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ECHO

ENGAGING CITIZENS IN SOIL SCIENCE: THE ROAD TO HEALTHIER SOILS

Deliverable 1.1
"Report on the state of the art of citizen science applied to soil"

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Short description of the deliverable

This deliverable is an overview of the current state of the art of citizen science initiatives and projects on soil health that summarise the collaborative work of the ECHO Task 1.1 ("State of the art on Citizen Science initiatives for monitoring soil health, soil biodiversity and pollution"). It examines the evolution and impact of soil-related citizen science projects, highlighting their role in environmental stewardship and policy development. The report begins with a historical context of soil-focused citizen science projects and reviews, setting the stage for understanding the momentum behind this deliverable. Methodologically, it outlines a multi-faceted approach to select and classify projects presented within the core of the deliverable. The latter shows a thorough overview of identified projects, their objectives, scientific, technological and engagement factors, as well as their influence in the scientific community and beyond. It details the collaborative nature of soil sampling and broader engagement initiatives, emphasising the dual role of citizens as data collectors and active participants in scientific inquiry. Additionally, it discusses non-soil health related citizen science projects for their relevant insights. The deliverable culminates in strategic recommendations, ensuring that ECHO not only contributes valuably to the field of soil health monitoring but also sets a precedent for future citizen science endeavours.

Versioning and contribution history

Version	Date	Modified by	Notes
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4	30/11/2023	Alba Peiro (IBERCIVIS)	Final version

Foreword

Soil is a vital, yet often disregarded, resource that supports life on Earth by providing the foundation for agriculture, forests, and various other natural ecosystems. However, soil degradation is a growing concern around the world, and it can have severe consequences for our planet like reduced crop yields, increased greenhouse gas emissions, and decreased biodiversity. The ECHO project aims to prevent this by bringing together citizens and volunteer scientists from around Europe to work towards a common goal of protecting and preserving our soils, thus contributing to the transition towards healthy soils of the EU Mission: "A Soil Deal for Europe".

ECHO will generate new data on the health status of EU soils, complementing existing soil mapping and monitoring in EU Member States and Scotland, including the EU Soil Observatory (EUSO). The project will develop and deploy 28 tailor-made citizen science initiatives across EU Member States and Scotland, considering different land-uses, soil types, and biogeographical regions, as well as stakeholder needs. With 16 participants from all over Europe, including 10 leading universities and research centres, 4 SMEs, and 2 Foundations, under the coordination of the Free University of Bolzano-Bozen, ECHO will assess 16,500 sites in different climate and biogeographic regions to achieve its ambitious goals.

The project aims to engage citizens in protecting and restoring soils by building their capacities and enhancing their knowledge. Citizens will thereby not only actively contribute to the project's data collection but also promote soil stewardship and foster behavioural change across the EU. The ECHOREPO, a long-term open access repository with a direct link to the EUSO, will make the citizen science data available for exploitation not only by scientists but also by citizens, policy makers, farmers, landowners and other end-users, providing added value to existing data and other relevant soil monitoring initiatives. ECHOREPO will thus provide valuable information about the state of soil health in various regions, and help citizens make informed decisions about land use and conservation.

We believe that the ECHO project will have a significant impact on soil health and citizen engagement across Europe and become an important step towards protecting and preserving our soil for future generations. By working together, we can ensure that our soil remains healthy and productive, and that we continue to enjoy the many benefits it provides.

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1. Introduction

Within the pages of this deliverable lies an exploration of citizen science as it intersects with the crucial domain of soil health, an aspect of environmental science that is pivotal yet frequently overlooked. As we navigate through this report, we delve into the evolution and potential of soil-centric citizen science initiatives, which have surfaced as influential forces in environmental stewardship and policy shaping. This deliverable stitches together a wide range of citizen science initiatives, providing a detailed landscape while identifying emergent patterns, establishing best practices, and pointing opportunities for significant advancement.

This deliverable begins by situating the recent surge in soil-focused citizen science within a historical framework (**Section 2**), highlighting the synergy between these modern initiatives and the critical European policy agendas driving the focus on soil health. This examination lays the groundwork for understanding the momentum of soil health monitoring and the distinct contributions of initiatives like the ECHO project. This background is vital for contextualising the subsequent sections, each of which builds upon the understanding that, while citizen science in soil health monitoring is a developing field, it is one rooted in an increasingly rich tapestry of research and practice.

The deliverable's methodological backbone is explained in **Section 3**, articulating our multi-faceted approach to the selection and classification of citizen science projects. Anchored by a science data lifecycle model, this section charts a path through the methodological landscape, ensuring a robust and inclusive review that overcomes geographical and linguistic barriers.

Section 4 ventures into the heart of the deliverable, presenting an in-depth overview of the projects that have been identified, scrutinising their goals, methodologies, and the influence they exert within the scientific community and beyond. This section categorises projects according to their soil health focus and the depth of citizen involvement, providing a snapshot of the current state of soil-focused citizen science.

Delving into the heart of citizen participation, this deliverable navigates the collaborative efforts of soil sampling and broader engagement initiatives (**Sections 5** and **6**), highlighting the synergy between direct scientific involvement and the expansive reach of community engagement. These sections reveal the dual nature of citizen science: on one hand, the tangible, hands-on experience of soil sampling, where community members become instrumental in data collection and analysis; and on the other, the wider embrace of projects that engage citizens in the full arc of scientific inquiry. Together, they illustrate a holistic approach to citizen science, where participants are not mere data collectors but are integral to problem-solving, interpretation, and the application of research findings. This integrated perspective of participation underscores the transformative potential of citizen science to not only contribute to the scientific fabric but also to weave new connections within communities, enhancing public understanding and stewardship of soil health.

Building on these analyses, **Section 7** introduces additional citizen science projects that, while not directly linked to soil health, contribute valuable insights and methodologies that can be adapted to enhance soil science practices.

The synthesis of the collective impact of these initiatives is discussed in **Section 8**, which delves into the implications of these projects for shaping the field of soil health, exploring their role in policy formation and community engagement.

Finally, **Section 9** encapsulates the essence of our findings, presenting key insights and strategic recommendations. At the same time, it stands as a testament to the successful completion of the review, aiming to guide future citizen science initiatives in soil health.

2. Background

Citizen science projects specifically focused on soils did not come into play until after the year 2010 (Ranjard, 2020; Gascuel et al., 2023a). However, the subsequent reviews available in the literature analysed citizen science projects only applied to environmental monitoring, in general. The review conducted by Conrad and Hilchey (2011) to support decision-making, or the more comprehensive one by Roy et al. (2012), stand out in that direction. In both studies, the smallest fraction of the projects reviewed were related to soil resources (Rossiter et al., 2015), thus not contributing significantly to the conclusions of the reviews. The reason is that, even though soil-related citizen science projects existed by that time, they tended to garner minimal interest in reviews compared to projects in other disciplines (Rossiter et al., 2015; Pino et al., 2022).

After that, soil-related citizen science projects had gained significance driven by the broader societal context. In Europe, soil issues had risen to prominence within public policy agendas, influenced by (Panagos, 2022; Gascuel et al., 2023a):

- The EU Soil Strategy for 2030 (European Commission, 2021a), which contributes to the objectives of the EU Green Deal, and it is part of the Biodiversity Strategy. This Strategy proposes specific actions in relation to citizen engagement.
- The EU Soil Observatory (EUSO; European Commission, 2020), which supports the implementation of the EU Soil Strategy 2030 and other relevant EU policies.
- The Common Agricultural Policy 2023-27 (CAP; European Commission, 2021b), which is a key EU land management policy and a central driver for the management of agricultural land.
- The EU Action Plan "Towards a Zero Pollution for Air, Water and Soil" (European Commission, 2021c), which contains several measures specifically targeting soils.
- The Mission 'Soil health and food' of the Horizon Europe, now called the Mission 'A Soil Deal for Europe' (European Commission, 2021d; Fig. 1), which is one of the five Research and Innovation Missions to bring concrete solutions in response to major societal challenges, meeting global commitments such as the Sustainable Development Goals (SDGs).

Figure 1. Mission 'A Soil Deal for Europe' of Horizon Europe (European Commission, 2021d).

In recent years, several reviews focus on citizen science and nature or environment, but still do not shed light on the state of the art of soil citizen science (e.g., Peter et al., 2019; Adamou et al., 2021; Hadjichambi et al., 2023). However, we would like to highlight below four recent reviews that might be relevant for ECHO.

Head et al. (2020) provide a review of existing citizen science methods and platforms for soil health monitoring which could be used to provide data for the SDGs indicators relevant to soil health. They considered the cost, reliability, and accessibility of the existing methods and toolkits of a total of 33 citizen science soil monitoring initiatives. They finally provided recommendations on what is required to enable farmers to contribute effectively to the SDGs on soil health.

The second one was conducted by **Ebitu et al. (2021)**. They approached articles in relation to citizen science and sustainable agriculture, and the first topic under which they grouped the reviewed articles was indeed soil health. They identified 4 projects that assessed the arsenic concentration on soils, field size or, mainly, earthworms' biodiversity and/or density.

The review provided by **Pino et al. (2022)** explores existing worldwide citizen science initiatives and projects in the context of soil connectivity beyond the methods being used. After reviewing more than 50 soil citizen science initiatives, they identified three main trends in how to link soil to different human areas and, therefore, in boosting soil connectivity through citizen science.

Lastly, **Gascuel et al. (2023a, b)** carried out the most recent ones. The former focused on identifying soil citizen science projects in France, gathering a total of 20 such initiatives. The authors determined that these projects aimed to raise awareness and to take soil into account in public policies, as well as to develop practical tools for evaluating soil biodiversity.

Predominantly, these projects targeted agricultural land, and to a lesser extent urban or natural areas. They primarily delved into the soil's biological and physicochemical properties, as well as management aspects (such as landscape or agricultural practices) and basic characteristics (like colour or texture). The authors highlight that none adopted a holistic approach to soil, even though the extensive range of properties they considered would have allowed such a comprehensive perspective. Gascuel et al. (2023b) continued this inventory and they have reviewed the use of citizen science on soils and agroecosystems across Europe. Many of them have generated soil biodiversity, vegetation cover and soil organic carbon data, and have reported the educational value and satisfaction (derived from meaningful scientific participation) as benefits for the citizen scientists. However, there are no available overviews of those lists of projects. In the case of Gascuel et al. (2023b), they provided a synthesis that for sure will be analysed more in detail in future publications.

3. Material and methods

3.1. The matrix constructing process

A detailed matrix has been constructed to offer insights into the state of the art for projects that have already involved citizens in monitoring soil health. This matrix is presented as a table, created in a spreadsheet (using Google Docs and Teams), serving as a repository for valuable resources (Fig. 1). The table is available at Ibercivis Foundation (2023). It enabled us to thoroughly explore previous citizen science initiatives in the field and, as a result, obtain a clear understanding and analysis of the present landscape.

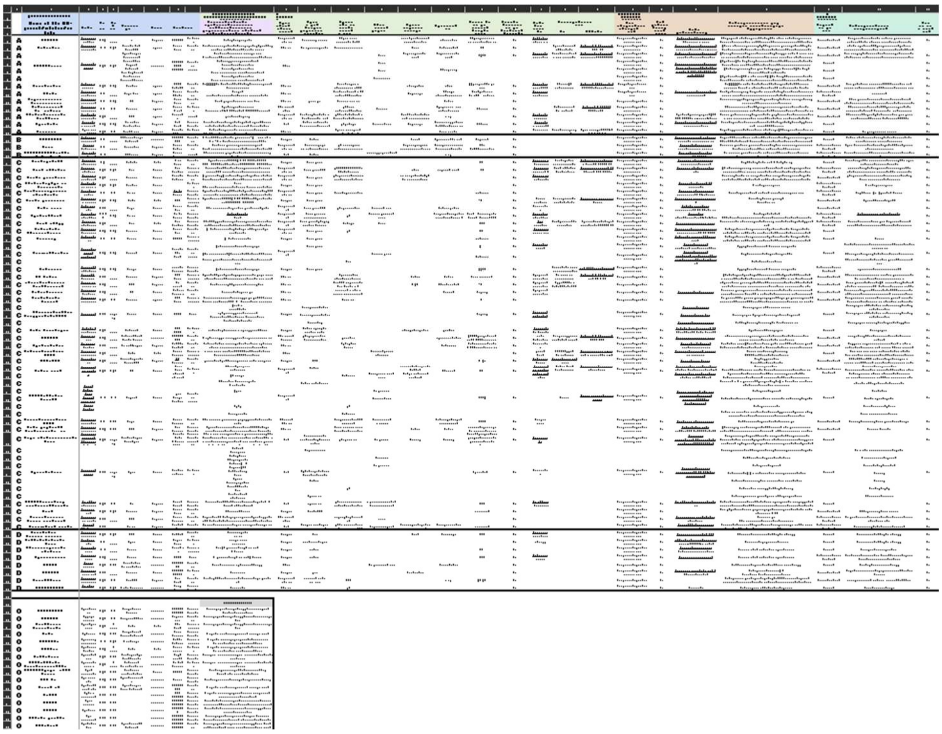


Figure 2. General overview of part of the matrix constructed and various projects reviewed by Ibercivis Foundation (2023).

The table was divided into six main sections (refer to Appendix 1 for further details), encompassing the following areas:

- General: this includes basic coordination information and contact details.
- Scientific: covers aspects of the citizen toolkit, scientific details, fieldwork process and sample analysis.
- Technological: mainly concerns the apps utilised.
- Citizen Engagement and Impact: details the type of citizen science and methods implemented, as well as the impact and the extent of the results achieved.

Each section was further subdivided into specific questions and columns to ensure comprehensive information collection. All factors considered were revised and endorsed by the ECHO partners involved in the task, prior to compiling the table with pertinent details from projects.

3.2. Literature review and online search

The literature review is the first step in any research endeavour, offering a comprehensive understanding of prior studies in a specific domain. In our case, it was an essential task for gathering the available reports or documents to identify the corresponding projects, initiatives or activities from both inside and outside the European Union (EU). This process led to completing the final matrix.

Our selection criteria for projects were that they must have:

- Focuses on soil health, encompassing both soil biodiversity and pollution.
- Carried out active engagement of citizens through citizen science approaches.

To source pertinent data within the EU, we initiated our search with the European Commission's public repository, the Community Research and Development Information Service (CORDIS, 2023). A targeted search using the terms 'soil' AND 'citizen' yielded 205 results. Each of these entries was scrutinised based on their titles, objectives, and results in brief to determine their relevance to ECHO. This repository not only provided us with the titles and general information about these projects, but also offered access to download public documents. Additionally, it guided us to the corresponding project websites and platforms, enabling a deeper exploration and further document collection. The 28 projects funded under Mission Soil have also been consulted at European Commission (2023).

Other national, European and international repositories have been consulted following the same process. Those are:

- EU-Citizen.Science (2023): the search of the term 'soil' yielded 3 results.
- Observatorio de la Ciencia Ciudadana en España (2023): the search of the term 'suelo' yielded 1 result.
- SciStarter (2023): the search of the term 'soil' yielded 32 results*.
- iNAturalist (2023): the search of the term 'soil' yielded 1006 results*.

* Searches in these repositories were very limited because they include the term 'soil' into general environment-related terms. For instance, iNaturalist only focus on monitoring biodiversity of specific species

(birds, amphibians, reptiles, mammals, fish, mollusks, arachnids, insects, plants, fungi and protozoans), and most of them are not directly related to soils. Nevertheless, some of the projects established a relationship between those species and soils and were of interest to ECHO.

After conducting this thorough review, Google and Google Scholar have served as useful tools too. They enabled us to verify the information and ensure comprehensiveness in sourcing projects, providing a holistic view ranging from academic articles to various online content. They facilitated the identification of relevant, current information, assisted in citation tracking, and aided in uncovering related initiatives. Google Scholar offered depth in academic content, encompassing research articles, whereas Google supplied a broad spectrum of sources, from websites to reports.

Lastly, we juxtaposed our list with those presented in prior reviews (Head et al., 2020; Ebitu et al., 2021; Pino et al., 2022; See section 2 of this deliverable for further information). While some projects from these sources had already been noted by us, others provided valuable additions. However, we did not include every project from these previous reviews, due to differences in scope. For example, Head et al. (2020) provided a review that also includes methods, or Pino et al. (2022) included documentaries and educational experiments, among others, that do not fully align with our concept of citizen science activities. Despite these variations, these studies undeniably enriched our review.

Authors acknowledge that many times citizen science occurs outside academia and these reviews cannot be considered as a definitive search. Local or community-based projects that occur at a very micro level, usually they do not publish on established channels, and they are very difficult to trace.

3.3. Interviews with key representatives

In the process of analysing projects for this review of the state of the art, we seldom encountered some limitations in accessing comprehensive information for certain initiatives. In some cases, the absence of a project proper website, linguistic barriers, or limited online documentation, hindered a thorough understanding of the project's objectives, methodologies or impact.

To bridge these gaps and ensure an accurate representation in our review, we carried out some direct interviews with key representatives or stakeholders associated with those projects (e.g. Latrobe Valley Dust Research, Tea Bag Index, Bridges). These interviews were conducted via email, facilitating a structured and detailed exchange of information. Engaging in these dialogues could strengthen our review, ensuring that no initiative was misrepresented due to the absence of digital documentation.

3.4. Partners contributions

3.4.1. From inside ECHO

Ibercivis (Spain) led this task, but every ECHO partner participated in it. As a result, all partners were recognized as contributors to the database within the matrix version of the project's Teams channel. We requested each partner to compile and consolidate information from projects identified during desk research. Additionally, they were asked to incorporate any projects that, to their knowledge, engaged citizens in monitoring soil health, which might have been overlooked during the review process.

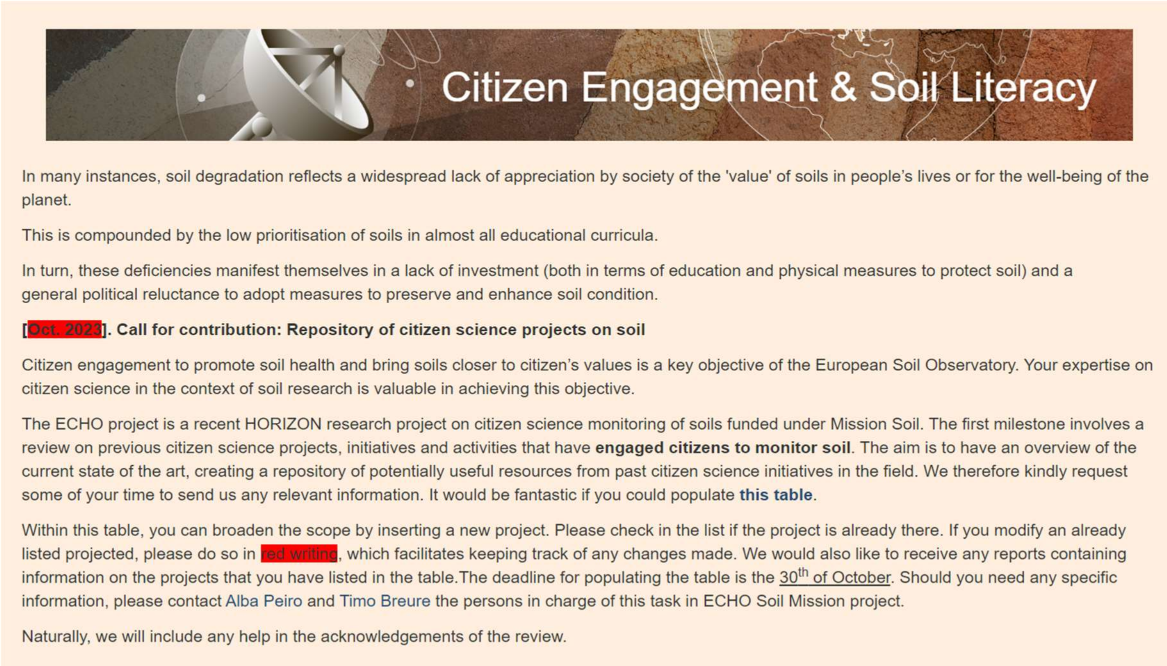
This collaborative approach was established through three online meetings and mailing threads with all partners, ensuring clarity in the process and addressing any concerns. One significant advantage of this method was the ECHO partners' ability to contribute to projects they were familiar with, had expertise in, or those initiatives presented in their native languages. It enabled us to tap into the deep understanding of local projects that ECHO partners could have led or participated in. They were able to identify relevant initiatives that had not been mentioned or referred to online or in the academic literature, perhaps due to their recent inception or their limited geographic scope.

3.4.2. From external entities

Collaborative efforts from external entities have significantly enriched our analysis. They were not directly part of our ECHO consortium but were also recognized as contributors to the database within the matrix version of Google Docs. Mainly, the Joint Research Centre (JRC) has distributed the table by the mailing lists of the European Network of Soil Awareness (ENSA) and the European Soil Data Centre (ESDAC; Fig. 3). All together have allowed its distribution through more than 13,000 participants.

An unknown number of those participants have suggested overlooked initiatives and provided details on projects already under our consideration, they have filled gaps and offered other perspectives. This kind of cross-institutional cooperation underscores the strength of collective expertise and emphasises the importance of networking and information sharing in advancing European citizen science efforts related to soil health.

It is important to clarify that these entities bear no responsibility for the conclusions or interpretations derived from the data presented in the table or the final classification of projects. Their participation was solely in the provision of information, and they were not involved in the analysis or the inferential processes that led to the conclusions drawn within this report. Their contribution was invaluable in enriching the content, but the responsibility for any conclusions or potential misunderstandings rests solely with the ECHO team.



Citizen Engagement & Soil Literacy

In many instances, soil degradation reflects a widespread lack of appreciation by society of the 'value' of soils in people's lives or for the well-being of the planet.

This is compounded by the low prioritisation of soils in almost all educational curricula.

In turn, these deficiencies manifest themselves in a lack of investment (both in terms of education and physical measures to protect soil) and a general political reluctance to adopt measures to preserve and enhance soil condition.

[Oct. 2023]. Call for contribution: Repository of citizen science projects on soil

Citizen engagement to promote soil health and bring soils closer to citizen's values is a key objective of the European Soil Observatory. Your expertise on citizen science in the context of soil research is valuable in achieving this objective.

The ECHO project is a recent HORIZON research project on citizen science monitoring of soils funded under Mission Soil. The first milestone involves a review on previous citizen science projects, initiatives and activities that have **engaged citizens to monitor soil**. The aim is to have an overview of the current state of the art, creating a repository of potentially useful resources from past citizen science initiatives in the field. We therefore kindly request some of your time to send us any relevant information. It would be fantastic if you could populate **this table**.

Within this table, you can broaden the scope by inserting a new project. Please check in the list if the project is already there. If you modify an already listed projected, please do so in red writing, which facilitates keeping track of any changes made. We would also like to receive any reports containing information on the projects that you have listed in the table.The deadline for populating the table is the 30th of October. Should you need any specific information, please contact Alba Peiro and Timo Breure the persons in charge of this task in ECHO Soil Mission project.

Naturally, we will include any help in the acknowledgements of the review.

Figure 3. Call for collaborative contribution to the ECHO T1.1 matrix published in October 2023 by the JRC and ESDAC.

3.5. Limitations

It is worth highlighting that even with the diverse methods used, this review should be considered representative rather than comprehensive. Although a substantial number of programs have been delineated, which facilitated the formulation of a typology, there remains the possibility that certain initiatives have eluded identification. It is also possible that part of the information related to some projects, provided to the table, might have not been the most accurate.

Such omissions can be attributed to the following main limitations and challenges we have encountered:

- Limited documentation: not all citizen science projects are visible online. Some might have been small, locally driven projects, or can suffer from low participation rates, which could make them hard to discover or analyse.
- Geographical gaps: our search process and the consulted repositories could have led us to identify more projects in some countries or regions and fewer in others, which possibly results in an uneven understanding of soil health across the world. Sociocultural differences further amplify this limitation, as perceptions and attitudes towards soil health and citizen science can differ across cultures.
- Temporal differences: projects carried out at different times might show different documentation levels available for this review. With the older ones, the probability of finding online errors, broken links and erased websites is higher.
- Access to specific data: in relation to the latter, some projects were visible online but did not have their data available for review, or it was behind paywalls or other access barriers.

- Language barriers: given the diversity of languages around the world, some relevant projects were documented in languages that were unfamiliar to us. When translating tools were not effective, it posed a challenge for unravelling the information of those projects.
- Heterogeneous methodologies: different projects might have used different methodologies, tools, or metrics for soil health, making it a challenge to fit with the table and to aggregate their results.
- Novelty and complexity of the subject matter: studying soils through citizen science initiatives is a relatively new area of exploration. This does not mean that there is necessarily a scarcity of projects or studies, but rather an array of approaches that can appear chaotic and unstandardized. This emerging status might also mean that there is ongoing evolution in how such projects are approached, further complicating the review process.

Despite all of this, we are confident that we have overcome these challenges by a systematic approach to the literature review, including sourcing from multiple databases, and potentially reaching out to some experts in the field to fill in gaps in the available literature. This review has been sufficiently broad in scope and has enabled us to glean meaningful insights from the identified projects.

4. Overview of projects identified

4.1. Number of projects identified

Following the already-mentioned methodology, we have identified a total of 91 projects. Out of these, 71 were fully aligned with our selection criteria, as detailed in Section 3.2, or have been considered of interest to ECHO (refer to Appendix 2 for further details). These encompass projects, initiatives, or activities that actively engage citizens in soil health topics. Among these (Fig. 4):

- More than half (55%) were sourced through literature review and *online searches, while the remaining (45%) were incorporated through the collaborative approach and joint effort of both ECHO partners and external entities.*
- They all are coordinated by universities, government agencies, museums, associations, foundations, institutes, NGOs or citizens, excluding possible projects coordinated by businesses or companies.
- The projects span both within and outside the EU but, as indicated in Section 3.5, our search may show geographical gaps, leading to a potential uneven representation of certain perspectives. The pilots' geographic spread across four continents is: Africa (2%), Oceania (7%), North America (14%) and South America (1%), and Europe being the most represented (at 66%). A subset (10%) of these projects has a global scope (they carry out citizen science activities within more than one continent).

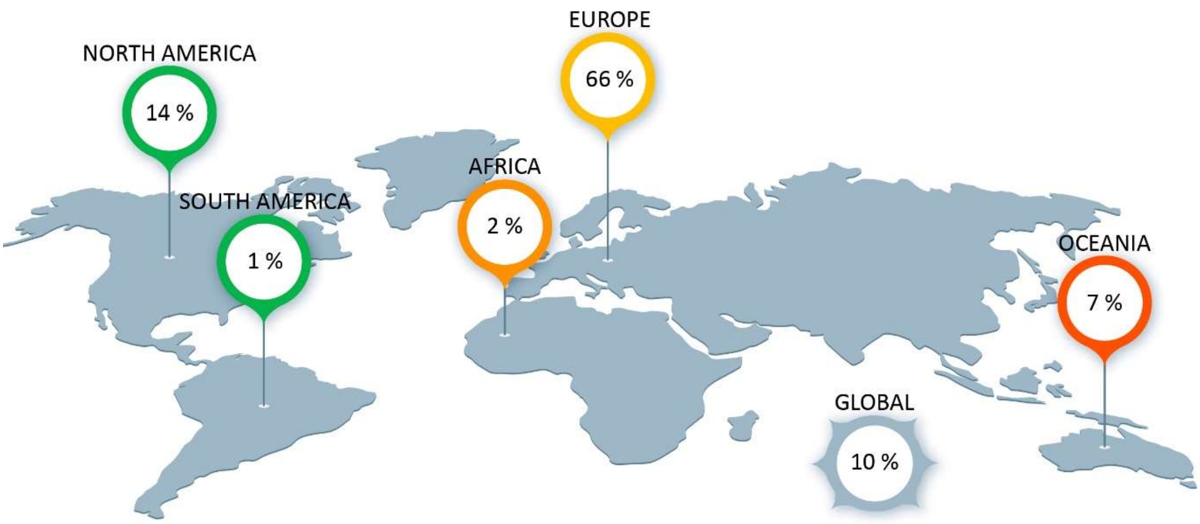


Figure 4. General geographic spread of the 71 identified projects.

Out of the 91 identified projects, 20 initiatives were ultimately excluded from this document for various reasons, such as conducting participatory activities that did not qualify as citizen science, soil sampling for purposes other than assessing soil health (like isolating fungi for medicinal research or recycling food for soil improvers) or because there was insufficient information for a detailed analysis (either due to lack of availability or because they were very recent).

4.2. Introduction to the classification of citizen science projects

The following sections 5-7 provide a general classification of the identified projects, using the degree of **citizen engagement** as a primary distinguishing factor. This criterion was selected because it captures the main differences between projects. The second distinguishing factor used in our classification is the **soil-centric** or **non-soil-centric** main objective of the projects. Within these factors, we also delve into specific scientific sub-criteria based on the different types of soil indicators in each case (see Appendix 2). This approach enabled us to classify projects into the following five types (Fig. 5A):

- **TYPE D:** General environmental citizen science projects, partially focused on soils, in which citizens only participated in soil sample collection and/or basic interpretations. These projects constitute 11% of the total identified.
- **TYPE C:** Soil-specific citizen science projects, in which citizens only participated in soil sample collection and/or basic interpretations. They represent 47% of the entire set of identified projects.
- **TYPE B:** General environmental citizen science projects, partially focused on soils, in which citizens were broadly engaged. These projects constitute 4% of the total identified.

- **TYPE A:** Soil-specific citizen science projects, in which citizens were broadly engaged. They represent 14% of the total of the identified projects.
- **TYPE O:** Additional projects of interest to ECHO. They represent 24% of the entire set of identified projects.

Types D and C can be considered as contributory projects, and types B and A as collaborative and co-created ones, according to the classification of public participation in scientific research projects established by Shirk et al. (2012). The former are generally designed by scientists and for which members of the public primarily contribute and, occasionally, analyse data. In collaborative projects, members of the public contribute data but also help to refine project design, analyse data, and/or disseminate findings. Finally, co-created projects are designed by scientists and members of the public working together and for which at least some of the public participants are actively involved in most or all aspects of the research process (Shirk et al., 2012) (Fig. 5B).

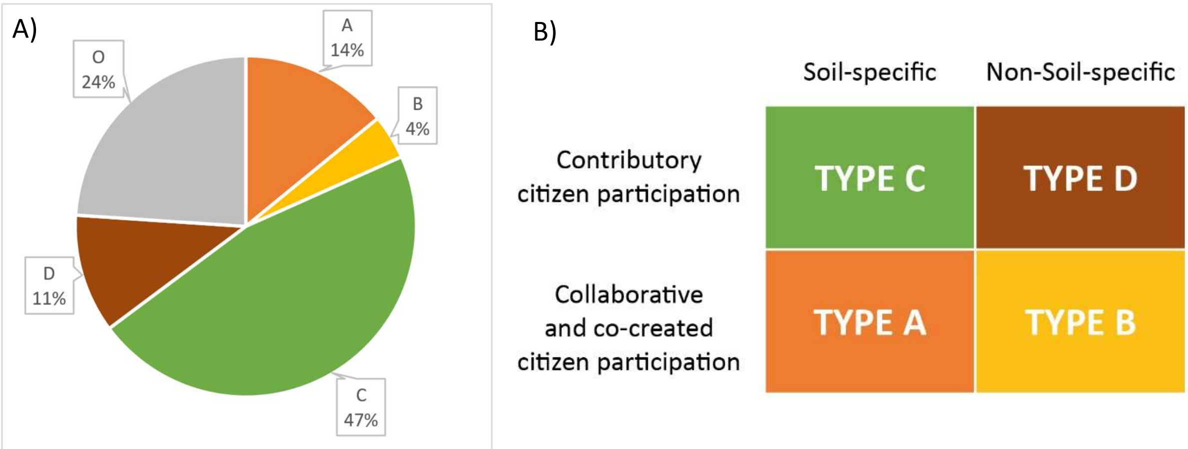


Figure 5. A) Graphical representation of the classification of projects followed in this deliverable. B) Relationship between the classification of public participation in scientific projects of Shirk et al. (2012), soil specificity and the classification of this deliverable.

Moreover, delving into the main soil-health-related aim of the projects, we use the broad classification of types of soil indicators or properties of Bünemann et al. (2018), who categorised these as either physical, chemical or biological. However, these categories are not always clearly delineated, as many properties reflect multiple processes (Lehmann et al., 2020). The identified projects assess the following types of soil indicators through citizen science activities (Fig. 6):

- Biological indicators: organisms' biodiversity and characteristics (bacteria, fungi, protozoa, insects, worms or other invertebrates), decomposition rate, etc. A significant 21% of the total identified projects are exclusively centred on these indicators.
- Chemical indicators: pH, SOC, SOM, pollution (trace metals or microplastics), etc. These indicators are the sole focus for 17% of the identified projects.

- Physical indicators: texture, structure, colour, moisture, water infiltration, temperature, etc. The 4% of the total identified projects were only focused on these indicators.
- Mixed indicators: for projects assessing indicators that span more than one category. They represent 34% of the entire set of identified projects. Notably, within this, 25% lean towards one type of indicator over others (biological predominance in 20%, chemical predominance in 4% and physical predominance in 1%).
- No indicators: for the other citizen science projects of interest that do not fit the above classifications. They represent 24%.

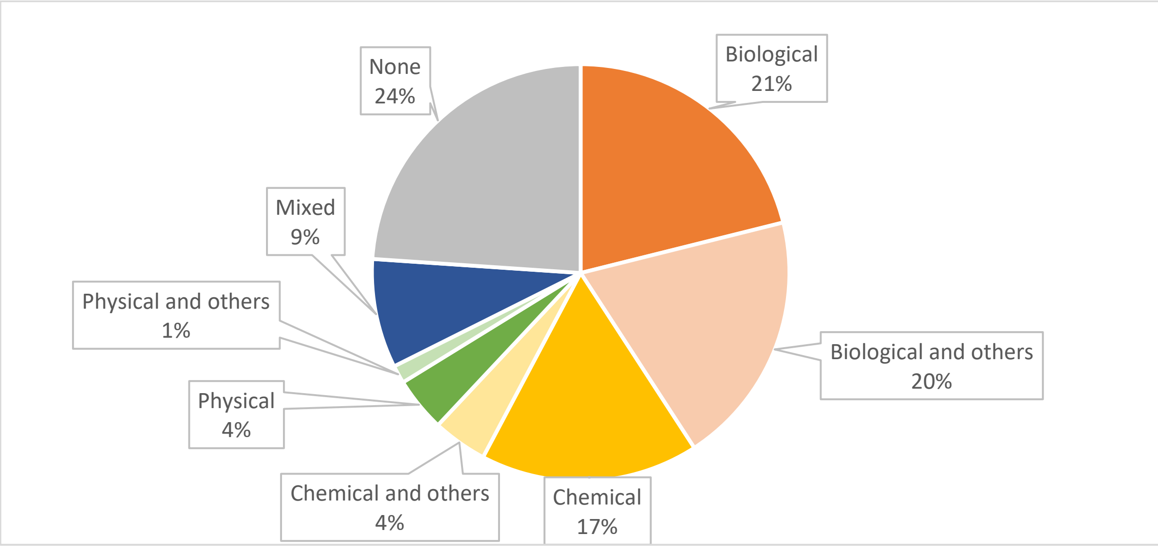


Figure 6. Main types of soil indicators assessed in the 71 identified projects.

5. Citizen science projects involving sampling collaboration

5.1. Non-soil-specific (TYPE D)

5.1.1. General factors

Eight of the identified projects, initiatives and activities have engaged citizens in monitoring general environmental aspects, with relevance to soil health. Nearly half of these are coordinated by researchers or universities (Fig. 7A). Pilots arising from these projects primarily operate on a national scale. The remaining projects operate in the European region, at a macro-regional scale (covering different countries) or regional scale (Fig. 7B). Most of these types of projects are relatively short-term, averaging a span of about 2 years. However, the *Observatoire agricole de la biodiversité* (2023) stands apart with a solid duration of 14 years, and it is still ongoing, representing a unique opportunity for research. Nearly half of the total number of projects are still in progress (Table 1).

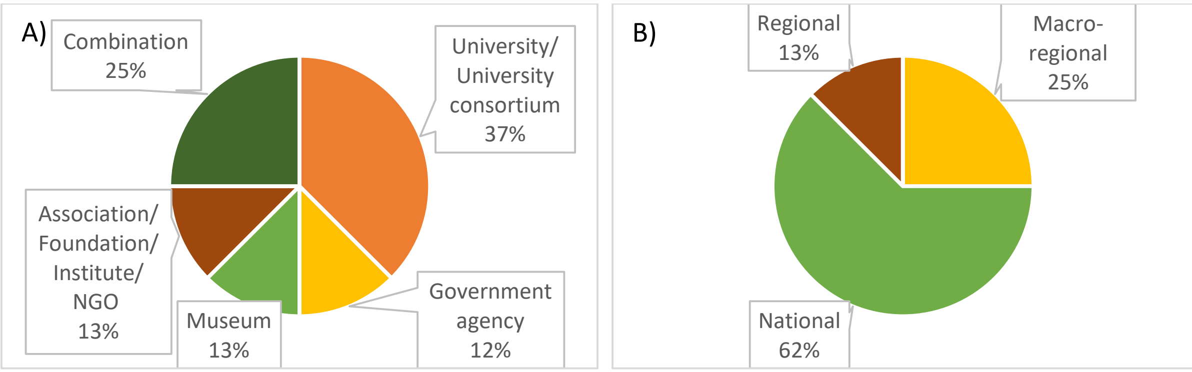


Figure 7. Coordination types (A) and geographical scope (B) for projects in Type D.

Table 1. Timeline and activity for projects in Type D.

Timeline and activity	Number
Duration ≥ 4 years	1
Duration < 4 years	7
Ongoing status	4
Finished status	4

5.1.2. Scientific factors, field work and analysis

The 8 projects categorised as D-type carried out citizen science activities that mainly are simple, when talking about the scientific citizen procedure, and educative, to spread awareness about the scientific objectives of the project. Predominantly, the primary soil indicators examined are biological, with 5 projects centring on monitoring biodiversity (such as mosses, biological and vegetation covers, or earthworms). The other projects focused on physical soil properties, like temperature or moisture levels, and on pH. What distinguishes this category from others is the broader, non-soil-centric objective. While these projects might have primarily targeted general biodiversity, environmental, or agricultural goals, they derived insights about soil health.

Of these D-type projects, 6 used toolkits comprising everyday household items, and the remaining ones employed more intricate protocols requiring specific tubes or detectors, which are supplied by the project coordinators. Participants were completely independent during all field work campaigns but needed specific guidelines in 6 projects. Within the latter, 5 guidelines were available online. Fieldwork campaigns typically involved defining an area of study and observing biodiversity in 5 of the total projects. Other protocols implied collecting samples and directly sending them to project coordinators or embedding detectors into the ground. Citizens undertook the task of analysing samples or observations in 6 projects, while in the others, experts took this responsibility. The latter had to draw general conclusions, discern the relationship between biodiversity and soil health or to execute specialised laboratory procedures. The results of these methodologies are available online for 2 projects, presenting the data in the form of maps that display sample locations and related information, hosted within the projects' apps. No publications or quality assessment frameworks are available online for these projects.

5.1.3. Technological factors

Three out of the 8 D-Type projects identified incorporate technological tools in the form of applications. Two projects have developed proprietary apps specifically tailored to their needs, while one project uses iNaturalist, a widely recognized social network that connects citizen scientists and encourages the sharing of biodiversity observations globally. Both the iNaturalist platform and one of the custom apps allowed users to map the locations and details of their samples. The second internally developed app is designed to collect and interpret data individually from detectors, without a community sharing feature. They are mainly compatible with the Android operating system, and occasionally with iOs.

5.1.4. Engagement and impact factors

In these initiatives, citizens' involvement was limited to collecting soil samples, with participants in 7 out of the projects also taking on the role of basic interpreters. Tasks such as species identification or evaluating parameters (like temperature, moisture, and pH) were among their interpretive responsibilities. Consequently, these can be categorised as contributory projects according to Shirk et al. (2012).

The audience targeted for 5 of the 8 projects includes educational sectors (students and teachers), families, and the general public. The rest focused on naturalists and farmers. Common engagement methods and notable communication and dissemination practices predominantly include punctual workshops held in the field or at events (such as the European Researchers' Night), as well as educational videos and online guidelines.

Consequently, the extent of the results obtained and the subsequent impact of all the D-type projects were primarily social, as one of their goals was the dissemination of scientific knowledge. However, 5 projects also yielded educational benefits using tailored materials. Additionally, a subset of 2 projects generated impacts that are scientific, political, or economic in nature; this is particularly evident in agricultural themes.

5.2. Soil-specific (TYPE C)

5.2.1. General factors

A total of 33 initiatives have been categorised as C-type projects, distinguished by their primary focus on soil health and the degree of citizen engagement. Approximately half of these projects are spearheaded by academic researchers or institutions, predominantly on a national level (Fig. 8). The remaining projects are largely managed by entities and governmental bodies, extending their reach globally and regionally. Most C-type projects tend to be short-term endeavours, and close to half are currently ongoing (Table 2).

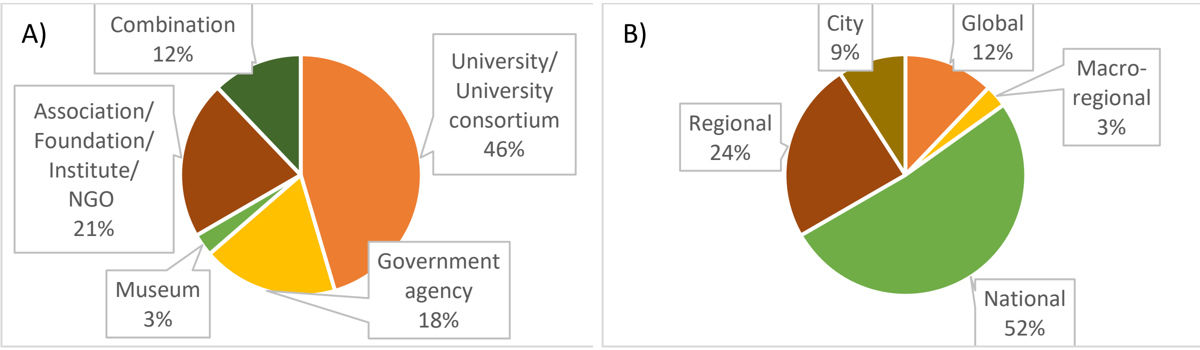


Figure 8. Coordination types (A) and geographical scope (B) for projects in Type C.

Table 2. Timeline and activity for projects in Type C.

Timeline and activity	**Number**
Duration ≥ 4 years	9
Duration < 4 years	24
Ongoing status	17
Finished status	16

5.2.2. Scientific factors, field work and analysis

There is a considerable diversity in the scientific scope of C-type projects, which span from complex endeavours that require careful handling to user-friendly and educational, while not necessarily sacrificing scientific rigour. Of these, 19 projects are dedicated to biological indicators, with a particular emphasis on soil decomposition studies. Some of them and other projects also assess a broader spectrum of indicators, encompassing chemical (such as pH, nitrates, microplastics, etc.) and physical parameters (including temperature, texture, moisture, etc.). The 33 projects identified as this type shed light on soil health, directly depending on the project.

Within this category, four primary clusters of projects have been identified:

- Two clusters of projects centre on soil decomposition: the first encompasses 9 initiatives based on the Tea Bag Index approach (TBI; Keuskamp et al., 2013), while the second includes 4 that implement the techniques outlined in the Soil Your Undies Challenge (SYUC; 2023).

- One cluster is focused on soil pollution: it encompasses 3 projects based on the 360 Dust Analysis (360DA; 2023).
- The last one refers to the other 15 projects, without implying common characteristics among them.

The toolkits for the TBI and SYUC typically involve cost-effective, readily available household materials. Within the 360DA it is made of the material to collect the soil sample and deliver it to the laboratory. Projects targeting other biological, chemical, or physical indicators adopt toolkits that range from the homemade to the complex. For chemical analysis, tools might span from specialised devices to simple substances like vinegar and hydrogen peroxide; physical analysis may involve deploying sensors or using standard thermometers; and biological studies could range from constructing traps to employing mustard solutions for extracting organisms.

Participants were completely independent during all field work campaigns, although they could follow detailed guidelines, always accessible online. Fieldwork campaigns are diverse too. For both TBI and SYUC groups, they entailed burying items to observe decomposition (for around 60 days). As said before, in the 360DA cluster they only had to collect the sample. In contrast, projects analysing microbial DNA necessitate rigorous methods to prevent contamination, while those mapping soil pollution require photographs and detailed descriptions. In 11 projects, citizens independently conducted the analysis of samples; in 11, scientists or specialists carried them out. Within the rest, a collaborative approach was adopted. Citizens identified species or made estimations based on guidelines, and scientists undertook more complex analyses, like calculating the TBI or performing DNA metabarcoding. Of all the C-type projects, the outcomes from 23 are transparently shared online, often through interactive maps on the projects' websites or applications, detailing the sample locations and associated data. Remarkable articles are available online for both TBI and 360DA, and for 5 projects more, and the quality assessment frameworks are accessible in 3 projects.

5.2.3. Technological factors

Out of all the initiatives categorised as C-type, 12 have developed or leverage specialised applications that ease data processing and sharing. Among these, one uses the well-known iNaturalist platform, while another uses the Jardibiodiv app, utilised in different projects to enhance understanding of soil-dwelling invertebrates. The 360DA group leverages the Map my Environment website. These applications facilitate user engagement by enabling participants to geographically chart their sampling sites along with accompanying information. Additionally, one project plays a role in a satellite mission that maps soil moisture levels. Despite their advanced functionality, these digital tools are licensed, and, in the case of the apps, they support both Android and iOS operating systems, ensuring broad accessibility.

5.2.4. Engagement and impact factors

Together with the 8 D-type initiatives, the citizen science activities undertaken in the 33 C-type projects can also be categorised as contributory as per the framework established by Shirk et al. (2012). Within this grouping, 14 projects engaged citizens in the collection of samples, and 17 went deeper allowing them to interpret analytical results to some degree.

In most of these projects, totalling 26, the target groups encompass a wide audience that includes the educational community (students at various academic levels and educators), families, and a general public with an interest in soil health. Additional participants drawn into these projects include rural communities and lifelong learners, as well as farmers, policy makers, scientific associations and experts. Engagement methods and communication and dissemination practices frequently feature interactive workshops in natural settings or at special events (like the European Researchers' Night), exhibitions that visually show project findings, online forums, and appealing and educational resources such as instructive websites, videos, and guides.

Contrary to the variance observed in scientific methodologies, there is a more uniform extent of the results obtained and the subsequent impacts of the 33 C-type projects. The main aim for 21 of these initiatives is educational, leveraging customised content and applying scientific methods depending on the educational level. Like the D-type projects, 17 have fostered a societal impact, through the dissemination of informative material about soil health and of scientific knowledge in general. Out of the total of initiatives, 25 projects have generated valuable data for research, marking a clear scientific impact. The latter do not always correspond with societal or educational influence, given the occasional minimal participant engagement beyond sample collection. Furthermore, other projects have yielded impacts that are political (engaging with regional policymakers), environmental (pollution recovery), economic (developing new tools), or cultural (through public exhibitions).

6. Citizen science projects involving broader engagement

6.1. Non-soil-specific (TYPE B)

6.1.1. General factors

Among all the initiatives identified, only 3 projects have significantly involved citizens in activities with non-soil-centric objectives. Two of these projects are spearheaded by academic researchers or universities and are relatively short-term, with a duration of three years, and are currently ongoing. The other one is said to be created “by farmers, for farmers”, constituting a long-lasting citizen-led coordination that likely brings significant connection benefits. These projects are conducted at an international, regional and city levels.

6.1.2. Scientific factors, field work and analysis

The main soil indicators investigated in these projects are biological, because they focus on the biodiversity of the soil, including earthworms, meso-, and macro-fauna. Additionally, two projects also include the measurement of chemical soil indicators (such as pH, nitrogen, and fertilizers, among others) and physical indicators (like soil structure, aggregate stability and infiltration). Like in the D-type projects, these may have set out with broader biodiversity (of birds and bats, for example) or agricultural objectives but have yielded valuable insights into soil health.

These 3 projects encourage participants to assemble their own toolkits, which can include a mix of common household items and more specialised materials. In any case, participants operated independently during fieldwork campaigns but were required to follow precise guidelines. One project's fieldwork involved defining a study area, using chemical agents to bring organisms to the surface, and then observing the biodiversity. This procedure has already been substituted by others with similar results but less invasive tools, already considered in some of the type-C projects. In this project, participants independently conducted organism observation and identification. The second project also focused on biodiversity observation, involving collecting soil samples and delivering them to the laboratories for the subsequent analysis. In this case, the analytical tasks were shared: citizens conducted organism identification while scientists performed DNA metabarcoding and other specialised soil-typing procedures. The third project suggests user-friendly procedures to also determine soil structure, aggregate stability and infiltration. Guidelines for all projects are accessible online, although the results of these methods are not yet available on the internet. No publications or quality assessment frameworks are available online for these projects.

6.1.3. Technological factors

To date, no technological tools have been integrated into 2 of the B-type projects. The third one created an online carbon calculator. It considers many indicators that farmers can measure (one of them being soil health), allows them to estimate their farm's carbon footprint and to get insight into their businesses.

6.1.4. Engagement and impact factors

In the 3 B-type projects, citizens played an essential role not only in providing data but also in refining the design of the initiatives in 2 projects, which aligns them with the 'collaborative projects' category as defined by Shirk et al. (2012). The third project is a citizen-led initiative, which actively involves at least some of the public participants in most aspects of the research process, therefore it can be classified as a co-created project.

One project is education-focused, engaging students, educators, and families who have an interest in soil health. The other 2 ones are mainly aimed at farmers, but also at landowners, policymakers, researchers, and the broader public. Engagement strategies applied by these projects are varied and innovative. One project has ranged from co-creating incentives to encourage farmers to adopt biodiversity practices in their agricultural processes, to creating compelling narratives for biodiversity conservation. Other initiatives utilise gamification and interactive events for education and data collection, as well as engaging participants in the redesign of green spaces influenced by project findings. Additional outreach efforts include the use of illustrative handbooks, instructional videos, updated websites, and educational games.

The extent of the results obtained, and the subsequent impact of the B-type projects are distinct in nature and scope. One project is expected to generate multifaceted outcomes: scientific discoveries due to biodiversity-friendly practices, political influence through sustainable land and soil management advocacy, economic benefits from novel farming techniques, and social advancements via the creation of empowered communities and a citizen observatory. A second project's impact is primarily social and educational, fostering a robust regional community with diverse participants and applying project findings in various contexts, such as urban planning initiatives. The third one works towards an environmental and economic impact, trying to minimise farming carbon emissions and maximise its carbon sequestration, produced by resilient and profitable farm businesses.

6.2. Soil-specific (TYPE A)

6.2.1. General factors

Within this category, we have classified 10 of the identified projects, initiatives, and activities, as they have successfully involved citizens in monitoring soil health, which is their primary objective. The majority are coordinated by academic researchers or institutions, operating primarily at a regional and city level (Fig. 9). Notably, one project is grower-driven (citizen-led), leveraging the collective knowledge of various growers to devise localized solutions for soil health issues. Most A-type projects are short-term endeavours and have already concluded (Table 3).

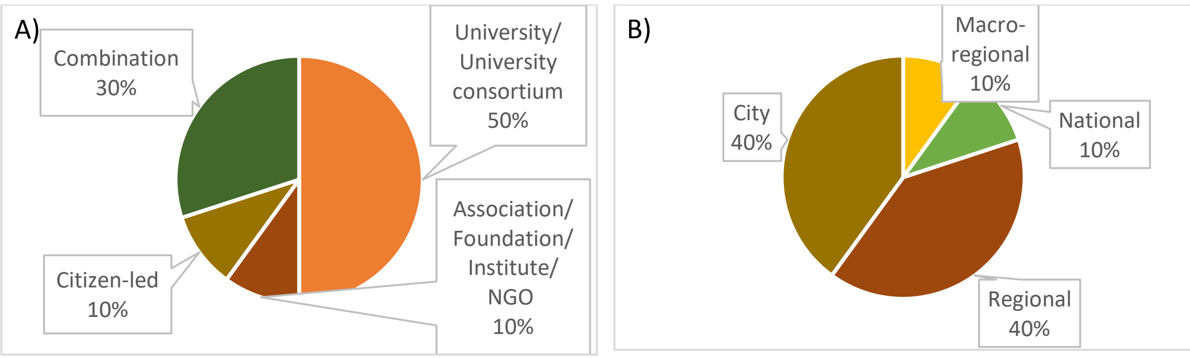


Figure 9. Coordination types (A) and geographical scope (B) for projects in Type A.

Table 3. Timeline and activity for projects in Type C.

Timeline and activity	Number
Duration ≥ 4 years	2
Duration < 4 years	8
Ongoing status	3
Finished status	7

6.2.2. Scientific factors, field work and analysis

The trend observed in the other identified projects, which focuses on analysing biological types of soil indicators, has shifted in projects of type A. Out of the 10 projects classified in this category, 6 are centred on measuring chemical aspects of soils. This includes the analysis of general pollution components like arsenic and other heavy metals, as well as soil fertility. The remaining projects in this category investigate biological indicators, such as microbial biodiversity, or physical aspects by measuring soil moisture.

Almost all the toolkits used in Type A projects are not complex, mainly facilitating the collection of soil samples by citizens for subsequent analysis in laboratories. An example is the project focused on moisture, where participants were required to insert specific detectors into the ground. A cluster of 3 projects, which employ phytomining techniques to address soil pollution, has been recognized. The toolkit for these projects is more sophisticated, comprising specific seeds and general soil sampling tools. Another chemical toolkit is designed for quick, on-site exploratory results via chemical reactions that occur within the instruments.

Possibly due to the limitations of the target audience and/or the need to gather valuable data for community benefit, the sampling process necessitated training sessions or expert assistance in half of the Type A projects. In the remaining projects, participants could work independently and relied on online guidelines for training. In the field, the phytomining projects primarily involved collecting soil samples for lab analysis and executing a customized planting process. Other projects' field activities included soil sampling for laboratory testing or, in one case, general tasks like counting bugs, determining soil colour or pH, among others. As said before, laboratory analysis was a crucial component in 7 of the Type A projects. In 2 other projects, the citizens conducted the analysis themselves, while in 1 project, it was a collaborative effort between citizens and scientists. Laboratory methods included near-infrared spectroscopy (for analysing specific soil and microbial activity parameters), inductively coupled plasma mass spectrometry (for arsenic concentrations), and moisture data processing. The final data from 6 projects are accessible online, and one project included a quality assessment framework. Notably, detailed articles were published for 5 of the Type A projects.

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6.2.3. Technological factors

Three of the 10 identified Type A projects incorporate technological tools in the form of applications. One project has developed a proprietary and tailor-made app, while two projects utilise a free and user-friendly mobile platform for collecting general data. The former is specifically designed to gather and interpret data from moisture detectors, featuring a community sharing option that facilitates the dissemination of crop suggestions and practices. They are compatible with both Android and iOS operating systems.

6.2.4. Engagement and impact factors

In the 10 A-type projects, citizens played an active role, participating in the redesign of 2 projects and co-creating 3 others. Strong communities or citizen observatories have been established in 5 of these projects. These characteristics align with the collaborative and co-created categories defined by Shirk et al. (2012).

For these projects, the main target group comprises growers, followed by local citizens concerned with the projects' main objectives. Researchers, smallholders, and policymakers have been involved in 2 of the 10 identified projects. Methods of engaging citizens and practices in communication and dissemination have varied but have notably impacted the communities. 3 projects emerged in response to a specific demand raised by the community, leading to regular joint discussions with citizen co-researchers and enabling almost real-time responses. One project established a network of over 10 thematic living labs in a city, while another formed 24 citizen observatories all over Europe. Notable engagement and dissemination practices included regular rural collaborative stays and the development of a podcast by some initiatives.

All Type-A projects have demonstrated significant social and participatory impact, primarily through the creation of empowered communities and the transfer of knowledge. Almost all these projects also aim to generate economic impact, such as long-term improvement in crop quality, and scientific outcomes beneficial to both academia and the community as feedback for their collaboration. Furthermore, the scope of the results in 2 projects extends to political aspects, promoting sustainable land and soil management practices and giving communities a voice in addressing real geopolitical pollution issues.

7. Additional projects of interest (TYPE O)

Out of all the initiatives identified, 17 projects did not fit neatly into our study's selection criteria. However, they hold significant relevance for ECHO and offer valuable insights into the broader context of initiatives related to soil health monitoring. Although most varied in public participation, their noteworthy or unconventional methods contribute to this evolving field.

Among these O-type initiatives, 3 projects aim ambitiously to **harmonise** datasets or soil information at both global and European levels. Two of them focus on engaging experts worldwide to create harmonised and comparable datasets; one for soil physicochemical and biological properties, and the other on soil micro-, meso-, and macrofauna in conjunction with soil functions. And the other is currently developing a monitoring framework for forest soils to support decision-making toward climate and sustainability goals.

Three projects have developed **technological** tools in the form of accessible applications. Two user-friendly apps enable citizens to interpret their soils (including soil quality indicators, soil threat indicators, vegetation cover, management data, etc.) by collecting and utilising global data. These could assist farmers, gardeners, land-use planners, and other natural resource managers with open-source tools. One of them provides an interactive soil quality assessment for agricultural productivity and environmental resilience, offering decision-makers tools for managing soil quality. The third app assists in locating and describing threatened areas, sometimes in relation to soil pollution or poor land and soil management.

Another 2 projects stand out for creating strong **communities** involved in soil health or related activities. One resulted in a network of professionals sharing knowledge on the prevention and control of soil diseases, and the other in a citizen community exploring urban food innovations to make cities greener, more inclusive, and environmentally resilient.

The final 2 projects strive to generate **scientifically robust** information valuable for soil health and pollution issues. One project produced an article establishing benchmarks for multiple soil health indicators across various soils and land uses. The other develops technology demonstrating the feasibility of mycoremediation in decontaminating aged industrial soils.

Within this category, we have included 7 projects also **funded by the Mission Soil** under Horizon Europe (European Commission, 2021d), and that can be of interest for this project. Together with ECHO, they can all work in synergy towards achieving the objectives of this mission. Two projects focus on new technologies beneficial for this initiative and will be available to the public: a state-of-the-art platform that will collect knowledge on soil carbon and a free app that combines AI and the latest soil health measurement techniques to help making changes to management practices. Another 2 projects are also dedicated to harmonization, focusing on co-develop and evaluate a multi-scale and multi-user focused monitoring framework for measuring soil health, or engaging and activating municipalities and regions to protect and restore soil health. The final three projects have educational objectives, such as providing an overview of the current level of soil related knowledge in different educational levels, developing teaching programmes and materials, creating and testing a learning pathway for existing and aspiring soil advisors, or creating awareness and knowledge on soil needs among stakeholders in regions across Europe.

8. Discussion

After reviewing more than 60 projects that have engaged citizens in monitoring soil health, we evidenced the notable potential of citizen science to significantly contribute to both scientists and citizens. These initiatives aim to gather field data for monitoring diverse conditions (Silvertown, 2009), yet their scope extends beyond this. They also serve to boost the scientific literacy of participants (Bonney et al., 2009) and establish a structure that bolsters and refines decision-making processes in contemporary society (Trumbull et al., 2000).

Our classification of citizen science projects offers a clear understanding of what each type enables, providing a summary of their respective strengths and weaknesses:

- **Type D, non-soil-specific involving sampling collaboration:** national-scale projects that engage citizens in monitoring various environmental aspects, one of which relates to soils. They focus on examining biological biodiversity indicators to derive insights about soil health. Participants are involved either in simple sample collection or in basic data interpretation, targeting educational sectors, families, and naturalists. General cost to individuals and researchers is low-intermediate. These initiatives yield educational impacts and can have economic implications, particularly in the field of agriculture.
- **Type C, soil-specific citizen involving sampling collaboration:** projects developed at national or regional scale that focus on carrying out educational activities exploring biological and chemical aspects of soil. Engagement targets a broad audience including the educational sector or rural communities, utilising workshops, exhibitions, and online resources. These projects primarily yield educational impacts, but offer limited opportunities for building trust, community engagement, and social outcomes.
- **Type B, non-soil-specific involving broader engagement:** regional-scale projects focusing on non-soil-centric objectives but an emphasis on soil biodiversity. They explore it with citizen-assembled toolkits for independent fieldwork and guideline-driven procedures. These projects integrate citizen contributions in research design and data analysis. Target audiences are broader and reach farmers, and policymakers, employing diverse engagement strategies like gamification or interactive events that require resources from citizens. Impacts of these projects span scientific, political, economic, social, and educational domains, influencing sustainable land management, urban planning, and farming practices.
- **Type A, soil-specific involving broader engagement:** regional/city-scale projects that are collaborative, co-created with academic institutions or grower-driven. Therefore, cost to individuals and communities is high, requiring commitment and responsibility. These projects analyse chemical soil indicators like heavy metals, with toolkits that require training or expert assistance. These projects establish strong communities or citizen observatories, where citizens play a significant role in project design and analysis. The cost for scientists is high to create them but low to maintain them. Target

groups include growers, local citizens, researchers, and policymakers, utilising methods like collaborative stays and living labs for engagement. These projects yield social, economic, and scientific impacts, influencing political aspects of land and soil management.

One of the most noteworthy issues that appears from this review is the low representativity of initiatives developed in low-income countries compared with developed countries. This can be attributed to the limitation related to geographical gaps in our search process, but also to the fact that soil citizen science has not shed light on these areas yet. Their potential of being part of this field is high but challenging, as there is an urgent need for sustainable land management interventions to reverse degradation of natural resources (Kelly et al., 2022).

Regarding duration and timing of the reviewed projects, all of them have been developed during the last 15 years, and they are predominantly short-term, averaging 2 to 3 years in duration. However, no definitive conclusions regarding the time variability of these projects have been drawn, as neither long-term nor short-term common characteristics have been clearly identified. Long-term initiatives (duration ≥ 4 years) have been developed in almost all types of projects, and many of them have started recently. Their development must respond to other factors that have not been considered in this review, but they have responded well in every context.

Clarity of the initial objectives is essential for a proper scientific approach in citizen science projects (Gascuel et al., 2023a). Our review shows that clear initial objectives regarding the scientific, technological and engagement factors are key for developing efficient methodologies and engaging citizens for all the project's length. The scope of each project must be defined, and that starts by determining the soil indicators to be assessed within the scientific factors, and by limiting to them during the whole project. All types of projects (A-D) can achieve this, but certain projects from types A and B have struggled more due to the possible subjectivity of collaborative and co-created objectives. Our review confirmed that a broad fan of soil indicators can be assessed at different levels of complexity through all types of citizen science. However, it emphasises the opportunity and need for the establishment of simplified, standardised methods aimed at bridging knowledge gaps and ensuring the collection of reliable and valuable information on all these indicators; this stands with the statements of Head et al. (2020).

There is a minority of projects that have used and published standardised citizen science procedures to soil sampling and measuring, one of them being the TBI by Keuskamp et al. (2013). The latter is an excellent example of projects that use easy-to-use toolkits and are as scientifically accurate as other proposals of meticulous toolkits. In any case, successful projects usually emphasised on user-friendly designs, especially when they aim to engage heterogeneous target groups of participants. This was the case of Ureta et al. (2022), where elders found difficulties in manipulating the smallest components, forcing the project coordinators to change several designs to make them easier to manipulate and use. Good practices related to this issue have been identified in all types of projects (A-D).

In our review we have included initiatives that comprise everyday household items, lab-designed tools or specific measuring detectors that are delivered to the participants. Regarding cost of toolkits, it is different for individuals, scientists or coordinators in any case. The apparent financial cost is evident for each actor, but it is not a limiting factor. The toolkit is not usually designed depending on it but on other aspects, like the extent of the results obtained, the type of data they want to collect or the level of citizen engagement with the process. Educational projects from types C-D suggest more homemade toolkits because they see its preparation process as one more enjoyable activity, or those expecting to monitor soil health periodically design tailor-made detectors, like some cases of types C-A. Regarding citizen engagement, it also differs in any type of toolkit, but a common aspect in all of them is that their design can determine whether citizens only participate in sample collection, as "citizen sensors", or they connect deeper with the process and the project community. Another important aspect to consider when designing toolkits for monitoring soil health is the time cost of use. Our review has not taken this aspect into account, but during its evaluation we saw the clear necessity to stress it. Head et al. (2020) affirm that time requirements are a more limiting factor than financial cost, but quick options available for robust soil assessments are limited. There is a clear need to develop appropriate methods that are low cost and, more important, quick to implement.

Toolkit implementation in the field by citizens needed, at least, training material in the form of guidelines in almost all the identified projects. Gascuel et al. (2023a) highlight as a point of success and attention of the soil-related citizen science projects to give support for a gradual increase in skills adapted to participants. These authors defend that programs must adapt to the infinite participant profiles and skills, and not the other way around. In our review, this approach is especially reflected in projects that mainly expect an educational impact, adapting that support to students and educators, or an economic impact, adapting it to farmers and growers' skills. When target groups are wide-spread, training is usually an obstacle for certain sectors as it is difficult to adapt it to every necessity. Therefore, citizen and stakeholder mapping and recruitment must go hand in hand with the training and support design. The already-mentioned need of standardised protocols for monitoring soil health could also be reflected in the design of these field guidelines.

Our review reveals that citizen training is not limited to guidelines. In fact, substantial improvements in projects' outcomes result from supporting citizens through in-person training in types A-B. Projects where experts spent time with the participants during training sessions or monitoring allowed involving citizens more deeply into the scientific process and the problem definition and analysis, as well as to create stronger communities. Therefore in-person training can be associated with our identified as collaborative and co-created projects (our type B and A; Shirk et al., 2012). Ebitu et al. (2021) identified the same pattern and explained that deeper training offers opportunities for dialog and mutual learning beyond the limited objective of data collection. This dialog allowed Ureta et al. (2022) to overcome the toolkit barriers found by certain citizen sectors. It also guarantees to a greater extent enhanced experiment completion rates, stronger researcher-citizen bonds and superior data collection quality (Lovell et al., 2009; Kremen et al., 2011; Gascuel et al., 2023a). Hsu et al. (2017) also pointed out that careful training to collect data improves the accuracy issues and suggest that another option consists in encouraging citizens to flag issues for an investigation that can be followed-up through established research or policy channels. However, it is worth highlighting that these training methodologies in types A-B require an important time cost, and therefore also financial cost, for the project. This entails that many short-term projects financially limited can struggle implementing them.

We have identified that setting and maintaining the citizen motivation during projects is a common challenge in all types of projects. Especially in types A-B, due to their special interest in leaving a deeper mark in communities. Different methods of engaging citizens and practices in communication and dissemination have been developed, at different levels within each type of project, and some of them stand out for their originality. However, despite the initial enthusiasm, signs of long-term fatigue can be identified in the participants, as reported by Ramirez-Andreotta et al. (2015) and Ureta et al. (2022). The need for support for volunteers by qualified mediators and activity leaders is one proposal of mitigation (Gascuel et al., 2023a).

Projects whose participants have received well-structured feedback from their scientific contributions have shown better results regarding motivation and engagement in all types of projects (A-D). During the review of Ebitu et al. (2021), the authors also identified that data feedback protocols helped ensure that farmers perceive results of the study as relevant, and that they answered their own questions. These protocols in our projects were simplified, adapting the scientific language and leveraging appropriate communicational skills. Then citizens have the option to decide what to do with that information and knowledge, enabling them to implement solutions at the individual level that can derive into community level. An example of this is any of the pollution-related projects, which allow citizens to solve local problems identified by the communities themselves and to take health precautions. With this feedback, the coordinators are recognising citizens' scientific contributions, giving meaning to the action and, therefore, boosting soil connectivity through citizen science (Pino et al., 2022; Gascuel et al., 2023a).

Other projects of interest to ECHO (type O) are starting to meet a well-known need in the studied area, which is the need for robust structured soil monitoring programmes alongside citizen science programmes to provide the unbiased and statistically robust framework on which other data can be integrated (Rawlings et al., 2017; Head et al., 2020). In fact, Head et al. (2020) suggest that, until this need is not covered, citizen science approaches cannot replace statutory and traditional soil monitoring.

Finally, we have already mentioned that this review should be considered representative rather than comprehensive, as we have found some limitations and challenges during the process. We would like to request that readers exercise caution when interpreting the data from this study, as some information may have been under- or over-estimated. Despite all of this, we are confident that this review allows getting a clear analysis of the current landscape of soil-related citizen science projects, that will be clarifying for the ECHO partners and their assigned tasks, and undoubtedly beneficial for the journey that remains ahead in the ECHO project.

9. Recommendations

This state of the art applied to soils allows us to propose recommendations to guide our project's trajectory. These suggestions are tailored to address challenges identified during the review, optimise methodologies, enhance participant engagement, and ultimately ensure that ECHO not only contributes valuably to the field of soil health monitoring but also sets a precedent for future citizen science endeavours. These recommendations are:

R1. Ensure the equal, active inclusivity of all pilots to avoid underrepresentation, as they are in countries across all income levels, and to ensure diverse and balanced perspectives in our soil health monitoring initiatives.

R2. Leverage the extended duration of ECHO, which is above average of similar projects, to develop and implement organised, refined and thoughtful both scientific and citizen science methodologies.

R3. Delve into the skills and knowledge of the citizen groups expected to be reached by the project, for determining the soil health indicators and measurements that are most appropriate for that context and the ECHO scope. This will allow the program to be adapted to the participants, and not the other way around.

R4. Assess the level of citizen participation in the scientific research accordingly, and therefore the type of citizen science methodology, to guarantee citizen connectivity with the project's community and soil. As all types show strengths and weaknesses, and the amount of expected citizen activities is high, different methodologies can be carried out at different scales and in different contexts.

R5. Adhere to scientific protocols whose standardisation has either been already published, is currently being established or is feasible to be determined in the future, to ensure consistency and reliability in the methodologies employed. Bonding with other projects focused on this issue can be key.

R6. Adopt a concept of the citizen toolkit that is broader than an ensemble of tools to be used for soil sample collection, as in many cases it is the only material from ECHO that citizens will receive and its potential to significantly influence the project's impact is high. Emphasise on user-friendly, not-time-consuming and, to a lesser extent, low-cost designs.

R7. Give support for a gradual increase in soil-related skills adapted to participants with, at least, guidelines that leave no loose ends and are visually attractive. Complement them with in-person expert training and workshops. Assess the creation of qualified mediators, stewards or activity leaders. All this result in stronger communities willing to stay partially or entirely engaged with ECHO, and superior data collection quality and accuracy.

R8. Highlight simplified but accurate feedback protocols for citizens that provide them with knowledge, recognise their scientific contributions and booster soil connectivity.

R9. Transmit the details and impact of participation to citizens through crystal-clear initial objectives and establish solid and fluent communication channels so that every voice in ECHO, regardless of its level of participation, is heard.

R10. Informed by the insights in Section 8, we recommend conducting regular impact assessments to evaluate how effectively the ECHO project's findings are shaping soil health policies. This will involve analysing the integration of citizen science data into policy decisions, ensuring that the project's contributions are not only recognized but also actively applied in shaping sustainable soil health strategies. Collaborate closely with policymakers to facilitate this integration, thus maximising the scientific and societal impact of the ECHO project.

Table 4. Connections between specific recommendations and corresponding tasks within the ECHO project. Please note that these associations are suggestive and certain recommendations may apply to additional tasks beyond those listed here.

R1	**Task 3.2.** Development of citizen science initiatives on soil health **Task 3.3.** Coordination of citizen science initiatives across Europe **Task 7.4.** Ethics issues
R2	**Task 2.1.** Selection of citizen science methods for monitoring soils **Task 3.2.** Development of citizen science initiatives on soil health **Task 3.3.** Coordination of citizen science initiatives across Europe
R3	**Task 2.1.** Selection of citizen science methods for monitoring soils **Task 2.2.** Development of a Citizen Science Toolbox **Task 3.1.** Mapping and engaging target citizen groups
R4	**Task 3.2.** Development of citizen science initiatives on soil health **Task 3.3.** Coordination of citizen science initiatives across Europe **Task 7.4.** Ethics issues
R5	**Task 2.1.** Selection of citizen science methods for monitoring soils **Task 2.2.** Development of a Citizen Science Toolbox **Task 5.4.** Interoperability of citizen data with existing databases **Task 5.5.** Connection with existing European soil monitoring systems
R6	**Task 1.2.** Assessment framework for citizen science methods **Task 1.3.** Citizen-generated Soil Data Quality assessment framework **Task 2.1.** Selection of citizen science methods for monitoring soils **Task 2.2.** Development of a Citizen Science Toolbox
R7	**Task 6.1.** Development of the project communication identity **Task 6.2.** Communication activities **Task 7.4.** Ethics issues
R8	**Task 2.3.** Development of the ECHO Citizen Science mobile app **Task 3.2.** Development of citizen science initiatives on soil health **Task 3.3.** Coordination of citizen science initiatives across Europe **Task 5.1.** Participatory technologies co-design in support of citizen soil observations **Task 7.4.** Ethics issues
R9	**Task 1.4.** Project Monitoring and Evaluation (M&E) framework **Task 2.3.** Development of the ECHO Citizen Science mobile app **Task 3.1.** Mapping and engaging target citizen groups **Task 3.2.** Development of citizen science initiatives on soil health **Task 3.3.** Coordination of citizen science initiatives across Europe **Task 5.1.** Participatory technologies co-design in support of citizen soil observations **Task 6.3.** Dissemination activities **Task 7.4.** Ethics issues
R10	**Task 1.4.** Project Monitoring and Evaluation (M&E) framework **Task 6.3.** Dissemination activities **Task 6.4.** Connecting with Mission Soil and other thematically related initiatives and projects **Task 6.5.** International replication of ECHO initiatives

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Appendix 1: Matrix structure

SECTION 1. General factors

Name of the project/initiative/activity	*Free response (FR)*
Website	
Start year	
End year	
Location (pilots)	
Scale	*Drop-down options of response (DOR): Global/Macro-regional/National/Regional /City*
Coordinator	*FR*

SECTION 2. Scientific factors

Citizen Toolkit	List of tools for field work and/or input devices (detectors or sensors) and their technical/scientific purpose of each one (maybe based on the indicators in the next box)	*FR*
Specific factors	Type of soil health indicator measured (biological, chemical, physical or mixed)	
	Organisms sampled if biological properties were measured (e.g., earthworms, bacteria, fungi etc) (if required)	
	Specific chemical variables measured if samples for chemical properties were collected (e.g., nitrate, dissolved organic carbon, antibiotics etc) (if required)	
	Physical properties measured (e.g., moisture, structure, infiltration etc) (if required)	
	Specific vegetation cover type	
	Specific land use	
	Total number of samples collected during the project	

	Availability of the location of samples (Latitude and Longitude)	*DOR: Yes/No*
	Link to data (if accessible)	*FR*
	Scientific publications (if existents): Title	
	Scientific publications (if existents): DOI/Website	
Field work factors	Citizen independence during field work	*DOR: People are independent/People are independent after training material/People are independent after training sessions/People depend on an expert*
	Field guidelines/Training material/Training methods	*DOR: Yes/No*
	Link to guidelines/Training material/Training methods (if required)	*FR*
	Brief description of citizen soil sampling, analysing, treatment and/or storing for shipping to scientists	
Analysis factors	Responsibility for sample analysis	*DOR: Citizens took it/Scientists at the lab took it/Both citizens and scientists at the lab took it*
	Brief description of the scientist's analysis process (if required)	*FR*
	Quality assessment framework	*DOR: Yes/No*
	Link to assessment framework (if required)	*FR*

SECTION 3. Technological factors

Apps names	*FR*
Developer	*DOR: Yes/No*
Organisation Repository	*FR*
App found in repository	

License	*FR*
Operating system	
Links to sources (if existent)	
Other resources used to produce relevant data through citizen participation	

SECTION 4. Engagement factors

Target group	*FR*
Public participation in scientific research projects (Shirk et al., 2012).	*DOR: Contributory/Collaborative/ Co-created*
Engagement methods	*FR*
Link to impact assessment framework (if existent)	
Outstanding communication and dissemination practices	
People actively participating in citizen science or data collection	
Extent of the results obtained	

Appendix 2: Identified projects

Project name	Website	Aim	Type
BRIDGES	https://www.progetto-bridges.it/	To propose experiments, in urban and rural areas, that bring together an extended community of people, on an issue that concerns everyone closely: soil fertility.	A
Garden Roots	https://citizensciencepartnerships.com/commu	To determine whether home garden vegetables had elevated levels of arsenic, to educate and increase community networking in resource-related issues in the community.	
GROW Observatory	https://growobservatory.org/	A Citizen Observatory that has empowered people and whole communities to take action on soils and climate across Europe.	
HeavyMetal Citizen	https://heavymetalcity	To investigate heavy metal pollution in soils and crops in urban areas.	
CiDéSol	https://www.cocreate.brussels/projet/cidesol/	To provide access to depollution techniques to professional market gardeners or citizens who cultivate polluted plots and who do not have access to industrial depollution methods.	
Using CS to develop solutions for healthy soils through phytomining	https://ec.europa.eu/research-and-	To understand good soil and generate science-based and application-oriented practices for a successful phytomining approach.	
Soils, Science and Community Action	https://iopscience.iop.org/article/10.1088/1748-	To explore community-led solutions to soil degradation by developing and trialling citizen science protocols for community diagnosis of soil health.	
The Citizen Science Soil Health Project	https://soilhealthproject.org/index.h	To find local solutions to our soil health implementation conundrum using the collective knowledge of our diverse growers.	
Open Soil Atlas	https://terrific-spike-fc0.notion.si	To learn about soil quality and support policy makers in the design of the urban environment.	
Nuestros suelos	https://jcom.sissa.it/article/pubid/JCOM_2101	To design and test a toolkit for the participative assessment of soil pollution, and to make visible the existence of alternatives to traditional soil pollution assessment procedures.	
SHOWCASE	https://showcase-project.eu/a	To the integration of biodiversity into farming practices, delivering innovative tools for the transition towards more sustainable farming.	B
Collectifs	https://collectifs-biodiversite	To discover urban biodiversity and improve the design and management of common spaces for a better living environment.	
FARM NET ZERO and Farm Carbon Toolkit	https://farmcarbontoolkit.org.uk/far	To measure, understand and act on farmers greenhouse gas emissions, while improving their business resilience for the future.	
Tea Bag Index	http://www.teatime4sci	Their main aim is to gather data on decomposition rate and litter stabilisation using commercially available tea bags as standardised test kits, based on Keuskamp et al. (2013).	C
TeaTime4Schools	https://www.teatime4s		
TeaComposition Project	https://teacomposition.		
The Tea Bag Experiment - Tepåseförsöket	https://forskarfredag.se/massexperi		
CS project on soil health and soil awareness as part of the Science Year 2020 Bioeconomy	https://forschung-sachsen-anhalt.de/pr		
TeaComposition Initiative	https://www.teacompo		
bodemleven	bodemleven.be		
Expedition Erdreich	https://expedition-		
TeaTime4App	https://www.teatime4sc		
Soil Your Undies Challenge - University of New England	https://www.unediscoveryvoyager.	Their main aim is to explore and investigate soil life, and soil health in general, using buried underpants, based on the Soil Your Undies Challnge.	
Plante ton slip	https://librairie.ademe.f		
Beweisstück Unterhose	https://www.beweisstu		
Alsóban az élet	https://www.elkh-		
360 Dust Analysis	https://www.360dusta	Their main aim is to map lead and other metals in home garden soils, to understand the soils and highlight the importance of healthy soils, based on the 360 Dust Analysis.	
Indiana Collaboration for Lead Action and Prevention	https://www.mapmyenvironment.c		
SoilSafe Aotearoa	https://soilsafe.aucklan		
Latrobe Valley Dust Research	https://www.epa.vic.go		
Observatoire de la QUalité Biologique des Sols	https://www.qubs.fr/	To assess the diversity and abundance of invertebrates which provide information on the state of soils.	
Bodemdierendagen	https://bodemdierend	To go on a "benthic animal safari" and discover who lives under their feets.	

Project name	Website	Aim	Type
MINAGRIS	https://www.minagris.eu/	To assess the impact of plastic debris in agricultural soils on biodiversity, plant productivity and ecosystem services and their transport and degradation in the environment.	C
Expedition Boden	Homepage - Expedition Boden/eab	To examine the soil in their garden and learn more about nutrients and pollutants in their soil.	
Soil Moisture Active Passive	https://www.citizenscience.gov/s	To validate soil moisture results measured by the community, associated to the GLOBE program.	
CALeDNA	https://ucedna.com/	To address problems in biodiversity monitoring by pairing volunteer community scientists with researchers to collect soil, sediment, and water samples.	
Earthworm watch	https://www.earthwormwatch.org	To conduct your own earthworm survey to help map where they are, better understand the vital benefits they bring, and ultimately, help protect them.	
OPAL Soil & Earthworm Survey	Soil and Earthworm Survey |	To find out more about soil and earthworms and investigate the relationships between earthworm species and habitats and soil types.	
CurieuzeNeuzen in de tuin	https://www.uantwerpen.be/nl/pr	To investigate heat and drought and map their effects, giving advice on preserving and protecting gardens against them.	
Soil Sampling Toolkit by Citizen Science Community Resources	https://www.csresources.org/proje	To teach how to sample and test your own soil, providing tools and resources to create healthy soil and gardens for healthier environments and communities.	
Programa de Conservación de Suelos	https://www.vitoria-gasteiz.org/	To diagnose the health status of different soils, promote sustainable agriculture and soil health in urban areas and create a database.	
Vigilantes del Suelo	https://vigilantesdelsuelo.es/	To diagnose the health status of different soils, educate on its importance and create a database.	
Missourians Doing Impact Research Together	https://modirt.danforthcenter.org/s	To conduct soil health surveys to collect and contribute data that will help scientists understand how soil health and soil-climate interactions are affected.	
MicroBlitz	https://scistarter.org/microblitz	To dig into the soil, look at the smallest building blocks of ecosystems, which is microbial DNA, and creating a map.	
Knoxville-Tennessee Environmental Soil and Stream Testing	https://sites.google.com/vols.utk.ed	To provide knowledge about soil and water quality and the health of local environments.	
Gärtner für den Umweltschutz	https://www.h-brs.de/de/iz	To study the climate and biodiversity issues examining soils from urban green spaces.	
Citizens of the Crust: a biocrust assessment project	https://www.inaturalist.org/project	To increase hiker awareness of biocrust, reduce crust-busting rates by hikers and gather data regarding the distribution and health of biocrusts.	D
SoilSkin – La Piel Viva del Suelo	https://ebryo.com/soilskin/	To know the distribution and ecological functions of biological soil covers, and to increase awarness of its importance.	
Observatoire agricole de la biodiversité	https://www.observatoire-agricole-	To offer protocols for observing ordinary biodiversity to interested farmers, with a view to better understanding ordinary biodiversity in agricultural environments.	
Vigie-nature école	https://www.vigienature	To monitor ordinary biodiversity, involve teachers in a research program, and become students better acquainted with the biodiversity around them.	
SCENT	https://scent-project.eu/	To engage citizens in environmental monitoring of land-cover/use changes and enable them to become the 'eyes' of the policy makers.	
NOCMOC	https://www.nocmoc.eu/#predstav	To encourage citizens to get out into nature, explore meadows, observe the plants around them and infer the type of soil.	
Grower CS Project	https://growercitizenscience.wordp	To help growers face the challenges of climate extremes by improving the health of their soils linked to improved water retention and microbial function.	
MAKING SENSE	http://making-sense.eu/	To show digital practices to make sense of their environments and address pressing environmental problems in air, water, soil and sound pollution.	
LANDSENSE	https://landsense.eu/	To aggregate innovative technologies to empower communities to monitor and report on their environment.	O
iSQAPER	https://isqaper-project.eu/	To provide soil quality assessment for agricultural productivity and environmental resilience, and provide decision makers with tools to manage soil quality and function.	
Land-Potential Knowledge System	https://landpotential.org/	To support farmers with tools that allow them to access knowledge and information, and collect, share, and interpret their own soil, vegetation cover, and management data.	
HoliSoils	https://holisoils.eu/	To tackle gaps in knowledge on forest soil processes and harmonise available soil monitoring information to support decision making towards climate and sustainability goals.	
LUCAS Soil	https://ec.europa.eu/eurostat/web/	To sample and analyse the main properties of topsoil and build a consistent spatial database based on standard sampling and analytical procedures.	
SOIL Bon	https://soilbonfoodweb.org/	To assess global drivers and functions of soil animal biodiversity and interactions in soil food webs.	
Best4Soil Project	https://www.best4soil.eu/	To provide information on the host status and damage sensitivity of crops for a large number of nematode species and soilborne pathogens.	
EdiCitNet	https://www.edicitnet.com/es/	To explore how urban food innovations can make cities around the world greener, more inclusive and more environmentally resilient.	
UK-SCAPE programme (SOC-D project)	https://uk-scape.ceh.ac.uk/	To undertake research and provide data and models designed to deliver new integrated understanding of the environment to tackle those challenges.	

Project name	Website	Aim	Type
LIFE mySoil	https://lifemysoil.eu/es/sobre/	To develop technology to demonstrate the feasibility of mycoremediation to remediate pollutants from contaminated soils.	O
Soil Health Benchmarks	https://soilhealthbench	To create a harmonised and cost-effective framework for measuring soil health.	
HuMUS	https://humus-	To engage and activate municipalities and regions to protect and restore soil health.	
LOESS	https://loess-project.eu/	To provide an overview of the current level of soil related knowledge in different educational levels and develop teaching programmes and materials.	
NBSOIL	https://nbsoil.eu/	To create and test a learning pathway for existing and aspiring soil advisors.	
ORCaSa - Impact4Soil	https://irc-orcasa.eu/about/	A state-of-the-art platform that will collect knowledge on soil carbon and make it available to the public.	
AI 4 Soil Health	https://ai4soilhealth.eu/	To create a free app that combines AI and the latest soil health measurement techniques to help farmers and growers.	
Prepsoil	https://prepsoil.eu/	To create awareness and knowledge on soil needs among stakeholders in regions across Europe.	