University of Reading

Investigating urban park soil health through corporate-based citizen science: linking engagement to sustainable actions

PhD in Environmental Sciences

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November 2025

Abstract

Nature-based Solutions (NbS), such as restoring and protecting urban forests, are increasingly promoted to build resilience to climate change and urbanisation. However, in urban environments, the management of soil beneath trees remains inadequate, largely because it is often overlooked in broader urban ecosystem planning for NbS.

The thesis examines how enabling employee participation in a corporate-based citizen science programme can advance research on urban soils, while also promoting organisational change towards sustainability.

The study draws on environmental data collected in urban parks across the UK and France (2018–2019), where employees and scientists assessed soil chemical, physical and biological properties to support holistic urban soil health monitoring. Citizen scientists' soil colour observations, calibrated using a spectrophotometer, were successfully used to estimate soil organic carbon (SOC), highlighting the potential of fast, low-cost, scalable methods to support traditional SOC analyses in the context of climate change.

In parallel, observational and survey data from eight employee-engagement programmes demonstrate how participation shaped pro-environmental behaviour by supporting changes in capability, opportunity, and motivation. Formal and experiential learning deepened environmental understanding and built *capability* for action. Social and physical *opportunity* were fostered through interactions with scientist and peers, trust-building, and the framing of sustainability as both a social norm and business opportunity. *Motivation* was primarily influenced through emotional engagement. Targeted science communication increased environmental concern, fostered a sense of collective responsibility, and promoted climate hope by encouraging participants to see themselves as *sustainability champions*. By combining hands-on, enjoyable and interactive experiences with time in nature, the programme fostered emotional connection that further motivated participants to act.

Overall, the thesis demonstrates the dual value of corporate-based citizen science in addressing urban soil knowledge gaps while expanding participation and supporting positive environmental transformation within organisations. The findings underscore the significance of not only cognitive, but also affective and contextual factors in driving behaviour change.

Declaration of original authorship

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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Table of Contents

Acknowledgments

I would like to take this opportunity to convey my heartfelt gratefulness to all the people who have inspired and accompanied me during the PhD journey.

First and foremost, I would like to express my deepest gratitude to RIP, Professor Joanna Clark. She was much more than a supervisor and her friendship, guidance, and unwavering confidence in me will not be forgotten.

Next, I want to thank Professor Liz Shaw and Dr. Anna Jackman for taking on the role of supervisors during the last part of my thesis. I feel very fortunate for their kindness and patience during times of struggle, as well as their valuable insights.

This work would also not have been possible without the funding provided by the University of Reading and Earthwatch Institute, as well as all the citizen scientists who actively participated in the project.

Last, but not least, I want to thank my mother and my beloved wife. Without their unconditional love, patience, support, and constant encouragement, this milestone would not have been possible.

List of Figures

List of Tables

Chapter 1 Introduction

Understanding Citizen Science: benefits, challenges, and applications in corporate engagement and urban soil research

Chapter 1 – Introduction.

Understanding citizen science: benefits, challenges, and applications in corporate engagement and urban soil research

This chapter asserts that the transboundary nature of environmental problems requires non-traditional partnerships and collaborative approaches. In this context, corporate based citizen science is presented as a method that can both advance scientific research through large-scale data collection and foster environmental awareness and action.

The chapter begins by introducing the concept of citizen science, describing its history and development, as well as outlining different forms of participation. Then, the chapter describes several potential benefits and challenges of using citizen science as research approach. Following this, it introduces an emerging typology in which citizen science is integrated into Captive Learning Programmes, highlighting its potential to engage the corporate sector and diversify participation beyond the traditionally involved, environmentally engaged public.

Subsequently, the chapter introduces a Captive Learning Citizen Science project – *Climate-Proof Cities* – which focuses on Nature-based Solutions (NbS) in urban environments. It outlines how this thesis engages with and utilises the project to address key research gaps in urban soil science, while also examining how corporate engagement influences learning, attitudes, and behaviours.

1.1. Transboundary environmental issues

The world is increasingly facing rapid and dramatic change, with the loss of habitats and species and the alteration of ecosystems posing detrimental impacts for people (Pocock et al. 2018). These unprecedented environmental challenges are at once global, unevenly experienced (Sultana, 2022) and require new ways and forms of collaboration across borders and sectors at all levels (Knack, 2017; Hecker et al. 2019).

In addition to regulatory and technical solutions, there is a growing recognition that significant lifestyle and societal changes are critical for achieving sustainable development (Schultz, 2011; Klaniecki et al. 2018). Thus, there is an urgent need to promote a "culture of sustainability," where the general public are aware of these issues and are empowered to behave in sustainable ways to enable environmental protection (Marans et al. 2015; Cogut et al. 2019). Change is required on both personal and collective levels, involving shifts in perceptions, individual actions, behaviours, and beliefs (Cruz et al. 2023)

Public input and collective engagement in science through approaches such as citizen science can be key for creating and informing scientific knowledge (Dickinson et al. 2012; Kosmala et al. 2016; Hecker et al. 2019) while raising awareness, cultivating, and encouraging positive environmental change to address complex socio-ecological problems (Brossard et al. 2005; Jörgensen and Jörgensen, 2021; Von Gönner et al. 2023).

1.2. What is citizen science?

Citizen Science is a form of research where non-scientists and scientists cooperate and together collect, share, and analyse data for authentic scientific research (Crall et al. 2012). The concept of public participation in scientific research is not new. Citizen science projects occurred informally from the start of modern science (Silvertown, 2009). For example, the National Weather Service put in motion the Cooperative Observer Programme in 1890 which is still ongoing to help understand national meteorological changes (Garbarino and Mason, 2016).

However, while citizen science projects occurred hundreds of years ago, the term was not conceptualized until the 1940s (Silvertown, 2009) and remained hardly visible as a discipline until it re-emerged in the 2000s (Silvertown, 2009). Citizen science gained popularity from 2010 onwards, coinciding with technological advancements that facilitated large-scale participation (Bonney et al., 2009b; Kullenberg and Kasperowski, 2016). Since then, participation in such projects has increased dramatically and expanded into diverse fields, connecting the public to professional researchers (Bonney et al., 2009b; Knack, 2017) and there has been a significant rise in publications (Kullenberg and Kasperowski, 2016). Birdwatching and amateur astronomy continue to be a core of activity but there are also a growing number of other disciplines such as medicine and engineering now engaging in citizen science (CS Track, 2021). This expansion has been driven by societal and technological trends such as higher education, more leisure time, increased life expectancy and improved accessibility due to internet and mobile devices (Silvertown, 2009; Kullenberg and Kasperowski, 2016).

As the field of citizen science has expanded, scholars have attempted to define citizen science and its different typologies (Haklay et al. 2021). The initial and often-used approach to classify citizen science projects is based on Bonney et al.'s (2009a) work, which takes in to account the different forms of "participation" in the scientific process and distinguishes between contributory, collaborative, and co-created projects. In contributory projects, scientists design the project, and participants are principally involved in data collection. For example, platforms such as Zooniverse and SciStarter offer a variety of initiatives designed and led by scientists, where participants contribute to a specific scientific cause of interest as data gatherers and adhere to fixed protocols (Land-Zandstra et al. 2021). Collaborative projects are also designed by scientists, but participants are involved in various stages of the research process such as analysing samples, interpreting data, and disseminating findings. Co-created projects represent the highest level of volunteer engagement, with participants collaborating in all stages of the research process and project design. Contractual projects, in which citizens take the lead and scientists are engaged in a secondary capacity, e.g. such as being hired to carry out specialist investigations or consulted for advice (Shirk et al. 2012), represent an additional category not accounted for in the earlier classification by Bonney et al. (2009a).

More recent classifications for citizen science projects have been suggested by other scholars. For example, similarly to Bonney et al. (2009a), Haklay (2013) categorizes citizen science activities by the degree of participation into four levels. Level one is referred to as crowdsourcing, where participants act as sensors. Level two is called distributed intelligence; here participants are interpreters. Level 3 is considered participatory science, where citizens are involved in defining the problem and data gathering. And lastly, level four is extreme citizen science, where the scientists and participants work together in the project design, data collection and analysis. Another alternative is Wiggins and Crowston´s (2011) work which identifies five categories in citizen science based on the goals of the study: action, conservation, investigation, virtual or education.

The broad diversity and variety of project types has made it challenging to reach a consensus on how to define the contours of citizen science (Haklay et al. 2021; Van Noordwijk et al. 2021). To ensure rigour and ethical integrity in this growing field, the European Citizen Science Association (ECSA) established *Ten Principles of Citizen Science*, which outline key criteria such as genuine scientific outcomes, mutual benefits for citizens and scientists, transparent data sharing, and ethical responsibility (ECSA, 2015).

1.3. Benefits of Citizen Science

Citizen science offers a range of benefits that extend beyond traditional scientific approaches including, (1) enhanced data collection, (2) public engagement and education, and (3) behavioural and social impacts.

1.3.1. Enhanced data collection

The main reason for the tremendous popularity of utilizing citizen science is the increasing realization among scientists of the advantages over conventional science of engaging volunteers in the collection and analysis of data (Silvertown 2009; Danielsen et al. 2014). Unpaid participation in citizen science makes it possible and affordable for researchers to obtain scientifically robust data at vast geographical scale (spatial), over long periods of time (temporal), and often beyond the scope of what a single researcher can accomplish and can even enhance resolution (Brossard et al. 2005; Dickinson et al. 2010, 2013; Liu et al. 2017). In fact, citizen science methods can generate three to four times the number of samples generated by traditional research for the same cost and substantially increase the speed that the science outcomes are disseminated (Gardiner et al., 2012). Not surprisingly, the collection of big data sets is the most common motivation given for scientists to be involved in citizen science as it can remedy some of the barriers associated with limitations in time and resources (Dickinson et al. 2010; Gardiner et al. 2012; Geoghegan et al. 2016; Knack, 2017). For example, by collecting information at bird feeders, volunteers have rapidly detected the spread of disease in house finches and other bird species across the USA through the Cornell Lab of Ornithology's FeederWatch programme (Altizer et al., 2004). Another citizen science project is helping scientist better understand proteins through a computer game called Foldit (Cooper et al. 2010).

For this reason, citizen science is playing an increasingly important role in advancing scientific knowledge and supporting more effective environmental management (Bonney et al, 2009b; Tulloch et al. 2013; Danielsen et al., 2014; Pocock et al. 2018). Thus, in this vein, a growing number of scientists are advocating for the involvement of non-expert volunteers in data collection and analysis to help meet research goals (Bonney et al, 2009b; Tulloch et al, 2013; Danielsen et al., 2014; Pocock et al. 2018). This collaborative approach, which enhances scientific rigour and enables more comprehensive responses to environmental challenges, aligns with *Principle 2* of the ECSA (2015) guidelines.

1.3.2. Public engagement and education

The other motive for the increasing uptake of citizen science projects is the realization of the benefits of involving the public for outreach. In fact, the second most mentioned motivating factor for scientists to adopt a citizen science approach is to foster science education (Trumbull et al. 2000; Bonney et al. 2009b; Geoghegan et al. 2016). Citizen science programmes have been reported to enhance understanding of the research topic (Bonney et al. 2009b; National

Academies of Sciences, 2018; CS Track, 2021), as well as improve scientific literacy from direct involvement in scientific practices and methods (Trumbull et al. 2000; Brossard et al. 2005; Shirk et al. 2012). The hands-on nature of citizen science research naturally aligns with "experiential learning" (Swan, 2022). Experiential learning refers to the theory that individuals can learn not only by "thinking," but also by "doing" (Itin, 1999). This concept was first coined by Dewey (1938) to explain how an individual´s experience can facilitate learning. Brossard et al.´s (2005) study was one of the first to use experiential learning theory to examine how participants research experience in citizen science affected their knowledge and attitudes toward science and the environment.

1.3.3. *Behavioural and social impacts*

In addition, it is debated that participation in citizen science itself can be valuable for individuals and consequently lead to societal impacts (Bonney et al. 2016; McKinley et al. 2017; Pocock et al. 2018; Hecker et al. 2019; Jørgensen and Jørgensen, 2021; Von Gönner et al. 2023). Active participation is presumed to lead to several benefits for the citizen scientist, such as increased understanding and appreciation of science (Trumbull et al. 2000; Brossard et al. 2005; Cronje et al. 2011), stronger interest in and support for nature conservation (Ellis and Waterton 2005; Brewer, 2006; Lawrence 2009), opportunities for social bonding and increasing social capital (Bell et al. 2008; McKinley et al., 2015, 2017) and even fostering stewardship by empowering individuals and communities and inspiring action (Lawrence, 2009; West and Pateman, 2016; McKinley et al., 2015, 2017; Pocock et al. 2018; Jørgensen and Jørgensen, 2021; Von Gönner et al. 2023). Further, the adoption of citizen science can also lead to policy impacts, such as more effective legislation and heightened civic participation (Fraisl et al. 2022). These benefits are consistent with several of ECSA's principles, particularly *Principle 3* (mutual benefits for science and participants) and *Principle 9* (promoting wider participation in science and policy) (ECSA, 2015).

1.4. *Challenges of citizen science*

While citizen science offers numerous advantages over conventional scientific approaches, it also presents several challenges. This section highlights three key issues commonly identified in the literature: (1) concerns with data quality, (2) limited transformative benefits for individuals and society achieved, and (3) lack of citizen diversity.

1.4.1. *Concerns with data quality*

Despite the growth in the number of citizen science projects, some scientists remain concerned about the accuracy of citizen science data (Crall et al. 2012; Gardiner et al. 2012; Aceves-Bueno et al. 2015). In fact, mistrust of non-expert generated data is the most frequently cited reservation about the citizen science approach (Riesch and Potter, 2013), with most research on citizen science focusing on ways of ensuring or improving the quality of the data of citizen science, so it can be used in professional scientific research contexts (e.g. Kaartinen et al, 2013; Sullivan et al, 2014; Lukyanenko et al. 2019). Mistrust of citizen science data extends to peer review which may partly explain why there are more citizen science projects than publications about citizen science (Gardiner et al. 2012), why scientists may not advertise the origins of the data included in publications (Theobald et al. 2015), or why scientists may be reluctant to get involved in citizen science because they are unsure if their results will get published (Riesch and Potter, 2013).

Although citizen science projects strive to meet the same standards of credibility as academic science, citizen science initiatives typically work within a different context. The most obvious of these challenges is the varied skill level of citizen-science participants, which could lead to inconsistencies among data points. Thus, initiatives require careful planning to navigate trade-offs (Freitag et al. 2016). Program designers must consider factors such as the number of participants, the age group, participants experience, the difficulty of the tasks, the resources available, time commitment required.

Nonetheless, citizen science projects are demonstrating their capacity to produce reliable data through the implementation of simple, yet well-designed methodologies (Kosmala et al. 2016; Fritz et al. 2022). For example, to enhance data accuracy and account for potential biases, a range of strategies can be used, including iterative project development, volunteer training and testing, in-person oversight, cross-comparison, expert validation, replication across volunteers, and statistical modelling of systematic error (Wiggins et al. 2011; Kosmala et al. 2016). Collectively, these approaches underscore the methodological rigour of citizen science and align closely with *Principle 6* of the ECSA (2015) guidelines, which emphasises its legitimacy as a robust scientific approach.

As a result, there has been growing acceptance of data produced through citizen science, evidenced by an increasing number of projects and peer-reviewed publications (Kosmala et al. 2016; Fritz et al. 2022). This acceptance is further reinforced by the emergence of numerous national and international associations dedicated to promoting citizen science as a means of opening scientific practice and advancing research though active collaboration with the public (Hecker et al. 2019; Roche et al. 2020).

1.4.2. Limited transformative outcomes and the need for new methods

Despite the exponential growth in the application of citizen science, its potential to generate transformative outcomes for science, citizens, and society remains under-realised (Bela et al. Theobald et al. 2015; Turbé et al. 2019; 2021; Day et al. 2022; Von Gönner et al. 2023). This can largely be attributed to three interrelated issues (1) the narrow focus of existing research, (2) the predominance of contributory project models, which restrict deeper forms of citizen engagement, and (3) the oversimplified evaluation of participation outcomes.

First, most research related to citizen science focuses on the concept itself and typologies (e.g. Wiggins et al. 2011; Shirk et al. 2012), and on ways of ensuring or improving data quality to meet scientific standards (e.g. Kaartinen et al, 2013; Sullivan et al, 2014). In contrast, comparatively little attention has been given to investigating the environmental and societal benefits that may result from participation (Bela et al. 2016; Adamou et al. 2021; Day et al. 2022; Von Gönner et al. 2023). Thus, while the "potential" benefits of involvement are frequently discussed (e.g. Bonney et al. 2009b; Conrad and Hilchey, 2011), there is no or little subsequent investigations informing whether the benefits are actually achieved (Walker et al. 2020; Adamou et al. 2021).

Second, despite the proliferation of typologies, most citizen science initiatives are still structured as primarily as contributory projects – designed and led by scientists with volunteers primarily involved in data collection (Wiggins et al. 2011; Chilvers and Kearnes, 2015; Kullenberg and Kasperowski, 2016; Land-Zandstra et al. 2021). Lawrence's (2009) analysis of 133 scientific papers revealed that such projects are geared towards scientific outputs, often with "extractive aims" such as increasing the amount of useful data available. This limited level of citizen involvement in other parts of the research process – such as project design or decision-making - is argued to restrict opportunities for deeper learning or participant empowerment (Haklay, 2013; Riesch, 2015). In comparison, co-created projects – those that emerge from citizen-defined questions or issues – enable greater participant involvement in all stages of the research process, fostering more meaningful engagement and broader societal impacts (Riesch and Potter, 2013; Wolley et al. 2016; McKinley et al. 2017; Wehn et al. 2021). Such initiatives are often seen to support community goals, build ownership, and cultivate enthusiasm and support for science, as well as civic action (Geoghegan et al. 2016; Wolley et al. 2016; McKinley et al. 2017; Wehn et al. 2021). For example, in the co-created citizen science project *Making Sense* (2016), participants from Netherlands, Spain, the UK, and Belgium were actively involved not only in the data collection and analysis, but also in the co-design of innovative solutions (e.g. sensors) to address local challenges related to noise and air pollution within their communities.

Third, the evaluation of citizen science projects often remains superficial in its assessment of engagement outcomes (Specht and Lewandowski, 2003; Somerwill and Wehn, 2022). For example, most impact assessments primarily quantify contribution outputs (e.g. number of participants, data points collected, participant retention rates, etc.) (Jordan et al. 2011; Phillips et al. 2012; Bela et al. 2016; Bonney et al. 2016). Instead, evaluation of the effects of citizen science on changes in attitude or behaviours are either undocumented (Phillips et al. 2012; Toomey and Domroese, 2013), based on untested assumptions rather than empirical observation (Bela et al. 2016), or rely heavily on self-report questionnaires – an approach widely criticised for its susceptibility to bias and questions around validity (Kormos and Gifford, 2014; Somerwill and Wehn, 2022).

As such, there is a growing recognition of the need for more holistic and context-sensitive evaluation tools in citizen science that capture the complex social, emotional, and behavioural processes that emerge through participation. Although environmental attitudes, behaviours, and knowledge are well-researched, these frameworks are not yet meaningfully integrated into citizen science practice (Somerwill and Wehn, 2022). This includes the use of immersive, qualitative methods such as participant observation, which can offer valuable insights into how individuals engage, learn, and change through participation. While widely used in anthropology and education, participant observation is uncommon in citizen science evaluation. However, it offers a unique lens for capturing affective dimensions of learning, social interactions, and complex behavioural shifts that may go unnoticed in more conventional approaches (DeWalt and DeWalt, 1998; Kawulich, 2005; Swan, 2022).

Overall, to ensure that citizen science fulfils its potential – not only as a tool for large-scale data collection, but also as a driver of social and scientific change – further research is needed to understand how it supports meaningful learning, behavioural change, and broader engagement (McKinley et al. 2017; National Academies of Sciences, 2018; Turbé et al. 2019; Adamou et al. 2021; Von Gönner et al. 2024). This includes the need to document more clearly *how* and *which* aspects of participation influence behavioural and societal outcomes (Bela et al. 2016; National Academies of Sciences, 2018; Turbé et al. 2019; Von Gönner et al. 2023).

This thesis positions participant observation as a valuable methodological contribution within this context. By embedding this approach in the evaluation of corporate-based citizen science initiatives, it seeks to deepen understanding of how engagement is experienced, and which elements may lead to more meaningful, long-term transformations.

1.4.3. Lack of citizen diversity

Although worldwide participation in citizen science has proliferated (Bonney et al., 2009b; Shirk et al. 2012; Knack, 2017) and there have been efforts to expand the number of people involved, it remains that many such projects are mostly found in industrialized countries in the Global North (Bonney et al. 2016; Theobald et al. 2015; Pocock et al. 2018), and there is a lack of diversity in citizen science participants (Hobbs and White, 2012; Pandya, 2012; Haklay, 2013; Raddick et al. 2013; West and Pateman, 2016; Soleri et al. 2016). For example, a large-scale survey conducted by CS Track in (2021) demonstrates citizen scientists in Europe tend to be white, middle-class, middle-aged men; akin to volunteering more widely. Notably, in environmental citizen science projects, participants tend to have previous knowledge and an active interest in science and are more informed about environmental issues and scientifically literate than the general public (Bruyere and Rappe, 2007; West et al. 2015; Geoghegan et al. 2016; CS Track, 2021).

Thus, although citizen science is open to anyone willing to participate, there remains a disproportionate adoption of citizen science by individuals who already possess specific skills, knowledge, or intrinsic motivation (Hobbs and White, 2012; Pandya, 2012; Raddick et al. 2013; West and Pateman, 2016; Lewandowski and Oberhauser, 2017; Land-Zandstra et al. 2021). As a result, there is a missed opportunity to involve a broader demographic and more diverse sectors of society – raising concerns that citizen science may be 'preaching to the converted' (Soleri et al. 2016; National Academies of Sciences, 2018).This underrepresentation reveals a critical tension with *Principle 1* of the ECSA guidelines, which emphasises the importance of inclusive participation (ECSA, 2015).

1.5. *Opportunities for broadening participation: corporate-based citizen science*

In response to these challenges, there is growing interest in expanding the reach of citizen science through more diverse and context-sensitive forms of engagement (West and Pateman, 2016; Agnello et al. 2022). One promising avenue is the integration of citizen science into *Captive Learning Programmes*, where participation is embedded within institutional settings – such as schools, corporations and museums – creating new opportunities to engage audiences who might not otherwise take part (Van Noordwijk et al. 2021).

These projects prioritise "engagement" and "education" for new audiences, and differ from traditional citizen science typologies in that participation is facilitated through institutional gatekeepers (e.g. teacher, employers) therefore, participants do not necessarily have to have a pre-existing interest in the scientific research topic or in engagement per say. Thus, in these settings the success of the educational experience largely depends on the "intermediaries" and their skills and capacity to deliver the programme and motivate participants (Van Noordwijk et al. 2021).

Given the private sector's central role in the transition towards a more sustainable future (Anderson et al. 2023), corporate-based citizen science offers a valuable opportunity to extend participation beyond science enthusiasts. By embedding engagement within workplace settings, such initiatives can raise awareness and foster pro-environmental behaviours among employees, while also contributing to organisational sustainability goals.

While businesses have not traditionally been a setting for citizen science, they can foster sustainability within their employee base, potentially facilitating the provision of "citizen" to diverse communities who may not already have an intrinsic motivation to take part (Anderson et al. 2023). In addition, integrating participation into the workday also helps overcome common barriers to volunteerism – such as time constraints – which are known to limit engagement in citizen science (Merenlender et al. 2016; West and Pateman, 2016; Anderson et al. 2023).

In this context, citizen science becomes not only a tool for scientific data collection but also serves as a mechanism for embedding sustainability into day-to-day decision-making, workplace practices, and corporate culture (Anderson et al. 2023; UNEP, 2022). In this vein, Anderson et al. (2020) affirm the value of adapting citizen science to organisational contexts and propose a framework to support its integration.

However, to date, the use of citizen science within businesses remains largely unexplored (Millar and Searcy, 2020). While the concept of "volunteerism" is well established in Corporate Social Responsibility (CSR) strategies (Saz-Gil et al. 2021), and shares some parallels with citizen science, the two are conceptually distinct (Geoghegan et al. 2016). A key difference lies in the nature of participation: citizen science involves direct engagement in the scientific process (Seymour and Haklay, 2017) and places strong emphasis on mutual benefits for both participants and science (Land-Zandstra et al. 2021).

As such, corporate-based citizen science represents a novel field of research. The first formal assessment of its presence in the private sector found that the term "citizen science" was generally absent from sustainability reports among 162 top-earning multinational firms (Millar and Searcy, 2020). However, companies are increasingly describing activities that could potentially be categorized as a form of citizen science, even if they are not labelled as such (Anderson et al. 2020; Millar and Searcy, 2020). For example, Anderson et al. (2020) identify eleven companies featured in the 2018 GlobeScan-Sustainability Leaders report that engaged in participatory environmental research. Thus, there appears to be a stronger tendency for these types of initiatives, highlighting that citizen science is an emerging area that may become more frequent in the business sector in the near future (Millar and Searcy, 2020).

1.6. Introduction to the wider research campaign and Climate-Proof Cities

Earthwatch Institute is an international non-profit environmental organisation known for using citizen science in employee Captive Learning Programmes aimed at fostering sustainability in business (Van Noordwijk et al. 2021). One such initiative is *FreshWater Watch*, a co-designed initiative between Earthwatch, university researchers, and HSBC, which formed part of the bank's Corporate Sustainability Programme from 2012 to 2017 (Earthwatch Institute, 2018). During this time, approximately 8,000 employees across 36 cities participated, contributing to freshwater ecosystem research while learning about their environmental impact and potential for climate action (FreshWater Watch, 2022). By 2016, the project had produced 20 peer-reviewed publications and was credited with enhancing environmental awareness, reducing personal impacts, and fostering more collaborative workplace dynamics (Earthwatch Institute, 2018; Mainstreaming Climate, 2018).

Following its success, the programme was extended for an additional three years, leading to the development of *Climate-Proof Cities* – a continuation of the corporate sustainability initiative, still targeting HSBC bank employees but with a new focus on how urban green spaces can increase cities' resilience to the effects of climate change (Earthwatch Europe, 2023). This thesis draws on the *Climate-Proof Cities* Corporate Sustainability Programme as its central case study.

The *Climate-Proof Cities* Corporate Sustainability Programme was implemented in 17 major cities around the world (Earthwatch Europe, 2023). The programme consists of immersive experiences, with a combination of classroom and outdoor based learning designed to equip bank employees (participants) with the knowledge, plans, and support to play an active role in championing sustainability and climate change-related issues relevant to the financial firm's sustainability strategy.

As part of the programme, employees take part in a citizen science project that involves collecting key environmental field measurements with the help of collaborating scientists to support research on Nature-based Solutions (NbS). NbS refers to strategies that use or mimic natural processes to address societal challenges. In recent years, NbS has gained increasing attention for its potential to support ecosystem functioning in urban environments while delivering co-benefits for people and the environment (EEA, 2019; European Commission, 2020).

There are several programmes, each examining different NbS applications, including urban parks, green roofs, wetlands, and bioswales (Earthwatch Europe, 2023). For example, in Abu Dhabi, citizen scientists study how trees in residential areas influence urban microclimates and thermal comfort. In the USA and Canada, research examines the capacity of bioswales to increase flood protection, support local groundwater recharge and reduce extreme temperature events (Earthwatch Europe, 2023). The overarching aim of the project is to produce evidence-based guidelines for the improved design and implementation of NbS in urban environments, with a particular focus on mitigating the impacts of climate change and urbanisation.

The thesis focuses on residential workshops conducted in the UK and France, where the scientific research examines the relationship between land management practices surrounding urban trees and soils, and the delivery of regulating ecosystem services. Corporate participants take on the role of citizen scientists, collecting data on tree health and productivity, local micro-climate conditions, soil hydrology, and soil nutrient and carbon levels. Partner institutions include the University of Reading, Imperial College London, INRA France, and CNRS. The University of Manchester University acted as an external partner, supporting soil biology training, data collection, and analysis.

Drawing on this case study, the thesis evaluates the outcomes of corporate-based citizen science engagement – both in terms of advancing urban soil science and improving understanding of the factors that drive sustainable behaviour within organisational contexts.

1.7.Urban trees and soil: challenges, gaps, and citizen science

Modern cities are characterized by high population density, industrial activity, impervious surfaces, and minimal vegetation cover (Pearlmutter et al., 2017). These characteristics contribute to environmental challenges such as elevated temperatures (the heat island effect), increased flood risks, and pollution of soil, water, and air (McMichael et al. 2003; Manning, 2008; Pearlmutter et al. 2017). Climate change further exacerbates these challenges, intensifying their impact on urban environments (EEA, 2015). According to a recent Europeans Commission Joint Research Centre study, 72% of the EU population currently lives in cities – a figure expected to increase rapidly (Melchiorri et al., 2018). As such, urgent and long-term sustainable solutions are required to build resilience against environmental challenges like climate change and urbanisation that adversely affect human health and quality of life in urban areas (Jansson, 2014; Mexia et al. 2017; Escobedo et al., 2018; UN, 2018; EEA, 2019; European Commission, 2020).

In response, Nature-based Solutions (NbS) has gained momentum as a means of addressing urban environmental degradation while restoring more natural functions and processes in cities (Escobedo et al., 2018). NbS are defined as actions that protect, manage, or restore ecosystems to address societal challenges, delivering both human well-being and biodiversity benefits (European Commission, 2020). In fact, the European Commission (2020) urges European cities to develop bold "Urban Greening Plans." Urban trees – found in parks, gardens, and along streets in tree pits – represent a key form of NbS for enhancing urban sustainability and resilience. They deliver a wide array of direct and indirect environmental ecosystem services (Brouwer et al., 2013), including energy conservation, carbon storage, reduced stormwater runoff, improved air quality, enhanced biodiversity (Brack, 2002; Escobedo et al., 2011; Liversley et al., 2016; EEA, 2019), and benefits to human health and well-being (Daily 1997; Brouwer et al. 2013; Escobedo and Nowak, 2009).

However, the potential of urban trees to function effectively as NbS is often compromised by poor planting conditions and limited long-term maintenance. Trees are frequently planted in locations ill-suited for growth and are exposed to multiple stressors (Sanders and Grabosky, 2014; Solomou et al. 2019). These include soil sealing, restricted rooting space, contamination, and compaction (Sanders and Grabosky, 2014). Urban trees are also more vulnerable to water deficits than forest trees, increasing susceptibility to pests and pathogens (Dale and Frank, 2017). Consequently, urban trees have significantly lower life expectancy than their rural counterparts (Roman and Scatena, 2011; Czaja et al. 2019; Hillbert et al. 2019), reducing their ability to deliver the ecosystem services they were intended to provide (Layman et al., 2016; Van Geel et al. 2019).

Soil health is a critical, yet frequently overlooked, factor in the success of urban trees (Jim, 1998; Layman et al. 2016; Hillbert et al. 2019). Realizing the full range of benefits that urban trees provide for people and the environment depend on strategies that also support healthy soils, which are integral to urban ecosystems functions and processes (Mao et al. 2014). Soils supply trees with necessary chemical and physical properties to sustain growth (Van Geel et al. 2019) like the correct structure to physically support them, a rooting medium with plant-available water, essential nutrients such as nitrogen and phosphorus, and oxygen for root respiration (Karlen, 2005; Blumlein et al. 2012). Despite this, urban soils are often a forgotten part of the urban ecosystem, and a treated as a neutral substrate for tree planting rather than a living, functional component of the urban ecosystem (Jim, 1998; McPhearson, 2011). and the need for functional soils in urban forest ecosystems has received little attention (Deeb et al. 2020; FAO, 2021; Head et al. 2021; O'Riordan et al. 2021)primarily because soils in cities are presumed to be strongly modified by human activities and predominantly degraded (Pouyat et al. 2010; Davies et al., 2011). Consequently, many urban soils are not well suited for tree growth, reducing urban tree health status and jeopardizing their capacity to support tree health (Roman and Scatena 2011; Dale and Frank, 2017). This neglect is evident in both practice and research: while extensive studies exist on urban tree planting and canopy cover, much less attention is paid to below-ground soil dynamics (Head et al. 2021; Deeb et al. 2020). .

Recognising this gap, the International Union of Soil Science (IUSS) established the SUITMA (Soils of Urban, Industrial, Traffic, Mining and Military Areas) working group to advance understanding of urban soils as distinct and dynamic systems. SUITMA research has shown that urban soils differ significantly from natural and agricultural soils in terms of structure, function, and composition, and play a crucial role in urban biodiversity, climate resilience, and ecosystem delivery (Lehmann and Stahr, 2007; Pouyat et al. 2010; Guilland et al. 2018).

Nevertheless, soil preparation techniques and protective standards are often absent from municipal and national guidelines (Greinert, 2015; Head et al. 2021). One underappreciated aspect of urban soil management is leaf litter removal, a routine practice in many cities, particularly in corporate and municipal green spaces. While intended to enhance aesthetics or reduce perceived hazards, removing leaf litter can disrupt essential soil processes such as nutrient cycling, moisture retention, and organic matter accumulation (Sayer, 2006). This tension between maintenance norms and ecological function illustrates the broader challenge of managing urban NbS effectively and sustainably.

Monitoring soil health in urban settings is both essential and complex. Conventional approaches – such as national monitoring networks – are costly, and often lack sufficient coverage, especially in densely populated marginal urban spaces (Head et al. 2021). In this context, citizen science presents a promising and underutilised strategy to address data gaps while engaging diverse urban populations (Rossiter et al. 2015; Daguitan et al. 2019; Head et al. 2021). Citizen science can enable large-scale data collection at lower cost, while fostering environmental awareness and stewardship among participants (Bonney et al. 2009b; Rossiter et al. 2015; Pudifoot et al. 2021). Soil-focused citizen science projects have a huge potential to accelerate progress in soil health monitoring efforts (Head et al. 2021). Citizen scientists can carry out measurements over a wider geographical region and at a higher frequency than would be available to research scientists alone and within the funding available (Bonney et al. 2009b; Dickinson et al. 2010; Gardiner et al. 2012; Pudifoot et al. 2021). Certain indicators are particularly well suited to citizen science due to their simplicity, accessibility, and low cost. One such example is soil colour, which serves as a proxy for organic matter content, moisture, and mineral composition (Viscarra Rossel et al. 2006). With the aid of simplified protocols, soil colour assessment becomes an intuitive and scalable method for non-experts, enabling the collection of data across a wide range of urban contexts (Aitkenhead et al 2021; da Silva et al. 2021).

In addition to generating valuable data to support scientific advancement in this field, soil-focused citizen science projects can raise awareness of the essential ecological services provided by soil, acting as important facilitators of soil connectivity (McBratney et al., 2014). This is particularly important because, to date, soil's critical role for the urban environment receives limited attention among the general public (Brevik et al. 2020). While citizen science has been widely adopted across various fields of research, its application to soil remains limited. For instance, Rossiter et al. (2015) highlighted that soil-focused citizen science projects have seen minimal uptake compared to other disciplines, citing barriers such as a lack of "attractiveness" of soil, no background knowledge in the subject-matter, as well as the need for fieldwork (Rossiter et al. 2015). A more recent review of existing soil-related citizen science initiatives by Pino et al. (2022) identified only 55 projects worldwide, the majority of which were launched in 2021 and concentrated in the USA.

Therefore, when embedded within structured programmes – such as corporate sustainability initiatives – citizen science has the potential not only to support soil health monitoring and inform more evidence-based and ecologically sound management practices, but also to foster pro-environmental attitudes and behaviours within organisations. In doing so, it can enhance both the social and institutional impacts of NbS in urban settings.

1.8.Objectives and research questions

The main objective of the PhD research is to evaluate the outcomes of corporate engagement in citizen science for advancing urban soil health research and improving understanding of what drives sustainable action in business settings.

Specifically, the study uses a corporate-based Captive Learning Programme - *Climate-Proof Cities* - as a vehicle to address the following research questions:

1. What is citizen science, and what are the key challenges and opportunities associated with its use in supporting environmental research and behavioural change, particularly in the context of urban sustainability and soil health?

2. How does tree leaf litter removal impact the health of urban park soils?

3. Can simple soil colour measurements collected by citizen scientists be used to estimate soil carbon at scale?

4. What aspects of employee-participation in a corporate citizen science programme support learning, shape attitudes, and drive pro-environmental behaviour in organisational settings?

This study draws on soil data collected over a two-year period during twenty-eight corporate sustainability training events conducted in urban parks across the UK and France. Data were gathered by both professional scientists and employee citizen scientists. Additionally, participant observation and survey data were collected during eight of the UK-based events, involving a total of 108 employee participants.

This thesis positions participant observation as a valuable methodological innovation for evaluating citizen science in corporate contexts.

1.9. Thesis outline

This thesis comprises of five chapters. Chapter 1 addresses research question 1. This is followed by an introduction to the co-created project *Climate-Proof Cities* which offers an avenue to engage the private sector and diversify participation for sustainable development in business. Next, the chapter outlines how the thesis will address research gaps in urban soil science understanding and identifies what aspects of science engagement impact learning and drive participants to act using the corporate-based citizen science project as a case study. Lastly, the chapter defines the research objectives and provides an outline of the thesis structure. Chapter 2 addresses research question 2, holistically assessing soil health in urban parks using soil physical, chemical, and biological indicators with data collected by citizen scientists and scientists. Chapter 3 explores research question 3 and provides a method to use simple colour observations to estimate soil organic carbon at large scales using citizen science. Chapter 4 explores the benefits of corporate-based citizen science, specifically focusing on identifying what aspects of engagement drive sustainable behaviours. In Chapter 5 the main contributions of the thesis are summarized, the limitations of the study are addressed, and recommendations for future work are discussed.

Chapter
2
Leave it be! Examining the impact of clearing litterfall on soil health in our city parks with the help of citizen scientists

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Abstract

Leaf and woody litter are key components of soil health in forest ecosystems, yet in urban parks, they are routinely removed without fully assessing the consequences. This study examines the impact of litterfall removal on soil health in two major UK parks. We analyse soil data gathered by both citizen scientists and researchers from park areas with and without leaf litter removal, assessing key physical, chemical, and biological properties to provide a comprehensive evaluation of soil health.

Our findings indicate that urban park soils, often overlooked, exhibit characteristics similar to natural forest soils, including relatively high organic carbon and biological activity. However, the continuous removal of leaf litter over the two-year period has led to a deterioration of soil health, with a significant decline in soil organic carbon (SOC) relative to unmanaged park areas where litterfall accumulated ($5.6 < 6.3$ %). Litterfall removal also increased soil compaction, indicated with significantly higher compressive loads ($2.16 > 1.28$ kg/cm^2) and bulk density ($1.05 > 0.92$ g m^{-3}), and decreased soil water infiltration ($2.44 < 4.57$ K cm/h). The microbial community also exhibited signs of stress (cy/pre ratio: $0.386 > 0.258$), and bioindicator species, such as Coleoptera, declined. However, while litter removal negatively affected soil health, park site was the dominant factor shaping soil communities, with a higher abundance and species richness found in Cannon Hill Park.

These findings emphasize the critical role of litterfall in maintaining urban soil fertility, structure, and biodiversity. However, they also highlight the necessity for further research to enhance understanding of the urban soil mosaic and to develop evidence-based, sustainable park management practices that support soil health. Additionally, this study underscores the value of citizen science in facilitating large-scale soil monitoring and advancing research in urban soil ecosystems.

Keywords: Urban soils; soil properties; leaf litter; soil community; soil health; citizen science

2.1. Introduction

Greening initiatives are high on the agenda in most EU countries as a key strategy for improving urban sustainability (FAO, 2015; UN, 2018; Zhu et al. 2018). Despite their size and degree of artificiality, urban green spaces, such as parks and gardens, represent the only natural area in cities and a growing part of the world's woodland (Tzoulas et al. 2007; Zupancic et al. 2008; Pouyat and Trammel, 2019). The provision of urban green spaces, such as these, is a Nature-based Solution (NbS) to multiple environmental stressors that are frequent in cities (Jansson, 2014; Mexia et al. 2017). Urban trees and soils provide valuable ecosystem services such as carbon sequestration (Molla, 2015), temperature and stormwater regulation, preservation of biodiversity, air pollution removal (EEA, 2019), as well as providing cultural and recreational benefits for people and their well-being (O'Brien et al., 2017; Zhu et al. 2018; EEA, 2019; O'Riordan et al. 2021).

However, realizing the wide range of benefits for people and the environment does not depend on tree planting initiatives alone, but on maintenance strategies that promote the health of these urban forest ecosystems, which to date, have been scarcely studied (Solomou et al. 2019). So far, recent investigations show that the average life expectancy of urban trees is relatively low in comparison to their rural counterparts (Czaja et al. 2019; Smith et al. 2019; Hillbert et al. 2019). Urban trees are usually planted in locations that are not ideal for their growth, and they are subjected to many adverse stress factors (Solomou et al. 2019). Evidence suggests that poor soil conditions may be among the most significant limiting factors for tree survival and the ecosystem services they can provide (Laymay et al. 2016; Hillbert et al. 2019).

Soils and trees are intrinsically linked, with huge impacts on each other and on the wider environment. Interactions between soil physicochemical and biological properties determine the availability of nutrients, water, and oxygen supporting tree growth and root function (FAO, 2015). This relationship is tacitly understood for forests, yet the need for functional soils in urban forest ecosystems has received little attention (Deeb et al. 2020; FAO, 2021; Head et al. 2021; O'Riordan et al. 2021). In fact, most tree planting studies in cities focus on the above-ground part and neglect the below-ground soil component, which is solely seen as a medium for tree growth (McPhearson, 2011; McGrath and Henry, 2014; Jim, 2019). This oversight has resulted in a lack of guidelines and management practices at national and regional scales to protect urban soils (Greinert, 2015; Head et al. 2021). In fact, a common practice in urban parks and gardens is to remove leaf and woody litter without understanding how this affects ecosystem functions (Sayer, 2006; Krishna and Mohan, 2017).

Litterfall comprises dead plant material such as leaves, pieces of bark, twigs and needles that have fallen to the ground. When left undisturbed in a natural setting, this dead organic material, together with dead roots, exudates, and other organic substances are decomposed by microorganisms and soil invertebrates. Over time, decaying litter enriches the soil with organic material and provides essential nutrients for tree growth (Sayer, 2006; Krishna and Mohan, 2017). In forest ecosystems, litterfall represents a major input of carbon, nitrogen and other nutrients that are directly related to tree productivity (Krishna and Mohan 2007). Decaying litter also has an immense influence on soil properties which in turn affect tree health and the delivery of key ecosystem services (Sayer, 2006). Leaf litter accumulates on the soil surface and forms an organic cover that acts as a protective layer for maintaining soil physical functions, like retaining soil moisture retention, buffering against soil temperature and compaction (Davidson and Janssens, 2006). The leaf litter layer also provides habitats and substrates for a wide range of soil fauna (Byrne, 2007; Sayer, 2006; Krishna and Mohan, 2017) which help facilitate decomposition of organic matter through physical and chemical processes, as well as aid in the activity and community assemblage of soil fungi and bacteria (Paul, 2015).

The important role of litter production and its decomposition processes on forest functioning have been documented from as early as the 1850s by a large number of studies worldwide. Thus, it is not surprising that findings show litterfall removal in forests gradually results in the depletion of soil organic carbon, lower primary productivity, and a decreased abundance and diversity of soil organisms (Sayer, 2006). Yet very few studies have been conducted on the impact of leaf litter clearing in urban forest environments (Sayer, 2006; Michopoulos, 2011; Pamela et al., 2015; Sun and Zhao, 2016; Krishna and Mohan, 2017). Consequently, a deeper understanding of the effect of periodic removal of fresh litter on soil functions in urban ecosystems is urgently needed (Bolund and Hunhammar, 1999; Pollak 2006; Byrne, 2007; Guilland et al. 2018).

Conventional data collection sources for soil health such as national monitoring programmes require significant resources to support the data sampling and analysis effort required and, to date, remain insufficient in coverage (Head et al. 2021). Instead, the use of Citizen Science, where members of the public participate in the scientific research process, is an example of an emerging non-traditional data source that could meet this shortfall and accelerate progress in this field (Rossiter et al. 2015; Daguitan et al. 2019; Head et al. 2021), particularly in cities where there are many citizens and soil health data is missing (Ferrando-Jorge et al. 2021). Citizen science methods can generate three to four times the number of samples generated by traditional research for the same cost and substantially increase the speed that the science outcomes are disseminated (Gardiner et al., 2012). Furthermore, public input and active engagement in science may also bring other benefits beyond the collection of large datasets, such as increased public awareness (Irwin and Horst, 2016; McKinley et al. 2017; Bonney et al. 2016; Van Noordwijk et al. 2021), of soil's critical role for the urban environment which, to date, receives limited attention among the general public (McBratney et al. 2014; Rossiter et al. 2015; Brevik et al. 2020).

Our work aims to examine the effects of the management of leaf litter on key measures of urban soil health. We collected soil data from beneath *Tilia europeae* (viz. common lime) trees in two major urban parks in the UK in areas where leaf litter was removed and where leaf litter was left *in situ* over a two-year period. We use a combination of soil measurements collected by scientists and citizen scientists to increase the scope of the data collection. The specific objectives were to examine the impact of litterfall removal on soil (1) physico-chemical and (2) biological properties to offer an integrative view of soil health. The attributes measured—soil infiltration, compaction, soil organic carbon (SOC), bulk density, pH, total nitrogen N, phospholipid fatty acids (PLFAs), and soil fauna—were selected to provide an assessment in relation to both broad ecosystem functioning and specific tree-supporting processes. Soil physical properties, assessed through infiltration, compaction, and bulk density, is critical for regulating stormwater infiltration, reducing surface runoff, and mitigating urban flooding, while also ensuring adequate aeration and root penetration for tree stability and water uptake. SOC contributes to carbon sequestration and climate regulation, while also enhancing soil fertility, microbial activity, and water-holding capacity, all of which are essential for tree growth and resilience to drought stress. Total N serves as a key indicator of soil fertility, supporting nutrient availability for tree productivity and canopy development. Soil pH influences nutrient availability and microbial community composition, shaping the conditions for root-associated microbial interactions that influence tree health. Biological indicators, including PLFAs and soil fauna, provide insight into microbial and faunal diversity, which underpin nutrient cycling, organic matter decomposition, pollutant breakdown, and pathogen suppression—functions that contribute both to overall ecosystem resilience and to maintaining tree vigor in urban environments. Our ultimate goal is to deepen the understanding of the health of soils in urban parks since they are major land covers in cities and their adequate management is paramount for achieving resilience.

2.2. Materials and methods

2.2.1 Study area and research design

The study was conducted in two urban parks in the UK: Kew Gardens, London (51.48 N, 0.29 W) and Cannon Hill Park, Birmingham (52.45 N, 1.90 W). These locations were selected due to their similar climatic conditions, with mean annual temperatures of 11°C in London and 9°C in Birmingham, and average annual precipitation of 690 mm and 769 mm, respectively (Climate-Data, 2020).

Tree selection and management categories

At each site, six mature *Tilia europaea* (viz. common lime) trees, approximately 30 years old, were selected for study. This species was chosen due to its widespread presence in urban environments and frequent use in streets and parks across Europe (Hansen et al., 2014). The selected trees were divided into two distinct management categories:

a) **Managed sites** (three trees per park) were characterized by routine removal of leaf and woody debris, as well as thinning and pruning operations to maintain open space conditions. These areas were publicly accessible.

b) **Unmanaged sites** (three trees per park) resembled natural forest environments with minimal human intervention. These areas had restricted public access and were characterized by high tree density, with no routine removal of leaf litter, mowing, or pruning operations.

Soil data collection

Topsoil data were collected by citizen scientists over 17 organized events held in summer and autumn 2018–2019, with each event spanning two consecutive days. Prior to data collection, participants attended a one-hour training session led by a research scientist to ensure consistency in field measurements and sampling techniques.

At each study site, soil data were collected from four designated points per tree, following a north-south transect beneath and outside the tree canopy. Sampling position 1 were located directly beneath the tree canopy facing North. Sampling position 2 was calculated by measuring the length between the tree trunk and the inner point with a measuring tape. Sampling positions 3 and 4 were calculated in a similar manner but in a South facing orientation. This sampling approach ensured a systematic assessment of soil conditions across different canopy positions. Figure A1 provides an example of the citizen science datasheet used for soil measurements.

At each of these points, citizen scientists:

1. Conducted direct soil measurements in the field.
2. Collected soil samples for subsequent laboratory analysis by scientists.

Integration with a larger research campaign

The data collected by citizen scientists and scientists formed part of a broader research campaign investigating urban soil and tree health in UK and French parks. The sampling design is outlined in Table A1 (Appendix), and a detailed protocol for citizen scientists is available in Pudifoot et al. (2021).

2.2.2 Soil quality assessment

To measure soil health, we used a set of soil quality indicators, or attributes, encompassing physical, chemical, and biological soil properties which reflect the capacity of the soil to fulfil its functions. Table A 5 in appendix provides a summary of the indicators measured, the methodology used for each and specifies whether they were recorded by citizen scientists or researchers.

2.2.2.1 Soil Physico-chemical Indicators

Soil infiltration data was collected by citizen scientists using a Tension Mini Disk Infiltrometer (Decagon Devices, Inc) with a 2.25-cm disk radius set at a 1.0 cm suction to accommodate the more compact soil with slower infiltration found at the study sites. Both the upper chamber and lower water reservoir were filled with water. The tension infiltrometer was placed on a smooth, level soil surface with vegetation removed to ensure good contact. The initial water volume (mL) was recorded and changes in the reservoir were logged at 1 min time intervals for 10 min. However, if the infiltration rate was particularly fast, participants recorded the water level at shorter intervals of 20–40 seconds. The infiltration data collected by participants was processed and used to calculate cumulative infiltration and estimate the hydraulic conductivity K*(h)* of the surface layer of the soil using Decagon (2005) infiltrometer user's manual:

First, Philip (1957) equation was used to calculate cumulative infiltration I (in centimetres) and square root of time t (in seconds) based on the gathered data (Equation (1):

$$I = S_e\sqrt{t}, \quad (1)$$

where S_e is the slope of the curve of the cumulative infiltration vs. the square root of time relationship.

Next, using Zhang's (1997) proposed method, the results from cumulative infiltration were fitted vs. time with the following function (Equation 2):

$$I = C_1\sqrt{t} + C_2 t, \quad (2)$$

where C_1(m x s^{-1}) and C_2 (m x s^{-1}) are parameters. C_1 is related to soil sorptivity, and C_2 is the hydraulic conductivity.

The $K(h)$ or saturated hydraulic conductivity was then calculated as follows (Equation 3):

$$K(h) = \frac{C_1}{A}, \quad (3)$$

where C_1 is the slope of the curve of the cumulative infiltration vs. the square root of time, and A is a value relating the van Genuchten parameters for "sandy loam" textural class for managed sites and "silt loam" for unmanaged, for a 2.25 -cm disk radius set at a 1.0 cm suction.

Soil compaction was measured by citizen scientists using a Eijkelkamp pocket penetrometer in the field. The piston was pushed downwards into the soil surface at a slow, steady vertical pressure on a patch of undisturbed soil with the surface vegetation removed. The resistance of the calibrated internal spring registered the penetration force on an engraved scale from 0 to 4.5 kg/cm^2. The reading is a quantitative measurement of soil penetration (vertical) resistance and is equivalent to unconfined compressive strength.

At each location, citizen scientists also collected soil for subsequent laboratory analysis by scientists. Topsoil samples (0–10 cm) were collected with a hand trowel and placed in soil bags (approx. 15 × 20 cm, instructed to be filled abundantly for analyses), and undisturbed soil cores (volume 150.6 cm^3) were collected using metal rings from the same depth.

Topsoil samples collected were sieved (5 mm) removing fresh plant litter and soil organic matter (SOM) content was measured in the laboratory using the percent weight loss on ignition (LOI) technique (% LOI, 2 h at 550°C) (Dean, 1974). Next, the content of soil organic carbon (SOC) was calculated by dividing SOM by a factor of 1.724 (Nelson et al. 1996). This conversion factor assumes organic matter contains 58% organic carbon. These SOC estimates were subsequently corrected using Total C (%) measured via dry combustion.

Bulk density (g m^{-3}) data were calculated using McKenzie et al., (2004) core sampling method by drying (105 °C for 2h) and weighing the samples.

Bulk density recordings were used to soil organic carbon (SOC) storage (Mg C ha^{-1}) in topsoil (10 cm) using the following equation:

SOC stock = H × BD × OC × 0.1

where H is soil depth (10 cm), BD is bulk density (g cm^{-3}), OC is soil organic carbon (%), and 0.1 is the conversion factor to Mg C ha^{-1}

Soil pH was calculated using 10 g of soil mixed with 50 mL of distilled water after shaking for 2 - 3 min and 2 min of settling. The pH meter was calibrated beforehand and between samples, and the pH probe was rinsed to avoid contamination.

A sub-set of samples was randomly chosen to determine soil texture and to quantify the amount of nitrogen and carbon in the soil.

Soil texture was determined using the TA method on air-dried soil (< 2 mm) to quantify the proportion of sand, silt, and clay.

Total C and N were measured with an automated FLASH 2000 Elemental analyser after dry combustion. Total C values were used to calibrate SOC estimates derived from LOI. A simple linear regression between total C (%) and SOC (%) from LOI ($y = 0.845x + 0.16$) (Fig. A 2) was applied to correct all SOC values.

2.2.2.2 Soil Biological Indicators

A sub-set of soil samples collected by scientists from the 48 sampling locations at the October 2019 events were frozen at -80 °C for storage prior to extraction and analysis of Phospholipid fatty acids (PLFAs). PLFAs extracted from the soil were used to give an estimate of community composition and biomass for bacteria and saprophytic fungi, whereas neutral lipid fatty acid (NLFA) biomarker 16:1ω5 were used to indicate arbuscular mycorrhiza (AM) fungal biomass as it has higher specificity, and is more responsive than the PLFA biomarker (Willer et al. 2015; Lekberg et al. 2022).

<u>Fatty acid analysis</u>

Fatty acids were extracted from 0.5 g of dry soil using the modified Bligh-Dyer extraction protocol described in detail (Buyer and Sasser, 2012) with 19:0 phosphatidylcholine (Avanti Polar Lipids) as the internal standard. Briefly, lipids were extracted from soil with a chloroform: methanol: citrate buffer mixture and separated into neutral lipids, glycolipids and phospholipids using a silicic acid column. The phospholipids were then subjected to a mild alkaline methanolysis, and the resulting fatty acid methyl esters were analysed using a gas chromatograph (7890B, Agilent Technology) fitted with a flame ionization detector (GC-FID). The standard nomenclature was used to identify the individual fatty acids.

The total biomass of the soil microbial community was calculated according to peak areas using the internal standard Methyl nonadecanoate fatty acid (19: 0) concentration to confirm the individual PLFA contents (nmol g-1 of dry soil) (Buyer and Sasser, 2012).

The relative abundance of individual PLFAs were calculated as the area of each PLFA peak relative to the summed area of all PLFA peaks and reported in mole percentages (mol%). PLFAs that were <14 C and >20 C in length and with a total in peak area lower than 0.5% were excluded. PLFAs 16:0 and 18:0 which are abundant in all soil microorganisms, including prokaryotes and eukaryotes, may not be sensitive indicators of the composition of the soil microbial community hence they were also excluded. Overall, 23 fatty acids were used for community composition analysis (Fig. A 3).

To evaluate patterns in PLFA composition among samples, individual fatty acids were utilized as biomarkers for different microbial groups. Fatty acids i14:0, i15:0, a15:0, Br 16:0, i16:0, i17:0, a17:0 and Br18:0 were used to characterise Gram-positive (G^+) bacteria; 16:1ω9, 16:1ω7c, 16:1ω7t, 17:0 cyclo, 17:1ω8, 2-OH 16:0, 18:1ω7 and 19:0 cyclo represented Gram-negative (G^-) bacteria; 10 Me 16:0, 10 Me17:0 and 10 Me18:0 characterized Actinobacteria; and 14:0, 15:0, 16:0, 17:0 and 18:0 were used as general bacterial markers (Willers et al. 2015). The sum of all the PLFAs considered to be predominantly of bacterial origin were used as an index of bacterial biomass. The sum of PLFAs 18:2ω6,9 and 18:1ω9c were used as an indicator of Saprophytic fungi, whereas NLFA 16:1ω5 as an indicator of Arbuscular mycorrhiza (AM) fungi (Lekberg et al. 2022), and the total quantity of these fatty acids were used as an index of fungal biomass. The ratio of fungal-to-bacterial (F/B) and gram-positive-to-gram-negative bacteria (G+/G-) were calculated to indicate the soil microbial community composition and the ratio of cyclopropyl fatty acids-to-monoenoic precursors (cy/pre) (17:0 cyclo + 19:0 cyclo/16:1ω7c + 18:1ω9c + 18:1ω7c) were calculated to determine the physiological state of the microbial communities (Willers et al. 2015). Table A 3 shows a summary of the microbial groups assigned for PLFA and NLFA biomarkers.

Soil arthropods

For soil fauna identification, two soil cores (12.0 cm depth × 10.0 cm width) were collected at each of the 48 sampling locations. Soil fauna were extracted from the soil samples ($V=1884.96cm^3$) using the standard Berlese-Tullgren extraction (1905) method after seven days. Specimens were identified by observing the head and mouth structures using a 10-40x magnification LEICA microscope and counted. Whiting's (2017) key to common insect order, together with primary literature, were used to aid in classification to order or family level.

The abundance of soil arthropods were expressed as the number of individuals per square meter. The relative abundance of the soil arthropod categories were calculated by dividing the number of individuals within each category by the total number of individuals across all categories.

Soil arthropod species diversity were calculated using the Shannon-Wiener diversity index (H'.):

$$H' = -\sum_{i=1}^{s}(Pi)(In\ Pi)$$

Where: H' is the diversity index.
Pi is the proportion of individual species.
S is the total number of species in the habitat and,
i is the proportion of S species (Begon et al., 2003)

2.2.3 Statistical Analysis

Shapiro-Wilk test was used to assess normality and Levene´s test for the homogeneity of variance among groups. If the distribution was not normal the natural logarithmic and root square transformations were used to ensure the normal or close to normal distribution.

Pairwise Pearson correlations were used to evaluate interlinkages between all determined soil physical, chemical, and biological variables.

Principal Components analysis (PCA) was conducted to summarise relationships among indicators, using Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Barlett's test of significance to confirm suitability.

Redundancy analysis (RDA) was used to examine coupled changes in soil physico-chemical properties and the soil community, with Monte Carlo Permutation test applied to evaluate significance (Pseudo-F statistic value).

For physico-chemical indicators, Mixed Effects Model (ANOVA) was used to investigate fixed and random controls on variability. Fixed effects were management type (leaf litter or no leaf litter), park site (Cannon Hill or Kew Garden), sampling orientation (north or south), and sampling position (inner or outer canopy). Random effects were sampling year (2018 or 2019), season (spring, summer, or autumn), and event number (1-17). Table A 2 in Appendix shows the list, type, and description of the predictor variables investigated.

For biological indicators, General linear model (ANOVA) was used to analyse variance with management type, park site, sampling orientation and sampling position as fixed factors. Principal Components Analysis (PCA) and RDA were used to summarize relationships among overall PLFA community composition, as well as relationships among soil arthropods groups.

All statistical analyses were conducted using Minitab for Windows 10 software or IBM SPSS Statistics 27 with a value of at least $\alpha \leq 0.05$ p for all significance tests.

2.3. Results

2.3.1 Effect of litter removal on soil physico-chemical indicators

Leaf litter management significantly affected all soil physico-chemical variables and explained most variance with the highest F-value in ANOVA, except soil carbon storage (Mg C ha^{-1}), which showed no significant differences (Table 2.1). Soil textural class was different between managed and unmanaged park areas. Most soils in managed park areas were categorized as "sand loams," in comparison to unmanaged sites, where soils were primarily "silt loams." Park site only had an effect on soil pH. Soil pH was influenced by all fixed effects, but leaf litter management had the greatest effect. Sampling orientation influenced soil pH and the amount of nitrogen found in the soil. Sampling position influenced the soil organic carbon (SOC) and soil pH. Random effects had little impact on soil indicators, excluding sampling event which affected soil pH.

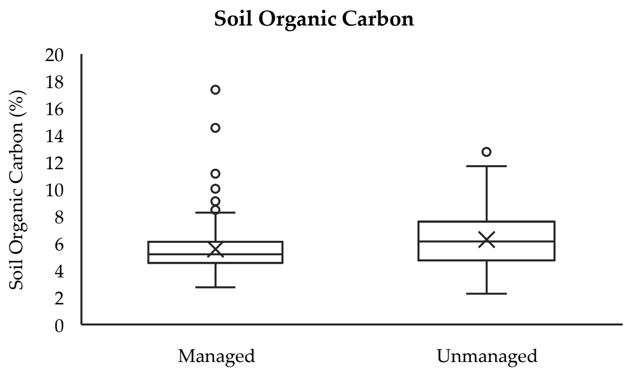
Table 2.1. Mixed Effects Model (ANOVA) investigating fixed and random controls on the variability of physical and chemical soil indicators. Bold values denote statistical significance of fixed effects (F- value) and random effects (Z- value) with thresholds for P- values 0.05, 0.01, and 0.001 summarised with asterisks *, **, *** respectively.

	Soil physico-chemical indicators						
Variables	SOC (%)	Soil C storage	Soil Compressive	Bulk density (g m−3)	Hydraulic conductivi	Soil pH	N%

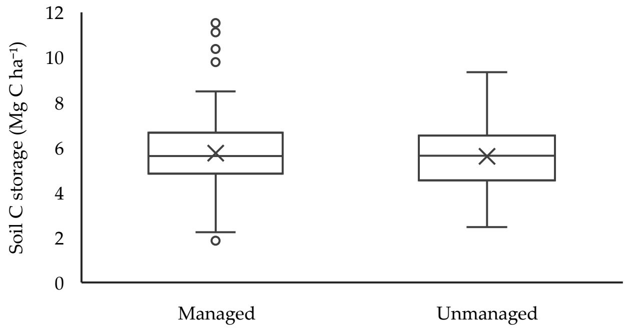
		(Mg C ha⁻¹)	Strength (kg/cm²)		ty K (cm/h)		
	Fixed effects (F- value)						
Management	**24.94*** **	0.89	**55.28*** **	**38.04*** **	**9.75** **	**213.91*** **	**18.07*** **
Site	0.07	1.99	3.07	0.10	0.00	**11.06** **	0.04
Sampling orientation	1.56	1.15	0.13	2.42	0.11	**6.37***	**6.85***
Sampling position	**12.32*** **	1.35	2.60	2.54	0.21	**8.38** **	1.48
	Random effects (Z- value)						
Sampling year	0.006	0.06	-	0.578	0.097	-	-
Season	0.629	-	-	0.471	0.274	0.523	-
Sampling event	0.556	1.23	1.123	1.372	1.391	**13.077*** **	-

Boxplots in Fig. 2.1 illustrate that, compared to managed areas where leaf litter was removed, average soil carbon content was significantly ($p<0.001$) higher in unmanaged areas ($TC_{unmanaged}$ = 6.3% vs. $TC_{managed}$ = 5.6%). Similarly, total N (0.46% vs. 0.33%) hydraulic conductivity (4.57 cm/h vs. 2.44 cm/h) and pH (pH 6.78 vs. pH 5.87) were all greater in unmanaged areas ($p<0.002$ in all cases). In contrast, bulk density and compressive loads were significantly higher in managed areas, with average values of 1.05 >0.92 g m^{-3} ($p<0.001$) and 2.16 > 1.28 kg/cm² ($p<0.001$), respectively.

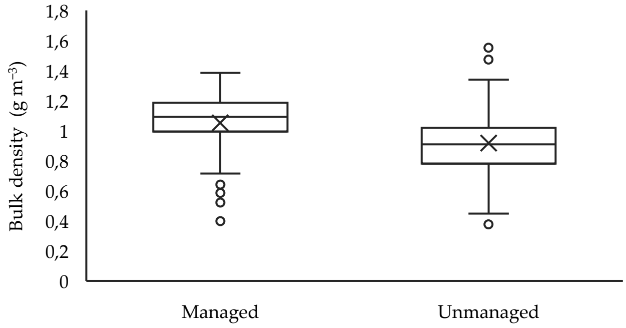
Data variation was high for all soil properties, with numerous outliers. Compressive strength values ranged from 0.4 to 4.5 kg/cm² for managed areas and 0.35 to 2.6 kg/cm² in unmanaged, and 4 outliers reaching up to 4.5 kg/cm². Soil pH ranged in managed park areas from 4.48 to 6.92 and in unmanaged park areas from 5.15 to 8.29.



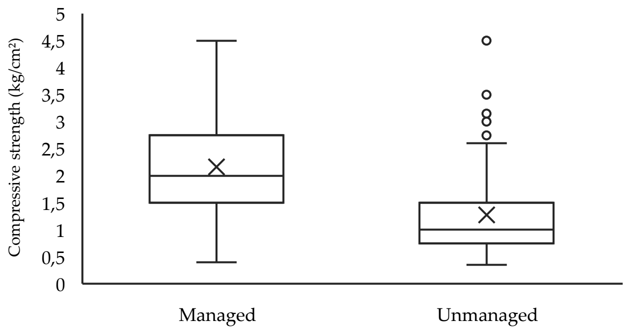
Soil C storage



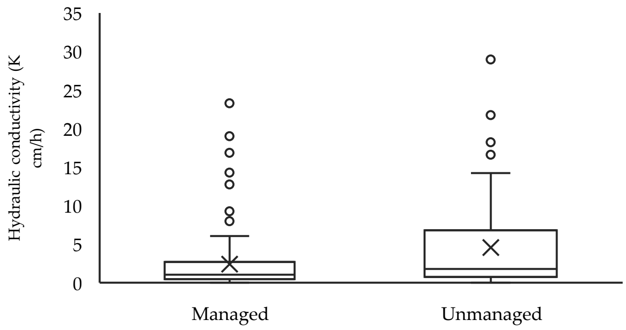
Bulk density



Compressive strength



Soil water flow



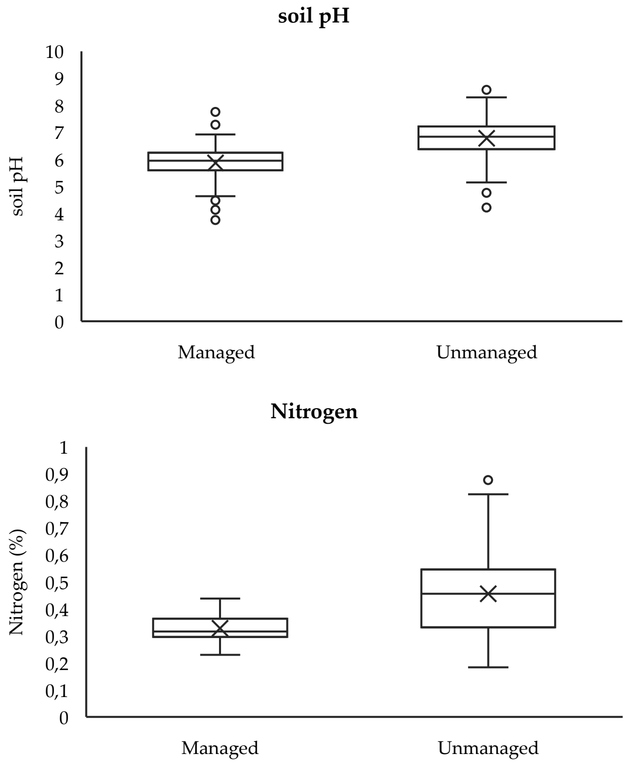


Fig. 2.1. Boxplots soil organic carbon, soil C storage, bulk density, compressive strength, hydraulic conductivity, soil pH, and nitrogen for managed and unmanaged park areas. Mean (X), median (Line through the box), edges of box denote interquartile range, and hollow circle (○) denote outliers.

2.3.2 Effect of litter removal on soil biological indicators

Table 2.2 shows that leaf litter management significantly influenced Fungal biomass and ratios for Bacteria G+/G- and cyclopropyl/monenoic precursors. There were significantly higher cy/pre ratio (0.386 > 0.258, P= 0.028) and bacterial G+/G- ratio (0.576 > 0.516, P= 0.007) in managed park areas.

However, park site explained most of the variation of soil biological indicators, indicated with the highest F-value, except for bacterial G+/G- ratio, and total soil arthropod abundance which were not affected by park site or any other of the investigated fixed controls. Nonetheless, park site significantly affected soil arthropod diversity, with a higher species richness found in Cannon Hill Park (1.25 > 0.78, P= > 0.001). Cannon Hill also had a significantly higher bacterial and fungal biomass than Kew Garden; mean 8.2 > 6.7 nmol g^{-1} of dry soil and 2.5 >1.6 nmol g^{-1} of dry soil, respectively.

Sampling position affected Bacteria G+/G- ratio and total PLFA biomass, including both bacterial and fungal biomass. Sampling orientation did not influence any soil biological indicator.

Table 2.2. General linear model (ANOVA) investigating fixed controls on the variability of biological soil properties. Bold F- values denote statistical significance of fixed effects with thresholds for P- values 0.05, 0.01, and 0.001 summarised with asterisks *, **, *** respectively.

Soil biological indicators								
Variables	PLFA biomass (nmol g-1 of dry soil)	Bacterial biomass (nmol g-1 of dry soil)	Fungal biomass (nmol g-1 of dry soil)	Fungal: bacterial PLFA (mol%)	Bacterial G+/G- PLFA (mol%)	Cyclopropyl /monoenoic precursors (mol%)	Arthropod abundance (m^2)	Arthropod diversity (H)
Fixed effects (F- value)								
Management	0.908	3.034	4.25*	1.692	**8.242****	**5.278***	0.686	2.538
Park site	**19.194*****	**10.642****	**53.59*****	**31.25*****	0.024	**7.541***	0.549	**22.284**
Sampling orientation	0.034	0.236	0.864	0.906	1.457	1.042	0.172	0.459
Sampling position	**8.938****	**7.709****	**9.29****	0.206	**3.962***	1.229	0.760	0.400

The effects of park site, management, sampling orientation and sampling position on the relative abundance (mol%) of different microbial groups are depicted in Fig. 2.2. Box plots illustrate that leaf litter management affected the relative abundance of Bacterial and Fungal PLFAs. Unmanaged sites had significantly higher G- bacteria in comparison to managed sites 36.7 > 33.7 mol % (P = < 0.001) which were characterized by a higher abundance of saprophytic fungi 18.6 > 15.3 mol% (P = < 0.001) and general bacterial markers 16.6 > 15.6 mol% (P = 0.01). Park site also affected microbial communities. There was a higher relative abundance of G+ and G- bacteria in Kew Gardens in comparison to Cannon Hill Park, 19.8 > 18.4 mol % (P = < 0.001) and 36.6 > 34.1 mol % (P = 0.002), respectively. Instead, Cannon Hill had a significantly higher abundance of saprophytic and arbuscular fungi, 18.6 > 15.3 mol % (P = < 0.001) and 19.6 > 12.2 mol% (P = 0.003).

Sampling position only affected G+ bacteria, with a significantly higher abundance in sampling points located in the inner tree canopy in comparison to the outer canopy, 35.8 > 34.9 mol% (P = 0.024).

Sampling orientation also had a strong effect on G+ bacteria and saprophytic fungi, with the south sampling orientation having a significantly higher abundance of G+ bacteria 19.6 > 18.6 mol% (P = 0.07) and lower abundance of saprophytic fungi 16.3 < 17.5 mol% (P = 0.048).

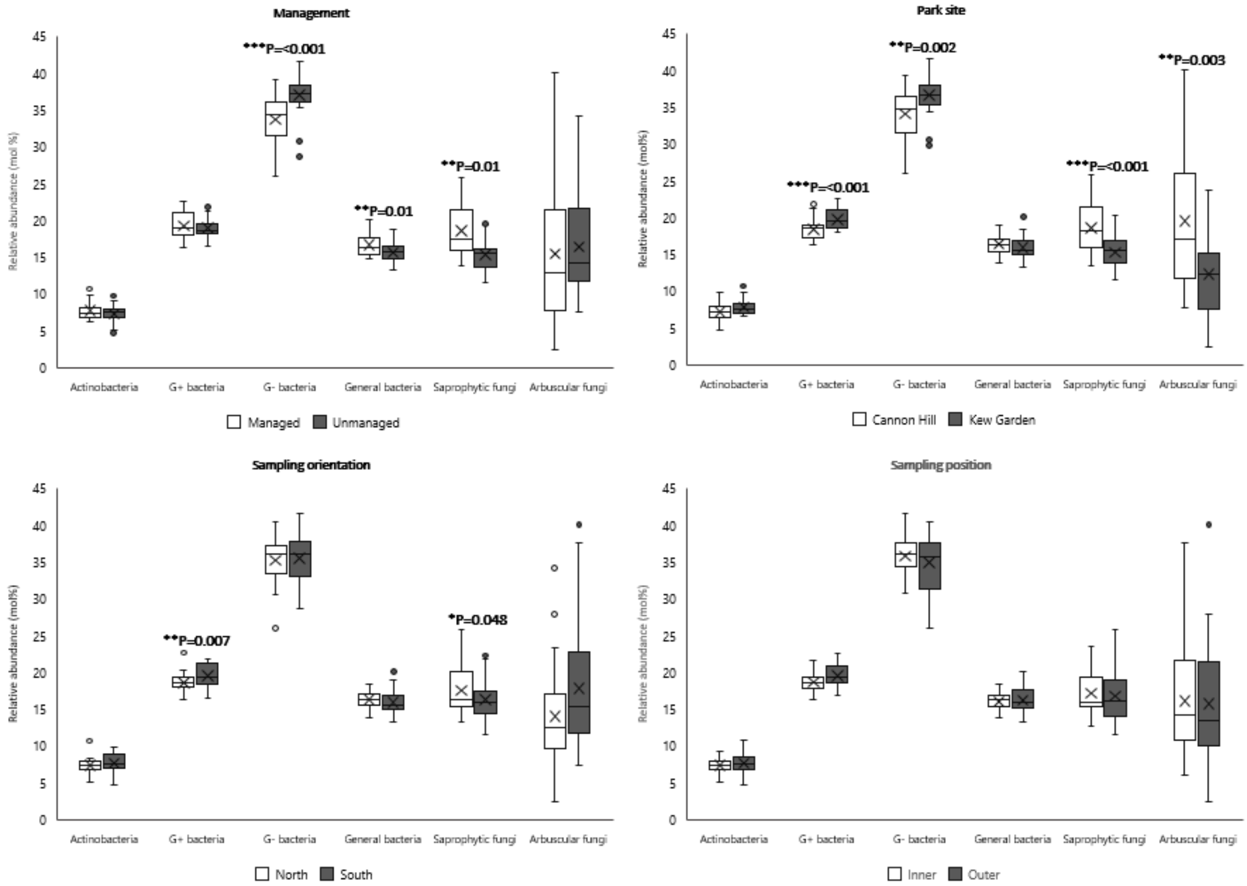


Fig. 2.2. Relative abundance (mol%) of bacterial and fungal groups by treatment, a) management, b) park site, c) sampling orientation and d) sampling position. Mean (X), median (Line through the box), edges of box denote interquartile range, and hollow circle (○) denote outliers. *, **, *** Thresholds for P- values 0.05, 0.01, and 0.001 respectively.

PCA results using mol% of total PLFA data shown in fig. 2.3a indicates 73.4% of the variation in the PLFA community data was explained by component 1 (PC 1) and 2 (PC 2) (KMO =0.496; Barlett's test = < 0.001). PC 1 explained 41.3% of the total variation and PC 2, 32.1%. PC 1 was predominantly affected by Actinobacteria and F/B ratio, whereas PC 2 was driven by Gram negative bacteria. The distributions of samples showed two separate clusters between both management type and park sites. Unmanaged sites were characterized by a large Gram-negative bacteria density, whereas managed sites were associated with higher fungal biomass and general bacterial markers. Cannon Hill Park site had a greater bacterial and fungal biomass overall in comparison to Kew Garden.

Redundancy analysis in fig. 2.3b reveals that the variations in soil microbial PLFA composition were strongly related to soil physico-chemical properties (Pseudo F= 0.525, p value= <0.0001), particularly soil pH, accounting for 8.9% of the variation, followed by compressive strength and soil nitrogen accounting for 6.5% and 4.6% of the variation, respectively. In total, soil physico-chemical properties explain 27 % of the variance.

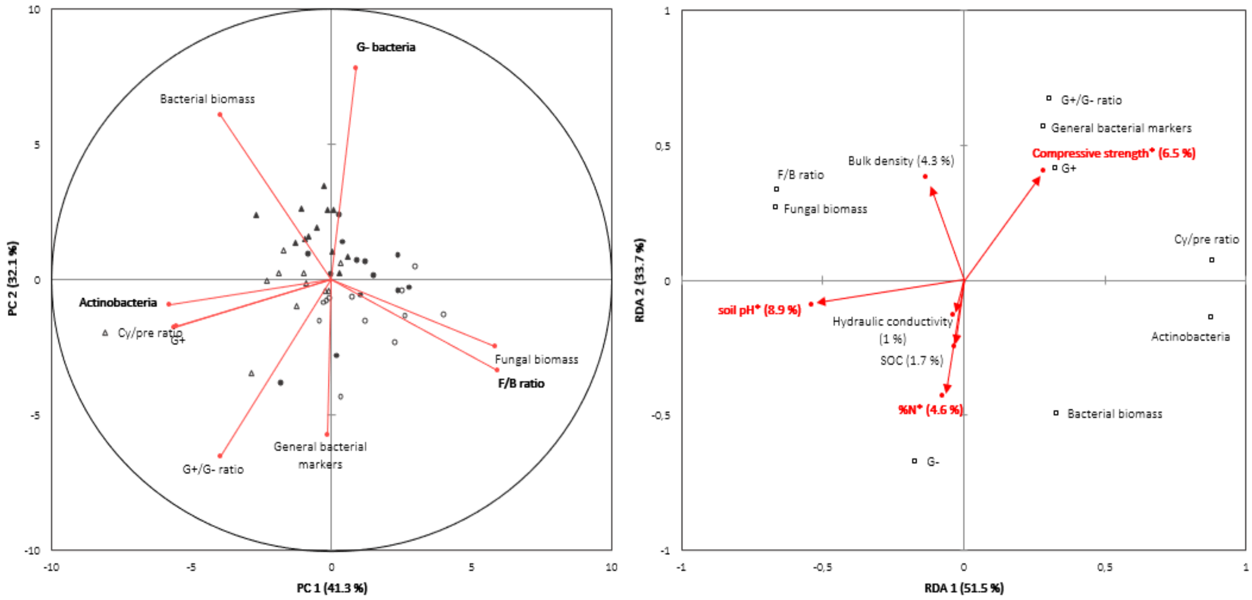


Fig. 2.3 (a-b). Biplots of (a) Principal Component Analysis (PCA) results using PLFA microbial groups. Red lines and circles represent microbial groups and significant predictors in bold. Sampling locations are represented by circles for Cannon Hill and triangles for Kew Garden, in black for unmanaged and white for managed areas, (b) Redundancy analysis of the relationship among soil physico-chemical properties and soil microbial community. Red arrows and circles represent soil properties. "*" denotes the significant predictors of variation with % variation explained in parenthesis.

Figure 2.4 illustrates the abundance and diversity of soil arthropods identified from Berlese-Tullgren extraction. Acari were the most abundant taxa, followed by Collembola. Acari make up ~ 39 % of the soil arthropods identified with approximately 533 individuals per meter squared, whereas Collembola accounted for ~ 22 % with around 275 individuals per meter square. The least abundant taxa identified were Diplopoda and Isopoda, representing less than 3 % of the population density, with approximately 24 and 18 individuals per square meter, respectively. Whilst total abundance of soil arthropods was not influenced by park site, management, sampling orientation or position (Table 2.2), certain taxa were affected by leaf litter management and park site (Fig. 2.4). For example, leaf litter removal in managed areas resulted in a significant decline in the abundance of Coleoptera species and Cannon Hill Park had a greater abundance of Symphyla (Fig. 2.4). Figure 2.4 also shows that diversity of soil arthropods was dependent on park site, with a greater diversity found in Cannon Hill in comparison to Kew Garden (1.25 > 0.90 H', $P = <0.001$). For example, Enchytraeied species were only found in Cannon Hill Park. Soil arthropod diversity was not affected by management of leaf litter, sampling orientation, or position.

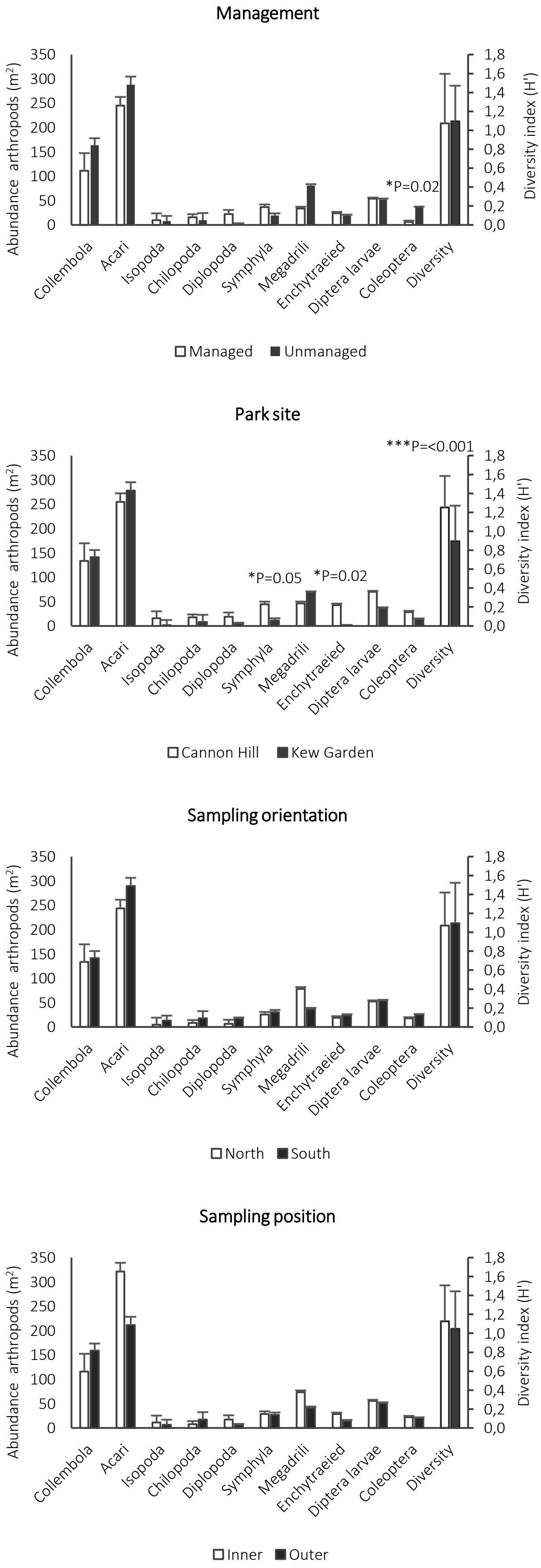


Fig. 2.4. Effect of (a) management, (b) park site, (c) sampling orientation and (d) sampling position on soil arthropod abundance and diversity (H'). Bars represent mean and error bar indicates standard deviation (n = 48). *, **, *** Thresholds for P- values 0.05, 0.01, and 0.001 respectively.

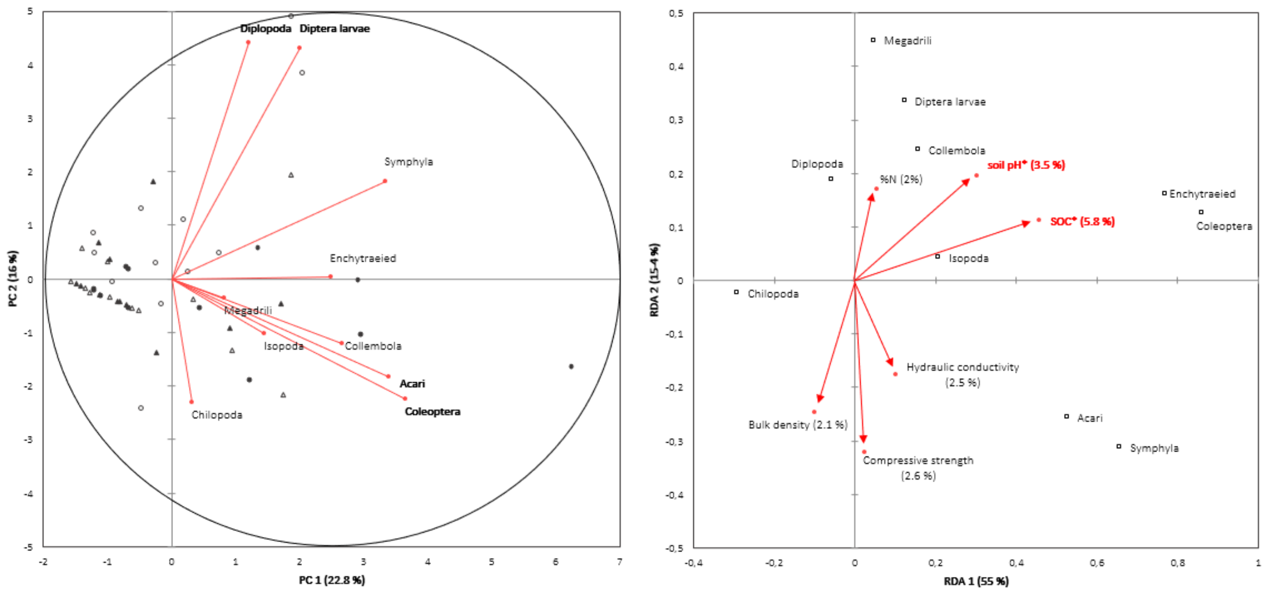


Fig. 2.5 (a-b). Results for (a) Biplot Principal components analysis (PCA) for soil arthropod abundance. Red circles and lines represent soil arthropods. Sampling locations are represented by circles for Cannon Hill and triangles for Kew Garden, in black for unmanaged and hollow for managed areas, (b) Triplot Redundancy analysis for coupled changes for physico-chemical properties and abundance of soil arthropods. Red arrows and circles represent the soil properties. "*" denotes the significant predictors of variation with % variation explained in parenthesis.

In fig. 2.5a, PCA results of soil arthropod communities show 38.8 % of the variation can be attributed to component 1 (PC 1) and 2 (PC 2) (KMO = 0.560; Barlett's test = 0.006). PC 1 explained 22.8 % of the total variation and PC 2, 16 %. The primary drivers of PC 1 were abundance of Coleoptera and Acari, whereas PC 2 was driven by Diplopoda and Diptera larvae. The distribution of samples cannot be clearly grouped into clusters by management type or park site location.

Redundancy analysis in fig. 2.5b reveal that the abundance of soil arthropods was correlated to soil physico-chemical properties, in particular, soil organic carbon (SOC) (5.8%) and soil pH (3.5%) were the strongest drivers. In total, 18.5% of the variation in soil arthropod abundance can be attributed to soil physico-chemical properties (F= 0.378; P-value= 0.018).

2.3.3 Interlinkages between physical, chemical, and biological indicators

In Table 2.3, a Pairwise Pearson correlation (2-tailed) between physical, chemical, and biological soil properties demonstrates most relationships were statistically significant. Soil compressive strength was correlated to all other indicators except for soil arthropod abundance or diversity, and F/B ratio. Soil carbon was associated to all indicators excluding soil pH and ratios for F/B, G+/G- bacteria, and cy/pre ratio. Abundance of soil arthropods was only influenced by the amount of carbon in the soil, whereas diversity was influenced by SOC, bulk density, soil pH, and microbial biomass. Microbial biomass was strongly affected by the amount of carbon found in soil and how compacted it was. Ratios for F/B and cy/pre precursors were predominantly affected by soil pH, whereas the ratio G+/G- bacteria by soil compressive loads. The strongest correlations were between SOC and bulk density, and nitrogen and soil compressive strength.

Table 2.3. Pearson correlation coefficients of the relationships between soil properties.

	SOC (%)	*Bulk density (g m^{-3})*	*Soil Compressive Strength (kg/cm²)*	*Hydraulic conductivity K (cm/h)*	*Soil pH*	*N (%)*	*Soil arthropod abundance (m²)*	*Soil arthropod diversity (H´)*	*Microbial biomass (nmol g^{-1})*	*F/B ratio*	*G+/G- ratio*	*Cy/pre ratio*
SOC (%)	1											
Bulk density (g m^{-3})	**- 0.752*****	1										
Compressive Strength (kg/cm²)	**- 0.517*****	**0.633*****	1									
Hydraulic conductivity K (cm/h)	**0.393****	**-0.394*****	**- 0.399****	1								
Soil pH	0.156	-0.036	**- 0.451*****	**0.405****	1							
N (%)	**0.451*****	**-0.570*****	**- 0.680*****	0.229	0.239	1						
Soil arthropod abundance (m²)	**0.409****	- 0.220	- 0.169	0.195	0.239	0.194	1					
Soil arthropod diversity (H´)	**0.305***	**-0.278***	-0.184	0.004	**0.275***	0.079	**-0.491*****	1				
Microbial biomass (nmol g^{-1} of dry soil)	**0.526*****	**- 0.364****	**- 0.303***	0.133	0.141	0.164	0.244	**0.363****	1			
F/B ratio	-0.069	0.251	-0.043	-0.046	**0.313****	-0.197	0.071	**0.296***	0.183	1		
G+/G- ratio	-0.179	**0.287***	**0.551*****	-0.066	-0.251	**-0.473*****	0.032	-0.005	-0.227	-0.134	1	
Cy/pre ratio	-0.056	-0.066	**0.304***	-0.149	**-0.592*****	-0.130	0.022	-0.266	**-0.354****	**-0.429****	**0.474*****	1

*Pearson correlation coefficient between selected soil properties (n= 48). *, **, *** Thresholds for P- values 0.05, 0.01, and 0.001 respectively. C = carbon; N = nitrogen.*

PCA results for all physical, chemical, and biological indicators shown in fig. 2.6a indicates 51.1% of the variation was explained by component 1 (PC 1) and 2 (PC 2) (KMO =0.702; Barlett's test = < 0.001). PC 1 was governed by compressive strength and SOC, whereas PC 2 by cy/pre and F/B ratio, accounting for 33.7% and 17.4% of the variation, respectively. The distributions of samples showed two separate clusters between managed and unmanaged areas. Managed sites were characterised by higher compressive strength, bulk density, G+/G- and cy/pre ratio, whereas unmanaged sites were associated with higher soil organic carbon, pH, F/B ratio and nitrogen in the soil.

Redundancy analysis in Fig. 2.6b reveal that the variations in soil community were strongly related to soil physico-chemical properties (Pseudo F= 0.557, p value= <0.0001), particularly soil pH, accounting for 7.7% of the variation, and SOC and compressive strength, accounting for 6.4% each. In total, RDA results show that soil properties explained 30.3% of the variation in soil community.

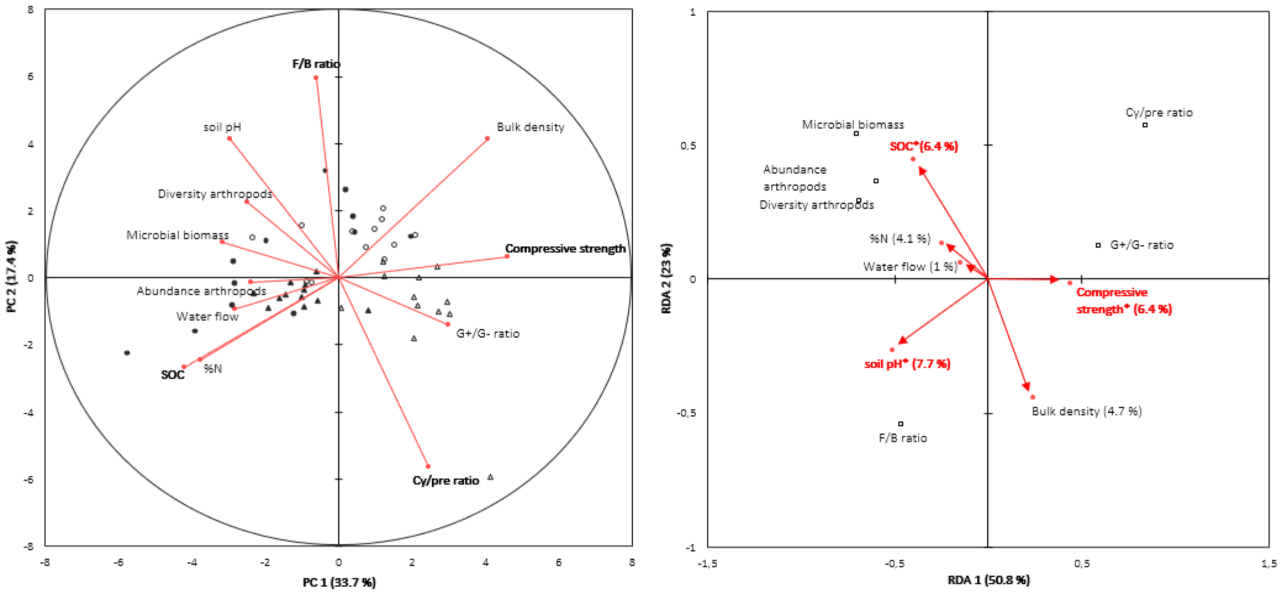


Fig. 2.6 (a-b). Results for (a) Biplot Principal components analysis (PCA) for all soil properties. Red circles and lines represent soil physical, chemical, and biological indicators. Sampling locations are represented by circles for Cannon Hill and triangles for Kew Garden, in black for unmanaged park areas and hollow for managed areas, (b) Triplot Redundancy analysis for coupled changes for soil physico-chemical properties and the soil biological indicators. Red arrows and circles represent the soil physico-chemical properties. "*" denotes the significant predictors of variation with % variation explained in parenthesis.

2.4. Discussion

We examined the effects of the management of under-tree leaf and woody litter on key physical, chemical, and biological indicators of soil health in two parkland sites in the UK. We compared soil properties in 'managed' park areas, where leaf litter was removed, to 'unmanaged' areas, where leaf litter was left *in situ*. PCA results in Fig. 2.6a illustrate the differences in soil physico-chemical properties, showing two separate clusters between managed and unmanaged park areas. Managed sites, where leaf litter was cleared, had a higher bulk density, and compressive strength, whereas unmanaged sites were associated with more favourable soil conditions, with higher soil organic carbon, water flow, soil nitrogen, and a more neutral soil pH. Therefore, the periodic removal of leaf litter led to a decline in soil health, with a degradation in physical and chemical qualities of soil (Fig. 2.1).

2.4.1. The role of leaf litter in soil protection and water regulation

Fallen tree leaves accumulated on the soil surface, forming a plant litter layer beneath the study trees in unmanaged park areas. The soil cover (also known as mulch) acts as a protective layer that maintains soil´s physical functions including, soil water retention, buffering against temperature extremes, and compaction (Eckstein and Donath, 2005; Davidson and Janssens, 2006; Adekalu et al. 2007). Our results indicate that the litterfall soil cover in unmanaged park sites reduced evaporation and surface runoff, and increased water infiltration into the soil, seen with higher hydraulic conductivities in unmanaged park areas (Fig. 2.1). Hydraulic conductivity of a soil is a measure of the soil's ability to transmit water and one of the most important soil properties controlling water infiltration and surface runoff (METER group, n.d). The steady state infiltration rate is approximately equal to the hydraulic conductivity (Zhang, 1997). In the long term, reduced water infiltration rates can increase the risk of flooding and droughts (Adekalu et al. 2007).

Soil water infiltration is closely related to soil compaction (Pitt et al., 2008; Yang and Zhang, 2011; Elliot et al., 2018). Soil compaction occurs when soil particles are pressed together, reducing macropore space within a soil. A high soil compaction can inhibit the rate of water infiltration and aeration, hinder root growth, result in loss of habitat and pore spaces for soil organisms thus affecting activity, nutrient cycling, plant productivity and ultimately, soil health (University of Minnesota, 2018; USDA 2020; FAO et al. 2020). Furthermore, once soil is compacted, it can take decades for the soil to recover (Etana et al. 2013) and it often results in increased surface runoff, soil erosion, nutrient leaching, and greenhouse gas emission (Powers et al., 2005). Our findings show managed park areas had a more compact soil, but on average, would classify as "good," undisturbed soils (McKenzie et al., 2004; Mukhopadhyay et al. 2019) and indicative of favourable soil structure, with aggregates and adequate pore space.

2.4.2 SOC formation from litter and relationships with soil functions

Our results showed that SOC was significantly higher in unmanaged soils. This difference likely arises from the slow decomposition of the plant litter layer by soil organisms, together with contributions from other “dead,” “decaying” and “living” organic materials, which together build soil organic matter (SOM) and component SOC and nutrients, such as nitrogen (N).

SOM is key to soil stability, as it is the main constituent that helps bind mineral particles into larger-sized aggregates. The organisation of soil particles is referred to as soil structure, and the number and size of micro and macro pores within it dictates how readily water, air, and roots can move through it (Dexter, 2004). In fact, SOC is suggested to be the single most important indicator for determining soil health as it is tied to all soil functions such as, soil aggregation and aeration, water retention, aeration, soil biodiversity, buffering capacity and the cycling and storage of plant nutrients (Krishna and Mohan 2007; Lehman et al., 2015; Obalum et al. 2017; Giweta 2020). Attesting to this, our findings show that all other soil physico-chemical properties were negatively affected by the lower SOC content found in managed park areas as a consequence of leaf litter removal (Table 2.3) and RDA analysis revealed that SOC was one of the strongest determinants affecting the soil community (Fig. 2.6b).

The decay of plant litter not only supplies soil with organic carbon material, but it is also the dominant pathway for nutrient return to the soil (Krishna and Mohan, 2007; Chang et al. 2007). For example, leaf litter chemical properties have high concentrations of nitrogen (N) (Tóth et al. 2011), which is an essential nutrient for soil health and tree growth (Krishna and Mohan, 2007; Chang et al. 2007). Soil N is mainly formed through the partial decomposition and transformation of plant residues (Yang et al. 2019). Thus, the reduced litter input in managed park areas resulted in significantly lower soil N (Fig. 2.1). The long-term removal of plant litter may result in lower N availability, which in turn could lead to soil degradation, and tree growth decline.

Leaf litter also has high concentrations of cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), thus a restricted input limits the ability to counteract the acidifying effect of acidic intermediates and humus compounds (Tóth et al. 2011). Thus, the moderate soil acidity in managed park areas could also be attributed to a depleted buffering capacity from reduced leaf litter inputs (Tóth et al. 2011). Instead, decaying leaves in unmanaged park areas likely enhanced Mg^{2+} and Ca^{2} input, and improved buffering capacity, resulting in a higher, more neutral soil pH.

Soil pH is a key component of soil health because it affects soil chemical (e.g. availability and mobility of nutrients), biological (e.g. microbial activity) and physical properties (e.g. aggregation of clay minerals) (Krishna and Mohan, 2017; Wei et al. 2020). For example, soil acidity may increase the solubility and accumulation of certain heavy metals which could be toxic such as Al, Fe, Mn, Cu and Zn (USDA, 1998). Therefore, a more neutral soil pH in unmanaged sites was considered more favourable.

Soil pH is intrinsically linked to soil texture, as it plays a critical role in the soil acid-buffering capacity (Wei et al. 2020). Soil textural class is an inherent property of a soil which does not change significantly with different management practices. A higher percentage of clay (and organic matter) is associated with soils with a high pH because they have a greater number of surface sites able to hold hydrogen ions that can resist a decrease in pH. In contrast, sandy soils tend to be more acidic because water percolates rapidly and they have a reduced buffering capacity due to low clay and organic matter contents (Wei et al. 2020). Consistently, using the TA method we found that soils in managed park areas which were predominantly characterized as "sandy loams" (with a higher percentage of sand) had a lower pH in comparison to unmanaged areas which were categorized as "silt loams," and had a higher pH (Fig. 2.1). In addition, Table 2.3 demonstrates there was a strong positive correlation between soil pH and amount of clay and a negative correlation with sand content.

2.4.3 Impacts of litter management on soil microbial and faunal communities

Our findings indicate that soil microbial and meso-/macro-bial communities were influenced by litter management practices. These changes in soil biology were driven by alterations in soil conditions resulting from litter removal. Fig. 2.6b shows that soil pH was the most important driver of soil biology, followed by SOC, and compressive strength. In particular, soil pH shaped the soil microbial community, as it was the major determinant of fungal and bacterial composition and cy/pre ratio of PLFAs. There was a significantly greater bacterial density in unmanaged park areas which had a more neutral pH (Fig. 2.3a-b). Consistent with other studies (e.g. Ni et al. 2021, Zhao et al. 2014), we found bacterial taxa were more prominent at high, alkaline pH ranges in comparison to fungi, which increased in lower, more acidic soils. The cy/pre ratio of PLFAs was negatively correlated with soil pH, similar to the findings of Zhao et al. (2014), signalling stress conditions in more acidic soils. Therefore, the substantially higher cy/pre ratio in managed park areas were indicative of microbial physiological stress (e.g. nutrient stress) (Trögl et al. 2015). In addition, a more acidic soil in managed park areas may have had cascading effects on abiotic factors such as SOC and soil N availability by effects on decomposers and the decomposition of leaf litter, in addition to biotic factors like biomass composition of bacteria and fungi (Wheeler et al., 1991; Beales, 2004; Ni et al. 2021). Diversity of soil meso and macrofauna were also affected by soil pH (e.g. Collembola) (Fig. 2.5b) however, soil organic carbon (SOC) and compressive strength were the most important drivers shaping soil fauna presence (Table 2.3).

SOC and compressive strength were key determinants of soil biology, accounting for 6.4% of the variation each (Fig. 2.6b). Mostly, a higher SOC content was associated with greater abundance and diversity of soil meso and macrofauna. This is due to their involvement in soil organic matter degradation (Beck et al. 2003; Culliney et al. 2013; Bagyaraj et al. 2016; Ghiglieno et al. 2020). Consistently, unmanaged sites in Cannon Hill Park, which overall had the highest SOC content had a greater population density and richness (Fig. A 4). In total, we found Acari (mites) and Collembola (springtails) were the most abundant of the 10 taxa identified, representing approximately 39 % and 22 % of the species, respectively (Fig. A 5). Many studies have explored in depth the use of Acari and Collembola taxa to define soil quality (Menta and Remelli, 2020). The greater abundance of Acari compared to Collembola in park soils suggests good soil quality and habitat stability (Menta and Remelli, 2020). This is because Acari, like Oribatida mites, are K strategist which require a stable environment in comparison to Collembola which are generally r-strategist and recover more quickly from disturbances (Coleman and Crossley, 1996). Instead, the lower abundance of certain taxa, like Coleoptera in managed park areas, suggest they were affected by substrate availability changes from litterfall clearing (Fig. 2.5a). Some Coleoptera species are very sensitive to habitat modifications (Pearce and Venier, 2005; Menta and Remelli, 2020) thus, they can be used as indicators of soil ecological status (Parisi et al. 2005; Santorufo et al. 2012; Socarras, 2013). The greater number of individual specimens (e.g. Ground beetles) in unmanaged park areas depicts a less disturbed environment (Fig. A 4). The least frequent taxa identified were Diplopoda and Isopoda, representing approximately 1.5 % and 1.6 % of the species, respectively (Fig. A 5.). The low density of Isopoda species points to a disturbed environment as this taxon is highly sensitive to habitat stress (Fraj et al. 2010; Vignozzi et al. 2019; Menta and Remelli, 2020). Given that leaf litter is one of the main sources of energy for soil microbes (Sayer, 2006; Krishna and Mohan, 2017), the larger substrate availability in unmanaged sites also resulted in a greater microbial biomass in comparison to managed sites. Particularly, there was a substantial increase in abundance of specific taxa like Gram negative bacteria (Fig. 2.2) which tend to rely more on plant-derived C sources (Fanin et al. 2019; Perreira et al. 2021). Instead, Gram-positive bacteria (and fungi) belong to oligotrophic communities associated with low substrate habitats (Six et al. 2006; Strickland and Rousk 2010; Chapin et al. 2011; Fang et al. 2020). Consistently, in managed park areas where leaf litter was cleared, there was a shift from bacteria towards fungi which are less susceptible to substrate changes, and a larger Gram-positive bacteria population density (Table 2.2).

However, PCA analysis revealed that altogether, these urban park soils were dominated by bacteria, in contrast to forest or highly productive agricultural soils which tend to be fungal dominated (Malik et al. 2016). Fungal dominated soils are generally associated with enhanced organic C accumulation since Fungi have a higher C use efficiency than bacteria due to enhanced fungal mediated soil aggregation (Six et al. 2006; Strickland and Rousk 2010; Fang et al. 2020). Fungal biomass is also more complex and resistant to decomposition than bacterial biomass, introducing a more stable form of organic C in the soil (Jastrow et al. 2007; Clemmensen et al. 2013; Pereira, et al. 2021). This underlines that these park soils will potentially store less carbon and in a form that is more readily degradable, particularly in Kew Garden which has a significantly lower fungal biomass (Fig. 2.2). This may be a consequence of microbial degradation over time (Fanin et al. 2019; Pereira et al. 2021), highlighting the wider impacts on soil health and the ecosystem service of soil C storage (Pereira, et al. 2021). Similarly, Gram positive bacteria tend to use C sources derived from SOM that are more recalcitrant, linked to more complex SOC (Fanin et al. 2019; Perreira et al. 2021). Thus, the lower abundance of Gram-positive bacterial PLFAs in comparison to Gram-negative bacteria suggests that organic C in park soils is more readily degradable and less protected from decomposition (Fanin et al. 2019; Pereira et al. 2021).

Soil compressive strength was also a major determinant of the soil community (Fig. 2.6b). A high soil compaction, particularly in managed park areas, affected certain species of soil macro and mesofauna. Specifically, there was a decline in Chilopoda and Diplopoda species in highly compacted soils (Fig. 2.5b). This may be because these groups spend most of their life cycle underneath the soil and require the possibility of digging for shelter to avoid dehydration (Tulande et al. 2018). The soil microbial community was also negatively affected by soil compaction (Fig. 2.3b). RDA analysis revealed that higher soil compactness was strongly associated with a reduction in total microbial biomass, consistently with other studies (e.g. Weisskopf et al. 2010). The higher soil compactness was also strongly associated with a lower soil N, particularly in managed park areas. This fall in soil N can be attributed to the removal of litterfall in managed park areas and its effects on soil biota and their associated ecosystem functions. Soil compactness likely affected soil microbial metabolism, limiting aerobic processes, such as nitrification and mineralization (Li et al. 2004). Attesting to this, in managed park areas we identified a lower soil N and a substantially higher cy/pre ratio that are indicative of microbial physiological stress, usually attributed to nutrient stress (Trögl et al. 2015). However, not all microbial groups exhibited a negative response to soil compaction (da Silva et al. 2011, Xu et al. 2021). For example, soil compaction can increase the quantity of smaller soil pores providing more habitats for certain microbiota, while providing protection from larger predators (da Silva et al., 2011). Consistently, in our study we found that substantially larger Gram-positive bacteria were negatively affected by soil being compressed, while Gram negative bacteria which are generally smaller, benefited from the reduced pore size.

2.4.4 Capturing the complexity of urban soil heterogeneity

The use of a combination of soil physical, chemical, and biological indicators in our study allowed us to provide a more complete soil health assessment of urban park soils in comparison to traditional approaches of soil evaluation that are predominantly based on soil physico-chemical indicators alone (Parisi et al. 2005).

A healthy soil will have all key aspects (chemical, physical and biological) functioning well since all elements are interdependent. However, altogether, there was a high variability in soil physico-chemical properties across and between sites (Fig. 2.1), suggesting urban park soil is heterogeneous, both spatially and vertically, with patches of different types of soil in close proximity (Greinert, 2015).

This heterogeneity makes it is difficult to compare soil characteristics across urban landscapes (Pouyat et al. 2010; Davies et al., 2011). First of all, because there is a lack of soil data available in urban environments because they are presumed to be predominantly degraded (Pouyat et al. 2010; Davies et al., 2011). Secondly, the urban soil "mosaic" tends to be patchy and inconsistent (Pouyat et al. 2010). Soil characteristics can vary widely, not only in comparison to other systems (e.g. Agricultural, forests) but also within types of urban environments (e.g. Tree pits, gardens, parks), making it difficult to define soil attributes for a specific soil type (Scharenbroch et al. 2005; Pouyat et al. 2010; Rota et al. 2014). This is a problem because soil data from one park area does not necessarily translate to surrounding parks or urban environments.

The wide variation across soil properties in our study confirms the highly heterogeneous nature of urban soils, with patches of different types of soil in close proximity. For example, while most park areas were not compacted, according to Murdock et al. (1995) index of penetration resistance, compressive strength data ranged from little-no compaction to severely compacted for managed areas and little-no compaction to slightly compacted in unmanaged park areas.

Similarly, soil pH also varied widely and was almost site specific, ranging from acidic to neutral in managed park areas, and acidic to alkaline in unmanaged park areas (Fig. 2.1).

These wide fluctuation in values are common in urban environments where soil is affected by numerous anthropic activities in comparison to "undisturbed" forest soil (Jim, 1998; Mao et al. 2014; Greinert, 2015).

For example, soil compaction in these urban parks is likely influenced by human trampling from passing visitors and from heavy, garden machinery, particularly managed park areas which were highly transited. Instead, unmanaged park areas were more secluded from the main paths, or in the case of Kew Garden they were located within a conservation area that was restricted to the public. This coincides with other urban soil studies that show that increasing visitors' pressure can result in soil compaction, with increased bulk densities (Sarah and Zhevelev 2007). Likewise, this spatial variation of soil pH can be seen in other urban soil studies which emphasise that soil pH is very sensitive to human activities (e.g. Mao et al. 2014).

The spatio-temporal heterogeneity in the structure of soil communities was even larger in our findings. Beck et al. (2003) argues it is difficult to define typical soil communities for specific soils because they form site-specific assemblages. Consistently, despite both park sites having similar conditions including, soil type, climatic conditions, vegetation characteristics, and litterfall management practices, we found park site location was the most important determinant of soil community. Specifically, Cannon Hill Park had a significantly greater and more diverse soil community compared to Kew Garden (Fig. 2.4).

To capture the complexity of the urban "soil mosaic," additional research is required. For example, new investigations (e.g. Pariente et al. 2015) are subdividing urban landscapes into smaller fragments or "microenvironments," which differ in soil and vegetation characteristics, to take into account this variability, and permit valid comparisons.

2.4.5 Urban park soils as vital ecosystems: Soil health, biodiversity and carbon

This study contributes to a better understanding of the health of urban park environments. These parks have been either gardens, parks, meadows, or conservation areas for over 200 years (Birmingham City Council, n.d; Encyclopaedia Britannica, 2020) and in many ways, resemble natural forest environments. This is important because to date, soils in urban areas are associated with land degradation and their environmental functions are often ignored (Edmonson et al. 2012, 2014; Vasenev and Kuzyakov, 2018). However, we demonstrate that these park soils support an array of soil organisms and provide beneficial ecosystem services in our cities. For example, soils underneath urban tree environments were fertile, loam soils, with a mixture of clay, sand, and silt, favouring water retention and nutrient holding capacity (AHDB, 2023) favouring tree growth and reducing risk of flooding and droughts (Adekalu et al. 2007).

Soil organic carbon (SOC) values across the study sites were considerably higher than those typically reported for urban soils (Bradley et al. 2005). This is particularly noteworthy given that current UK carbon inventories assign either 0 t C ha-1 to urban soils or allocate only half the carbon density of the same soil series under pasture (Bradley et al. 2005). Similarly, in many other countries, urban soils are excluded from national carbon inventories altogether (Edmonson et al. 2012). In contrast, our results show a mean total soil carbon storage of 5.67 Mg C ha^{-1}, demonstrating the often-overlooked role of urban soils in carbon sequestration. This aligns with a growing body of evidence (e.g. Edmondson et al. 2012; Vodyanitskii et al. 2015; Vasenev and

Kuzyakov, 2018; Canedoli et al. 2020) suggesting that urban ecosystems —particularly long-established parks and gardens— may constitute a significant, yet under-recognised, urban carbon sink. Our findings also indicate that leaf litter removal can reduce the soil's capacity to store C, particularly in stable forms protected from decomposition. Management altered SOC% and surface organic matter dynamics, affecting microbial activity and soil health, with potential long-term implications for urban soil C storage and associated ecosystem services (e.g. Fanin et al. 2019; Pereira et al. 2021). Although total soil C stocks did not change significantly over the two-year study—likely reflecting the longer timescales over which soil C pools respond — these findings highlight how even short-term interventions can influence the quality, stability, and ecosystem function of soil C over time.

In addition, although urbanisation may have detrimental effects on many animal taxa, increasing evidence is showing that places like parks and gardens, can support a great array of soil organisms, as observed in our study and others (e.g. Rota et al. 2014; Mexia et al. 2017; Milano et al. 2017). Some studies are even finding that abundance of specific species is even greater than in their rural surroundings (e.g. Magura et al. 2010). In this way, green spaces in cities such as parks and gardens are of potential significance for the maintenance of biodiversity. Maintaining a high biodiversity in the soil community can make an ecosystem more resilient in the face of disturbance (Murphy et al. 2011; USDA, 2020). For this reason, it is important to understand how ecosystem modifications like removing leaf litter can threaten biodiversity and in turn, key ecosystem processes. We measured biodiversity by calculating the Shannon Weiner diversity index (H′) and found that there was no correlation with leaf litter management, but park site did influence species richness (Table 2.2). Cannon Hill park had a greater diversity (average-1.25 > 0.90 diversity index) of soil mesofauna in comparison to Kew Garden, specifically a larger number of Diptera larvae, and Enchytraeied species (potworms) which were only found in Cannon Hill Park. Our work demonstrates there is a relatively high diversity of soil fauna, similarly to other urban studies (e.g. Rota et al. 2014) with Shannon's index values between 1.1-1.6 in Italy. Rota et al.´s (2014) study discusses that the high species richness among patches in urban landscapes is known as "beta diversity" and it results from the variability of available habitats, resulting from the size, morphology, history, structure, and management of these urban landscapes.

However, it is important to be able to identify the number of species as well as to understand the specific role soil organisms play in the soil environment (Bot and Benites, 2005; Byrne, 2007; Murphy et al. 2011) since they affect soil processes in different ways (Bot and Benites, 2005; Byrne, 2007; Murphy et al. 2011). In addition, increasing evidence suggests that instead of investigating individual species in isolation, efforts to understand biological communities and how they are affected (and affect the environment) should focus on studying "arthropod-microorganisms associations" as an integrated unit, also known as "holobionts," since soil organisms are intimately linked across multiple scales in intricated trophic interactions (Schapheer et al. 2021; Olayemi et al., 2022). In our findings, strong associations between soil organisms were evident. Generally, we found a positive correlation between soil mesofauna involved in the physical fragmentation of plant-derived materials and microbiota involved in the second stage of litter decomposition. For example, between Diplopoda and Saprophytic fungi (Table A 4., Appendix). Diplopoda (millipedes) are detritivore invertebrates which aid in the incorporation of fragmented leaf litter into the soil. By reducing leaf litter and increasing the contact surface, Diplopoda facilitate further decomposition by Saprophytic fungi (da Silva et al., 2017). Interactions between these Diplopoda and microbiota increase soil aggregation, levels of nitrogen and labile phosphorus thus, in conjunction, they positively affect soil health (da Silva et al., 2017; Schapheer et al. 2021). We also found a strong, positive correlation between Saprophytic fungi and Enchytraeid worms (Table A 4, Appendix). This coincides with other studies (e.g. Rantalainen et al. 2004), which found that Enchytraeid worms aid the horizontal dispersion of soil fungi in soil. In fact, Rantalainen et al.´s (2004) study shows virtually no saprophytic fungi were able to disperse through the mineral soil matrix in the absence of both enchytraeid worms and corridors.

Yet, while we have examined effects of leaf litter management on several soil properties, there is still much to uncover, particularly impact on soil biological activity. So far, biological attributes are among the least monitored parameters at national levels in Europe (Nielsen and Winding, 2002) and suitable baselines are not yet available (Black et al. 2010). Soil-focused citizen science projects such as this one are still limited, but they have a huge potential to accelerate progress in soil health monitoring efforts. Citizen scientists can carry out soil measurements over a wider geographical region and at a higher frequency than would be available to research scientists alone and within the funding available (Bonney et al. 2009b; Dickinson et al. 2010; Gardiner et al. 2012; Pudifoot et al. 2021). In fact, citizen science methods can generate three to four times the number of samples generated by traditional research for the same cost and substantially increase the speed that the science outcomes are disseminated (Gardiner et al., 2012).

Our results show that using quick and easy-to-perform soil measurements (e.g. soil compaction, soil infiltration), citizen scientists have helped with large scale data collection to better understand the health of our urban environments. In fact, soil and tree measurements from this citizen science research project have been published in scientific journals, advancing the field of soil science (e.g. Pudifoot et al. 2021; Ferrando-Jorge et al. 2021; Cárdenas et al. 2021). At the same time, the involvement of the public in this type of projects can raise awareness on the importance of soils which, to date, receives limited attention among the general public (McBratney et al., 2014; Rossiter et al. 2015; Brevik et al. 2020). In addition, this project also promotes the value of green spaces in cities. While urban parks are obviously different environments than a natural forest, they can be managed and maintained to emulate the natural setting of a forest using sustainable management practices like not removing litterfall that defy traditional public notions and nuisance issues of leaf litter.

2.5. Conclusion

Altogether, our results indicate that removing litterfall deteriorated the health of urban park soils over the two-year period. Litterfall removal negatively affected soil physical, chemical, and biological functions, reducing soil health and its provision of ecosystem services. It limited the carbon and nitrogen return to the soil, led to a decreased soil water infiltration, and a more degraded, acidic, and compacted soil, in turn altering the soil community. Therefore, the presence of a plant litter layer is important for maintaining soil fertility under *Tilia* tree stands in urban parks.

Nevertheless, this research shows that despite urban landscapes being highly altered by human activities, park soils such as these can exhibit favourable soil properties and relatively high rates of biological activity and richness of species. With this capacity, urban park soils have the potential to provide various beneficial ecosystem services such as mitigation for flood risk, carbon storage, and biodiversity. Thus, together with increasing evidence, this study contributes to a better understanding of the unacknowledged potential of urban park soils and highlights the need to promote management practices (e.g. Not removing leaf litter) aimed at long-term improvement of soil health and related ecosystem services in cities.

However, although the combination of soil physical, chemical, and biological indicators in our study allowed us to provide a more complete soil health assessment of urban park soils, there is still much to uncover. Further research is required to better understand soil communities and how they are impacted by management practices such as litter removal, particularly effects on arthropod-microorganism associations and key ecological functions. There is also a need to establish thresholds and suitable baselines for biological indicators. In addition, more data-collection is required in urban environments to detect general trends that capture the complexity of the urban soil "mosaic."

Soil-focused citizen initiatives such as this one can help advance soil mapping and monitoring efforts, and at the same time, raise awareness on the importance of soil health and sustainable landscapes practices.

Chapter 3
Measuring Soil Colour to Estimate Soil Organic Carbon Using a Large-Scale Citizen Science-Based Approach

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Published in Sustainability 2021, 13(19), 11029; https://doi.org/10.3390/su131911029

Abstract

Rapid, low-cost methods for large-scale assessments of soil organic carbon (SOC) are essential for climate change mitigation.

Our work explores the potential for citizen scientists to gather soil colour data as a cost-effective proxy of SOC instead of conventional lab analyses. The research took place during a 2-year period using topsoil data gathered by citizen scientists and scientists from urban parks in the UK and France.

We evaluated the accuracy and consistency of colour identification by comparing "observed" Munsell soil colour estimates to "measured" colour derived from reflectance spectroscopy, and calibrated colour observations to ensure data robustness. Statistical relationships between carbon content obtained by loss on ignition (LOI) and (i) observed and (ii) measured soil colour were derived for SOC prediction using three colour components: hue, lightness, and chroma.

Results demonstrate that although the spectrophotometer offers higher precision, there was a correlation between observed and measured colour for both scientists ($R2 = 0.42$; $R2 = 0.26$) and citizen scientists ($R2 = 0.39$; $R2 = 0.19$) for lightness and chroma, respectively. Foremost, a slightly stronger relationship was found for predicted SOC using the spectrophotometer ($R2 = 0.69$), and citizen scientists produced comparable results ($R2 = 0.58$), highlighting the potential of a large-scale citizen-based approach for SOC monitoring.

Keywords: Munsell soil colour Charts; quantitative colour analysis; spectroscopy; CIELAB; soil carbon prediction; citizen scientists

3.1. Introduction

Soils are the second largest active pool of carbon after the oceans, and account for more than three times the amount of carbon stored in the atmosphere and terrestrial vegetation combined (Lefèvre et al. 2021). The carbon storage capacity of soils has been a subject of great interest in recent environmental literature, exemplified by an increasing number of publications in mapping soil carbon stocks (Scharlemann et al. 2014). Globally, it has caught the attention of a wide audience, including policymakers, NGOs, and land managers. This growing interest is mainly due to the realization of soils' key role as either a natural sink of carbon for climate change mitigation (Merrington et al. 2006; Kumar et al. 2016) or as a potentially large and uncertain source of CO_2 emissions (Zomer et al. 2017). Whether soils accumulate or lose carbon—and thus function as carbon sinks or sources—depends on several factors, such as the type of management practices, biomass input levels, and on climatic conditions (Zomer et al. 2017).

Globally, soils are thought to have lost between 50% to 70% of the carbon they once held (Lal, 2004). Nonetheless, our ability to monitor soil organic carbon (SOC) changes are still limited. Accurate baselines of soil carbon are missing for many countries. Where baseline data are present, reported values vary considerably among authors since there is no standardised approach for the measurement (Lefèvre et al. 2021, Wills et al. 2007; Liles et al. 2013; Smith et al. 2019). A wide range of data sources and methodologies are used, which has led to sources of error in SOC determination at the sample, profile, plot, and landscape scales (Angelopoulou et al. 2020; Vanguelova et al. 2016). Whilst conventional laboratory methods, such as loss on ignition (LOI) and elemental analysis, can quantify SOC precisely, they are inadequate for large-scale monitoring because they require direct measurements of many samples to capture the inherently dynamic nature of SOC, making them slow and expensive [Lefèvre et al. 2021, Wills et al. 2007; Liles et al. 2013; Smith et al. 2019; Angelopoulou et al. 2020; Vanguelova et al. 2016). Laboratory methods also require access to specific equipment, narrowing the scope of who can make these measurements and how many measurements can be made.

Hence, there is a need for methods that can rapidly, inexpensively, and relatively easily characterize SOC status for reliable monitoring and reporting (Lefèvre et al. 2021, Wills et al. 2007; Liles et al. 2013; Angelopoulou et al. 2020). This knowledge is crucial to understand where we should seek to preserve or increase SOC stocks to provide the best opportunities to mitigate and adapt to climate change (Lefèvre et al. 2021). This is particularly the case for cities, which are relatively understudied and are likely to become net sources of GHG emissions if not managed appropriately (Liles et al., 2013; Smith et al. 2019).

Soil colour determination could be a cost-effective and time-saving method for the spatio-temporal monitoring of SOC (Wills et al. 2007; Angelopoulou et al. 2020; Gholizadeh et al. 2020). Soil colour descriptions have long been used by soil scientists in the field to aid soil classification and mapping [Soil Survey Staff, 1999). Soils can exhibit a wide range of colour: grey, black, white, reds, browns, yellows, and greens (Brady and Weil, 2008). These colours result from the different processes and conditions that the soil is subjected to, the mineralogy of the soil, and the soil organic matter (SOM) content (USDA, 2020). Organic matter content is the most important pigment that influences soil colour (Aitkenhead et al. 2013), which is why there is a long history of relating soil colour darkness to SOM content (Wills et al. 2007; Brady et al. 2008; Torrent and Barrón, 1993; Konen and Sandor, 2003). In general, darker soil colours often indicate an increase in decomposed organic matter known as humus. These carbon-containing polymers absorb most visible wavelengths of light, giving soils rich in organic matter a dark brown, nearly black appearance (Vodyanitskii and Savichev, 2017).

Qualitative estimates of soil colour made using Munsell soil colour charts (1975) have been routinely made by pedologists in soil surveys for >60 years to describe the normal range of colours found in soils (Rabenhorst et al. 2015). This method involves the visual determination of colour by comparison with standard chips systematically arranged according to their Munsell notation. In this system, colour is characterized by three parameters: Hue, which refers to the dominant wavelength or basic colour; value, which represents the overall brightness or lightness; and chroma, which expresses the saturation or intensity of hue. For example, a brown soil may be noted as Hue Value/Chroma (10YR 5/2). The most recent edition of the Munsell soil colour chart (MSCC) consists of 443 colour chips, divided among 13 pages. This perceptual colour system was designed by artist Albert H. Munsell to allow for direct comparison of soils anywhere in the world for any observer with a normal colour vision, under controlled illumination conditions.

Hence, given the MSCC's ease of use and that capturing SOC status requires many observations spread over time and space, this method could be used in a large-scale citizen science-based approach to overcome some of the current limitations of conventional SOC analysis mentioned (Smith et al. 2019; Angelopoulou et al. 2020; Dickinson et al. 2010; Liu et al. 2017). The main challenge with the Munsell colour scheme is that several problems have been routinely mentioned in the literature with the consistency and accuracy in colour determination (Torrent and Barrón, 1993; Barret, 2002; Sánchez-Marañón et al. 1995; Sánchez-Marañón et al. 2005; Sánchez-Marañón et al. 2011; Marqués-Mateu et al. 2018). This is because the perception of colour attributes is affected by numerous psychophysical factors, such as environmental conditions (e.g., moisture content, illumination conditions) (Mouazen et al. 2007), sample characteristics (e.g., size, roughness), difficult statistical analysis (e.g., limited colour chips, cylindrical colour coordinates) (Kirillova et al. 2014), and the observer's sensitivities (e.g., colour blindness, subjectivity, poor colour memory, eye fatigue) (Torrent and Barrón, 1993; Sánchez-Marañon et al. 2011; Mouazen et al. 2007; Kirillova et al. 2014; Stiglitz, 2016; Post et al. 1993).

These shortcomings mean that soil scientists have generally used colour data descriptively despite its potential in the application of soil carbon determination [Gholizadeh et al. 2020; Soil Survey Staff, 1999; IUSS Working Group, 2006). Instead, the rapid development of modern technologies and instrumental methods, such as UV VIS spectrophotometry, allow a more precise and quantitative approach to colour quality control (Viscarra-Rossel et al. 2006; Aitkenhead et al. 2013; Bloch et al. 2021). They overcome some of the limitations of the Munsell method by removing the human 'judgement' from the analysis and using standard values, such as observer viewing angle and fixed lighting conditions to control the conditions of the measurement (Lal, 2004; Wills et al. 2007; Viscarra-Rossel et al. 2006; Rabenhorst et al. 2015; Warr, 2015; Turk and Young, 2020). For this reason, quantitative measures of colour (e.g., spectrophotometers) have seen apparent exponential growth worldwide and there are new applications of colour data in different fields (Viscarra-Rossel et al. 2006; Bloch et al. 2021).

However, despite the consensus that quantitative assessments of colour increase precision and that they are available, they have not been widely adopted by soil scientists for a variety of reasons, including costs, speed, lack of portability, familiarity with the Munsell method, and small-scale heterogeneity (Stiglitz, 2016). Consequently, field colour assessment using Munsell soil colour charts are likely to prevail as the standard practice, particularly in the Global South (Liles et al. 2013; Viscarra-Rossel et al. 2006; Torrent and Barrón, 1993; Rabenhorst et al. 2015; Post et al. 1993; Warr, 2015).

Thus, given that limited and controversial data exists regarding the uncertainty in colour determination using MSCCs, its prevalence in soil science, and the use of this data for important soil applications, our work evaluates the consistency and accuracy of colour observations collected by scientists and citizen scientists and explores its potential for reliable SOC prediction. The objectives were to (1) develop an objective, quantitative measure of soil colour using a spectrophotometer; (2) compare scientists' and citizen scientists' Munsell colour observations with spectrally derived colour, to validate the former; (3) calibrate colour observations using spectral readings for data robustness; (4) measure how well the colour dimensions (hue, lightness, and chroma) can be related to SOC obtained by laboratory analysis (viz. loss on ignition method) for reliable soil colour-SOC predictions.

3.2. Materials and methods

3.2.1. Study area and research design

Soil data were collected by citizen scientists during 28 organised events in Spring and Autumn 2018–2019 over 2 consecutive days. Citizen scientists attended a 1h training session led by professional scientists prior to the data collection to better understand urban soils and the methods used.

The study was conducted at three urban parks: Kew Gardens (London) and Cannon Hill Park (Birmingham) in the UK, and Les Fontaines Campus of Capgemini (Chantilly) in France. These areas experience similar climatic conditions (average annual temperature): 9, 11, and 11 °C and average annual precipitation: 641, 575, and 600 mm in Birmingham, London, and Chantilly, respectively (Climate Data, 2020).

At each site, there were 6 study trees, approximately 30 years old, of genus *Tilia* species (viz. Lime tree). For each tree studied, citizen scientists took a series of direct soil and tree measurements in the field and collected samples for analysis in the laboratory by scientists. Measurements and samples were collected below and outside of the canopy across a north-south transect. Trees were selected within each park to fall within one of three management categories to compare the effect of management in other related work. Management categories were managed, unmanaged, or street trees. Managed sites were defined as those where the majority of leaf and woody litter was cleared; unmanaged sites where debris was left in situ and had no human intervention; and street trees, those in tree pits where all debris and undergrowth vegetation was removed. The data collected by citizen scientists were part of a wider research campaign looking at soil and tree health in urban areas (Earthwatch Europe, 2023).

From the soil data available, we selected a subsample of topsoil (0–10 cm) Munsell soil colour data collected in the field by trained citizen scientists (n = 270 measurements) and paired readings of the same samples, which were carried out in the laboratory by scientists (n = 270 measurements). Additionally, spectrally derived colour assessments were selected from within that sub-set (n = 90 measurements). In total, for the 30 sampling locations, we analysed 540 soil colour observations collected by scientists and citizen scientists using the Munsell method, and 90 quantitative colour measurements derived from spectral data.

Soil samples were analysed for soil organic carbon (SOC) content using the percent weight loss on ignition technique, referred to as 'loss on ignition' (% LOI) (Dean, 1974). This is one of the most widely used methods for measuring the content of organic matter in soils [Dean, 1974; USDA, 2017). The content of organic carbon was calculated by multiplying the total C content by a factor of 1.724 (Nelson and Sommers, 1996). This conversion factor assumes organic matter contains 58% organic carbon.

The study was designed to test the reliability of the observed soil colour estimates taken by scientists and citizen scientists in comparison to soil colour measured using the spectroscopic method, and to explore the soil colour–SOC relationship for SOC prediction. For soil colour–SOC predictions, only data from UK sites were used for the analysis since these sites have a similar soil landscape, experience comparable environmental conditions, and undergo the same management practices. Table 3.1 shows a summary of the variables for the 30 sampling locations selected and soil measurements.

Table 3.1. Variables of the sampling locations and soil measurements.

Sampling Location						Number of Colour Measurements			
	Park Site	Land Management	Tree Number	Orientation	Canopy Position	Citizen Scientists	Scientists	Spectral	SOC by LOI (%)
1	Cannon Hill	Managed	1	North	Inner	8	8	3	7.1
2	Cannon Hill	Managed	1	South	Outer	8	8	3	5.8
3	Cannon Hill	Managed	2	North	Inner	8	8	3	7.5
4	Cannon Hill	Managed	2	South	Outer	8	8	3	6.4
5	Cannon Hill	Managed	3	North	Inner	8	8	3	5.8
6	Cannon Hill	Managed	3	South	Outer	8	8	3	5.8
7	Cannon Hill	Unmanaged	4	North	Inner	8	8	3	4.0
8	Cannon Hill	Unmanaged	4	South	Outer	8	8	3	3.7
9	Cannon Hill	Unmanaged	5	North	Inner	8	8	3	11.3
10	Cannon Hill	Unmanaged	5	South	Outer	8	8	3	6.1
11	Cannon Hill	Unmanaged	6	North	Inner	8	8	3	9.4
12	Cannon Hill	Unmanaged	6	South	Outer	8	8	3	9.3
13	Kew Garden	Managed	7	North	Inner	9	9	3	6.3
14	Kew Garden	Managed	7	South	Outer	9	9	3	5.1
15	Kew Garden	Managed	8	North	Inner	9	9	3	6.4
16	Kew Garden	Managed	8	South	Outer	9	9	3	7.0
17	Kew Garden	Managed	9	North	Inner	9	9	3	6.4
18	Kew Garden	Managed	9	South	Outer	9	9	3	4.7
19	Kew Garden	Unmanaged	10	North	Inner	9	9	3	7.4
20	Kew Garden	Unmanaged	10	South	Outer	9	9	3	8.4
21	Kew Garden	Unmanaged	11	North	Inner	9	9	3	7.9
22	Kew Garden	Unmanaged	11	South	Outer	9	9	3	6.4
23	Kew Garden	Unmanaged	12	North	Inner	9	9	3	8.3
24	Kew Garden	Unmanaged	12	South	Outer	9	9	3	7.5
25	Les Fontaines	Street tree	13	North	Inner	11	11	3	-
26	Les Fontaines	Street tree	14	North	Inner	11	11	3	-
27	Les Fontaines	Street tree	15	North	Inner	11	11	3	-
28	Les Fontaines	Managed	16	North	Inner	11	11	3	-
29	Les Fontaines	Managed	17	North	Inner	11	11	3	-
30	Les Fontaines	Managed	18	North	Inner	11	11	3	-

Managed, removal of leaf and woody litter; unmanaged, leaf and woody litter left in situ; street tree, in tree pits with all debris and undergrowth vegetation is cleared; SOC, Soil Organic Carbon; LOI, Loss on Ignition (%). SOC by LOI data not applicable for Les Fontaines site (-).

3.2.2. Visual determination of soil colour

Colour was visually determined by comparison of soil samples with the colour chips in the Munsell soil colour chart (MSCC) (Munsell, 1975). The Munsell soil colour system consists of approximately 250 coloured chips arranged on hue cards. On the Munsell colour chart, hue is denoted categorically by the letter abbreviation of the colour of the spectrum (R = red, YR = yellow-red, Y = yellow) followed by numbers from 0 to 10. Within each letter range, the hue becomes more yellow and less red as the numbers increase. Value and chroma are both denoted on a numerical scale. Value, or lightness, is on a scale from 0 (absolute black) to 10 (absolute white). Chroma, or saturation, is on a scale from 0 for neutral greys (the achromatic point) to a maximum value of 20. Each sample was assigned the nearest integer unit of hue, value, and chroma. All colours were estimated to the nearest whole chip. This colour notation will be referred to as “observed.”

Citizen Scientists

Soil colour was estimated in field visits by citizen scientists. Individuals were trained to visually identify and match colour at each of the sampling locations using a copy of the 7.5 YR extract of the Munsell soil colour book. The method was adapted by preselecting a single chart following preliminary work at the field sites to facilitate data collection for citizen scientists. To ensure consistency under varying field conditions, if the soil was dry and formed a ped, it was broken down, and water was added to slightly moisten samples before colour determination.

Scientists

In the laboratory, 3 scientists familiar with the Munsell method independently assessed soil colour for the same samples under controlled lighting conditions. Soil was sieved prior to the analysis to 2 mm following standard soil analysis procedures. Soil colour was determined for moist soil samples to be broadly consistent with conditions in the field. This is important because moisture content is one of the main factors that affect soil colour, making it appear darker than dry soil.

3.2.3. Determination of colour from spectroscopic analysis

After all visual analysis of colour was complete, we used spectral reflectance data to calculate the true or “measured” soil colour from the water-extractable carbon samples.

For each sample, soil was sieved (2 mm) and a soil solution was created using 45 mL of ultrapure water to extract 4.5 g of soil (ratio 1:10 soil to solution), shaken on an over-head shaker for 24 h, and filtered using first a Whatman GF/A filter paper and next through a 0.45 μm cellulose nitrate filter. The visible reflectance of the water-extractable carbon sample was measured between 390 and 700 nm at 2nm increments using a Jenway 7315 spectrophotometer in the laboratory. The illumination source was a xenon lamp, which is regarded as the universal reference illuminant and represents mean daylight (Illuminant D65, ~6504 K).

The differences in the relative reflectance across the spectrum were recorded and visualized as a curve. Following the three equations of Wyszecki and Stiles (1982), each spectral reflectance curve was converted into three figures or tristimulus values (RGB) that define the colour perceived as a numerical value (Wyszecki and Stiles, 1982):

$$R = \int_{390nm}^{700nm} S(\lambda) \cdot I(\lambda) \cdot \bar{r}(\lambda)$$

$$G = \int_{390nm}^{700nm} S(\lambda) \cdot I(\lambda) \cdot \bar{g}(\lambda)$$

$$B = \int_{390nm}^{700nm} S(\lambda) \cdot I(\lambda) \cdot \bar{b}(\lambda)$$

$S(\lambda)$ is the spectral reflectance; $I(\lambda)$ is the wavelength dependent power of the illuminant, and $r(\lambda)$, $g(\lambda)$, and $b(\lambda)$ are the colour matching functions.

The calculations were made with a 10 nm step and using Stiles and Burch (1958) RGB colour matching functions for the illuminant D65 and 10° standard observer (Stiles and Burch, 1958). The method used is similar in all respects to the procedure described in detail by Shields et al. (1968) and Fernández and Schulze (1987), except that we used water-extractable soil carbon solution (Shields et al. 1966; Fernández and Schulze, 1987).

Subsequently, we converted the RGB tristimulus values to the Munsell HVC system for comparison. Figure 3.1 shows a summary of the steps of transformation from the soil solution to the determination of the Munsell soil colour.

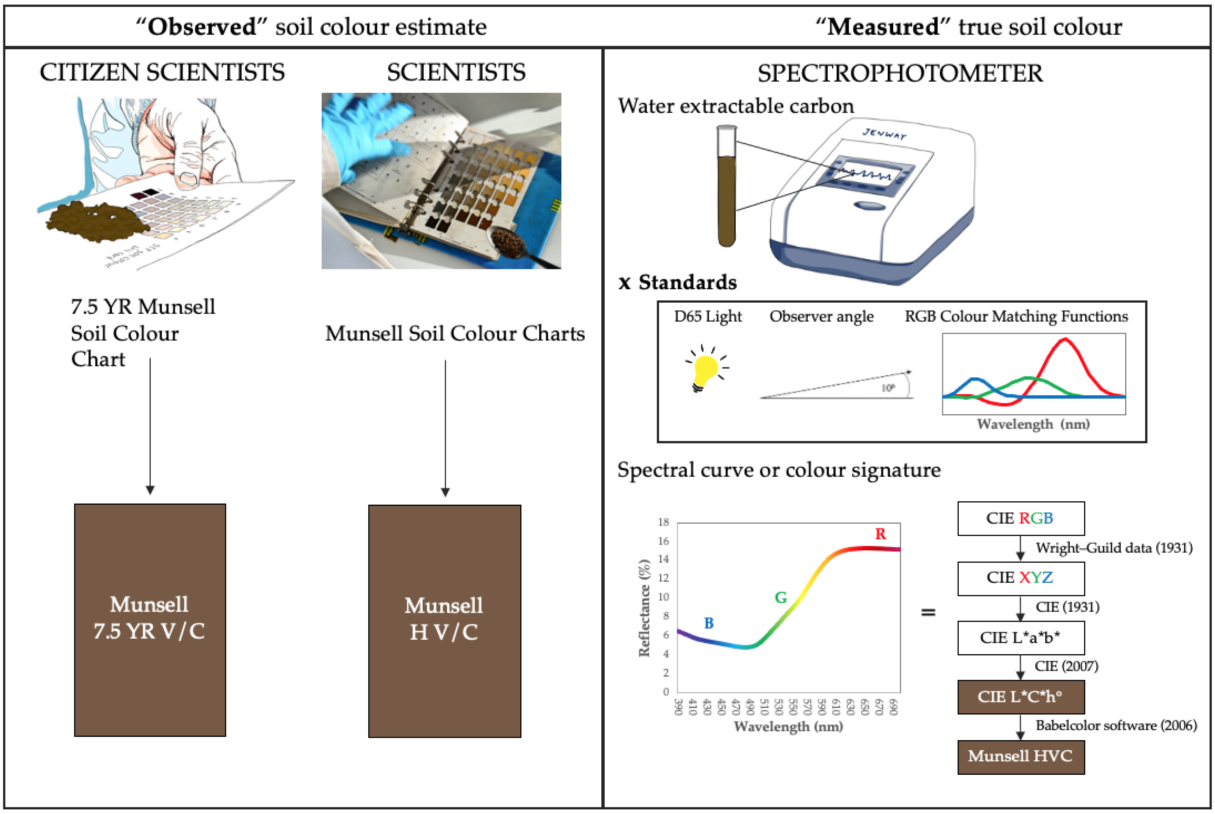


Fig. 3.1. Conceptual diagram of colour transformations required for comparison between observed and measured colour.

3.2.4. Colour transformations for data analysis

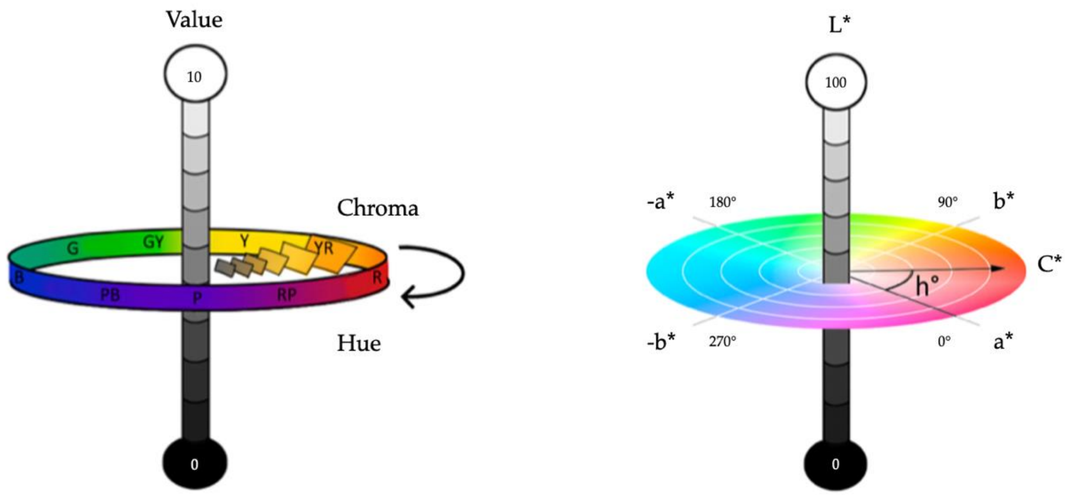
In order to compare "observed" and "measured" soil colour, all data was converted to: Munsell HVC, CIELAB, and CIELCh (based on CIELAB). Figure 3.1 shows a conceptual diagram of the steps required for the colour transformations for data analysis. RGB tristimulus values were first converted into CIE XYZ by using CIE (1931) $3 \times 3\ M^{-1}$ conversion (Guild, 1931), and from this, data were transformed to the CIELAB and CIELCh colour space using different colorimetric equations (CIE, 2007). The formulas and methods of transformation between colour spaces are well documented in the literature. All the conversions were made using the D65 CIE Standard illuminant and an observer angle of 10°.

CIELCh coordinates were translated into equivalent Munsell values, and vice versa, using Babelcolor software (2006), which uses the official Munsell renotation data from the Munsell Color Science Laboratory at Rochester Institute of Technology (RIT). The data can be downloaded from RIT: https://www.rit.edu/science/munsell-color-science-lab-educational-resources#munsell-renotation-data (accessed on 1 April 2021). The CT&A Help manual contains many sections dedicated to technical information, including detailed equations for formulas and conversions between colour spaces: https://www.babelcolor.com/tutorials.htm (accessed on 1 April 2021).

For quantitative data analysis involving Munsell measurements, Munsell hue was converted into a numerical scale of continuous values (hue number) as suggested by Hurst (1977) according to the redness rating (RR) (Hurst, 1977). In this system, the hue charts of interest for our soil dataset were numbered as follows: 5 R was 5, 7.5 R was 7.5, 10 R was 10, 2.5 YR was 12.5, 5 YR was 15, 7.5 YR was 17.5, 10 YR was 20, and 2.5 Y was 22.5. The Munsell value and chroma retained the same numerical value. The choice was made to conduct the analysis using these colour spaces for several reasons. Although using the Munsell soil colour chart (MSCC) is the prevalent practice in soil science, several problems have been described with the consistency of colour identification using this qualitative method. Thus, we chose to use the CIELAB and CIELCh colour systems, which are contemporary colour spaces defined by the International Commission on Illumination (CIE) that supersede Munsell by offering advantageous properties during statistical analysis, while retaining the same perceptual framework, which is familiar to soil scientists (Vodyanitskii and Kirillova, 2016). In fact, there is almost a 1:1 correlation between the Munsell hue, value, and chroma attributes and the equivalent hue (h°), lightness (L*), and saturation (C*) polar coordinates (Warr, 2015). Figure 3.2 illustrates the relationship between HVC and CIELCh. Results are displayed in both colour spaces so that it is easier to interpret and apply data in subsequent studies.

Moreover, we used the CIELAB system to pick up on small differences in soil colour since these coordinates have a direct physical meaning, describing colour in the range from green (–a*) to red (+a*), and from blue (–b*) to yellow (+b*). The lightness dimension, represented by L*, ranges from pure black (0) to diffuse white (100) (Fig. 3.2). For this reason, it is possible to calculate the magnitude and direction of colour error and quantify colour differences. We used CIELAB to calculate the average difference between the "observed" and "measured" colour values of each sampling locations for parameters: ΔL*, Δa*, and Δb*.

By using this assessment, we were able to calculate the average deviation for each parameter (L*, a*, b*) from the true, spectrally derived colour and apply this difference to obtain a calibrated colour value. This "calibrated" colour was used in our study as the benchmark or true soil colour for each sample location.



(**a**) (**b**)

Fig. 3.2. A 2-D representation of the 1:1 correlation between colour spaces (**a**) Munsell HVC and (**b**) CIELCh. Munsell hue (dominant wavelength) or CIE hue angle (h°); Munsell value and CIE lightness (L*); and hue chroma or CIE chroma (C*) is the distance from grey. The h° is the angle

between the hypotenuse and 0° on a* axis, varying from 0 to 360°, 0° (red colour); 90° + b* (yellow); 180°-a* (green) and 270°-b* (blue).

3.2.5. Data analysis

Descriptive Statistics

Descriptive statistics (max., min., mean, mode, SD, CV%) were used to summarise the characteristics of the spectroscopic and visual estimates of colour taken by scientists and citizen scientists. While both the standard deviation (SD) and coefficient of variation (CV) measure the variation of the data, CV also calculates the variability relative to the mean. We defined minimally acceptable values in life sciences for SD as <2 and for CV <30% as acceptable, 10–20% good, and <10% as very good.

Correlation and Regression Analysis

Correlation and regression analysis of the above data were conducted using SPSS statistical package. We equated $p < 0.05$ with statistical significance.

Colour Difference Calculations

"Observed" and "calibrated" colour estimates by scientists and citizen scientists were tested against spectral measurements using the criteria defined by the USDA standard methods (USDA, 2020). Colorimetric accuracy was based on the assumption that spectral laboratory measurements were the true soil colour.

Levels of colour difference were divided into 3 groups or contrast classes: faint, distinct, and prominent: "faint," where colour difference is evident only on very close examination; "distinct," where colour difference is readily seen and contrasts only moderately with the colour to which it is compared; and "prominent," were colour contrasts strongly. The criteria for determining contrast class can be found in USDA (2017) Soil Survey Manual (Climate-Data, 2020). The colour contrast class was calculated using (a) the three Munsell parameters: hue, value, and chroma (HVC); and (b) only value and chroma (VC).

3.3. Results

3.3.1. Reproducibility of spectral measurements

Spectroscopic data were used to evaluate the accuracy of the visual soil colour measurements; hence, we evaluated the level of precision afforded by the spectrophotometer by taking five measurements of the same soil solution. Table 3.2 depicts the magnitude of variation between the spectrally derived colour values for the Munsell parameters: hue, value, and chroma.

Table 3.2. Descriptive statistics for five repeated measurements of spectrally derived colour.

	Hue Number	Munsell Value	Munsell Chroma
Range	11.7 to 20.5	3.5 to 3.6	0.9 to 1.3
Mean	16.7	3.6	1.1
SD	3.1	0.04	0.1
CV (%)	18.3	1.1	12.8

Munsell hue number, basic colour; Munsell value, lightness, or darkness of a colour; Munsell chroma, saturation of a colour; SD, standard deviation; CV, coefficient of variation.

Measured values ranged from 11.7 to 20.5 for Munsell hue (on average 16.7); from 3.5 to 3.6 for the Munsell value (on average 3.6); and from 0.9 to 1.3 for Munsell chroma (on average 1.1). A low standard deviation was observed for the Munsell value (SD = 0.04) and chroma (SD = 0.1), whereas Munsell hue measurements were more spread out and had a high SD (SD = 3.1). Similarly, Munsell value measurements had the lowest coefficient of variation (CV = 1.1%), whereas there was a slightly greater level of dispersion for the Munsell chroma measurements (CV = 12.8%), and Munsell hue measurements exhibited the highest variation from the mean (CV = 18.3%).

3.3.2. Comparison of visual and spectroscopic soil colour measurements

Table 3.3 shows a statistical summary of the range, mean, and mode of colour attributes Munsell hue, value, and chroma determined by scientists, citizen scientists, and a spectrophotometer.

Table 3.3. Descriptive statistics for the Munsell colour attributes (hue, value, and chroma) determined by scientists, citizen scientists, and a spectrophotometer.

	Munsell Hue Number				Munsell Value				Munsell Chroma			
	Range	Max. – min.	Mean	Mode	Range	Max. – min.	Mean	Mode	Range	Max. – min.	Mean	Mode
Scientists	15.0 - 20	5.0	19.2	20	1.0 – 4.0	3.0	2.7	3.0	1.0 – 4.0	3.0	1.6	2
Citizen Scientists	17.5	0	17.5	17.5	3.0 – 8.0	5.0	5.0	5.0	2.0 – 8.0	6.0	5.1	6.0
Spectroscopic	13.3 – 23.2	9.9	18.5	18	3.5 – 3.8	0.3	3.7	3.6	1.3 – 3.5	2.2	2.4	2.5

Max., maximum; Min., minimum; Munsell hue number, basic colour; Munsell value, lightness, or darkness of a colour; Munsell chroma, saturation of a colour.

The reflectance data revealed that in our dataset, the soil colour (hue) ranged from 3.2 yellow-red (YR) to 3.2 yellow (Y), with approximately 77% of the soil samples in the yellow-red (YR) category, and 23% in the yellow (Y). A narrower hue range was determined by scientists in comparison with the spectrophotometer recordings, extending between three categories: 5 YR, 7.5 YR, and 10YR. 10YR was the most frequent hue page selected for soil samples. Citizen scientists used a single page (viz. 7.5 YR) from the 13 Munsell soil colour charts available for colour determination; hence, the analyses were not applicable for Munsell hue.

The range for the spectroscopic Munsell value was very narrow in comparison to the observed colour Munsell value for the same samples. The spectroscopic Munsell value varied from 3.5 to 3.8 (on average 3.7). Instead, citizen scientists had a highly dispersed range for the Munsell value from 3.0 to 8.0 (on average 5.0). Likewise, scientists' range for the Munsell value varied from 1.0–4.0 (on average 2.7). A similar trend was observed for Munsell chroma, exhibiting the broadest range for citizen scientists' visual assessments in comparison to spectroscopic recordings. While spectrally derived Munsell chroma values ranged from 1.3 to 3.5 (on average 2.4), citizen scientists' chroma extended from 2.0 to 8.0 (on average 5.1). Instead, scientists' Munsell chroma range was similar to spectrophotometer-measured chroma, varying from 1.0 to 4.0 (on average 1.6).

The relationship between observed colour parameters and those derived from spectral reflectance is plotted in Figure 3.3. There is a linear relationship between the observed and measured colour assessments for the same perceptual phenomena: Munsell value and chroma. The Munsell value shows the strongest correlation, with an $R^2 = 0.42$ for scientists and $R^2 = 0.39$ for citizen scientists compared to Munsell chroma: $R^2 = 0.26$ and 0.19 for scientists and citizen scientists, respectively. Instead, no linear relationship was found for hue. Measured soil colour (Hue) extended from 44 to 88 degrees, yet visual estimates had a narrower range, from 59 to 74 degrees. On average, both observed and measured hue values fell within the yellow–red (YR) category.

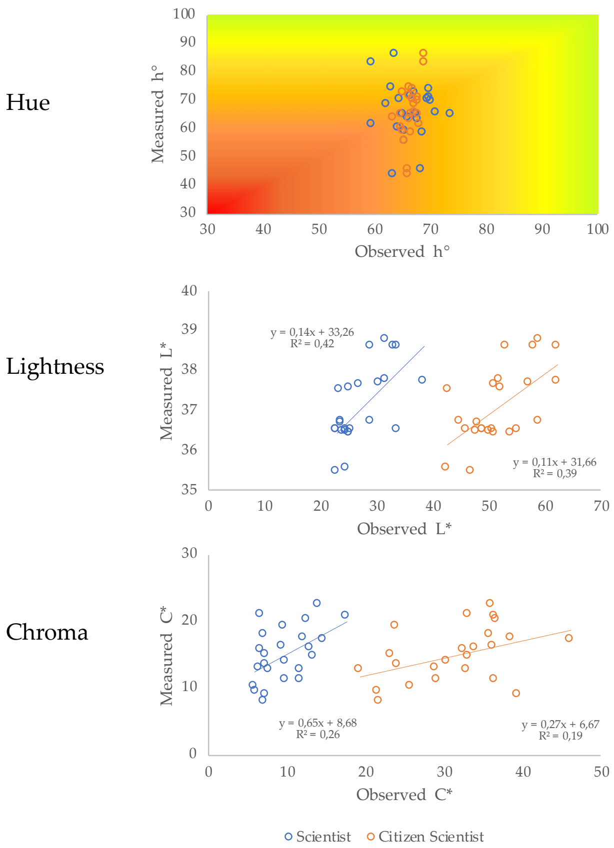


Fig. 3.3. Relationship between observed and measured colour values for hue (h°), lightness (L*), and chroma (C*) for scientists (in blue) and citizen scientists (in orange).

We calculated the total colour difference between the observed and measured colour to validate the former, based on the assumption that spectrally derived colour measurements were the true soil colour. The relative frequency bar graph (Fig. 3.4) shows there were significant differences between associated colours. Examining the three colour parameters hue, value, and chroma (HVC), 23% of scientists' colour observations were classed as "prominent" errors (in red), contrasting strongly with true soil colour whereas 73% of citizen scientists' colour assessments were "prominent" (Fig. 3.4a). For the Munsell value and chroma (VC), colorimetric accuracy improved slightly for citizen scientists from 73% "prominent" errors to 67%, and improved greatly for scientists, with no "prominent" errors and 85% of the observations falling within the "faint" category, where the degree of colour difference is very low and only evident on very close examination (Fig. 3.4b).

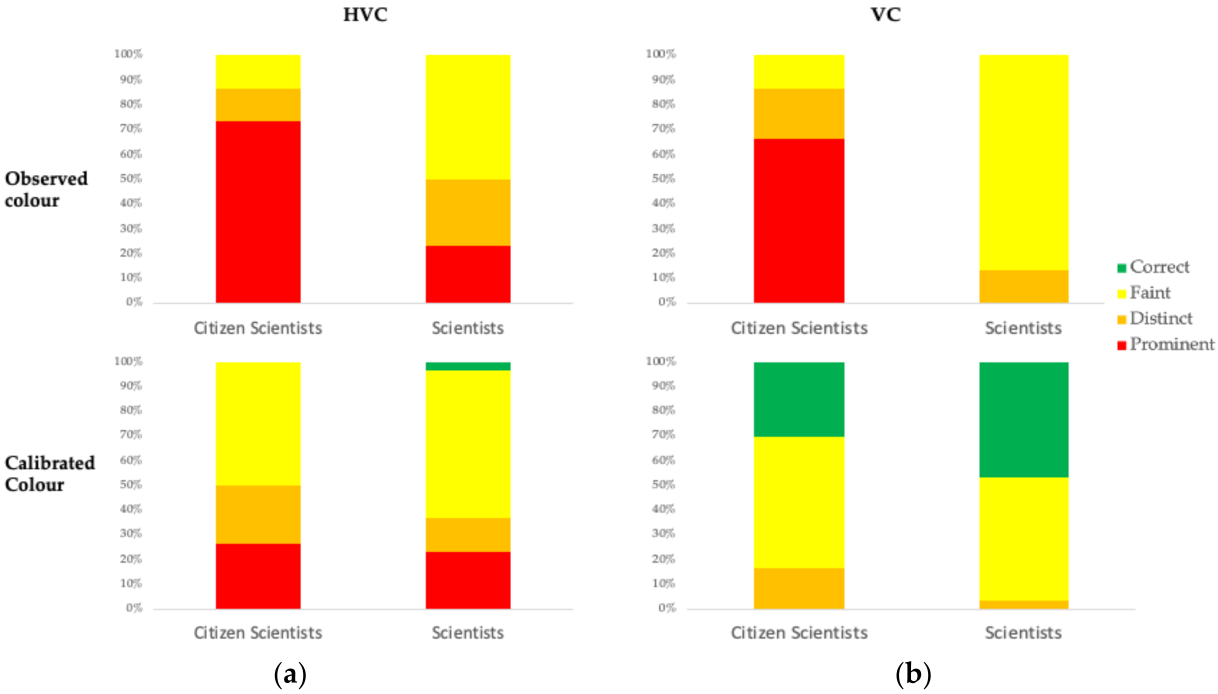


Fig. 3.4. Contrast class category for observed and calibrated visual estimates compared to spectroscopic measured colour for 2 groups: citizen scientists and scientists. (**a**) Contrast class for Munsell parameters: hue, value, and chroma (HVC), (**b**) Contrast class for Munsell attributes: value and chroma (VC).

Colorimetric accuracy for calibrated colour observations improved significantly for both groups. Examining the three parameters (HVC), calibrated citizen scientists' colour values improved from 73% of the measurements in the "prominent" category to 27% and it elevated the number of "faint" differences in colour from 13% to 50% (Fig. 3.4a). Likewise, for scientists, the category of "distinct" or moderate colour errors (orange) lowered and the percentage of "faint" colour differences increased. This improvement was greatest when focusing only on the Munsell value and chroma attributes (Fig. 3.4b). For citizen scientists, "prominent" errors lowered from 67% to 0%, the percentage of observations in the "faint" category increased to 53%, and 30% of the values showed an exact colour match (green) with the spectroscopic-measured colour. As for scientists, 47% of the calibrated values were classed as "correct," and only 3% of the calibrated colour observations were categorised as "distinct" errors (orange).

3.3.3. Soil colour and carbon

Figure 3.5 shows the extent to which "measured" spectrally derived colour attributes can be related to SOC. There is a negative, linear relationship for lightness (Munsell value or L*), saturation (Munsell chroma or C*), and dominant wavelength (hue number and h°) and SOC. The L* value or CIE lightness is the best predictor of SOC (R^2 = 58). The CIELAB colour space improves the statistical relationship, with a higher R^2 for the different colour components than the Munsell HVC system.

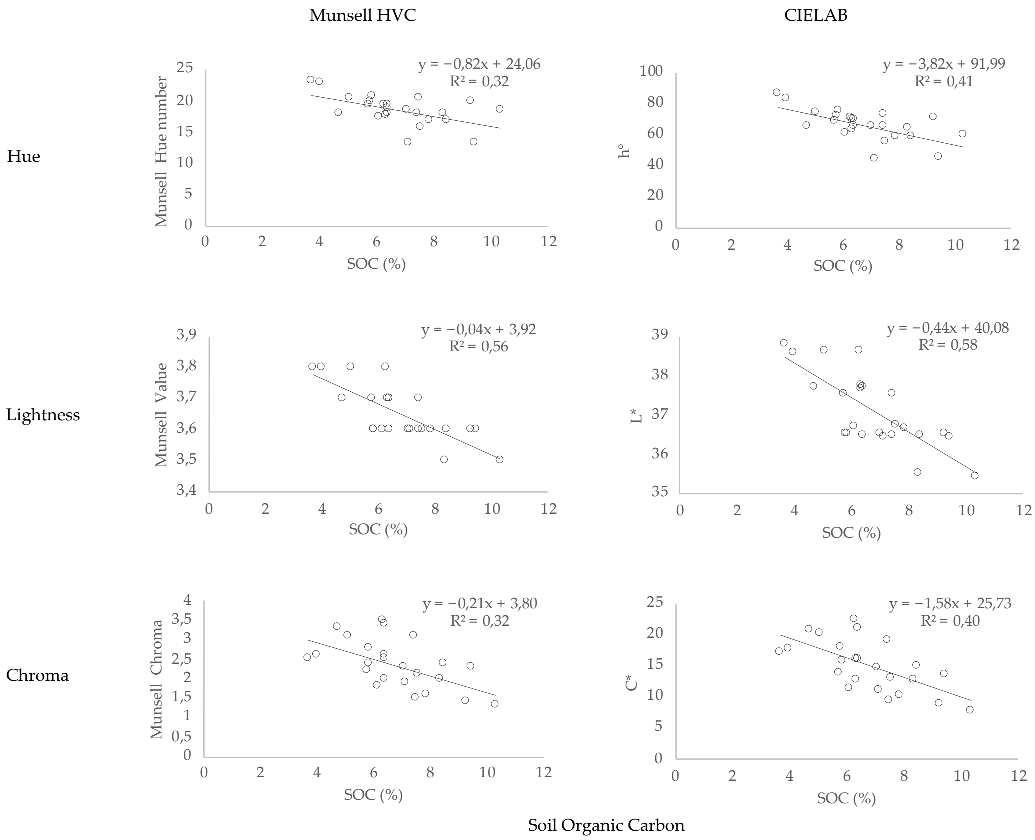
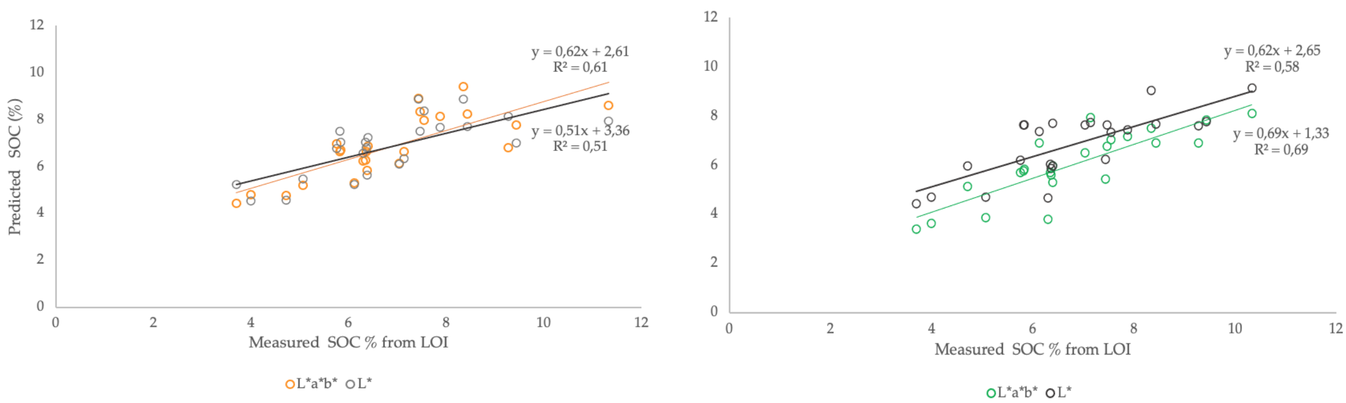


Fig. 3.5. Relationship between soil organic carbon (SOC) and hue, lightness, and chroma in both the Munsell HVC and CIELAB colour space.

Figure 3.6 shows the relationship between the measured SOC from LOI with predicted SOC using a simple regression (L*) in black and a three-factor regression equation (L+A+B) for citizen scientists in orange, and spectrophotometer in green. The three-factor regression equation raised the correlation coefficient from $R^2 = 0.58$ to 0.69 for spectrally derived colour and from $R^2 = 0.51$ to 0.61 for citizen scientists.



(**a**) (**b**)

Fig. 3.6. Relationship between measured SOC from LOI with predicted SOC using simple regression in black and the three-factor regression equation for (**a**) citizen scientists in orange and (**b**) spectrophotometer in green.

3.4. Discussion

Measurement of soil organic carbon (SOC) stocks requires a large number of samples that are costly and time-consuming to analyse (Liles et al. 2013). Thus, this study sought to evaluate efficient and accurate methods of predicting SOC contents using simple and rapid Munsell soil colour assessments as an alternative to conventional laboratory analyses, such as loss on ignition.

Our results support the immense potential for citizen scientists with minimal training to collect reliable soil colour data using the Munsell soil colour chart (MSCC). During 28 organized events, trained citizen scientists participating in our research project collected over 600 soil colour measurements, as well as other soil data that will be used in subsequent studies (Pudifoot et al. 2021). These big data sets that are collected rapidly go beyond the scope of traditional field researchers (Dickinson et al. 2010; Liu et al. 2017) and can help to overcome some of the barriers associated with current limitations in time and resources required for SOC reporting and mapping (Wills et al. 2007; Angelopoulou et al. 2020; Gholizadeh et al. 2020).

Here, we analysed a sub-sample of 540 visual soil colour measurements collected by citizen scientists and professional scientists by comparing them to each other and to an objective assessment of colour using a spectrophotometer. We found that the agreement in visual soil colour observations between appraisers over time for the same sample points or "repeatability" was low for our experiment for both scientists and citizen scientists alike. Colour observations from both groups had a wider range for the Munsell value and chroma than corresponding spectrophotometer readings. This is consistent with other studies that have found a lower percentage agreement for these colour attributes because observers making these measurements show a preference for extreme numbers to differentiate amongst similar colours (Barrett, 2002; Marqués-Mateu et al. 2018). This work brings up the potential biases in observer colour perception, and the dilemma of uncertainty in colour determination using MSCC that is routinely mentioned in the literature (Torrent and Barrón,1993; Marqués-Mateu et al. 2018; Stiglitz, 2016; Gómez-Robledo et al. 2013).

Yet, despite the variation between observers and the comparison of very different methods of colour identification, our data shows a linear relationship between traditional Munsell soil colour estimates and quantitative colour analyses for the same perceptual phenomena: value and chroma (Fig. 3.3). The relationship is coherent but weak for both scientists (R^2 = 0.42; R^2 = 0.26) and citizen scientists (R^2 = 0.39; R^2 = 0.19) for lightness and chroma, respectively. Instead, no relationship was found for hue. Nevertheless, spectrally derived Munsell hue could not be used confidently in our study because the reproducibility of this parameter was low, showing a high dispersion from the mean (SD = 3.1) (Table 3.2).

We assessed the colorimetric accuracy or levels of colour difference between "observed" and "measured" colour attributes using the USDA standards (2017), based on the assumption that spectrally derived measurements were correct (USDA, 2017). Our results demonstrate that the Munsell method can lead to significant errors for both scientists and citizen scientists. Although scientists determined colour more accurately than citizen scientists, overall, there was a high percentage of observations that contrast strongly with the spectrally derived colour values. For example, analysing three parameters (HVC), 23% of the colour observations for scientists were classified as "prominent" and contrasted strongly from spectral recordings for the same sampling locations whereas 73% of citizen scientists' colour measurements were classed as "prominent". These results contrast with earlier findings in the field that suggest there is a high overall agreement using this method. One of the most cited studies in the literature is Post et al.'s (1993) experiment, which states that 52% of soil scientists agreed on all three colour components (Post et al. 1993). Instead, our findings are similar to more recent studies that indicate a very low overall agreement of appraisers vs. the standard, such as Marqués-Mateu et al.'s (2018) experiment (<5%) (Marqués-Mateu et al. 2018). Like Marqués-Mateu et al. (2018), we examined a larger data set and used an objective standard (viz. spectrophotometer) to assess the reliability of the Munsell method, whereas past experiments were based on very few samples (<20) and only tested consistency in colour-matching between appraisers (Marqués-Mateu et al. 2018; Post et al. 1993).

This work brings up one of the primary drawbacks of using the MSCC for any observer: the variation in individual perception of soil colour (Konen et al. 2003; Sánchez-Marañón et al. 2011; Mouazen et al. 2007; Kirillova et al. 2014; Stiglitz, 2016; Gómez-Robledo, 2013; Post et al. 1993). However, aside from the observer's sensitivities, there are numerous other psychophysical and physical factors that users have identified as potential sources of discrepancy in the results (Bloch et al. 2021), including (1) sample characteristics (e.g., size, roughness), (2) environmental conditions (e.g., moisture content, lighting conditions) (Mouazen et al. 2007), and (3) difficult statistical analysis (e.g., limited colour chips, cylindrical colour coordinates) (Kirillova et al. 2014).

Instead, our results demonstrate that using the spectrophotometer allowed a more sensitive and precise measure of colour. We took five repeated measures of the same soil solution and the low standard deviations and coefficient of variations for the Munsell value and chroma showed the high reproducibility of this technique (Table 3.2). A quantitative approach to colour determination can overcome some of the limitations of the Munsell method by removing the human 'judgement' from the analysis and controlling the conditions of the measurement (e.g., using standard values for the observer viewing angle and fixed lightning conditions). This is on par with studies showing that modern technologies and instrumental methods, such as UV VIS spectrophotometry, offer an accurate means for analysing and measuring soil colour (Wills et al. 2007; Liles, 2013; Viscarra-Rossel et al. 2006; Aitkenhead et al. 2013; Vodyanitskii and Savichev, 2017; Rabenhorst et al. 2015; Barrett, 2002; Bloch et al. 2021; Warr, 2015). For this reason, quantitative measures of colour have seen apparent exponential growth worldwide and there are new applications of colour data in different fields (Viscarra-Rossel et al. 2008; Bloch et al. 2021).

Nevertheless, at this point, spectrophotometers are not a simple replacement for Munsell soil colour books because they are substantially more expensive, require a laboratory, and are time-consuming (Wills et al. 2007; Bloch et al. 2021). Thus, pending the development of portable and affordable spectrophotometers or other quantitative field devices (Angelopoulou et al. 2020; Sánchez-Marañon et al. 2011), colour assessments using Munsell charts will remain the standard practice for a variety of reasons, including cost, facility, rapidity, and familiarity with the measurement process, particularly in the Global South (Wills et al. 2007; Rabenhorst et al. 2015; Bloch et al. 2021; Warr, 2015).

Therefore, in our study, we tested the opportunity of improving the reliability of Munsell visual estimates by calibrating observations through spectroscopy using the CIELAB colour space. Our results indicate that the calibration was successful, with colorimetric accuracy increasing significantly for both groups, particularly when focusing only on the following colour components: Munsell value and chroma (Fig. 3.4b). For citizen scientists, "prominent" errors dropped from 67% to 0%, the percentage of "faint" errors increased to 53%, and 30% of the calibrated observations were an exact match and labelled as "correct". As for scientists, 47% of the calibrated values were classified as "correct", and there were only 3% "distinct" errors. These results suggest that this is a promising avenue to complement traditional Munsell colour assessments, while ensuring more reliable colour identification. Moreover, it emphasizes the importance of using the contemporary CIELAB colour space in soil science to calibrate soil colour observations using ΔL^*, Δa^*, and Δb^*, and for numerical statistical or predictive analyses (Viscarra-Rossel et al. 2006; Konen et al. 2003; Vodyanitskii and Savichev, 2017; Hurst, 1977). This colour space overcomes many of the limitations of the Munsell, while retaining a similar perceptual framework that is familiar to soil scientists (Kirillova et al. 2014; Warr, 2015; Hurst, 1977).

Further work in this area is essential because soil colour is relied on heavily in soil science for a wide variety of practical applications. In particular, our results indicate the importance of calibrating Munsell soil colour assessments for their potential use in SOC estimation. We found that there is a strong negative correlation between soil lightness (L*) and SOC. In other words, soil lightness decreases linearly as the content of organic matter increases. This trend is well documented in the literature and widely accepted (Wills et al. 2007; Liles et al. 2013; Viscarra-Rossel et al. 2006; Torrent and Barrón, 1993; Konen et al. 2003; Vodyanitskii and Savichev, 2017). However, our results demonstrate that to account for the SOC in soils more accurately, it is important to use all three colour components (L + A + B) instead of a single linear regression with soil lightness (L*). This three-factor regression strengthens the statistical relationship from $R^2 = 0.51$ to 0.61 for citizen scientists (Fig. 3.6a) and $R^2 = 0.58$ to 0.69 for the spectrophotometer (Fig. 3.6b). It supports that the organic carbon content not only affects the lightness or neutralization of white pigments but also influences other colour pigments (e.g., red, yellow, and green). These results coincide with work by Liles et al. (2013) and Vodyanitskii and Savichev (2017) that supports the use of three-factor regressions for stronger soil colour–SOC predictive relationships (Liles et al. 2013; Vodyanitskii and Savichev, 2017).

Furthermore, this study demonstrates that soil colour gathered by citizen scientists for soil colour–SOC estimations is comparable with results obtained from spectrally derived colour ($R^2 = 0.58 \sim 0.69$). This reinforces the potential use of calibrated Munsell soil colour measurements collected by citizen scientists as a cost-effective and time-saving method for the spatio-temporal monitoring of SOC. Widespread participation in colour determination could significantly accelerate the work of traditional scientists because of the capacity of these projects to provide large sample numbers and survey vast geographical areas (Wills et al. 2007; Angelopoulou et al. 2020; Gholizadeh et al. 2020; Kosmala et al. 2016). This would overcome some of the barriers associated with conventional laboratory methods, such as loss on ignition, which are inadequate for large-scale monitoring of SOC stock changes since they are time- and cost-intensive and laborious (Lefèvre et al. 2017; Wills et al. 2007; Liles et al. 2013; Smith et al. 2019; Angelopoulou et al. 2020; Vanguelova et al. 2016; Kosmala et al. 2016). Soil colour–SOC predictions could provide a detailed assessment of SOC over time and space, which is key to better understanding SOC changes within and between landscapes to implement effective SOC management strategies (Lefèvre et al. 2017).

We suggest further developments to (1) establish universal protocols for soil spectroscopy to be able to calibrate observations and compare data amongst studies (Angelopoulou et al. 2020; Moritsuka et al. 2014); (2) explore soil colour–SOC relationships using the CIELAB space in conjunction with other important climate and soil characteristics, such as illumination, moisture, and texture for stronger soil colour–SOC predictions similarly to recent studies (Sánchez-Marañón et al. 2011; Moritsuka et al. 2014; Spielvogel et al. 2004; Mirzaee et al. 2016; Moreno-Ramón et al. 2014); and (3) increase the size of the dataset and the study area to construct a robust database that is representative of soil variability (Wills et al. 2007; Angelopoulou et al. 2020).

3.5. Conclusions

This work sheds light on the use of simple Munsell soil colour assessments for estimating SOC. The main challenge is that soil colour determination using the MSCC is subjective and there is concern over low overall agreement amongst measurements made by scientists and citizen scientists. Therefore, we developed a quantitative method to measure "true" soil colour using a spectrophotometer and calibrated soil colour observations using the modern CIELAB colour system to increase their accuracy.

Our results indicate that colorimetric accuracy increased significantly for both groups, particularly when focusing on the colour components: Munsell value and chroma. This work represents an important step towards improving visual colour determination in soil science for reliable SOC estimation.

Additionally, our findings demonstrate that soil colour–SOC estimations from data collected by citizen scientists are comparable to scientists and to spectrally derived colour predictions, highlighting the potential use of these projects as an alternative to support or, to some extent, replace time-consuming and more expensive SOC laboratory analyses with methods, such as loss on ignition.

Similar to other studies, our results show that soil colour lightness (L*) (or Munsell value) is an effective predictor of SOC, with soil lightness decreasing linearly as organic carbon increases. However, we emphasize the importance of using a three-factor regression, with all the three colour characteristics (L + A + B), to account for organic carbon in soils more accurately.

The next steps are to strengthen soil colour–SOC predictions with important soil characteristics, such as moisture and texture data, and construct a robust database that is representative of different soil landscapes.

Chapter 4

Driving environmental action through corporate-based citizen science: insights from participant observation and behavioural theory

Nerea Ferrando-Jorge, Anna Jackman, Liz Shaw, Joanna Clark, and Hilary Geoghegan

Abstract

Wicked environmental problems such as climate change necessitate collective mobilisation. Given the private sector's role in the transition to a more sustainable world, corporate-based citizen science initiatives offer promising opportunities to raise awareness and cultivate positive environmental change within business and beyond.

This chapter examines the outcomes of employee-engagement in a corporate-based citizen science programme, where participants collected environmental data and contributed to research on Nature-based Solutions (NbS) in cities, while learning about climate change and urbanisation. This initiative was co-created between HSBC, the environmental NGO Earthwatch, and academic researchers from multiple institutions.

Drawing on participant observation and survey data from eight programmes involving 108 employees, the chapter examines what aspects of engagement in the programme were important in shaping pro-environmental attitudes and influencing behaviour, focusing particularly on the benefits of experiential learning in citizen science research. Participant observation provided a situated view of employee engagement, with data analysed inductively to identify emergent themes, followed by deductive analysis using the COM-B model of behaviour change. NVivo 12 software was used to analyse survey responses and qualitative data from reflective exercises to quantitatively assess shifts in participants' understanding, confidence, and motivation to act. This triangulated approach strengthened the validity of the findings.

Results show that initiative acted as a catalyst for environmental action, increasing participants' understanding and concern for climate change and empowering them to behave more sustainably with a sense of responsibility as 'sustainability champions.' Findings emphasised the value of being outdoors in nature and engaging in hands-on data collection as particularly meaningful aspects of the experience. These elements, alongside visible role models within the bank, peer interaction, and collaboration with scientists, were especially influential in shaping engagement, helping to deepen learning, foster trust and acceptance in science more widely, and sustain motivation.

This chapter demonstrates the potential of citizen science in corporate contexts to engage new audiences beyond science enthusiasts, enhance scientific literacy, and support wide organisational change towards sustainability.

Keywords: Citizen science; experiential learning; corporate social responsibility; pro-environmental behaviours; COM-B model; participant observation

4.1. Introduction

The world is facing rapid and increasingly dramatic change, with the loss of habitats and species and the alteration of ecosystems posing detrimental impacts for people (Pocock et al. 2018). These unprecedented environmental challenges are at once global, unevenly experienced (Sultana, 2022) and require new ways of collaboration across borders and sectors at all levels (Knack, 2017; Hecker et al. 2019). In addition to regulatory and technical solutions, there is a growing recognition that significant lifestyle and societal changes are critical for achieving sustainable development (Schultz, 2011; Klaniecki et al. 2018). Thus, there is an urgent need to promote a “culture of sustainability,” where the general public are aware of these issues and are empowered to behave in sustainable ways to enable environmental protection (Marans et al. 2015; Cogut et al. 2019).

Public input and collective engagement in science through approaches such as citizen science may be key for cultivating positive environmental change (Brossard et al, 2005; Jörgensen and Jörgensen, 2021; Von Gönner et al. 2023). Citizen science is defined as a form of research where non-scientists and scientists cooperate, working together to collect, share and/or analyse data for scientific research (Crall et al. 2012).

Citizen science varies in approach, including contributory projects which are science-led, community activism, and contractual specialist scientific investigations (Van Noordwijk et al. 2021). Citizen science can enhance data collection for scientific advancement by providing advantages over conventional science. It makes it possible and affordable for researchers to obtain scientifically robust data at vast geographical scale (spatial), over long periods of time (temporal), and can even enhance resolution (taxonomic) (Bonney et al, 2009b; Tulloch et al, 2013; Danielsen et al., 2014; Pocock et al. 2018).

Aside from helping to generate the environmental data needed to understand and address environmental challenges, several characteristics of citizen science make it a promising avenue for fostering environmental change (Bela et al. 2016). Importantly, citizen science projects are understood as a form of experiential education, whereby participation can foster environmental understanding and influence related behaviour, increase support for science more broadly (Trumbull et al. 2000; Brossard et al. 2005; Bonney et al, 2009b; Cronje et al. 2011), help create stronger bonds with nature (Ellis and Waterton, 2005), empower individuals and communities (Conrad and Hilchey, 2011; McKinley et al. 2017; Pocock et al. 2018), and inspire action (Bonney et al., 2009b; Brossard et al. 2005; Crall et al., 2012; McKinley et al. 2015, 2017; West and Pateman, 2016).

However, the potentially transformative impacts of citizen science are yet to be fully and comprehensively understood (Conrad and Hilchey 2011; Theobald et al. 2015; Bela et al. 2016; Day et al. 2022; Von Gönner et al. 2023). The majority of citizen science studies have primarily focused on quantifying contribution outputs (e.g. numbers of participants, data collection points, participant retention, etc.) (Jordan et al. 2011; Phillips et al. 2012; Bela et al. 2016; Bonney et al. 2016). Evaluation of the impacts and effects of citizen science on attitude and behaviour are often undocumented (Phillips et al. 2012; Toomey and Domroese, 2013) or based on assumptions rather than empirical observation (Bela et al. 2016), with the common use of self-reporting questionnaires remaining oversimplistic in understanding and evaluating the impact (Specht and Lewandowski, 2003; Somerwill and Wehn, 2022) and have been criticised by many, due to the inherent biases caused (Kormos and Gifford, 2014). This is important as only "potential" transformative benefits of involvement in citizen science are typically discussed (e.g. Bonney et al. 2009b; Conrad and Hilchey, 2011; Roche et al. 2020) but there are seldomly subsequent investigations informing whether the benefits are achieved (Walker et al. 2020; Adamou et al. 2021). Thus, there is a necessity for further research to document *how* and *what* specific aspects of engagement in citizen science influence behavioural outcomes (Bela et al. 2016; National Academies of Sciences, 2018; Turbé et al. 2019; Von Gönner et al. 2023).

Moreover, although worldwide participation in citizen science has proliferated (Bonney et al. 2009b; Shirk et al. 2012; Knack, 2017) and there have been efforts to expand the number of people involved, it remains that many such projects are predominantly found in industrialized countries in the Global North (Bonney et al. 2016; Theobald et al. 2015; Pocock et al. 2018), and there remains a lack of diversity in citizen science participants (Hobbs and White, 2012; Pandya, 2012; Raddick et al. 2013; West and Pateman, 2016; Soleri et al. 2016). For example, a large-scale survey conducted by CS Track in 2021 demonstrates citizen scientists in Europe tend to be white, middle-class, middle-aged men; akin to volunteering more widely (CS Track, 2021). Further, in environmental citizen science projects, participants tend to have previous knowledge and an active and greater interest in science, as well as being more informed about environmental issues and scientifically literate, than the general public (Bruyere and Rappe, 2007; West et al. 2015; Geoghegan et al. 2016; CS Track, 2021).

Thus, although citizen science is open to anyone willing to participate, there remains a disproportionate adoption of citizen science by those who already have particular skills, knowledges and motivations, and as such citizen science may commonly be understood as 'preaching to the converted' (Hobbs and White, 2012; Pandya, 2012; Raddick et al. 2013; West and Pateman, 2016; Lewandowski and Oberhauser, 2017; Land-Zandstra et al. 2021). It can therefore be argued that there remains a missed opportunity to engage wider and more diverse sectors of society in citizen science (Soleri et al. 2016; National Academies of Sciences, 2018).

While organisations such as businesses have not traditionally been a setting for citizen science, they can nonetheless foster sustainability within their employee base, potentially facilitating the provision of citizen science to diverse communities who may not already have an intrinsic motivation to take part, while also removing some of the barriers of volunteerism (Anderson et al. 2023). By allocating a set time for participation in-the workplace, organisations can ease the difficulty of balancing participation in citizen science against other activities (e.g. work, caretaking, household upkeep, hobbies) (Evans et al. 2005; Anderson et al. 2023), particularly as time constraints are identified as an important obstacle hampering participation in citizen science (Merenlender et al. 2016; West and Pateman, 2016).

In addition, the private sector is recognized to play a fundamental part in the transition towards environmental sustainability (Acceture, 2011; Engert and Baumgartner, 2016). Thus, there is an increasing societal pressure pushing firms to set concrete sustainability goals and targets (Anderson et al. 2023; UNEP, 2022).

Nonetheless, environmental sustainability at the organisation level remains largely shaped by and dependent on individual-level pro-environmental behaviour (Afsar et al. 2018). Hence, firms are increasingly leveraging Corporate Sustainability Programmes to raise awareness and embed sustainability into day-to-day decisions, practices, and organisational culture (Anderson et al. 2023; UNEP, 2022).

In this vein, this chapter examines the impact of employee-engagement in citizen science within a Corporate Sustainability Programme co-created by Earthwatch Institute and HSBC bank. Earthwatch Institute is an environmental, non-profit organisation, that incorporates citizen science into "Captive Learning Programmes" as part of employee training initiatives aimed fostering sustainability in business (Van Noordwijk et al. 2021).

Captive Learning Projects are focused on "engagement" and "education" for new audiences and have a limited participant group size (Van Noordwijk et al. 2021). Van Noordwijk et al. (2021) argue that such approaches differ from other citizen science typologies, as participation happens through gatekeepers (e.g. employers) and therefore participants do not necessarily have a pre-existing interest in the scientific research topic.

The programme (initiative) in question consists of a two-day residential workshop, with a combination of classroom and outdoor based learning designed to equip bank employees with the knowledge, plans and support to play an active role in championing sustainability and climate change-related issues relevant to the financial firm's sustainability strategy.

As part of the programme, employees take part in an environmental citizen science research project called *Climate-Proof Cities* led by the Earthwatch Institute. Employees collect key soil and tree data, supported by scientists from different universities collaborating in the project, including the University of Reading. The overarching aim of the scientific study is to create clearer guidelines for improved implementation of Nature-based Solutions (e.g. urban trees and soil), in order to enhance the delivery of ecosystem services that mitigate the impacts of climate change and urbanisation in cities.

In this chapter, we examine what aspects of participation in the programme were important in shaping pro-environmental attitudes and influencing behaviour, focusing particularly on the benefits of direct engagement in the corporate-based citizen science project – *Climate-Prof Cities*. We review existing theories on behaviour change and experiential learning, and following Ajzen´s Theory of Planned Behaviour (Ajzen, 1991; 2011), we examine behavioural intention as it has been shown to be the most important variable in predicting behaviour change.

In contrast to other projects which primarily use self-report surveys to evaluate behaviour change (Brossard et al. 2005; Crall et al. 2012; Santori et al. 2021; Somerwill and Wehn, 2022), we use participant observations as the primary method of research. Participant observation refers to "the process enabling researchers to learn about the activities of the people under study in the natural setting through observing and participating in those activities" (Kawulich, 2005, p. 1). This qualitative research strategy is commonly used in social science as it allows a more in-depth understanding of the context and perspective of participants and their experience (Kurz, 1983; DeWalt and DeWalt, 1998; Kawulich, 2005). We use this method to better capture the effect of engagement in the corporate-based citizen science project on participants learning, attitudes, and behaviours.

4.2 Methodology

4.2.1. Basic study parameters

This study examines whether participation in a corporate-based citizen science programme – *Climate-Proof Cities* - influences employee's **intention** (or willingness) to behave more sustainably. The two-day programme was taken by 108 employees, and the study draws upon eight such events held in the UK during 2019.´

The programme was co-created by HSBC, the environmental NGO Earthwatch, and academic researchers from multiple institutions. Participants were drawn from a range of managerial roles within the bank. The study was designed to capture employee experiences and perceptions *in situ*, providing insight into how corporate citizen science might support environmental learning and behaviour change in organisational contexts.

The research employed a **mixed methods approach**, combining qualitative and quantitative data to provide a comprehensive understanding of the programme's impact. Qualitative methods included overt participant observation and open-ended survey questions designed to capture participants' reflections on their motivations, experiences, and perceived impacts. Quantitative data were collected through pre- and post- participation surveys, which assessed self-reported changes in environmental understanding, confidence, and motivation to act on sustainability.

While the study focused primarily on qualitative insights, quantitative data served to triangulate the findings, and enhance the validity of results (Creswell, 2003).

4.2.2. Sampling and recruitment description

The Corporate Sustainability Programme consisted of a two-day residential workshop targeted at organisation employees in the finance team to learn about global environmental threats, sustainable development opportunities, and the participating bank's sustainability strategy. The 'Captive Learning' programme was designed to increase participant awareness and understanding of environmental issues, to build awareness and buy-in for the bank's sustainability strategy and to promote actions to be taken within their roles in the bank.

Part of the training consists of employees working alongside scientists from the University of Reading and Imperial College London, in the field to collect key environmental measurements. This participatory research is part of the *Climate-Proof Cities* project led by Earthwatch Institute and is badged as 'Citizen Science.'

The participant recruitment process was internally led by the corporate organisation and was not disclosed but was on a voluntary basis. However, the bank confirmed that some of the participants were approached directly and encouraged to attend and participate in the initiative. This is a key characteristic of Captive Learning Programmes. This signifies that motivation, and engagement may be lacking compared to other groups of citizen science participants.

Participants were recruited from different sectors of the bank in high leadership positions. From the 108 participants, only 51 specified their position in the bank, with approximately 70% being "directors", and 30% being "managers."

In total, we gathered data at 8 events with 108 participants - 70 male (65%); 34 female (31%); 4 did not disclose gender (4%). On average, participants were approximately 43 years old, with the youngest participant being 24 and the oldest 57. The sample set was not intended to represent the average citizen, but rather reflected predominantly middle age corporate employees at a particular career stage (i.e. in high leadership positions). For many participants, this programme was their first introduction to the scientific process. In this way, the programme offered the opportunity to broaden participation in science by making it accessible to citizens who are not normally engaged in science, opening new pathways of belonging.

4.2.3. Data collection and processing procedures

4.2.3.1.Quantitative data

Quantitative data collection

Quantitative data were collected through participant responses to closed-ended survey questions completed at the end of the programme. A pre-test–post-test research design was employed to assess the impact of participation (see Supplementary Information S1).

The survey aimed to 1. Evaluate changes in (i) **Understanding**, (ii) **Self-confidence**, and (iii) **Motivation,** before and after taking part in the programme; and 2. Evaluate the perceived **usefulness** of specific programme components.

In the Pre- and Post-Participation Self-Assessment, participants were asked to rate, on a scale from 0 to 10, their current and pre-programme levels of:

i. **Understanding**

- Understanding of climate change issues
- Understanding of the environmental sustainability implications of urbanisation
- Understanding of the bank's sustainability strategy
- Understanding of the significance of the citizen science research project they contributed to

ii. **Self-confidence**

- Confidence in their ability to take environmentally sustainable action as individuals
- Confidence in their ability to act within their role at the bank

iii. **Motivation**

- Motivation to consider environmental sustainability in professional decision-making
- Motivation to consider environmental sustainability in personal decision-making

In the **Pre- and Post-Participation Self-Assessment**, participants also rated the usefulness of individual programme components, including *Walk and talk, Urban living in a changing climate, Bank strategy introduction, Citizen science research, Meeting the challenges of the future, and Identifying personal action* (see Table 4.1 for programme content details). Usefulness of the research component for their learning was rated on a 5-point Likert scale ranging from 0 (*Not at all useful*) to 4 (*Very useful*).

Quantitative Data Analysis

Responses to an 11-point interval scale were analysed using paired t-tests to determine statistically significant differences in participants' understanding, self-confidence, and motivation before and after the programme (two-tailed significance).

Responses to the ordinal Likert scale regarding perceived usefulness were analysed using a Chi-square non-parametric test to assess whether frequencies across categories differed significantly. All statistical analyses were conducted using Minitab for Windows 10 software and a value of at least $\alpha \leq 0.05$ p was used for all significance tests.

4.2.3.2.Qualitative data

<u>Overt participant observation</u>

The primary method of capturing observational data was using overt (i.e. not covert) participant observation. Participant observation refers to "the process enabling researchers to learn about the activities of the people under study in the natural setting through observing and participating in those activities." (Kawulich, 2005, p. 1). This is a qualitative research strategy commonly used in social sciences to observe, document, and interpret what has been observed (Kurz, 1983; DeWalt and DeWalt, 1998; Kawulich, 2005). This type of data collection method is unobtrusive and allows a more in-depth understanding of the context and perspective of participants (Kurz, 1983; DeWalt and DeWalt, 1998; Kawulich, 2005).

Observational data was gathered at 8 Corporate Sustainability Programmes during 2019 (Table 4.2). Each programme event consisted of 6 hours of fieldwork and 10 hours of environmental education, with approximately 15 corporate participants. Formal learning – was delivered through presentations. However, unlike traditional school settings, and open-ended seating arrangement was used to encourage engagement and interaction. This was complemented by experiential activities, including *Walk and Talk* discussions and hands-on citizen science research.

Table 4.1. Overview of the main sections of training programme.

Corporate Sustainability Programme	
Activity	**Description of activity**
DAY 1	
Walk and Talk	An outdoor reflective exercise using interactive activities and storytelling to explore key sustainability concepts such as ecological interconnectedness and circular systems (e.g. Indian vulture crisis, how the rewilding of wolves saved Yellowstone)
Urban living in a changing climate	Presentation to learn about the impacts of climate change and urbanisation.
Citizen science research	Take part in citizen science research with local scientists to support Nature-based Solutions (NbS) in cities for climate resilience in managed study sites.
Sustainability leadership stories	An informal session led by guest speakers from the bank, including former ambassadors of the training programme, who shared personal stories and reflections on sustainability leadership within the organisation.
DAY 2	
Meeting the challenges of the future	Presentation to learn about NbS and other climate mitigation opportunities and the role of business.

Bank strategy introduction	Presentation about the bank´s strategy for sustainable development
Citizen science research	Take part in citizen science research with local scientists to support NbS in cities for climate resilience in unmanaged study sites.
Identifying personal actions (action plan or pledge)	Identifying personal actions to implement in their role, focusing on their sphere of influence.

In line with participant observation methodologies, the researcher recorded diary style reflective entries, labelled with date and times, and structured by programme activity (Table 4.1). This approach enabled easily cross-referencing information from different events. The observational data collected was used to help answer the main research question: *What aspects of employee-participation in a corporate citizen science programme support learning, shape attitudes, and drive pro-environmental behaviour?* The idea was to actively observe and describe with careful attention to detail participant's: behaviours, interactions, conversations, motivations, activities. Observations also included jottings, maps, and diagrams.

Fig. 4.6. Photograph of participants taking part in citizen science research.

<u>Researcher role, access, and rapport in participant observation</u>

Participant observation was used to gain insight into behavioural patterns and engagement dynamics during the Corporate Sustainability Programme. The emphasis was on observing rather than actively participating, although the balance between observation and involvement varied depending on the researcher's role at each event (Table 4.2). At some events, the researcher led the delivery of the soil research as a science leader, resulting in greater involvement and interaction with participants. At others, the role was primarily observational, with less direct engagement.

Table 4.2. Researcher's role across events.

Date (2019)	Number of participants	Park site	Researcher´s main role
29-30 May	17	Kew Garden	Science leader
10-11 June	16	Cannon Hill	Science leader
13-14 June	8	Cannon Hill	Participant observation
10-11 July	13	Kew Garden	Participant observation
3-4 September	13	Kew Garden	Science leader
2-3 October	15	Cannon Hill	Participant observation
8-9 October	15	Cannon Hill	Science leader
28-29 October	11	Kew Garden	Participant observation

Diary-style notes were maintained throughout the programme, both during and after each event, to systematically capture participant behaviours, interactions, conversations, and contextual observations. These notes also included researcher reflections on the event and personal responses, enabling the researcher to monitor how their presence might influence participants (Emerson et al., 2011). This approach aligns with established ethnographic and qualitative research practices, supporting transparency, reflexivity, and the rigour of data collection (Braun and Clarke, 2006; Kawulich, 2005). The structured, activity-based recording allowed cross-referencing of observations across different programme events, providing a comprehensive basis for analysis of participant engagement and behaviour dynamics.

Participant observation data analysis

Participant observation notes were transcribed and analysed using a multi-stage qualitative approach that incorporated both inductive and deductive strategies.

Initially, an **inductive thematic analysis** was conducted, following the approach outlined by Braun and Clarke (2006, 2012), which enabled the identification of patterns and themes directly from the data without the use of a pre-existing coding framework. This data-driven process allowed flexibility in capturing contextually grounded insights and facilitated the exploration of emerging behavioural phenomena that may not be well captured in existing theory.

Emergent themes and subthemes that recurred across programme events were further developed through connection to relevant behavioural constructs (Ragin & Amoroso, 2011). A **semantic approach** to coding was used to focus on the explicit content of participants' expressions and to prioritise themes most closely related to the central research question: *What aspects of employee-participation in a corporate citizen science programme support learning, shape attitudes, and drive pro-environmental behaviour?*

In parallel, **exploratory thematic analysis** was conducted to examine tentative themes drawn from relevant literature in citizen science, science communication, and behaviour change.

Finally, a **deductive, theory-driven thematic analysis** was undertaken to organise the final themes within the COM-B model of behaviour change (Michie et al., 2011). This framework was used to classify themes into the domains of Capability, Opportunity, and Motivation, providing a structured understanding of the psychological, social, and contextual drivers underpinning behaviour change as observed in the programme.

<u>Other qualitative data processes</u>

Qualitative data were also collected through participant observation and open-ended questions posed during the programme events. These questions explored participants' perceptions of the experience, focusing on:

(i) their **initial motivation for participating**, and

(ii) their overall **perception of the programme and level of satisfaction**.

To explore **initial motivations**, participants were asked: "*What are your expectations for the programme*?" (see Fig. 4.1, post-it note exercise from event 3–4/09/2019).

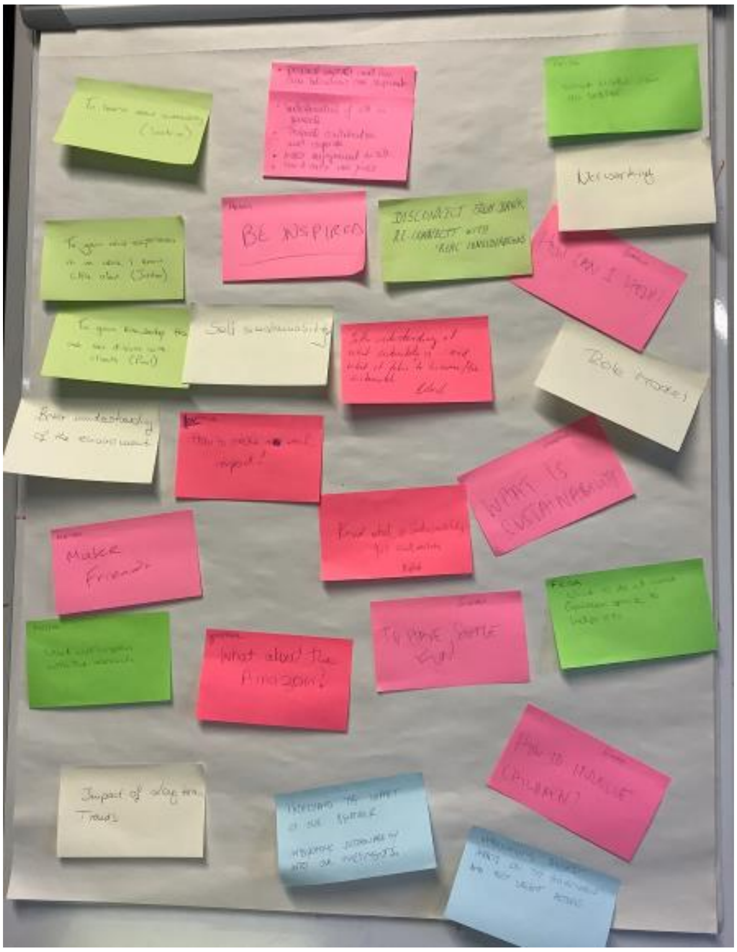


Fig. 4.1. Photograph of post-it note exercise with participants initial motivations to participate in the event 3-4/09/2019.

To assess **programme perception and satisfaction**, they responded to the prompt: "*What three words would you use to describe your experience*?"

Participants were invited to provide free-text responses. In total, responses were collected from 87 participants across six of the eight programme events. Open-ended responses were analysed using NVivo 12 software. A word cloud analysis was conducted to identify the most frequently used words describing both motivations to participate and perceptions of the event. Stemmed words and synonyms were grouped for consistency in the analysis.

4.3. Results

4.3.1. Quantitative results

Self-reported measures in Fig. 4.2. shows that there is a significant increase (p-value = < 0.001) in understanding, self-confidence, and motivation to act after taking part in the programme. The biggest percentage increase was in the level of understanding of the citizen science research (258%), increasing from an average score of 2.1 to 7.6.

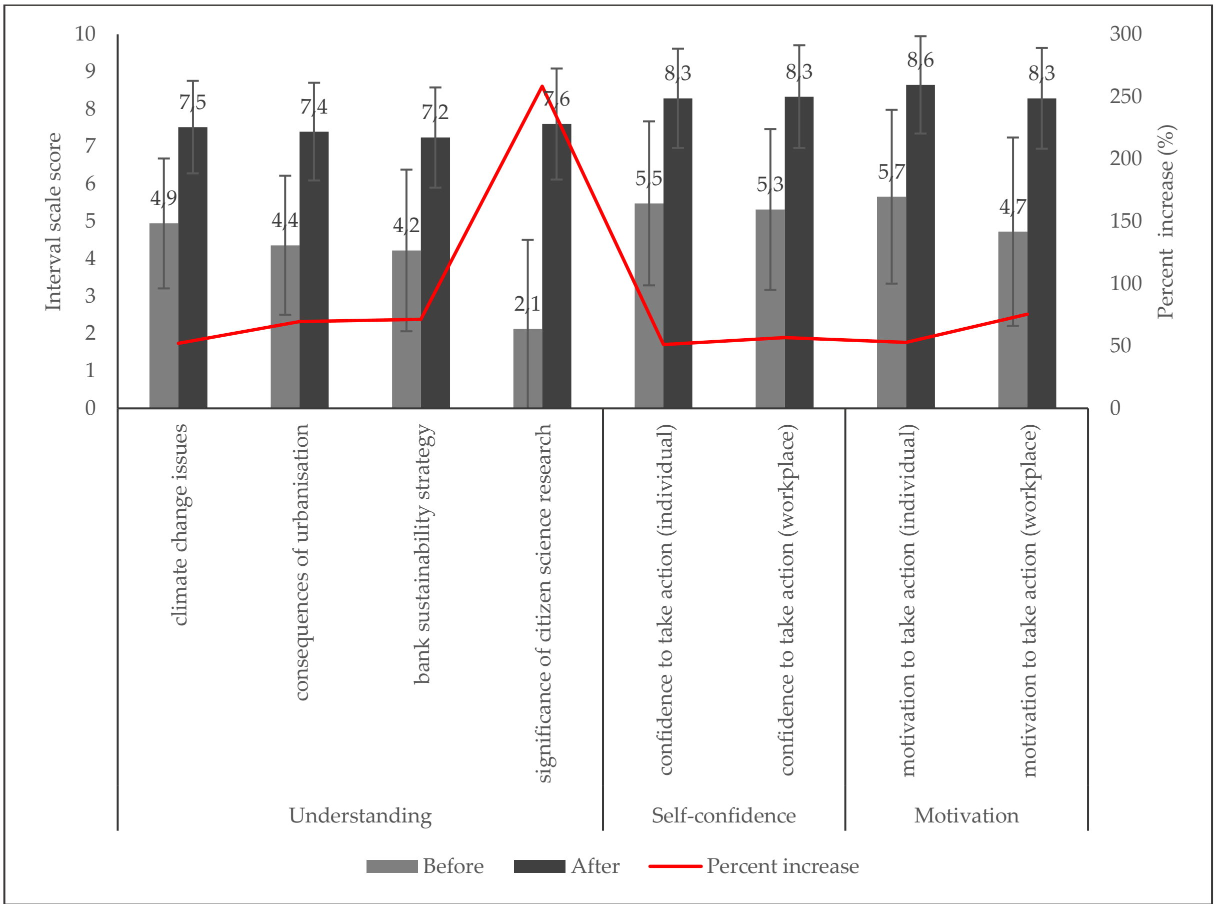


Fig. 4.2. Participant's average score (and standard deviation SD) for level of understanding, confidence in ability to act, and motivation to consider environmental sustainability in decision-making before taking in part in the programme (grey) and after (black).

Participants initially reported stronger motivation to consider environmental sustainability in their personal lives than at work (mean scores of 8.6 > 8.3). However, the percentage increase in confidence and motivation post-participation was greater in the workplace: 56 > 51% for confidence, and 75 > 53% for motivation.

Usefulness of programme

Figure 4.3 shows the relative frequency distribution for participants perception of "usefulness" for different programme activities for learning. The activity "Meeting the challenges of the future" was most favourably rated by participants, followed by "Urban living in a changing climate" and "Bank strategy introduction." "Developing an action plan" was ranked as the least useful activity. The citizen science research was mostly categorized as "useful" or "very useful," accounting for 96% of the rankings. 4% "neither" useful nor useless, and 1 participant out of 108 attendees, found it was "not particularly useful."

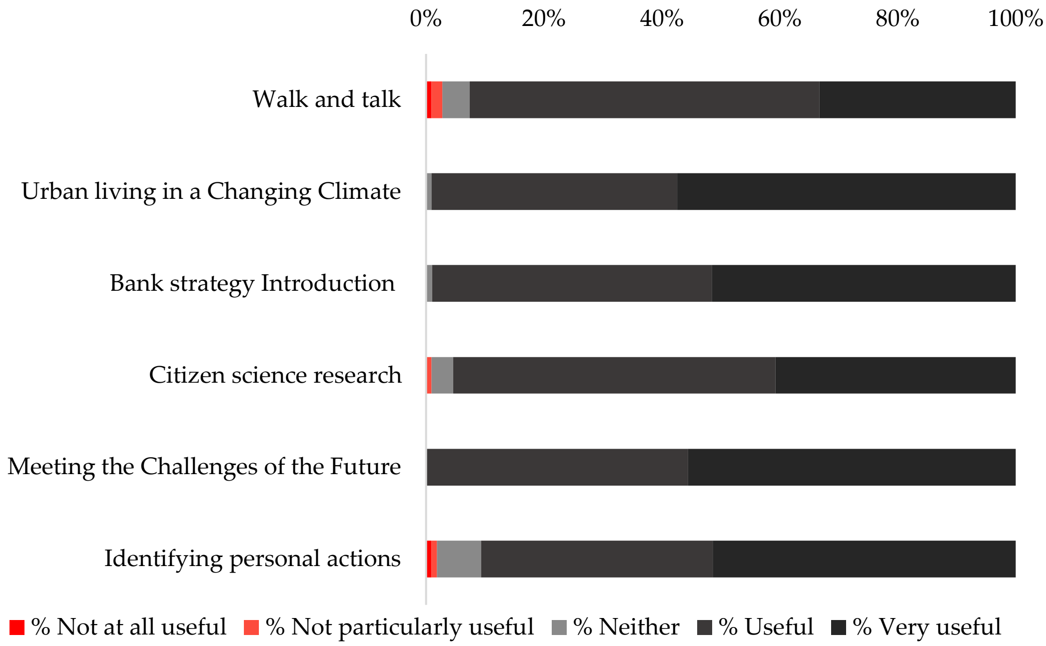


Fig. 4.3. Survey results for perceived "usefulness" of different programme activities.

4.3.2. *Qualitative results*

Initial motivations for participation

Initial motivations for participating in the Corporate Sustainability Programme were predominantly work-related. Based on coded responses, 50.3% of comments referenced work or organisational interests, 30.5% referred to increasing scientific understanding, and 19.2% reflected personal motives (e.g. family-related). Only 8.5% (15 out of 177 comments) explicitly referred to the citizen science research.

Fig. 4.4. Word cloud formed by 20 most frequently used words from participant's initial motivation to join the programme.

A word cloud generated from participant responses (Fig. 4.4) showed "sustainability" (including stemmed forms) are the most frequently used word (54 mentions; 8% weighted). This was followed by "understand/understanding" (38 mentions; 5.6%) and "bank" (23 mentions; 3.4%). The term "clients" and "customers" appeared 13 and 7 times, respectively, together accounting for 3%. Less frequently mentioned words included "personal" (10 mentions; 1.5%) and "research" (9 mentions; 1.2%).

Examples of responses referring directly to the research included:

"Seeing sustainability in action" (event 10-11 June 2019)
"Participate in practical RESEARCH" (event 8-9 October 2019)
"Get some practical understanding" (event 8-9 October 2019)
"Learn more about the works (scientists) and research that is being done" (event 28-29 October 2019).
"Experience of real-life research and how this is applied" (event 28-29 October 2019).

Perception of the experience and level of satisfaction

Participants described their experience of the programme using 3 words. The results from the word cloud show in Fig. 4.5. that the most frequently used word was "informative" (including stemmed words like "information") used 30 times, accounting for 9.4% of the words used. The second most repeated word was "fun," counted 20 times and represented 6.3% of the words used. Similar words conveying positive connotations including "enjoyable" "interesting" and "worthwhile" were also used to describe the experience as pleasant. Other frequently used words such as "inspiring" and "enlightening" demonstrate their motivation to act.

Other words were used by participants to refer exclusively to their feelings towards the "scientists" and/or their work including: "admiration," "convincing," "knowledgeable," and "professional."

Fig. 4.5. Word cloud from participants responses summarizing the event in 3 words.

<u>Results from participant observations</u>

Qualitative data collected through participant observations at eight programme events revealed key aspects of the corporate-based initiative that influenced shifts in pro-environmental behaviour among participants (Table 4.3). Programme inputs and observed outcomes are organised according to the COM-B model of behaviour change - Capability, Opportunity, and Motivation (Michie et al., 2011).

Table 4.3. Key drivers of environmental action identified through analysis of participant observation notes, organised according by the COM-B model of behaviour change.

Dimensions of behaviour	**COM – B model of behaviour change**		**Programme inputs: key aspects that influenced behaviour change**	**Main outcomes from engagement**
Cognitive	Capability	Psychological capability	Formal learning: understanding and awareness	• Environmental knowledge and awareness • Understanding of the bank's Sustainability Strategy

		Physical skills	Experiential learning in citizen science research	• ESG skills (e.g., Sustainable banking practices, green finance) • Scientific skills & applied knowledge (e.g., Inquiry-based thinking, systems thinking)
Contextual	Opportunity	"Enabling" Social environment	Normative influence & behaviours	• Perception of shared norms in sustainability • Perception of role models & leadership in sustainability • Barriers: scepticism and distrust towards the bank
		Physical environment	Availability of resources & tools	The programme offered: • Time & structured space for reflection and engagement • Logistical support • Barriers: competing interests, lack of incentives.

Affective	Motivation	From "Automatic" (immediate responses) to "Reflective" motivation (attitudes, beliefs, values)	Emotionally-driven motivations influenced by science communication	• Emotional connection to climate crisis (e.g. fear, urgency, anxiety, guilt, hope) • Shift in environmental attitude towards climate change (e.g., environmental concern, Sense of responsibility)
			Socially-driven motivations driven by interactions with scientists, bank role models, and peers.	Interaction with peers and bank role models in sustainability: • Confidence to act as a collective ("sustainability champions" • Sense of belonging and support (e.g., "the cohort") Interaction with scientist: • Trust in science and scientists
			Experiential-driven motivation from emotional connection to immersive experience.	• From automatic (e.g., Enjoyment in nature, curiosity) to • Belief in the value of participating in immersive, nature-based activities

The Venn diagram in Figure 4.6 visualises the key aspects of engagement that influenced pro-environmental behaviour. Bolded categories indicate the parent themes—namely, the core elements of the programme that shaped behavioural intention. The intersections illustrate that these categories are not mutually exclusive; rather, important subthemes emerged as overlaps. Accompanying examples highlight how these subthemes were observed in practice.

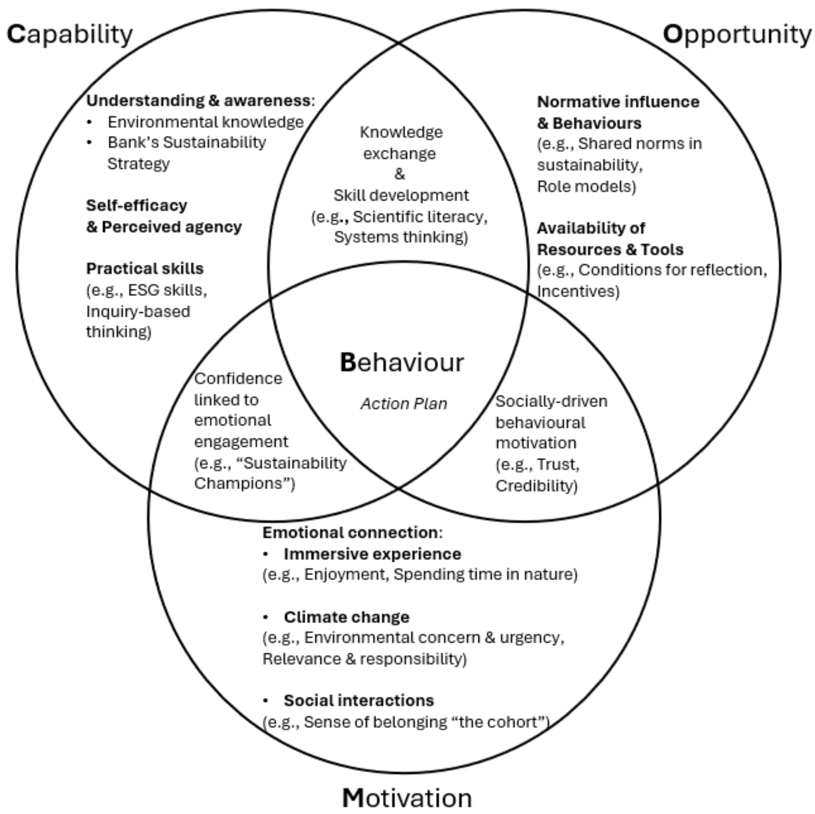


Fig. 4.7. COM-B Venn diagram with main determinants of behaviour change in the programme.

Table B 1 in appendix includes illustrative examples of overt observations from participant responses and behaviours noted across programme events. These examples illustrate how individual and social experiences within the programme shaped behavioural intention.

4.4. Discussion

This discussion explores the outcomes of employee participation in the *Climate-Proof Cities* corporate-based citizen science programme. Guided by the COM-B model of behaviour change (Michie et al. 2011), the analysis examines how the programme supported changes in participants' psychological capability, social and physical opportunity, and motivation. Drawing on participant observation, open-ended survey responses, and pre- and post-programme survey data, the chapter identifies key processes and conditions that influenced participants' willingness to engage in sustainability-related behaviours.

Psychological capability was enhanced through structured learning and science communication. Formal sessions helped reduce psychological distance from climate change and contextualised environmental issues such as climate change and urbanisation. Citizen science activities reinforced learning through direct engagement, while informal dialogue with scientists helped address doubts and increase credibility in science and science processes.

Confidence and self-efficacy also contributed to psychological capability. Participants described feeling more capable of taking environmental action, particularly in their professional roles. As one participant put it, "*My sustainability journey started today… and I'm quite excited about* *what's to come*" (event 8–9/10/2019, p. 55). Quantitative data reflected this shift, with a 75% increase in motivation to integrate sustainability at work, and the largest gains in professional confidence (56%). These findings suggest the emergence of pro-environmental identity and the sense of becoming a "sustainability champion" (Whitmarsh et al. 2021).

Social opportunity emerged through interpersonal dynamics and relationship-building. Interaction with scientists during fieldwork helped break down stereotypes and foster respect for scientific knowledge. Participants described scientists as "knowledgeable," "professional," and "convincing" (Fig. 4.5). Meanwhile, sustainability was framed by internal role models and bank speakers as a business imperative. One speaker stated, "*This is at the core of what you do! This is what business needs to be about*" (28–29/10/2019, p. 8). These influences supported alignment between personal values and institutional messaging (Bertels et al., 2010).

Physical opportunity was created by the programme's structure and setting. Citizen science encouraged dialogue and flattened hierarchies with an informal setting that created time and space for reflection, learning, and connection. Participants appreciated the integrated experience of strategy, science, and nature, with one noting, "*I really like the combination of the strategy, the science, and applying that outdoors*" (event 8–9/10/2019, p. 45).

Motivation was shaped primarily by emotional engagement. Participants described feelings of concern, urgency, and responsibility triggered by immersive learning, reflective activities, and science communication that moved from concern to hope. One participant shared, "*There's still high mountains in front of us... but there are blue skies*" (event 2–3/10/2019, p. 18). These emotional responses helped foster a sense of empowerment and reflect the importance of affective engagement in behaviour change.

In addition, emotional connection to the lived experience further sustained motivation. Being outdoors was described as a salient part of the programme, with 96% of participants rating the citizen science component as "*useful*" or "*very useful*" (Fig. 4.6). Enjoyment, fascination, and a renewed appreciation for nature are recognised predictors of pro-environmental behaviour (Kals et al. 1999; Mayer and Frantz, 2004; Schultz, 2011). These results reinforce the value of designing citizen science programmes that are not only informative, but also immersive and emotionally engaging (AAAS, 2016).

Nevertheless, several barriers to sustained engagement were observed. Some participants voiced scepticism about the bank's motives or questioned the lack of visible leadership. Others described sustainability as "*extra work*" rather than part of their formal role. These barriers reflect broader challenges related to institutional trust and perceived behavioural control in workplace settings (Blok et al., 2014; Bhattacharya, 2016).

Using participant observation alongside surveys offered a richer understanding of how the programme influenced behaviour. Observational data captured emotional reactions, social dynamics, and interactions in real time, providing context-rich insights into how aspects like interactions with scientists, and opportunities for reflection contributed to shifts in perception and intention. However, for such observation to be meaningful, gaining trust was essential in this closed organisational setting. Many employees were initially uneasy about being observed, so clarifying independence and the research purpose helped foster openness and ensure informed consent. Establishing credibility while remaining approachable enabled access to informal norms, backstage culture, and subtle social dynamics that might otherwise have remained hidden (Kawulich, 2005), while also mitigating social desirability bias (Nederhof, 1985). For example, during a break, a participant joked about being a “guinea pig” for the research. This provided an opportunity to explain that observational notes were used to improve the programme, such as incorporating feedback on enjoying outdoor activities, illustrating how trust-building facilitated meaningful engagement with participants (event 3–4/09/2019, p. 23).

Furthermore, by embedding citizen science into a structured, workplace-based initiative, this programme broadened access to environmental engagement (Anderson et al. 2023). This study suggests that while citizen science is often associated with public participation, it also has value in corporate contexts, where it can engage new audiences and support environmental learning and behaviour change. Participation in traditional citizen science tends to be skewed toward individuals with pre-existing interest in science or the environment (Bruyere and Rappe, 2007; West et al. 2015).

Overall, this study applies COM-B in a corporate sustainability context, where it has rarely been used, and offers a useful behavioural lens for understanding how citizen science can support learning and behaviour change in the workplace. However, behaviour change is not a one-off event. As findings suggest, sustained change requires continued reinforcement, supportive leadership, and integration of sustainability into everyday organisational practices (Anderson et al. 2023). Without such structures in place, even highly engaging experiences such as this one may fail to translate into long-term shifts in behaviour.

4.5 Conclusion

This study demonstrates that embedding citizen science within a corporate sustainability programme can foster pro-environmental behaviour by influencing employee’s capability, opportunity, and motivation for action. Formal and experiential learning deepened environmental understanding and awareness of the organisational strategies, building capacity. Opportunity was shaped through meaningful social interactions with scientists, peers and role models, supported by trust-building and the framing of sustainability as both a business opportunity and an emerging social norm. Motivation was primarily driven by emotional engagement - through targeted science communication, positive immersive experiences in nature, and a sense of empowerment as *sustainability champions*– which helped instil climate hope and personal sense of responsibility

Participants reported increased understanding, stronger motivation, and greater confidence to take environmental action both at work and in their personal lives. These findings underscore the importance of addressing not only cognitive, but also affective and contextual factors in driving behaviour change.

The study contributes to emerging research on workplace-based pro-environmental behaviour and highlights the value of integrating citizen science into programme design. Effective interventions should combine formal education with hands-on, emotionally engaging activities, promote peer and expert interaction, and be supported by institutional structures that reinforce action.

This chapter also demonstrates the utility of using participant observation as a method for capturing real-time, context-rich insights into how employees engage with sustainability interventions. While the findings are promising, further longitudinal research is needed to evaluate the lasting impact on individual behaviour and broader organisational change.

Chapter 5
Discussion and Conclusion

This thesis explores the benefits of corporate engagement in citizen science for soil science advancement, and for raising awareness and sustainable practices in business.

The research used observational and survey data gathered from employee´s participating in a corporate-based citizen science programme, as well as soil data collected by both participants and scientists from urban parks.

Chapter 5 summarizes the findings from the previous chapters and their significance. Next, the limitations of the study are addressed by chapter~~s~~, together with recommendations for future research, and followed by concluding remarks.

5.1 Summary and contribution of findings

Chapter 1

Chapter 1 defines and describes citizen science, its development, different forms of public participation, benefits and challenges it faces as an approach, including data quality, the limited transformative benefits achieved, and the lack of diversity of participants.

Later, it introduces Captive Learning as a new typology of citizen science and presents Climate-Proof Cities as a promising avenue to engage the private sector and diversify participation for sustainable development in business.

Lastly, the chapter outlines how the thesis will address research gaps in urban soil science understanding (e.g. soil health status of urban parks; best management practices for soils) and identifies what aspects of engagement drive participants to act using the corporate-based citizen science project as a case study.

Chapter 2

Chapter 2 addresses research question 2 (section 1.8), holistically assessing the effect of tree leaf litter removal on soil health in urban park~~s~~ soils with data collected by citizen scientists and scientists.

Data collected on soil physical, chemical, and biological properties reveal that soil health is negatively impacted by leaf litter removal over a two-year period. For example, litter removal altered the soil community, limited the carbon and nitrogen return to the soil, decreased soil water infiltration, and led to a more degraded, acidic, and compacted soil. These findings highlight the importance of encouraging management practices (e.g. not removing leaf litter) to support soil health.

Nonetheless, despite being highly transited and modified urban landscapes, overall, these park soils exhibited favourable soil physico-chemical properties and relatively high rates of biological activity and richness. This aligns with increasing evidence in the field demonstrating the unacknowledged potential of semi-natural soils such as those found in parks and gardens to provide various beneficial ecosystem services such as mitigation for flood risk, carbon storage, and biodiversity (e.g. Edmondson et al., 2012; Morel et al. 2015; Vasenev and Kuzyakov, 2018; Canedoli et al. 2020; Pouyat et al. 2020).

This study contributes to a better understanding of the state of urban soils and demonstrates the value of soil-focused citizen initiatives such as this one, as a cost-effective method to help advance soil monitoring efforts by contributing to large scale data collection using simple measurements. At the same time, soil-related citizen science can raise awareness on the importance of soil health.

Chapter 3

Chapter 3 explores research question 3 (section 1.8), providing a method to reliably use simple colour observations to estimate soil organic carbon (SOC) at large scales using citizen science.

First, it evaluates the reliability of Munsell soil colour observations, concluding there is low overall agreement amongst scientists and citizen scientists alike compared to "true" soil colour measured using a spectrophotometer. Similar to recent studies, we demonstrate spectrally-derived colour allows more precise, non-subjective, quantitative soil colour determination (e.g. Viscarra-Rossel et al. 2006; Rossel et al. 2008; Marqués-Mateu et al. 2018). After, we used spectrally derived colour in the laboratory to calibrate and improve colorimetrical accuracy of visual colour assessments for more reliable soil colour-SOC estimation.

We measured SOC from LOI and examined the relationship between soil colour and SOC content using both Munsell and the more modern, CIELAB colour space which supersedes it. Our results coincide with other studies showing soil colour lightness (L* or Munsell Value) is an effective predictor of SOC content, with soil lightness decreasing linearly as organic carbon increases (e.g. Schulze et al. 1993; Viscarra Rossel et al. 2006). Furthermore, we used a 3-factor regression, with all the three colour characteristics (L+A+B) to strengthen the statistical relationship between organic carbon content and soil colour, and account for organic carbon in soils more accurately, similarly to Vodyanitskii and Savichev, (2017) study.

This work represents an important step towards improving the precision and accuracy of conventional, visual assessments of colour in soil science using a spectrophotometer in the laboratory which provides quantitative, non-subjective soil colour determination. In addition, it emphasizes the importance of utilizing the contemporary CIE colour space in Pedology. Values in CIE colour space can be interpolated with Munsell, but it supersedes as it allows statistical analysis (Viscarra-Rossel et al. 2006; Vodyanitskii and Kirillova, 2016) and accounts for organic carbon in soil more accurately by using all three colour characteristics (L + A + B) instead of focusing on dependence of lightness alone (e.g. Vodyanitskii and Savichev, 2017).

This study is both timely and significant because improving colorimetric accuracy could allow soil colour-based SOC estimations to serve as a useful alternative to costly and labour-intensive laboratory analyses. This is crucial, as reliable and up-to-date SOC data is vital for informed planning and decision-making to address climate change. The use of citizen science-soil colour collected data at large scales could accelerate the widespread prediction of soil organic content.

Chapter 4

Chapter 4 examines the transformative effects of corporate involvement in citizen science through a Captive Learning Programme, with a particular focus on identifying the engagement factors that shape employees' environmental attitudes and promote sustainable behaviours in the workplace.

Capturing transformational outcomes from citizen science projects can be challenging (Roche et al. 2020). Most studies rely on self-report surveys (Brossard et al. 2005; Crall et al. 2012; Santori et al. 2021; Somerwill and Wehn, 2022), which have been criticized for the biases they introduce (Kormos and Gifford, 2014; Somerwill and Wehn, 2022). However, unlike other projects, the use of participant observation as a research method in this study allowed for a deeper understanding of the context, perspectives, behaviours, and experiences of corporate employees from an insider's viewpoint, providing insights that would not have been possible in this closed environment (Fry, 1973; Kurz, 1983).

Data from observations and surveys conducted during eight two-day programmes (with 108 participants) highlight the key engagement factors that influenced participants' attitudes and behavioural intentions. These factors include learning through both formal science education and experiential learning (e.g. hands-on data collection), close interactions with scientists and peers, experiencing strong emotional responses (e.g. heightened environmental concern and responsibility), and being empowered with a sense of self-efficacy and confidence, and having opportunities to make a positive impact.

To the best of the researcher's knowledge, this study is one of the first of its kind to examine in depth the impact of corporate citizen science programmes on employee behaviour. The research highlights the advantages of utilizing Captive Learning Programmes within a corporate setting, expanding participation in citizen science beyond just science enthusiasts, and involving organisations in sustainability efforts to align business culture with urgent environmental challenges. Additionally, the study emphasizes the importance of science engagement opportunities focusing on creating memorable experiences and evoking emotional responses, rather than merely increasing understanding and awareness. For example, building trust and cultivating a sense of environmental responsibility are key in shaping attitudes and influencing future behaviours. While most citizen science literature has traditionally focused on public or community engagement, this study extends the application of citizen science into the corporate context, contributing to the emerging field of workplace-based pro-environmental behaviour (PEB).

The findings resonate with broader trends in PEB research. Lu et al. (2021) provide an overview of the evolution of pro-environmental behaviour literature since the 1970s, showing increasing interest in workplace sustainability practices. Blok et al. (2014) highlight that, as employees spend a significant portion of their day at work, organisational settings are essential sites for promoting environmentally sustainable behaviours. More recently, Smith et al. (2021) and Zaida and Azmi (2024) note the growing academic and practical attention to workplace PEB, with the latter offering the first systematic and quantitative review of the field.

Zaida and Azmi’s (2024) review of 209 articles from 1993 to 2021 underscores the recent emergence of key areas such as corporate social responsibility (CSR), organisational citizenship behaviour towards the environment (OCBE), and green human resource management (HRM) as significant themes. Importantly, they conclude that no single theoretical model sufficiently captures the complexity of PEB, though the theory of planned behaviour (TPB), value-belief-norm (VBN) theory, and protection motivation theory have been most commonly used to date. This study contributes to that evolving literature by applying the COM-B model—originally developed for health behaviours—to corporate sustainability engagement, offering a comprehensive and adaptable framework for understanding behavioural drivers.

5.2 Limitations and future work

Chapter 2

Although the combination of soil physical, chemical, and biological indicators in our study allowed us to provide a more complete soil health assessment of urban park soils, there is still much to uncover.

A greater focus on urban soils is needed as it remains a poorly researched area, with a lot of soil information being outdated, incomplete, or non-existent (O'Riordan et al. 2021). First and foremost, large scale data-collection is required in urban environments to increase understanding of the state of urban soils. So far, biological, and microbial attributes are among the least monitored parameters at national levels in Europe (Nielsen and Winding, 2002). For example, more data is necessary for the effectiveness of mesofauna as bioindicators of soil quality to be made (George et al. 2017; Menta and Remelli, 2020; UKCEH, 2023). Surveys lack extensive detail on soil communities and only Megadrilli (earthworms) have been used a measure of biological activity in national-level monitoring programmes (UKCEH, 2023).

Second, it is important to establish thresholds and suitable baselines in order to compare soil properties to "target" values. To date, suitable baselines are not yet available (Black et al. 2010). For example, although PLFA profiling is frequently used as a quantitative indicator of soil disturbance (Kaur et al. 2005; McKinley et al. 2005; Bertram et al. 2012; Quideau et al. 2016) there are several limitations with the association of individual PLFAs to specific microbial groups, thus analysis needs to be exercised with caution (Frostegård et al. 2011), particularly because contradictory results have been reported (Kaur et al. 2005; Bertram et al. 2012 ; Quideau et al. 2016).

It is important to continue future research in the emerging field of urban soil health assessment and baselines in order to be able to detect general trends that capture the complexity of the urban soil "mosaic," and determine the best practices for the delivery of beneficial ecosystem services. This is a promising avenue since increasing evidence demonstrates the unacknowledged potential of semi-natural soils such as those found in parks and gardens to provide various beneficial ecosystem services such as mitigation for flood risk, carbon storage, and biodiversity (e.g. Edmondson et al., 2012; Morel et al. 2015; Vasenev and Kuzyakov, 2018; Canedoli et al. 2020; Pouyat et al. 2020). For example, urban park soils in Milan were found to have higher SOC stocks compared with croplands in the region (Canedoli et al. 2020). Similarly, Edmonson et al.´s (2012) analysis of Leicester (UK), found that urban SOC storage was significantly greater than in surrounding agricultural soils.

Chapter 3

This study emphasizes the need to improve Munsell colour assessments. The literature has documented inherent problems with using the Munsell method, such as inconsistencies between different observers (Post et al. 1993; Marqués-Mateu et al. 2018), variations in light conditions affecting colour perception (e.g. Sánchez-Marañón et al. 2011; Turk and Young, 2020), and difficulty in assigning colours because they fall midway between two reference chips (Rabenhorst et al. 2015).

Despite these limitations, we found that Munsell colour assessments are likely to prevail as the standard practice, particularly in the Global South for a variety of reasons, including cost, facility, rapidity and familiarity (Wills et al. 2007; Rabenhorst et al. 2015; Bloch et al. 2021; Warr, 2015). Thus, we emphasize the need to improve error-prone Munsell colour assessments as they are widely used in soil science for a variety of practical applications, and will continue to be used until quantitative methods gain popularity or become more affordable enabling a wider range of users (Turk and Young, 2020).

We recommend further studies to explore and establish relationships between visual soil colour estimates, and other more precise technologies that are now available like spectroscopy which increase the precision and accuracy of soil colour determination.

As advances in colour identification technology continue, the use of quantitative measures of colour have seen apparent exponential growth worldwide, marking a promising avenue for soil science. Although adoption is currently limited, these quantitative methods for colour determination are slowly gaining popularity within the field (Bloch et al. 2021).

For example, recently, more affordable and portable, battery-operated colorimeters devices are being developed enabling a wider range of users (Turk and Young, 2020). These are easier to operate and less expensive than spectrophotometers which frequently cost upwards of several thousand USD, compared to < 500 USD for low-cost colorimeters like CS-10, Cube, Nix Pro, and Color Muse or Munsell soil colour chart (approx. 200 USD) (Moritsuka et al. 2019). For example, the Nix Pro™ colour sensor has been reported to provide accurate colour prediction, in multiple studies in various fields (e.g. paint and print, the food industry, soil and agriculture) (Mancini et al. 2020; Nodie et al. 2023) even in varying moisture conditions (Floyd et al. 2016; Stiglitz et al. 2016; 2017). There are also other studies using smartphone-captured images to determine the colour digitally in controlled settings (e.g. Gómez-Robledo et al. 2013; Kirillova et al. 2018) and directly, in the field (e.g. Nodi et al. 2023). However, this is an emerging field of research and further studies are required to develop these new methods to make a robust and accurate identification.

Likewise, further research is needed to enhance the reliability–of soil colour-SOC estimations. The next steps are to include other important soil variables such as moisture and texture to strengthen the statistical relationship and improve predictions.

In addition, the samples in this study represent a relatively narrow range of SOC content, limiting robust extrapolation of the findings. Since spectroscopy-based SOC predictions may yield more promising results with larger, more diverse, datasets, future efforts should focus on developing a more comprehensive database that is representative of a broader spectrum of soil landscapes and SOC contents (Kuang and Mouazen, 2011).

Chapter 4

The findings and implications of this study should be interpreted considering its limitations. First, a large limitation is the difficulty of isolating the effects of each of the programme components from the broader set of influences that may shape participants' understanding, attitudes, and behaviours. Second, while participant observation can provide valuable insights, it also requires careful interpretation. Observers may capture participants "performing" in socially desirable ways, which may not reflect their actual behaviours. For example, participants may express support for sustainable actions during the programme, but may not carry them out in practice. Moreover, while this work provides a greater depth into understanding the drivers of pro-environmental behaviour in a corporate context, the generalisability of the findings is limited. The interpretative nature of qualitative data analysis relies on the individual researcher's perspective, and although it yield detailed, contextual insights, the findings may not be applicable to other projects or across different organisational settings.

Furthermore, although engagement influenced participants behavioural intentions towards sustainable practices, intention does not immediately translate into notable behaviour changes (Venghaus et al. 2022; Somerwill and Wehn, 2022). In fact, although intention is the most important variable in predicting behaviour change, there is a gap between behavioural intentions and actions (Kollmuss and Agyeman, 2002). This gap has been referred to by the Sustainable Development Commission (2006) as the "value-action gap". Environmental issues such as climate change are prone to this discrepancy, where despite an increasingly supportive attitude towards climate change mitigation, individuals act in ways that contradict or fails to support their values. Kollmuss and Agyeman (2002) found that an individual's willingness to act in an environmentally friendly manner is often outweighed by other factors such as cost considerations, convenience, and old habits (Kollmuss and Agyeman, 2002; Venghaus et al. 2022). Among this, habitual behaviour is one of the largest barriers to pro- environmental action, but it is often overlooked in the literature on constraints to sustainable behaviour (Kollmuss and Agyeman, 2002). This coincides with DEFRA´s (2007) report supporting the low-cost/high-cost model of decision making; people choose the pro-environmental behaviours that demand the least cost, in terms of time and effort needed, thus favouring actions that fit with existing routines.

Therefore, it is important to measure the long-lasting effects of the impacts of participation on individuals and their actions. Hughes (2013) proposes using post-visit activities. In the context of the corporate-based programme, follow-up activities could include re-engaging participants with similar questions on environmental sustainability, checking whether they have fulfilled their action plans, and whether they joined the cohort network or took on ambassador roles in support of the organisation´s sustainability strategy. This is particularly relevant given that participant observations revealed several barriers to action, including habitual behaviours, competing priorities, scepticism about the bank's commitment, and a lack of tangible incentives. Understanding these barriers in workplace contexts is crucial for designing more effective interventions (Norton et al. 2015).

Although this study focused on a single organisation, it highlights the potential for broader corporate engagement in citizen science as a tool for public-private partnerships collaboration on sustainability. However, while this study recognises the potential of its application to enhance science education and promote sustainable practices in business, caution must be taken. The integration of citizen science into corporate contexts raises important ethical and conceptual questions. For instance, can such initiatives still be considered "citizen" science when embedded within corporate structures, and are participants acting as citizens or corporate actors? (Mirowski, 2018). As Mirowski (2018) argues, science produced in the private sector may diverge from the "participatory" and "democratising" rhetoric that characterises much discussion around citizen science. As Del Savio et al. (2017) suggest, projects that fail to democratise science should not be classified as citizen science. Thus, for future application of citizen science in organisational contexts it is important to examine how firms are framing and defining the concept of "citizen science."

Lastly, in future application of citizen science in corporate contexts, we stress the importance of greater involvement of participants in other stages of the research process aside from data collection in order to extend the benefits of "experiential" citizen science education. In this way, participants learning experience will move away from a more passive to an active involvement in science research (Swan, 2022).

5.3 Concluding remarks

The outcomes of this work suggest the value of developing a corporate form of citizen science to ensure that citizen science lives up to its vast potential. We demonstrate that this non-traditional partnership can support both science and societal outcomes needed to solve the transboundary nature of environmental problems.

Large scale soil data gathered by corporate participants in the corporate-based citizen science programme helped build understanding on the state of urban soils, addressing a research gap in urban soil science studies. Data on soil physical, chemical and biological properties provided a holistic assessment of soil health and the effect of leaf litter removal. In addition, simple and fast soil colour observations were calibrated using a spectrophotometer to improve their reliability, and used to estimate carbon, demonstrating the potential of soil colour-SOC predictions as an alternative to support or, to some extent, replace time-consuming and more expensive SOC laboratory analyses.

Observational and survey data gathered from eight programmes demonstrate the value of citizen science in influencing learning, attitudes, and behaviours. Framed through the COM-B model of behaviour, the findings show that participation enhanced capability by increasing environmental knowledge and awareness, while also positioning participants as sustainability leaders. Opportunity was supported by encouraging employees to see themselves as sustainability leaders within the organisation and promoting sustainability-led changes as a core business issue and opportunity. Motivation was influenced through immersive and emotionally engaging experiences that deepened environmental concern, fostered a sense of responsibility, and positively shifted attitudes towards nature and science.

Yet, although we recognize the potential benefits of using citizen science in a corporate context, we acknowledge that caution must be taken in the development of this emerging field so that engagement remains genuinely “participatory” and aligned with the broader aim of “democratising” science. In addition, to extend the benefits of participation, future corporate applications should prioritise deeper involvement of participants across multiple stages of the research process, beyond data collection alone.

Altogether, corporate-based citizen science offers a promising avenue to broaden participation, expand the scale and scope of data collection in support of urban soil science, and promote environmental stewardship within business for sustainable development.

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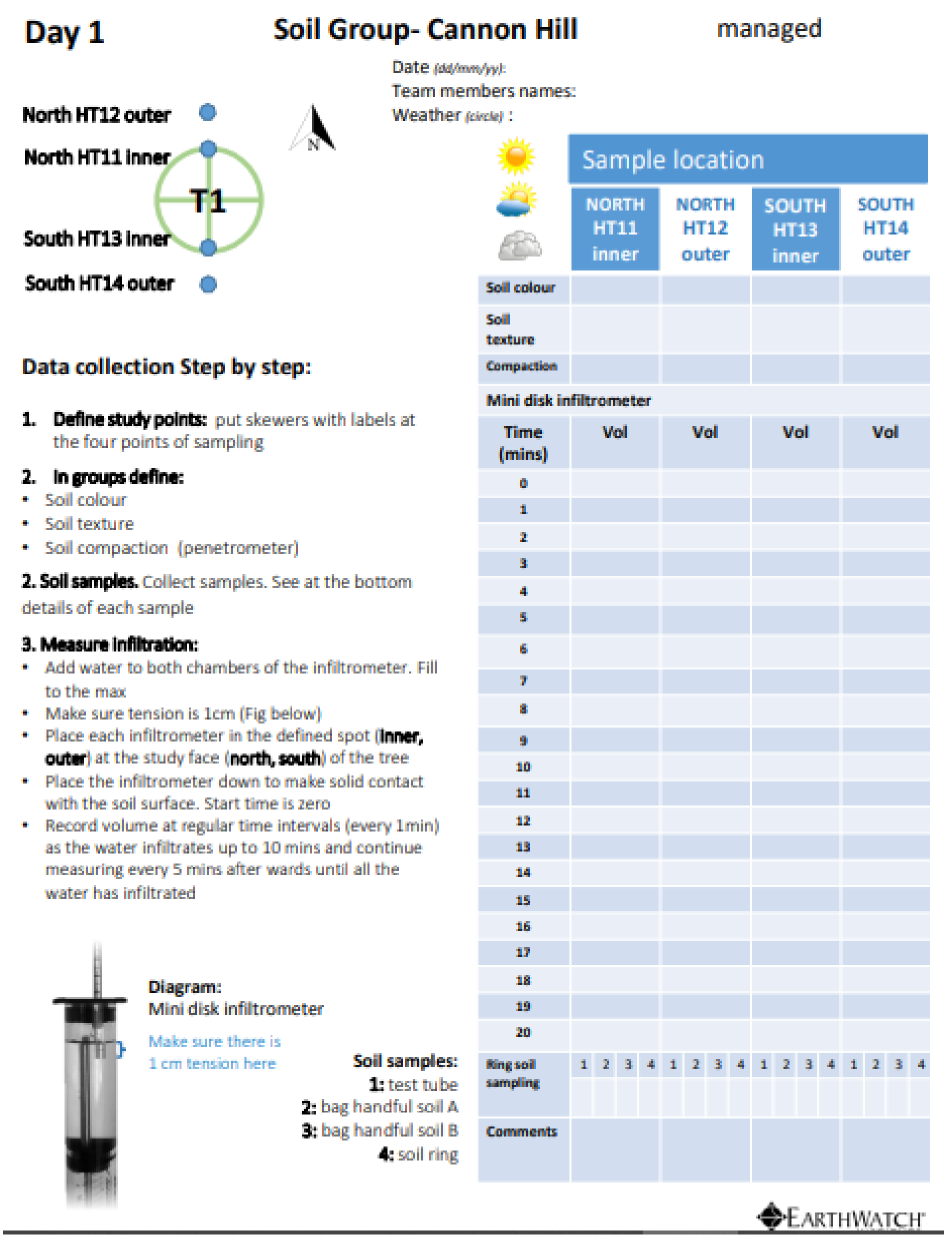
Appendices

Appendix A

Table A 1. Sampling design and variables investigated for soil sampling.

		Fixed effects				Random effects		
Sampling location	**Lat, Long**	**Park site**	**Park Management**	**Sampling orientation**	**Sampling position**	**Tree number**	**Number of events**	**Season**
1 – 24	52.45 N, 1.90 W	Cannon Hill	Managed (no litter) or Unmanaged (litter)	North or South	Inner or Outer	1 - 6	2	Spring
							2	Summer
							4	Autumn
25 – 48	51.48 N, 0.29 W	Kew Garden	Managed (no litter) or Unmanaged (litter)	North or South	Inner or Outer	7 - 12	3	Spring
							1	Summer
							5	Autumn



Day 1 Soil Group- Cannon Hill managed

Date (dd/mm/yy):
Team members names:
Weather (circle) :

North HT12 outer
North HT11 inner
T1
South HT13 inner
South HT14 outer

N

Data collection Step by step:

1. **Define study points:** put skewers with labels at the four points of sampling
2. **In groups define:**
   - Soil colour
   - Soil texture
   - Soil compaction (penetrometer)

2. Soil samples. Collect samples. See at the bottom details of each sample

3. Measure infiltration:
- Add water to both chambers of the infiltrometer. Fill to the max
- Make sure tension is 1cm (Fig below)
- Place each infiltrometer in the defined spot (**inner, outer**) at the study face (**north, south**) of the tree
- Place the infiltrometer down to make solid contact with the soil surface. Start time is zero
- Record volume at regular time intervals (every 1min) as the water infiltrates up to 10 mins and continue measuring every 5 mins after wards until all the water has infiltrated

Diagram:
Mini disk infiltrometer

Make sure there is 1 cm tension here

Soil samples:
1: test tube
2: bag handful soil A
3: bag handful soil B
4: soil ring

Sample location	NORTH HT11 inner	NORTH HT12 outer	SOUTH HT13 inner	SOUTH HT14 outer
Soil colour				
Soil texture				
Compaction				
Mini disk infiltrometer				
Time (mins)	Vol	Vol	Vol	Vol
0				
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
Ring soil sampling	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Comments				

EARTHWATCH

Fig. A 1. Sample of citizen science datasheet for soil measurements for tree number 1 in managed areas in Cannon Hill park.

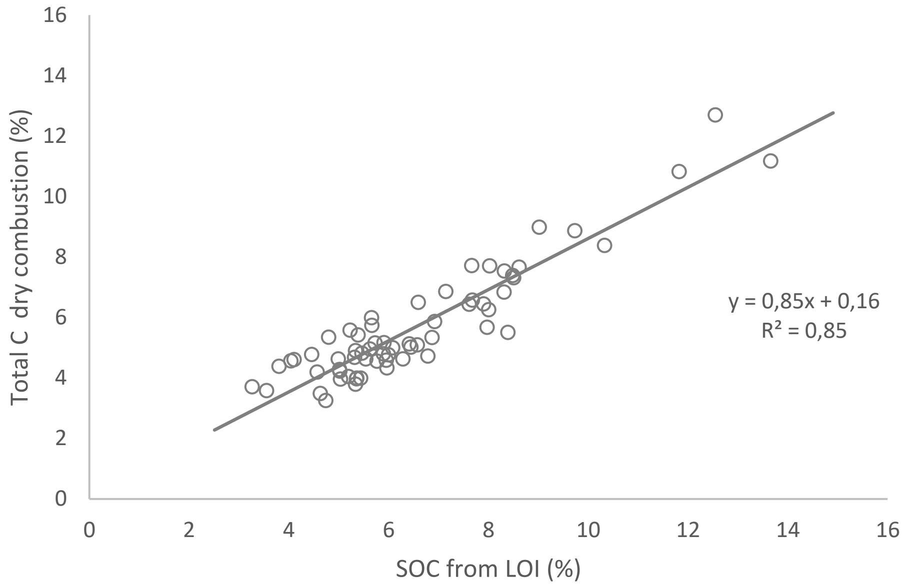


Fig. A 2. Relationship between total carbon measured by dry combustion (%) and soil organic carbon estimated by loss-on-ignition (%).

Table A 2. List, type, and description of the variables investigated through ANOVA mixed effects models.

Variables	Type	Level	Description
Fixed effects			
Management type	Binary	2	Managed or Unmanaged
Site	Binary	2	Kew Gardens or Cannon Hill Park
Sampling orientation	Binary	2	North or South
Sampling position	Binary	2	Inner canopy or Outer canopy
Random effects			
Sampling year	Binary	2	2018 or 2019
Sampling season	Nominal	3	Spring, Summer or Autumn
Sampling event	Nominal	17	Event number

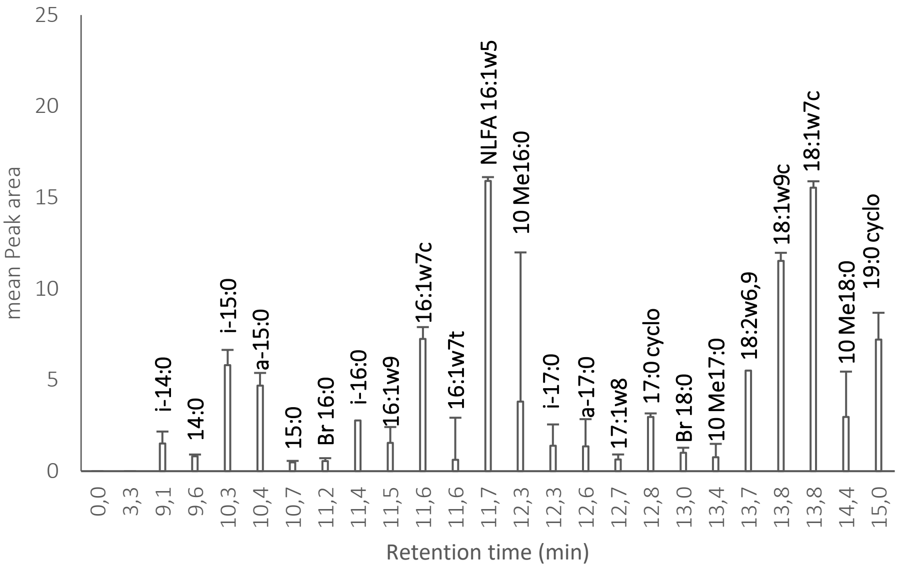


Fig. A 3. Retention times and corresponding PLFAs and their peak area for 23 representative peaks identified and used to measure community composition.

Table A 3. Signature PLFA and NLFA biomarkers used for specific groups of microorganisms.

Biomarkers for fungi		**PLFA biomarkers for bacteria**			
NLFA Arbuscular mycorrhiza markers	**PLFA Saprophytic markers**	**Gram positive bacteria (G^+) markers**	**Gram negative bacteria (G^-) markers**	**Actinobacteria**	**General Bacterial markers**
16:1ω5	18:2ω6,9 18:1ω9c	i14:0 i15:0 a15:0 Br 16:0 i16:0 i17:0 a17:0 Br18:0	3-OH 14:0 16:1ω9 16:1ω7c 16:1ω7t 17:0 cyclo 17:1ω8 2-OH 16:0 18:1ω7 19:0 cyclo	10 Me 16:0 10 Me17:0 10 Me18:0	14:0 15:0 16:0 17:0 18:0

Fatty acids are designated by standard nomenclature as total number of carbon atoms followed by a colon and the number of double bonds, with the position counted from the aliphatic end indicated by "ω". The suffixes "c" and "t" refer to the cis and trans configurations, respectively. Methyl branching at the iso and anteiso positions and at the 10th carbon atom from the carboxylic end are named by the prefixes "i", "a" and "10Me", respectively. Cyclopropane fatty acids are denoted by the prefix "cyclo". "OH" indicates a hydroxyl group.

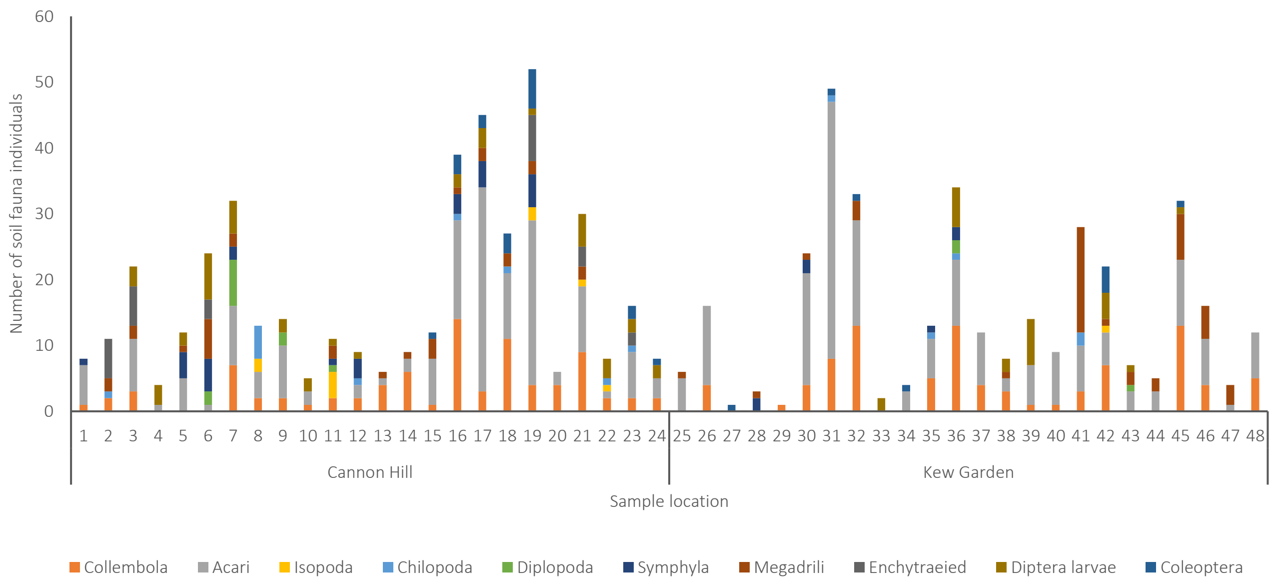


Fig. A 4. Number of soil fauna individuals found by taxon from Berlese-Tullgren extraction for all sampling locations.

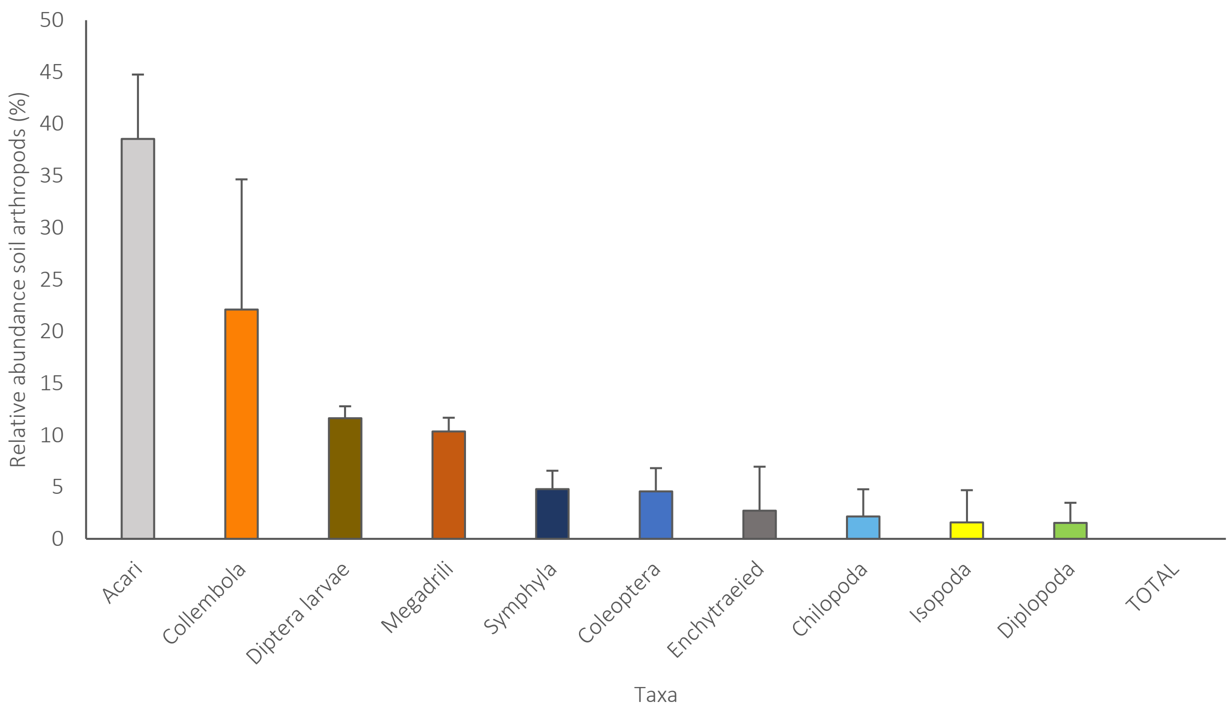


Fig. A 5. Relative abundance of soil arthropods by taxon from Berlese-Tullgren extraction

Table A 4. Pearson correlation coefficients of the relationships between soil biological properties, specifically microbiota and soil meso and macrofauna.

Correlations																	
		Collembola	Acari	Isopoda	Chilopoda	Diplopoda	Symphyla	Megadrili	Enchytraeied	Diptera larvae	Coleoptera	Actinobacteria	G+ bacteria	G- bacteria	General bacteria	Saprophytic fungi	Arbuscular fungi

Collembola	Pearson Correlation	1	,462**	-0,012	0,113	0,132	0,038	0,126	-0,027	0,124	,343*	-0,209	0,117	0,022	-0,021	-0,051	0,043
	Sig. (2-tailed)		0,001	0,933	0,443	0,372	0,797	0,394	0,853	0,4	0,017	0,155	0,428	0,884	0,889	0,733	0,773
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Acari	Pearson Correlation	,462**	1	-0,01	0,04	-0,002	,315*	0,043	0,133	0,005	,466**	-0,096	0,127	0,106	-0,085	-0,157	-0,027
	Sig. (2-tailed)	0,001		0,944	0,788	0,991	0,029	0,772	0,366	0,975	0,001	0,517	0,389	0,473	0,565	0,288	0,853
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Isopoda	Pearson Correlation	-0,012	-0,01	1	0,259	0,015	0,125	-0,017	0,193	0,04	0,237	0,235	-0,03	-0,207	-0,147	0,203	0,004
	Sig. (2-tailed)	0,933	0,944		0,075	0,92	0,397	0,911	0,188	0,788	0,104	0,108	0,842	0,157	0,319	0,166	0,977
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Chilopoda	Pearson Correlation	0,113	0,04	0,259	1	-0,069	-0,048	0,124	-0,015	-0,109	0	0,196	0,039	-0,165	-0,011	0,122	-0,057
	Sig. (2-tailed)	0,443	0,788	0,075		0,642	0,745	0,399	0,917	0,462	1	0,182	0,794	0,261	0,942	0,41	0,702
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Diplopoda	Pearson Correlation	0,132	-0,002	0,015	-0,069	1	0,245	0,054	-0,028	,450**	-0,132	-0,031	-0,176	-0,186	0,002	,305*	0,101
	Sig. (2-tailed)	0,372	0,991	0,92	0,642		0,094	0,717	0,849	0,001	0,37	0,835	0,231	0,205	0,989	0,035	0,494
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Symphyla	Pearson Correlation	0,038	,315*	0,125	-0,048	0,245	1	0,071	0,277	,333*	,338*	-0,065	-0,032	-,320*	0,228	0,194	0,083
	Sig. (2-tailed)	0,797	0,029	0,397	0,745	0,094		0,633	0,056	0,021	0,019	0,659	0,829	0,027	0,119	0,185	0,575
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Megadrili	Pearson Correlation	0,126	0,043	-0,017	0,124	0,054	0,071	1	0,104	-0,014	0,01	-0,06	-0,173	0,167	-0,093	-0,06	-0,036
	Sig. (2-tailed)	0,394	0,772	0,911	0,399	0,717	0,633		0,482	0,923	0,947	0,687	0,24	0,256	0,531	0,686	0,809
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Enchytraeied	Pearson Correlation	-0,027	0,133	0,193	-0,015	-0,028	0,277	0,104	1	0,18	,326*	-0,083	-0,117	-0,282	0,257	,347*	0,262
	Sig. (2-tailed)	0,853	0,366	0,188	0,917	0,849	0,056	0,482		0,22	0,024	0,575	0,429	0,052	0,077	0,016	0,072
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Diptera larvae	Pearson Correlation	0,124	0,005	0,04	-0,109	,450**	,333*	-0,014	0,18	1	0,03	0,046	-0,264	-0,095	0,211	0,202	0,12
	Sig. (2-tailed)	0,4	0,975	0,788	0,462	0,001	0,021	0,923	0,22		0,842	0,754	0,069	0,519	0,149	0,169	0,415
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48

Coleoptera	Pearson Correlation	,343*	,466**	0,237	0	-0,132	,338*	0,01	,326*	0,03	1	-0,242	0,108	0,021	-0,064	-0,138	0,128
	Sig. (2-tailed)	0,017	0,001	0,104	1	0,37	0,019	0,947	0,024	0,842		0,097	0,463	0,886	0,667	0,35	0,387
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Actinobacteria	Pearson Correlation	-0,209	-0,096	0,235	0,196	-0,031	-0,065	-0,06	-0,083	0,046	-0,242	1	,417**	-0,264	-0,2	-0,054	-,523**
	Sig. (2-tailed)	0,155	0,517	0,108	0,182	0,835	0,659	0,687	0,575	0,754	0,097		0,003	0,069	0,173	0,716	0
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
G+ bacteria	Pearson Correlation	0,117	0,127	-0,03	0,039	-0,176	-0,032	-0,173	-0,117	-0,264	0,108	,417**	1	-0,198	0,065	-,488**	-0,249
	Sig. (2-tailed)	0,428	0,389	0,842	0,794	0,231	0,829	0,24	0,429	0,069	0,463	0,003		0,178	0,661	0	0,088
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
G- bacteria	Pearson Correlation	0,022	0,106	-0,207	-0,165	-0,186	-,320*	0,167	-0,282	-0,095	0,021	-0,264	-0,198	1	-,530**	-,639**	0,123
	Sig. (2-tailed)	0,884	0,473	0,157	0,261	0,205	0,027	0,256	0,052	0,519	0,886	0,069	0,178		0	0	0,406
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
General bacteria	Pearson Correlation	-0,021	-0,085	-0,147	-0,011	0,002	0,228	-0,093	0,257	0,211	-0,064	-0,2	0,065	-,530**	1	0,241	0,11
	Sig. (2-tailed)	0,889	0,565	0,319	0,942	0,989	0,119	0,531	0,077	0,149	0,667	0,173	0,661	0		0,099	0,456
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Saprophytic fungi	Pearson Correlation	-0,051	-0,157	0,203	0,122	,305*	0,194	-0,06	,347*	0,202	-0,138	-0,054	-,488**	-,639**	0,241	1	0,02
	Sig. (2-tailed)	0,733	0,288	0,166	0,41	0,035	0,185	0,686	0,016	0,169	0,35	0,716	0	0	0,099		0,895
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Arbuscular fungi	Pearson Correlation	0,043	-0,027	0,004	-0,057	0,101	0,083	-0,036	0,262	0,12	0,128	-,523**	-0,249	0,123	0,11	0,02	1
	Sig. (2-tailed)	0,773	0,853	0,977	0,702	0,494	0,575	0,809	0,072	0,415	0,387	0	0,088	0,406	0,456	0,895	
	N	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
** Correlation is significant at the 0.01 level (2-tailed).																	
* Correlation is significant at the 0.05 level (2-tailed).																	

Table A 5. Soil indicators selected for soil health assessment of study sites.

Indicator of Soil Conditions	Method	Scientists	Citizen Scientists
Physical Indicators			
Bulk density	Core method	✓	_

Soil compressive strength	Vertical penetration resistance	–	✓
Hydraulic conductivity K(h)	Tension Mini Disk Infiltrometer	–	✓
Chemical Indicators			
Soil Organic Carbon (SOC)	Loss on ignition (x 0.58) and regression analysis from dry combustion	✓	–
C/N	Dry combustion	✓	–
Soil pH	1:2 soil:water, standard pH electrode system	✓	–
Biological Indicators			
Total microbial biomass Bacterial biomass Fungal biomass F/B ratio G+/G- ratio	PLFA Profiling:	✓	–
Macroarthropod abundance A (individuals m²)	Berlese-Tullgren funnel extraction	✓	–
Shannon-Wiener diversity index () macroarthropods			

Table A 6. Number of measurements and average values of soil physico-chemical and biological parameters

Soil properties		*Management type*		*P value*
	N of measurements	**Managed**	**Unmanaged**	
Calibrated SOC from LOI (%)	401	5.57 ±1.43	6.29 ±2.01	**> 0.000**
Soil C storage (Mg C ha⁻¹)	307	5.75±0.126	5.61±0.125	0.437
Bulk density (g m⁻³)	307	1.05 ±0.19	0.92 ±0.22	**> 0.000**
Soil Compressive Strength (kg/cm²)	212	2.16 ±0.95	1.28 ±0.82	**> 0.000**
Hydraulic conductivity K (cm/h)	208	2.41 ±3.94	4.57 ±5.99	**0.002**
Soil pH	360	5.87 ±0.61	6.78± 0.78	**> 0.000**
C/N	68	14.47 ±1.76	15.02 ±2.24	0.159
N (%)	68	0.33 ±0.05	0.46 ±0.17	**> 0.000**
Total biomass (nmol g⁻¹ of dry soil)	48	220.95±12.27	234.08±13.03	0.43
Total biomass (nmol g⁻¹ of dry soil)	48	220.95±12.27	234.08±13.03	0.43
Bacterial biomass (nmol g⁻¹ of dry soil)	48	168.49±10.79	188.23±12.13	0.35
Fungal biomass (nmol g⁻¹ of dry soil)	48	52.45±16.69	45.85±15.76	0.39
F/B ratio	48	0.31	0.24	-
G+/G- ratio	48	0.46	0.42	-

Soil arthropod abundance (individuals m²)	48	1817±11.08	2149±9.42	**0.05**
H′ diversity index (soil arthropods)	48	2.23	2.27	-

Appendix B.

Table B1. Examples of overt observations for each theme from the corporate-based citizen science programme.

	Parent themes: main drivers of behaviour	**Programme outcomes**	**Examples of overt observations from events**
Capability	Formal learning	Environmental knowledge and awareness	During the presentation 'Urban living in a changing climate' a participant exclaims: "*I don´t understand how anyone can deny climate change with graphics like these*" (28-29/10/2019, p. 21).
		Understanding of the bank's Sustainability Strategy	Towards the end of the programme, participants reported greater understanding of the importance and relevance of sustainability in business, and motivation to support the implementation of the strategy (Fig. 4.2).
	Empowerment: self-efficacy & perceived agency	Confidence to act	Fig. 4.2. also shows there was a significant increase in participants self-confidence (autonomy) to act, particularly in the workplace setting.
			Feeling empowered and capable of influencing change as "sustainability champions" "*My sustainability journey started today, or yesterday* (first day of programme) *and I´m quite excited about what´s to come*" (event 8-9/10/2019, p. 55). Participant: chooses an egg which has just been cracked into a pan. "*It´s still cooking, but it hasn´t fried yet*." It reminds her that there are "*different possibilities, but don´t know how I will end. Not cooked yet*" I joke that I will call her in 6 months' time to see if it has cooked. She jokes that she likes her eggs sunny side up, implying it won´t take so long for her to act.

	Experiential Learning	ESG skills (e.g., Sustainable banking practices, green finance)	Bank-led sessions go beyond theory and provide learning opportunities: - Overview of ESG and why it matters in financial services (e.g. regulatory drivers, reputational risk, client demand) - Introduction to frameworks (e.g. TCFD, SFDR, SASB). - Discussion of case studies (e.g. analysing real ESG dilemmas) - Guest speakers (e.g. experts in ESG)
		Scientific skills & applied knowledge development (e.g., Inquiry-based thinking, systems thinking)	The Earthwatch educator uses an analogy to compare how the skills used in scientific process could be applied to the bank to achieve sustainable finance: "*what is the data that I need to collect, to deliver, for that strategy to be successful*." Ask yourself questions she says: "*what do I need to do to get to that point*?" She also compares scientific peer review and testing before reaching a conclusion by saying that they should not only use one source, "*you need at least 3-5*" and explains that they should be contrasted and checked before deciding: "*who wrote it? Who's paying for it? Why are they doing it? What is the specific outcome?*" She insists that this will be a "*collective effort*." (event 29-30/05/2019, p. 30). Participant: "Any action can make a magnified impact. If two people do something, then two more might follow, and then those four might encourage eight; especially if it's your boss." (event 29-30/05/2019, p. 22). A participant refers to the butterfly story from the *Walk and Talk* activity where participants learn about systems thinking. She says assertively: "*It makes me think that every bit counts… that one person does matter*." The participant sounded incredibly inspired and motivated to act. (event 29-30/05/19, p. 16). During the research wrap up, participants from the soil group were asked to explain the measurements they had taken in the field to the leaf group, and vice-versa. Several participants interpret the results. One participant suggests "*managed areas have more carbon dioxide from exhausts, and this is what increases the chlorophyll… There´s more photosynthesis*." Another participant explains that the results may portray the

			competition between trees and plants. A participant asks curiously, "*what was the initial hypothesis?*" A participant quickly jumps in before the Earthwatch scientist has time to respond: "*will it be a trade-off… since other things influence, (there are) other factors… like how close (the study sites were) to the traffic? How do you fit that in (the analysis)*?" (event 2-3/10/2019, p. 29).
Opportunity	Social opportunity: normative influence & behaviours	Perception of sustainability as a shared norm and strategic business opportunity	Investing in the programme serves to communicate that sustainability is important to the bank and relevant to employees. In the bank learning material, sustainability was promoted as the social norm and a financial opportunity, making an economic case for the strategy relevant to employees, and encouraging sustainable practices in the workplace. Bank speaker: "*This is at the core of what you do! This is what business needs to be about. It affects business, and you will be caught in it.*" He implies it´s now a business opportunity that offers a competitive advantage, but if they don´t act, they will be left behind (event 28-29/10/2019, p.8) This makes climate change relevant to employees, giving it "proximity." In this way, achieving sustainability becomes part of the organisation´s values and priorities making it easier for workers to be on board (Bertels, 2010).
	Physical opportunity	Time & structured space for reflection (e.g. action planning) and engagement	Time for reflection and action planning: Providing dedicated time and space for reflection during the programme was important for participants to reflect upon their values and beliefs about nature, science and scientists, and sustainability. These moments of reflection in supporting shifts in participants' understanding, perceptions, motivations, and sense of empowerment, helping to translate these into potential positive environmental actions. During the action plan session, the educator encouraged participants to "reflect" on the kinds of actions they might take, while also asking them to consider how much "*time you (participant) are willing to put*" and reminding them that "*you (participant) can´t change a system overnight.*" This framing

			emphasises that behaviour change is not about taking one or two actions and then returning to old habits, but about committing to a longer-term process. The educator's deliberate use of the word "system" is important here – it reinforces the idea that one action can trigger another, and another, creating a ripple or cascading effect. This reflects systems thinking, which was introduced earlier in the programme during the Walk and Talk activity, where participants explored the interconnectedness of ecosystems. Through this, the programme encourages participants to see sustainability not as a set of isolated actions, but as something relational and ongoing – part of a wider system change.
		Logistical support & incentives	Throughout the programme, the bank strives to reassure employees its commitment to sustainability and in supporting their "sustainability journey:" Employees were given the physical opportunity (agency) to make their own individual plan of action for embedding sustainability in their role in the bank. Employees were encouraged to be innovative with their actions: Towards the end of the event, participants are asked to write an action plan. The educator says with a confident attitude: "*Go bold and big… There's a push from (the bank speaker, with a prominent role, and the bank*)." This encourages participants to think and go beyond what's expected because they have the support from the bank. The bank speaker jokes: "*there's a lot of industry and business potential, aside from plastic cups*" (insinuating to go beyond simple actions) (event 29-30/05/2019, p. 31). The educator encourages participants to act in their role at the bank: "*although as individuals you may feel like you don´t have a very big impact, the doors are open* (in the workplace)." She explains that the bank is a "*large, powerful, influential corporation*." So "*drive the change. You have the support*"(from the bank) (event 10-11/06/2019, p. 23). Barriers to action: e.g. Lack of incentives. A participant protests that the main challenge for implementation is that they (bank employee´s) need incentives because "*it's a lot of extra work*" and moans angrily: "*what's in it for me?*" Around the room there

			seems to be consensus amongst many participants, with people nodding (event 29-30/05/19, p. 22). The bank speaker talks passionately about green loans and their potential. However, one of the participants doesn´t buy it: "*why would I do extra work? The green loan is extra work. And there is no pricing discount*" He sounds very serious. The bank speaker attempts to convince him otherwise. "*it´s small – that´s what I´m trying to get across.*" Yet, the participant remains sceptical: "*but... a lot of work probably goes into those 4 bullet points*." He refers to the PowerPoint slide, making a joke about the work that will need to go in to implement the green loans. This is such a good point. Without the incentive, people will just continue with business as usual. This barrier keeps on coming up at different events. The bank speaker goes over the bullet points, one by one and keeps on getting questions. Most participants are very interested, whether it's to understand how to implement them or to criticise them. The bank speaker tries to reassure people that it´s not that much extra work repeatedly. He sounds like he is trying to convince himself. "*I mean... It´s pretty generic… It´s not that much extra…*" He is out of time. And asks if there´s anything else people what to know. Several hands go-up straight away and participants laugh. Clearly, there are still lots of questions and doubts (2-3/10/2019, p. 23). Persistent scepticism towards the bank's sustainability agenda Despite the bank's visible efforts to support sustainability—such as investing in training, strategic frameworks, and NbS research—many participants remained sceptical of its motives. At all events, suspicions of a hidden agenda surfaced repeatedly. e.g. The event has been quite confrontational, particularly towards the bank speakers. The educator asks for feedback from participants as the event is coming to a close: "*what do you feel was useful for your action plan?*" There is no response from participants. She continues showing case studies, "*what do you feel?"* She tries to initiate dialogue, but participants do not seem very engaged and are not very responsive. The other educator comments, in a worried tone: (you are) "*all very quiet*." A participant breaks the silence and answers: "*I guess.* (I´m feeling) *still a bit negative*." She sounds disappointed. The educator

			continues trying to get more people to share their feelings. She asks: "*How are people feeling about climate scepticism? Carbon*?" A participant which has had a very dominant (and confrontational) voice throughout the event answers rapidly, in a defying tone: "*if the bank is making a statement that they are going to be carbon neutral, they should know what it is*" His comment is directed at the high-ranking bank speaker. He has no mercy and is ruthless. A lot of the participant laugh in acknowledgment. The bank speaker replies, apologetically: "*we will need to investigate it*." He sounds a bit ashamed. This strong opposition towards the bank and particularly, towards the high-ranking bank speaker is bold. It´s interesting that at other event, there seems to be more approval towards this speaker - or at least inspiring. Instead, at this event, they are not holding back in criticising him directly, nor the other bosses. (event 10-11/06/2019, p. 27).
Motivation	From "automatic" motivation with immediate emotional responses to "reflective" motivation	From immediate emotional arousal to climate crisis (e.g. fear, urgency, anxiety, guilt) lead to increased environment concern, to climate hope.	Throughout the event, participants emotions were leveraged in an emotional pathway from fear to hope to prompt feelings of environmental concern and compel urgent action. The following excerpts exemplify negative emotional responses from participants including fear, guilt, or despair that elevated climate risk perceptions and concern: At the start of the second day of the programme participants were asked to choose an image that represented how they were 'feeling.' A participant picks up a photograph of a lightning storm and points to the thunderbolt as he says, "*we could get to this level of terrible stuff… quite steep*." He is worried about the threats posed by climate change (event 3-4/09/2019, p. 20). At the start of the second day of the programme participants were asked to choose an image that represented how they were 'feeling.' A participant chooses a picture of a large mountain. He explains that it is "*ironic*." "*When you climb something, you feel proud* (when you reach the top). *Ironically, we are on the top of that canyon – and what is the legacy that we leave behind*"? (He asks rhetorically). "*It´s a stark feeling*." He feels guilty for not being more sustainable and implies that the bank (and bank employees) should be doing more, especially considering future generations (event 2-3/10/2019, p. 17). The Earthwatch facilitator asks participants directly for their input on the presentation: "*from that 1h, 1h and a half, what did you take?* "A participant blurts out

			sounding a bit distraught: "*it´s HUGE*!" Another participant also responds: "*the data is there… and there´s not a lot of time*." He claims it's "*frightening*," and says, "*from what I can gather… the math, the numbers (referring to the presentation slides), I´m not sure if something can be done*." He sounds hopeless. (event 2-3/10/2019, p.10). Towards the end of the programme, there was a transformational shift from participants feeling disempowered to feelings of climate optimism for climate change mitigation: A participant chooses a picture of a person overlooking a mountainous landscape and makes a comparison to how he is feeling about climate action: "*There´s still high mountains in front of us… Many obstacles to overcome, but there are blue skies*." (He is hopeful about positive environmental change). (event 2-3/10/2019, p. 18).
	Reflexivity and emotional connection to climate crisis	Emotional connection to climate crisis and sense of collective responsibility	Feelings of hope for climate change mitigation were a consequence of the programme positively shaping their perception of themselves as potential "*leaders or champions of sustainability*" with a responsibility to do the "*right thing*" and the capacity due to their position in the bank of influencing the transition to a net-zero carbon economy: Participants are referred to as "*leaders*" or "*champions*" several times by both the bank speakers and Earthwatch´s team to instil a sense of responsibility. The Earthwatch educator insists they have the "*opportunity to do the right thing*" and employ "*good business practices*." They are being persuaded into believing that they have a central role to play in the battle against climate change. Moreover, the educator has created a false dichotomy or choice. The question becomes 'which' team they want to be in, the good or the bad. Not acting would be morally wrong since they are envisioned as part of the solution for the future of the planet. Therefore, they have a moral responsibility to act. (event 29-30/05/2019, p. 31).
	Socially-driven motivations	Sense of belonging and support (e.g., "the cohort")	The training programme also attempts to assure employees there is a network of support in the bank community referred to as "the cohort." The educator reminds participants that they are not alone, as "*over 2,000 bank employees have participated in the programme*" so there is a "*movement*' of people in

			business with this understanding (event 29-30/05/19, p. 4). This helps build a sense of belonging to the bank community (relatedness) with shared values, skills, and attitudes towards sustainability and a collective purpose: to help deliver the bank's sustainability strategy. We found that several team building exercises in the programme, and engaging in the citizen science research, helped build support and foster a sense of belonging. Particularly, during the research, the enjoyable and relaxed outdoor environment provided opportunities for social interaction and community building. Employees had the opportunity to connect and bond with other bank employees, develop network ties, and even form relationships from friendly interactions. In addition, during the citizen science research, all employees become equal learners and random grouping forces employees to reorganize around skills, collaboration, and shared purpose, regardless of existing hierarchies based on rank (Barker et al. 2011). Relationship-building was mostly achieved during the citizen science research and lunch or coffee breaks. The more informal and relaxed atmosphere therein incited participants to be more forthcoming, prompting one-to-one conversations and richer discussions away from their "bosses." The intense emotions, both positive and negative, elicited during the programme also facilitated relationship development as these experiences presented many opportunities for exchange, bonding, sense-making, support-seeking.
		Trust in science and scientists	Working alongside scientists in the informal and relaxed environment during the citizen science research prompted participants to ask questions and clarify concepts, and address specific environmental questions and concerns. In this way, we found citizen science serves as an important tool to help dispel myths about science and misinformation associated with specific scientific topics During the citizen science research, I have time to discuss doubts and concerns that arose during the rest of the programme. For example, I spoke to the participant who had doubts about the log decomposing and methane emissions. I first claim that I have a background is soil science and then

			explain there are complicated feedback loops between soil organisms, warming/temperature, and activity/soil respiration. Two other participants join the discussion. They seem to gain trust in my scientific understanding/expertise, and this prompts them to ask more science-related questions. (event 2-3/10/2019, p. 11). Although respondents were not specifically asked about this relationship, participants did comment upon their views of scientists and their approach. For example, participants referred directly to the scientists and/or their work as an important part of their experience, as demonstrated in the word cloud (Fig. 4.5). Some of the words the participants used to describe scientists they worked with during the programme were: "*professional*," "*knowledgeable*," "*admiration*," "*confidence*," and "*convincing*."
	Reflective motivation tied to immersive experience	Enjoyment of immersive experience	World cloud results in Fig. 4.5. show that participants chose words such as "*inspiring*" and "*enlightening*" to summarise their experience, demonstrating their motivation to behave more sustainably after participation. Direct experience in the citizen science research was central to achieving this emotional connection. Enjoyment of the event was identified as an important component of building a positive emotional connection. In fact, word cloud results show that the second most used word to describe the experience was "*fun*," and similar words such as "*enjoyable*" "*interesting*" and "*worthwhile*" were also frequent (Fig. 4.5.). Feelings of enjoyment were mostly attributed to spending time outdoors in nature during the citizen science research, with most participants referring to the research as an integral part of their experience.
		Positive experience in nature	Spending time in "*nature*"" or "*being outdoors*" in the fieldwork were mentioned by the majority of participants as a salient part of their experience. Engagement in the citizen science project provided an opportunity for employee´s to get away from their regular work routine and enjoy being outdoors, in nature. (During the citizen science research, I talk to a group of participants. They explain they are enjoying taking part in the science research, hands-on). Participant:

			"*It´s so different from what we normally do; sitting around in the office*." They mention valuing "*getting to be outdoors*" (event 3-4/09/2019, p. 26). Direct experience in the citizen science research was central to achieving this emotional connection. World cloud results in Fig. 4.5. show that participants chose words such as "*inspiring*" and "*enlightening*" to summarize their experience, demonstrating their motivation to behave more sustainably after participation. Enjoyment of the event was identified as an important component of building a positive emotional connection. In fact, word cloud results show that the second most used word to describe the experience was "*fun*," and similar words such as "*enjoyable*" "*interesting*" and "*worthwhile*" were also frequent (Fig. 4.5.). Feelings of enjoyment were mostly attributed to spending time outdoors in nature during the citizen science research, with most participants referring to the research as an integral part of their experience. Spending time in "*nature*"" or "*being outdoors*" in the fieldwork were mentioned by the majority of participants as a salient part of their experience. Engagement in the citizen science project provided an opportunity for employee´s to get away from their regular work routine and enjoy being outdoors, in nature. (During the citizen science research, I talk to a group of participants. They explain they are enjoying taking part in the science research, hands-on). Participant: "*It´s so different from what we normally do; sitting around in the office*." They mention valuing "*getting to be outdoors*" (event 3-4/09/2019, p. 26). Positive emotions identified amongst participants that were considered important for fostering an emotional affinity towards nature included, enjoyment of the activity and being outside, feelings of affection for nature, feelings of relaxation in nature, and/or fascination with nature. A participant tells me: "*I prefer this site. It´s wilder! I feel closer to nature; Calmer*" I respond a bit surprised and ask: "*Calmer?*" The participant responds with a

			smile: "*Yeah, less cars*." I smile back and respond: "*me too*." The unmanaged park areas are more secluded. They are in an area where visitors don´t pass by as often whereas the managed park areas was situated next to a busy road. It was loud. (event 2-3 October 2019, p. 24). We found, the experience in nature resulted in many participants developing a new interest in the natural world or strengthening their emotional affinity towards nature and motivating them to spend more time outdoors. (In an activity, participants were asked to choose an image that represented how they were 'feeling' at the start of the second day of the event. A participant chooses a picture of a person in the wilderness, enjoying nature. Participant: "*I like to go to nature to re-energize. I want to go there... Maybe this afternoon for the research*?" He smiles and continues: "*I really like the combination of the strategy, the science, and applying that outdoors*." (event 8-9/10/2019, p. 45). (At the end of the event, participants individually thank the scientist, and emphasize they enjoyed the citizen science research, specially getting to be outdoors). Participant: "*I should do it more often, it was really fun*" (event 10-11/06/2019, p. 28).