendix, Text S1) provided independent evidence to our findings from the marketing analysis (Fig. 4c). It highlighted the role of outreach, especially in Western Europe, and the key role of direct contact. Specifically, we observed the impact of people who were not directly contacted by us spreading the word about the project (Fig. 4c): many joined not because of "direct contact" from a local coordinator, but because another person from the same or a different company, or even a friend, told them about the project.

Beyond understanding what worked, semi-structured interviews with the local coordinators helped us reveal the main barriers to recruitment across Europe (Fig. 4d; Materials and Methods; SI Appendix, Text S3 and Dataset S4), as well as some regional differences (Kruskal-Wallis $\chi^2$=7.0777, df=2, p-value=0.029). The most frequently mentioned barrier, especially in Southern and Eastern Europe, was bureaucracy and hierarchy (Fig. 4d). Indeed, administrative and organizational obstacles within countries, and their public and private organizations, were common, including difficulties reaching decision-makers, complex approval processes, and rigid hierarchical structures. The second most common obstacle was resistance from foresters to join due to a lack of time. Understandably, it is a challenge to commit to frequent monitoring over a five-year project duration. However, external circumstances, including the war in Ukraine, also contributed to the decision not to participate. On the local coordinators' side, challenges in effectively conveying project fundamentals and identifying optimal recruiting strategies for each target group in a cross-cultural context were reported (Fig. 4d). For example, one coordinator said, "I learned that every region and even province has its own way of forestry" (SI Appendix, Dataset S4). Concerns related to the project itself, including its scientific objectives, were relatively rare (Fig. 4d), even though concerns about introducing foreign genetic material and resistance from participants located outside the distribution range of the target species occurred. Indeed, the legislative landscape of Europe concerning the introduction of non-native tree species is complex and lacks transparency in some countries (71). On the positive side, despite most local coordinators being female (SI Appendix, Table S1) and forestry being a male-dominated sector in most countries, gender was never reported as a barrier.

The allocation of resources to different recruitment strategies for future NGCS is a non-trivial question, and the academic literature lacks information about the factors that influence participation in CS projects (29, 72–74). In marketing, saturation refers to the point at which increased media spending yields diminishing returns, meaning that each additional dollar spent yields smaller sales or engagement gains. In MyGardenOfTrees, direct contact with the target population, combined with outreach support items, appeared to be the

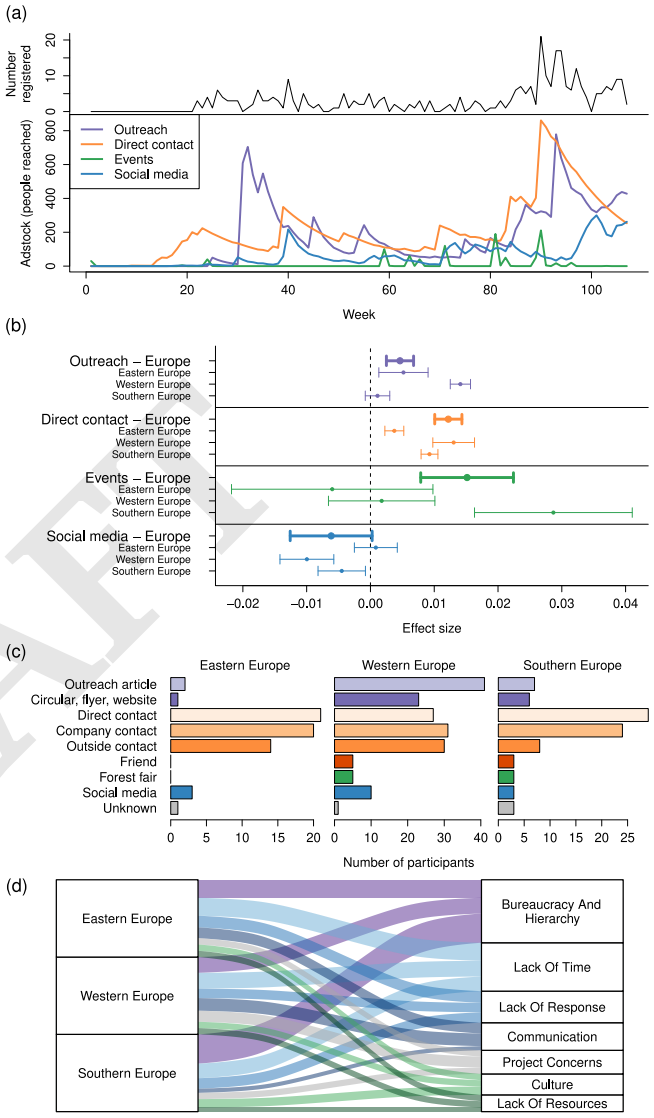


**Fig. 4.** (a) Timeline of participant recruitment in MyGardenOfTrees across the 107 weeks: the top panel shows the number of registrations, while the bottom panel shows the number of people reached by the recruitment actions after applying the adstock function (see Materials and Methods). (b) Effect sizes were estimated for each recruitment action across Europe and in each region, based on a marketing mix model approach. (c) Participant answers to the marketing attribution question of the registration form (SI Appendix, Text S1). (d) Frequencies of coded interview sequences, with a focus on barriers to recruitment indicated by the semi-structured interviews with the local coordinators.

DRAFT

best strategy. We recommend investing personnel and monetary resources in creating a few high-quality outreach support materials, such as a website, magazine article, or flyer, and supplementing them with direct contact via email or phone in the local language. It is also best if a locally respected person or authority delivers the message. Additionally, as others have recognized, respect for the volunteers and the country's culture and administration is essential and should be studied before the recruitment process (73, 75, 76).

## Design and implementation of a continent-wide transplant experiment

Once participants are recruited, the implementation of a CS project is constrained by the capabilities, spatial location, and availability of participants. There is a major emphasis in the CS literature on these constraints (77), and it has only recently emerged that some of these aspects, such as the dispersed location of the participating citizens, can also facilitate hypothesis-driven experimental research. For example, participatory plant breeding leverages the power of farmers who are located all across a country, and the heterogeneity across local farm conditions is ideal for breeding because farmers are also the end users of the new varieties (34, 78–80). Similarly, in ecology, so-called gradient experiments that span a gradient of environmental conditions (instead of replicates) in the same environment (81, 82) have been recognized as an efficient way to overcome context dependency (3). Indeed, the use of many small experimental units that are placed across environmental gradients aligns extremely well with the concept of CS (Fig. 3a). Yet, while the idea is appealing, it requires thinking out of the box in terms of experimental design, observation protocols, and statistical models.

Study designs in ecological experiments, such as factorial, block, or split-plot, must have a sufficient number of replicates for each group and treatment for decomposition and comparison of variances within and between groups (83). Gradient or distributed experiments instead should ensure that the environmental gradients of interest are thoroughly explored using appropriate randomization of the experimental units. In MyGardenOfTrees, we employed an anticlustering method to partition a set of units (84–86), specifically different genetic units, into groups represented by the various environments of the micro-gardens. The anticlustering approach is the reverse of clustering analysis and is intended to achieve high within-group diversity (see Materials and Methods). This approach was ideally suited to overcome the difficulty that not all genetic units could be tested in all gardens, while ensuring all genetic units are represented across the same wide range of environmental gradients to estimate their reaction norms (Fig. 5).

Today's most popular type of CS project, targeting the general public at large spatial scales and without a specific protocol for data collection (Fig. 1c), can lead to data quality issues, survey inconsistencies, observer biases, communication issues, and other types of errors (20, 88–90). Projects where participants receive in-person training (23, 76, 91), where expert validation is incorporated, and where there is replication across volunteers can partially resolve data quality issues (92, 93). CDEs or NGCS projects leverage the potential of highly trained participants, potentially leading to more and higher data quality, thanks to the background knowledge of

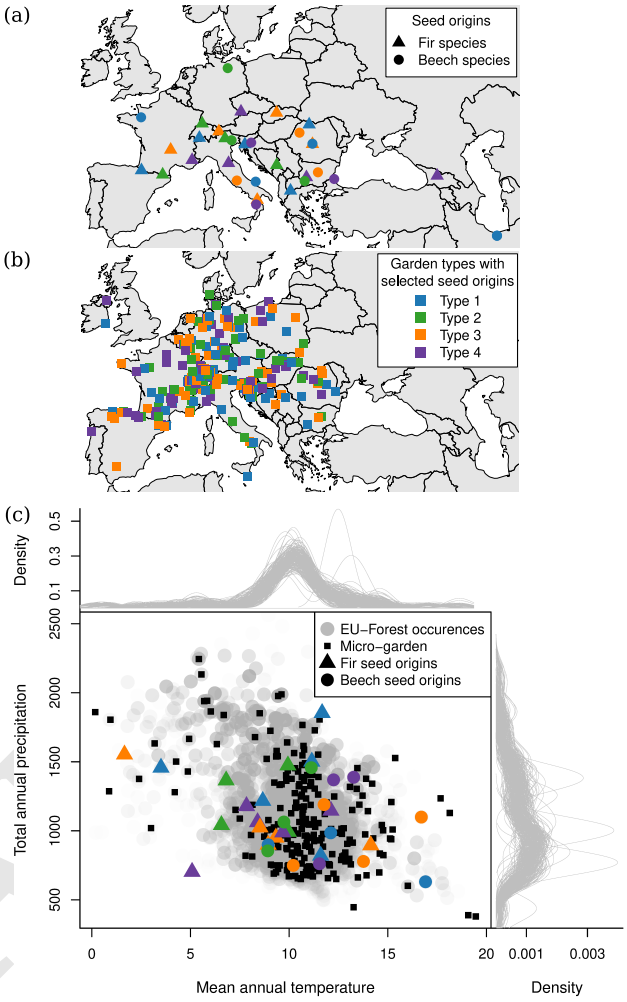


**Fig. 5.** The realized experimental design of MyGardenOfTrees. (a) Seeds were sampled from 19 fir and 14 beech species and populations, with an average of 10 trees (families) per location. Only a selection of seed origins was distributed to each of the experimental gardens, defined by the type of garden. (b) The realized experimental design effectively represents the climate space of fir and beech forests in Europe (as defined by the EU-Forest database (87)), and the tested 285 families (represented by gray density curves) are well-represented across the environmental gradients.

the participants. Indeed, in MyGardenOfTrees, foresters easily adhered to our complex protocols, which requested the selection of an appropriate forest area for the experiment, proper storage of the forest reproductive materials upon receipt, and sowing of seeds of 25 different origins with appropriate labeling (SI Appendix, Text S2). Similarly, submitting observations about the spring and autumn phenology, survival, and damage of seedlings was natural to them. However, data collection, aggregation, and quality control would not have been possible without smartphones and the development of open-source form formats, such as the Open Data Kit (ODK, https://docs.getodk.org) (94). ODK provides software and standards that underlie various solutions for form design and implementation, offering offline data collection, such as Enketo, Ona, and KoBoToolbox. ODK has revolutionized humanitarian data collection and enhanced clinical research in developing countries, but it also has emerging applications in agriculture (95). Its applications in academic research are

still scarce, where researchers often opt for standalone app development or CS dedicated platforms specific to image recognition/annotation, such as Zooniverse, or maps, such as SPOTTERON (see details in (96)). MyGardenOfTrees uses Ona (ona.io) as a server provider and offline forms that can be filled in using ODKCollect (Android) or the web tool Enketo (Android and iPhone). The collection of the data at a centralized server enabled efficient tracking of the participants' work and correction of errors, as well as the creation of an R Shiny interface, where the participants could track their observations in near-real time. The tools mentioned above have significantly improved even within the timeframe of the project, and we anticipate further developments.

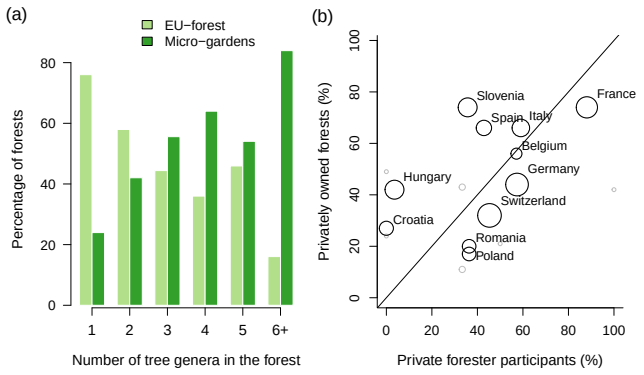


**Fig. 6.** (a) The number of tree genera in the forested areas of Europe, according to the EU-Forest database and the number of tree genera in the experimental micro-gardens of MyGardenOfTrees. (b) The percentages of privately (vs. publicly) owned forest areas across the European countries with at least five participants in MyGardenOfTrees, and the percentages of foresters with a private (vs. public) status who are participating in MyGardenOfTrees.

## The future of citizen science in ecology and evolution

In this paper, we advocate the use of NGCS for hypothesis-driven fundamental science as a tool for dealing with context dependency. While CS is increasingly employed in ecology for producing large, longitudinal datasets, these datasets are still seldom integrated in academic publications (22, 77), and the use of CS in evolutionary biology is lagging. MyGardenOfTrees, along with advances in participatory breeding (34), challenges the common assumption that citizens cannot conduct experiments and engage in long-term monitoring to address fundamental ecological and evolutionary questions (36). We argue that CS is not merely a complement to hypothesis-driven approaches (97) and that NGCS can be a principal research tool for understanding mechanisms behind ecological patterns. In fact, several outstanding questions in ecology and evolution, coupled with ongoing societal challenges, could benefit from an NGCS approach. Beyond the study of local adaptation in various forest tree species that we have showcased, distributed experiments may also be used to test and compare reforestation methods, such as direct seeding or planting, as proposed in a CDE (63). Groom et al. (98) called for "next-level" citizen science to study species interactions with CS experiments, along with alien species management (99, 100). Research addressing the global concern arising around declining pollinator abundances could also be tackled using NGCS. Cultivating native plant species in urban gardens (101) and promoting high plant species diversity (102) may foster pollinator activity. While CS initiatives are already being used to increase pollinator activity in private gardens and public green spaces, they remain local and correlative (103, 104). Finally, in the most advanced field of participatory breeding, Santamarina et al. (34) even proposes performing experimental evolution experiments to track variants driving co-adaptation in crop mixtures in collaboration with farmers.

A fundamental strength of NGCS is that, by involving professionals from the start, it makes use of the wealth of local knowledge and perceptions of the stakeholders, acknowledging them as actors from the beginning. (105). Working with participants who hold a tertiary level of education is recognized as an inherent inequality in benefit sharing in CS (106). NGCS overcomes this limitation by working with professionals who can contribute to the research content in a meaningful way and enhance the integration of research findings into policy and action (107). Stakeholder involvement enhances the societal acceptance of findings, facilitates implementation, and improves trust and information flow between research and practice in the country (108). For example, in Canada, it was found that AM was better accepted in regions where researchers invested in outreach (109). In MyGardenOfTrees, we found that in some countries, notably in Slovenia, Croatia, and Hungary, more public owners joined the project than expected based on the proportion of publicly owned forests in these countries (countries above the line on Fig. 6b), suggesting trust in research and forest governance. Independent evidence based on the proportion of certified Forest Stewardship Council (FSC) forest area in these countries (110) also suggests a high trust in the public forestry sector in the countries, as mentioned above. A similar effect was expected in Baltic and Scandinavian countries and the UK; however, MyGardenOfTrees did not have participants in these countries. Finally, we also observed a bias towards participants who already own and/or manage a diverse forest (Fig. 6a), thus those who are already managing their forest with consideration for biodiversity. This finding raises the question of whether participating in CS projects would merely connect those who already know about the studied issues. Even so, is it our responsibility as researchers to arm these participants with more knowledge, thereby making their participation more likely to lead to transformative changes at the societal level.

Dealing with context dependency by increasing the scale of experiments through NGCS has been demonstrated in agricultural and forestry contexts. However, challenges remain related to the human aspects and the characterization of the environment and ecologically relevant traits. First, large-scale and long-term experiments inherently involve linguistic and cultural barriers and challenges related to maintaining participant motivation. Indeed, the work does not stop at recruitment but continues with efforts to motivate and retain participants (74, 111), which raises challenges similar to CDEs (10). Second, observations are limited to those visible with the naked eye, even though the installation of cameras or the analysis of posted samples (such as plant parts and feces) is also possible. Still, these aspects require the capacity of research labs to process a large number of samples. Connecting citizen observations with remote sensing is a promising avenue (112). Third, measuring relevant confounding fac-

DRAFT

tors locally and/or relevant aspects of the environment can be challenging because the number of observations must remain reasonable to avoid overburdening the participants. Interpolated climate, soil, and remote sensing data (satellite) are commonly integrated to replace local measurements. However, the importance of the microclimate is increasingly recognized (113), calling for local measurements.

## Materials and Methods

**Dataset of citizen science (CS) projects.** We collected information on CS projects from Global (https://scistarter.org), North American (https://www.citizenscience.gov, https://science.gc.ca/site/science/en/citizen-science-portal), Australian (https://biocollect.ala.org.au), Indian (https://citsci-india.org/projects), and European (https://eu-citizen.science, https://data.jrc.ec.europa.eu/dataset, https://www.mitforschen.org, https://www.citizen-science.at, https://www.citizenscience.uzh.ch) websites. We only included projects initiated by and/or involving universities or research institutes, using "institution type" as "academia" in the European databases and funding sources as "Smithsonian" or "National Science Foundation" in the SciStarter and US Government databases. For the other databases, we searched all environmental projects to select those involving a research institution. We focused on CS projects relevant to ecology and evolution, using only the following keywords: "Ecology and Environment," "Plants," "Animals," "Agriculture," "Biology," "Birds," "Ocean, Water, Marine Terrestrial," and "Insects and Pollinators." We entered projects multiple times if they proposed more than one action in which citizens could engage. Our dataset includes 628 CS projects and 12 coordinated distributed experiments (CDEs) (SI Appendix, Dataset S1).

We extracted the country where the project was initiated, the start date of the project, and the target public, either from the CS databases searched or directly from the project websites. The term "general public" was used when no selective criteria were given. "Public subset" was used when the project targeted only a specific age class, sex, physical address, or language group. "Public with affinity" was used for projects that included participants with an affinity/sensitivity towards the research question and/or the study species and/or participants who have a hobby that brings them to the correct location and/or time when the observations are being made. "Public with special knowledge" was used when participants had to possess prior knowledge acquired through formal (e.g. farmers, foresters, rangers, or scientists) or informal education (e.g. bird watchers or divers). The project protocol relied on the fact that participants had this previous knowledge. We assessed the level of participant engagement according to a set of simple criteria (Table 1) that could be reliably extracted from the project website or protocol. We calculated an engagement score by assigning a value of one to each fulfilled criterion and summing them up. The lowest score was zero, and the highest was eight. We analyzed the evolution of CS using a linear filter on the time series of the engagement score, target population, and geographic extent from 1978 to 2024, employing a moving average implemented in the "convolution" method in the `stats` package in R (version 4.4.2).

**Recruitment data analysis.** Initially, we targeted all European countries for recruitment. However, some countries had to be abandoned early on because the recruitment of a local coordinator was not successful and/or the target species were of limited interest for local forestry (i.e. Baltic and Scandinavian countries, United Kingdom, Greece), or because the country was small (e.g. Andorra, Liechtenstein) or had low forest cover (e.g. Portugal), which was sometimes coupled with a unique official language (e.g. Montenegro). In the target countries that could be assigned to a local coordinator (SI Appendix, Table S1), we undertook various advertising activities, subsequently called recruitment actions (Table 2). Every local coordinator reported the recruitment actions they performed across Europe, specifying the target country, language, item type, media type, publication date, and number of people reached. A total of 273 recruitment actions were recorded (complete list in SI Appendix, Dataset S2) between July 1, 2022 and March 31, 2024. We measured recruitment as the number of foresters who completed the registration form implemented in LimeSurvey and made available on the project website (see all questions and their order in SI Appendix, Text S1). We collected basic socio-economic data, the type of forest for the future micro-garden, and a marketing attribution question asking where the participant had heard about the project. Attrition rates were low; out of 381 foresters who began filling out the registration form, 302 (79%) completed the entire registration process, received the materials, established a micro-garden in the forest, and submitted the first field observation form about the experiment (SI Appendix, Dataset S3).

We used marketing mix modeling (MMM) to estimate the impact of recruitment actions on registrations (see Materials and Methods). Using marketing language, we had a single "product": participation in MyGardenOfTrees. This was our "sales", thus the response variable. Our main objective was to determine the most effective recruitment action type, thereby providing information on how to optimize recruitment in a similar project in the future. We described the effect of each action by "marketing reach", i.e. the number of people who were reached by our actions. We used various proxies to measure this. For outreach recruitment, we utilized Google and YouTube analytics for the project websites and videos, while for articles in newspapers and magazines, we relied on the number of subscribers. For direct contacts, we counted the number of persons directly targeted, such as unique email addresses or participants in video calls, or the number of recipients when the email was sent to a mailing list. For events, we counted the number of outreach materials taken from the project's stand, such as flyers and printouts. Finally, for social media, we used the number of likes from Facebook and LinkedIn for posts related to the project, as well as the number of followers of the Facebook page of the project. We aggregated both the response variable and the number of people reached by actions to weekly sums, as is usual in marketing analysis.

We used adstock theory (114) to model how awareness of a product declines over time. For direct contact, events, and social media action types (Table 2), we used a simple decay model:

$$A_t = T_t + \lambda A_{t-1}, \qquad [1]$$

where $A_t$ is the advertising stock at time $t$, $T_t$ is the advertising spend at time $t$, and lambda is the adstock decay rate. We implemented the function using the `filter` function's recursive method (R package `stats`). For the recruitment action type, outreach, we attempted to use a delayed decay model (eq. 3 in (115)), including an adstock decay parameter, $\lambda$, the delay of the peak effect, $\theta$, and the maximum duration of a carryover effect. While the model could be fitted and the parameters estimated ($\theta = 4$ weeks, $L = 6$ weeks), a model with a simple decay function for outreach provided a better fit. We jointly estimated the $\lambda$ parameters and the effect sizes of the different recruitment action types using the `nlsLM` function in the R package `minpack.lm`. Analysis scripts are available at https://github.com/kcsillery/MyGardenOfTrees.

Additionally, we conducted a semi-structured interview with 12 local coordinators to gather information on their recruitment strategies and the barriers they encountered (SI Appendix, Text S3). The interviews were conducted between March and May 2024, in English, and lasted around 30 minutes. We analyzed transcripts of the interviews using a mixed-methods approach that combines deductive and inductive thematic analysis (116), employing MAXQDA (117). The first step in coding the interviews was to use word clouds and word frequency analysis to find emergent themes (themes that were repeated within and across the interviews). We identified three main themes: strategy, barrier, and lessons learned. In the following section, we focus on barriers because they provided complementary information to the analysis of recruitment actions that centered on "what worked". We classified the barriers into several sub-themes (SI Appendix, Dataset S4) and compared them between Eastern, Western, and Southern Europe (Fig. 4d).

**Data on European forests.** We used EU-Forest (87) to extract the areas of Europe where (*Abies*) and (*Fagus*) are currently growing, based on harmonized data from national forest inventories. We used these occurrences to establish the climate envelope of the current distribution for Fig. 5c (see below). From EU-Forest, we also extracted the number of forest tree genera per unit area. We compared it with the number of tree species/genera that the participants reported in their forest, where they planned to establish their micro-garden, using a Spearman rank correlation test (Fig. 6). We retrieved data on

DRAFT

the proportions of forests that are privately vs publicly owned from FAO's Global Forest Resources Assessment 2010 report (118). In all studied

**Experimental design.** Seeds were collected from 19 fir (*Abies*) and 14 beech (*Fagus*) provenances, with an average of 10 families per provenance, resulting in a total of 285 genetic units to be tested across 302 environments, represented by the participant micro-gardens. This required the preparation of 302 unique seed parcels, each containing four replicates (to be established as blocks) of 25 unique genetic units (Fig. 3b; SI Appendix, Text S2). To minimize errors during parcel preparation and ensure logistical feasibility, we divided the provenances into four groups, each containing five fir and three to five beech provenances. Each block contained three replicates of a provenance represented by different families. We defined the groups to ensure that the main genetic and geographic clusters of the species were described based on our existing knowledge (119, 120). Further, we ensured that each participant received an "exotic" species of fir or beech, as there was high interest among foresters in obtaining such seeds. We then assigned each micro-garden to a garden type based on its climate and applying the method of anticlustering (85).

We characterized the climate using longitude, latitude, elevation, and the CHELSA dataset and its bioclimatic variables for the time range 1981–2010 (121), extracted for each approximate micro-garden location as communicated by the participant on the registration form. We performed anticlustering using the R package `anticlust` on the climatic distance matrix, calculated using the R package `ecodist` on scaled climate variables. We used the diversity criterion option, which maximizes between-group similarity by maximizing within-group heterogeneity, with K=4 representing the number of micro-garden types, and the method of (86) with 5000 repetitions. We then randomly assigned families to the garden types, ensuring each block had 25 unique genetic units and respecting the available seeds. This was done to ensure that participant observations corresponded to a unique seeding spot, while allowing flexibility in the sowing order for establishment of the experiment (SI Appendix, Text S2). Note that although the experimental design was done with the CHELSA data, Fig. 5 shows the environmental space with the Copernicus ERA5 dataset because it also includes the year of the experiment, 2024 (122) (Accessed on May 1, 2025).

**Supporting Information Appendix (SI).**

- Table S1: Profile of local coordinators responsible for recruitment and their countries of responsibility
- Text S1: MyGardenOfTrees registration form questions, including the informed consent form
- Text S2: General information sent to participants along with the "SetUpMyGarden" form
- Text S3: Semi-structured interview questions for local coordinators

***SI Datasets.***

- Dataset S1: Dataset of citizen science (CS) projects and coordinated distributed experiments (CDEs)
- Dataset S2: Recruitment actions of MyGardenOfTrees
- Dataset S3: Registrations to participate in MyGardenOfTrees (anonymised)
- Dataset S4: Coded segments of the semi-structured interviews with local coordinators – barriers

All SI datasets and analysis scripts are available at https://github.com/kcsillery/MyGardenOfTrees.

**ACKNOWLEDGMENTS.** We are indebted to the 302 foresters who took confidence in this research, signed up for MyGardenOfTrees, and contributed numerous hours of field work to this project. We also thank the numerous forest services and forestry companies of countries that made their participation possible. We thank all the local coordinators for their amazing work, namely Sevil Cosgun, Marta Curman, Bernadett Fodor, Nancy Koller, Violeta Kotova, Mirjam Kurz, Azzurra Pistone, Bogdan Radu, Boris Rantaŝa, Camilla Stefanini, Fabian Suter, Karol Tomczak, and Maria Viota. KC thanks the ERC LS8 panel and the reviewers for believing that this project was possible. We thank Ona (ona.io) for their support of MyGardenOfTrees, and we acknowledge their excellent customer service.

DRAFT

**References.**

1. I Mc Arthur, T Steeves, An experimental study of vascular differentiation in geum chiloense balbis. *Bot. Gazette* **133**, 276–287 (1972).
2. KS Shrader-Frechette, ED McCoy, How the tail wags the dog: how value judgments determine ecological science. *Environ. Values* **3**, 107–120 (1994).
3. JA Catford, JR Wilson, P Pyšek, PE Hulme, RP Duncan, Addressing context dependence in ecology. *Trends Ecol. & Evol.* **37**, 158–170 (2022).
4. J Brian, J Catford, *Ecological scale and context dependence*. (CRC Press), pp. 63–79 (2023).
5. SE Kuebbing, et al., Long-term research in ecology and evolution: A survey of challenges and opportunities. *Ecol. Monogr.* **88**, 245–258 (2018).
6. G Arnqvist, D Wooster, Meta-analysis: synthesizing research findings in ecology and evolution. *Trends Ecol. & Evol.* **10**, 236–240 (1995).
7. KJ Gaston, TM Blackburn, *Pattern and process in macroecology*. (Wiley Online Library), (2000).
8. DM Leigh, et al., Opportunities and challenges of macrogenetic studies. *Nat. Rev. Genet.* **22**, 791–807 (2021).
9. A Shade, et al., Macroecology to unite all life, large and small. *Trends ecology & evolution* **33**, 731–744 (2018).
10. LH Fraser, et al., Coordinated distributed experiments: an emerging tool for testing global hypotheses in ecology and environmental science. *Front. Ecol. Environ.* **11**, 147–155 (2013).
11. AK Knapp, et al., Past, present, and future roles of long-term experiments in the lter network. *BioScience* **62**, 377–389 (2012).
12. JM Cocciardi, et al., The value of long-term ecological research for evolutionary insights. *Nat. Ecol. & Evol.* **8**, 1584–1592 (2024).
13. ET Borer, et al., Finding generality in ecology: a model for globally distributed experiments. *Methods Ecol. Evol.* **5**, 65–73 (2014).
14. KJ Liepe, CA Rieckmann, HS Mittelberg, M Liesebach, Phenotypic variation in 1,100 provenances of picea abies measured over 50 years on 33 german trial sites. *Sci. Data* **11**, 854 (2024).
15. G Woodward, et al., Continental-scale effects of nutrient pollution on stream ecosystem functioning. *Science* **336**, 1438–1440 (2012).
16. HL Gholz, DA Wedin, SM Smitherman, ME Harmon, WJ Parton, Long-term dynamics of pine and hardwood litter in contrasting environments: toward a global model of decomposition. *Glob. Chang. Biol.* **6**, 751–765 (2000).
17. L collaborators, The lotic intersite nitrogen experiments: an example of successful ecological research collaboration. *Freshw. Sci.* **33**, 700–710 (2014).
18. SR Keller, DR Taylor, History, chance and adaptation during biological invasion: Separating stochastic phenotypic evolution from response to selection. *Ecol. letters* **11**, 852–866 (2008).
19. FJ Alberto, et al., Potential for evolutionary responses to climate change - evidence from tree populations. *Glob. Chang. Biol.* **19**, 1645–1661 (2013).
20. JL Dickinson, et al., The current state of citizen science as a tool for ecological research and public engagement. *Front. Ecol. Environ.* **10**, 291–297 (2012).
21. R Bonney, et al., Public participation in scientific research: Defining the field and assessing its potential for informal science education. a caise inquiry group report. *Online submission* (2009).
22. EJ Theobald, et al., Global change and local solutions: Tapping the unrealized potential of citizen science for biodiversity research. *Biol. Conserv.* **181**, 236–244 (2015).
23. A Johnston, E Matechou, EB Dennis, Outstanding challenges and future directions for biodiversity monitoring using citizen science data. *Methods Ecol. Evol.* **14**, 103–116 (2023).
24. H Kobori, et al., Citizen science: a new approach to advance ecology, education, and conservation. *Ecol. Res.* **31**, 1–19 (2016).
25. P Soroye, N Ahmed, JT Kerr, Opportunistic citizen science data transform understanding of species distributions, phenology, and diversity gradients for global change research. *Glob. Chang. Biol.* **24**, 5281–5291 (2018).
26. MJO Pocock, et al., *A Vision for Global Biodiversity Monitoring With Citizen Science*, Advances in Ecological Research, eds. DA Bohan, AJ Dumbrell, G Woodward, M Jackson. Vol. 59, pp. 169–223 (2018).
27. GBIF, The global biodiversity information facility: What is gbif? (Available from https://www.gbif.org/what-is-gbif) (2024).
28. K Hoeffner, et al., Reliability of earthworm data from citizen science: Lessons from 7 years of a french national monitoring protocol. *Appl. Soil Ecol.* **214**, 106329 (2025).
29. O Nov, O Arazy, D Anderson, Scientistsathome: what drives the quantity and quality of online citizen science participation? *PloS one* **9**, e90375 (2014).
30. C Anhalt-Depies, JL Stenglein, B Zuckerberg, PA Townsend, AR Rissman, Tradeoffs and tools for data quality, privacy, transparency, and trust in citizen science. *Biol. Conserv.* **238** (2019).
31. D Barbato, A Benocci, M Guasconi, G Manganelli, Light and shade of citizen science for less charismatic invertebrate groups: quality assessment of inaturalist nonmarine mollusc observations in central italy. *J. Molluscan Stud.* **87** (2021).

32. J van Etten, et al., Crop variety management for climate adaptation supported by citizen science. *Proc. Natl. Acad. Sci.* **116**, 4194–4199 (2019).
33. I Goldringer, et al., Agronomic evaluation of bread wheat varieties from participatory breeding: A combination of performance and robustness. *Sustainability* **12**, 128 (2020).
34. C Santamarina, et al., Agroecological genomics and participatory science: optimizing crop mixtures for agricultural diversification. *Trends Plant Sci.* (2025).
35. M Schröter, et al., Citizen science for assessing ecosystem services: Status, challenges and opportunities. *Ecosyst. Serv.* **28**, 80–94 (2017).
36. B Castagneyrol, B Bedessem, R Julliard, Is ecology different when studied with citizen scientists? a bibliometric analysis. *Ecol. Evol.* **13** (2023).
37. DM Brown, PL Sieswerda, ECM Parsons, Potential encounters between humpback whales (megaptera novaeangliae) and vessels in the new york bight apex, usa. *Mar. Policy* **106**, 8 (2019).
38. RG Shaw, JR Etterson, Rapid climate change and the rate of adaptation: insight from experimental quantitative genetics. *New Phytol.* **195**, 752–765 (2012).
39. S Trumbore, P Brando, H Hartmann, Forest health and global change. *Science* **349**, 814–818 (2015).
40. J Wessely, et al., A climate-induced tree species bottleneck for forest management in europe. *Nat. Ecol. & Evol.* pp. 1–9 (2024).
41. C Senf, R Seidl, Persistent impacts of the 2018 drought on forest disturbance regimes in europe. *Biogeosciences* **18**, 5223–5230 (2021).
42. CD Allen, DD Breshears, NG McDowell, On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere* **6**, art129 (2015).
43. AA Hoffmann, CM Sgrò, Climate change and evolutionary adaptation. *Nature* **470**, 479–485 (2011).
44. SN Aitken, JB Bemmels, Time to get moving: assisted gene flow of forest trees. *Evol. Appl.* **9**, 271–290 (2016).
45. MV Talluto, I Boulangeat, S Vissault, W Thuiller, D Gravel, Extinction debt and colonization credit delay range shifts of eastern North American trees. *Nat. Ecol. & Evol.* **1**, 0182 (2017).
46. M Isaac-Renton, et al., Northern forest tree populations are physiologically maladapted to drought. *Nat. Commun.* **9**, 5254 (2018).
47. SN Aitken, JB Bemmels, Time to get moving: assisted gene flow of forest trees. *Evol. applications* **9**, 271–290 (2016).
48. M Hällfors, SE Dalrymple, *Conservation Translocations*. (Cambridge University Press), p. 331 (2022).
49. AL Angert, MG Bontrager, J Ågren, What do we really know about adaptation at range edges? *Annu. Rev. Ecol. Evol. Syst.* **51**, 341–361 (2020).
50. F Valladares, et al., The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. *Ecol. letters* **17**, 1351–1364 (2014).
51. T Fréjaville, N Vizcaíno-Palomar, B Fady, A Kremer, M Benito Garzón, Range margin populations show high climate adaptation lags in european trees. *Glob. Chang. Biol.* **26**, 484–495 (2020).
52. F Blanquart, O Kaltz, SL Nuismer, S Gandon, A practical guide to measuring local adaptation. *Ecol. letters* **16**, 1195–1205 (2013).
53. AL Gibson, EK Espeland, V Wagner, CR Nelson, Can local adaptation research in plants inform selection of native plant materials? An analysis of experimental methodologies. *Evol. applications* **9**, 1219–1228 (2016).
54. JM Alexander, JM Diez, SP Hart, JM Levine, When climate reshuffles competitors: a call for experimental macroecology. *Trends Ecol. & Evol.* **31**, 831–841 (2016).
55. S Schwinning, CJ Lortie, TC Esque, LA DeFalco, What common-garden experiments tell us about climate responses in plants (2022).
56. K Donohue, Why ontogeny matters during adaptation: Developmental niche construction and pleiotorpy across the life cycle in *Arabidopsis thaliana*. *Evolution* **68**, 32–47 (2014).
57. A Kuparinen, O Savolainen, FM Schurr, Increased mortality can promote evolutionary adaptation of forest trees to climate change. *For. Ecol. Manag.* **259**, 1003–1008 (2010).
58. TE Juenger, Natural variation and genetic constraints on drought tolerance. *Curr. Opin. Plant Biol.* **16**, 274–281 (2013).
59. K Csilléry, N Buchmann, B Fady, Adaptation to drought is coupled with slow growth in marginal silver fir (*Abies alba* Mill.) populations. *bioRxiv:531806* (2019).
60. D Montwé, M Isaac-Renton, A Hamann, H Spiecker, Cold adaptation recorded in tree rings highlights risks associated with climate change and assisted migration. *Nat. Commun.* **9**, 1574 (2018).
61. CM Zohner, BM Benito, JC Svenning, SS Renner, Day length unlikely to constrain climate-driven shifts in leaf-out times of northern woody plants. *Nat. Clim. Chang.* **6**, 1120–1123 (2016).
62. JR Stinziano, DA Way, Autumn photosynthetic decline and growth cessation in seedlings of white spruce are decoupled under warming and photoperiod manipulations. *Plant, cell & environment* **40**, 1296–1316 (2017).
63. AB Leverkus, et al., Restoring oak forests through direct seeding or planting: Protocol for a continental-scale experiment. *PLoS One* **16**, e0259552 (2021).
64. SC Stearns, The evolutionary significance of phenotypic plasticity. *Bioscience* **39**, 436–445 (1989).
65. ZD Blount, RE Lenski, JB Losos, Contingency and determinism in evolution: replaying life's tape. *Science* **362**, eaam5979 (2018).
66. A Mauri, D De Rigo, G Caudullo, Abies alba in europe: distribution, habitat, usage and threats. *Eur. Atlas forest tree species* pp. 48–49 (2016).
67. M Kurz, C Sperisen, K Csilléry, Tracking the geographic origin of introduced Oriental beech (*Fagus orientalis*) in Western Europe, (Swiss Federal Research Institute WSL), Technical report (2019).
68. K Prendergast, et al., Potential and pitfalls of citizen science with children: Reflections on pollinators in the playground project. *Austral Ecol.* **47**, 189–195 (2022).
69. AG Hart, et al., Understanding engagement, marketing, and motivation to benefit recruitment and retention in citizen science. *Citiz. Sci. Theory Pract.* **7** (2022).
70. K Jacobs, G Garfin, M Lenart, More than just talk: Connecting science and decisionmaking. *Environ. Sci. Policy for Sustain. Dev.* **47**, 6–21 (2005).
71. E Pötzelsberger, et al., Mapping the patchy legislative landscape of non-native tree species in europe. *For. An Int. J. For. Res.* **93**, 567–586 (2020).
72. R Bonney, et al., Next steps for citizen science. *Science* **343**, 1436–1437 (2014).
73. SE West, RM Pateman, Recruiting and retaining participants in citizen science: What can be learned from the volunteering literature? *Citiz. science: Theory practice* (2016).
74. JK Parrish, et al., Hoping for optimality or designing for inclusion: Persistence, learning, and the social network of citizen science. *Proc. Natl. Acad. Sci.* **116**, 1894–1901 (2019).
75. F Requier, A Fournier, Q Rome, E Darrouzet, Science communication is needed to inform risk perception and action of stakeholders. *J. Environ. Manag.* **257**, 9 (2020).
76. D Fraisl, et al., Citizen science in environmental and ecological sciences. *Nat. Rev. Methods Primers* **2**, 64 (2022).
77. A Johnston, E Matechou, EB Dennis, Outstanding challenges and future directions for biodiversity monitoring using citizen science data. *Methods Ecol. Evol.* **14**, 103–116 (2023).
78. S Ceccarelli, S Grando, Participatory plant breeding: who did it, who does it and where? *Exp. Agric.* **56**, 1–11 (2020).
79. A Brestovitsky, D Ezer, A mass participatory experiment provides a rich temporal profile of temperature response in spring onions. *Plant Direct* **3**, 11 (2019).
80. D Danial, J Parlevliet, C Almekinders, G Thiele, Farmers' participation and breeding for durable disease resistance in the andean region. *Euphytica* **153**, 385–396 (2007).
81. D Tilman, Secondary succession and the pattern of plant dominance along experimental nitrogen gradients. *Ecol. Monogr.* **57**, 189–214 (1987).
82. J Kreyling, et al., To replicate, or not to replicate–that is the question: how to tackle nonlinear responses in ecological experiments. *Ecol. Lett.* **21**, 1629–1638 (2018).
83. GP Quinn, MJ Keough, *Experimental design and data analysis for biologists*. (Cambridge university press), (2002).
84. TA Feo, M Khellaf, A class of bounded approximation algorithms for graph partitioning. *Networks* **20**, 181–195 (1990).
85. M Papenberg, GW Klau, Using anticlustering to partition data sets into equivalent parts. *Psychol. Methods* **26**, 161 (2021).
86. MJ Brusco, JD Cradit, D Steinley, Combining diversity and dispersion criteria for anticlustering: A bicriterion approach. *Br. J. Math. Stat. Psychol.* **73**, 375–396 (2020).
87. A Mauri, G Strona, J San-Miguel-Ayanz, EU-Forest, a high-resolution tree occurrence dataset for europe. *Sci. data* **4**, 160123 (2017).
88. A Dickson, et al., Can citizen science inform science? evaluating the results of the bellingen riverwatch citizen science program and a complimentary government monitoring program. *Front. Environ. Sci.* **11**, 17 (2024).
89. M Bison, NG Yoccoz, B Carlson, A Delestrade, Comparison of budburst phenology trends and precision among participants in a citizen science program. *Int. J. Biometeorol.* **63**, 61–72 (2019).
90. B Balázs, et al., Data quality in citizen science. *The science citizen science* **139**, 978–3 (2021).
91. AIT Tulloch, JK Szabo, A behavioural ecology approach to understand volunteer surveying for citizen science datasets. *Emu-Austral Ornithol.* **112**, 313–325 (2012).
92. F Danielsen, et al., Linking public participation in scientific research to the indicators and needs of international environmental agreements. *Conserv. Lett.* **7**, 12–24 (2014).
93. YN Golumbic, B Fishbain, A Baram-Tsabari, Science literacy in action: understanding scientific data presented in a citizen science platform by non-expert adults. *Int. J. Sci. Educ. Part B* **10**, 232–247 (2020).
94. C Hartung, et al., Open data kit: tools to build information services for developing regions in *Proceedings of the 4th ACM/IEEE international conference on information and communication technologies and development*. pp. 1–12 (2010).
95. T Ouma, et al., Open data kit (odk) in crop farming: Mobile data collection for seed yam tracking in ibadan, nigeria. *J. Crop. Improv.* **33**, 605–619 (2019).
96. HY Liu, D Dörler, F Heigl, S Grossberndt, *The science of citizen science*. (Springer Cham), (2021).
97. JL Dickinson, B Zuckerberg, DN Bonter, *Citizen Science as an Ecological Research Tool: Challenges and Benefits*, Annual Review of Ecology Evolution and Systematics, eds. DJ Futuyma, HB Shafer, D Simberloff. Vol. 41, pp. 149–172 (2010).
98. Q Groom, et al., Species interactions: next-level citizen science. *Ecography* **44**, 1781–1789 (2021).
99. CB van Rees, et al., A framework to integrate innovations in invasion science for proactive management. *Biol. Rev.* **97**, 1712–1735 (2022).
100. M Di Febbraro, et al., Different facets of the same niche: Integrating citizen science and scientific survey data to predict biological invasion risk under multiple global change drivers. *Glob. Chang. Biol.* **29**, 5509–5523 (2023).
101. J Fukase, A Simons, Increased pollinator activity in urban gardens with more native flora. *Appl. Ecol. Environ. Res.* **14**, 297–310 (2016).
102. AA Majewska, S Altizer, Planting gardens to support insect pollinators. *Conserv. Biol.* **34**, 15–25 (2020).
103. AS Persson, V Hederström, I Ljungkvist, L Nilsson, L Kendall, Citizen science initiatives increase pollinator activity in private gardens and green spaces. *Front. Sustain. Cities* **4**, 1099100 (2023).
104. FE Fonturbel, et al., Do exotic plants and flower colour facilitate bumblebee invasion? insights from citizen science data. *Flora* **298**, 152200 (2023).
105. A Cornwall, Unpacking 'participation': models, meanings and practices. *Community development journal* **43**, 269–283 (2008).
106. M Haklay, Participatory citizen science. *Citiz. science: Innov. open science, society policy* pp. 52–62 (2018).
107. L Dunlap, A Corris, M Jacquart, Z Biener, A Potochnik, Divergence of values and goals in participatory research. *Stud. Hist. Philos. Sci.* **88**, 284–291 (2021).
108. EJ Sterling, et al., Assessing the evidence for stakeholder engagement in biodiversity conservation. *Biol. conservation* **209**, 159–171 (2017).


DRAFT

109. G Peterson St-Laurent, S Hagerman, R Kozak, What risks matter? public views about assisted migration and other climate-adaptive reforestation strategies. *Clim. change* **151**, 573–587 (2018).
110. M Maesano, et al., Forest certification map of europe. *iForest-Biogeosciences For.* **11**, 526 (2018).
111. S Martellos, et al., Volunteers recruitment, retention, and performance during the csmon-life (citizen science monitoring) project and 3 years of follow-up. *Sustainability* **13** (2021).
112. A Antonelli, KL Dhanjal-Adams, D Silvestro, Integrating machine learning, remote sensing and citizen science to create an early warning system for biodiversity. *Plants, people, planet* **5**, 307–316 (2023).
113. J Kemppinen, et al., Microclimate, an important part of ecology and biogeography. *Glob. Ecol. Biogeogr.* **33**, e13834 (2024).
114. S Broadbent, One way TV advertisements work. *J. Mark. Res. Soc.* **21**, 139–166 (1979).
115. Y Jin, Y Wang, Y Sun, D Chan, J Koehler, Bayesian methods for media mix modeling with carryover and shape effects. *Google Res.* pp. 1–34 (2017).
116. KA Neuendorf, *Content analysis and thematic analysis.* (Routledge), pp. 211–223 (2018).
117. S VERBI, Maxqda 2022 (computer software). *MAXQDA 2022 [computer software]* (2021).
118. Food, AO of the United Nations. Forestry Department (Rome), *Global forest resources assessment 2010: Main report.* (Food and Agriculture Organization of the United Nations), (2010).
119. S Liepelt, et al., Postglacial range expansion and its genetic imprints in *Abies alba* (Mill.) - A synthesis from palaeobotanic and genetic data. *Rev. Palaeobot. Palynol.* **153**, 139–149 (2009).
120. D Magri, Patterns of post-glacial spread and the extent of glacial refugia of European beech (*Fagus sylvatica*). *J. Biogeogr.* **35**, 450–463 (2008).
121. DN Karger, et al., Climatologies at high resolution for the Earth's land surface areas. *Scientific Data* **4**, 170122 (2017).
122. H Hersbach, et al., Era5 hourly data on single levels from 1940 to present. *Copernicus climate change service (c3s) climate data store (cds)* **10** (2023).

DRAFT