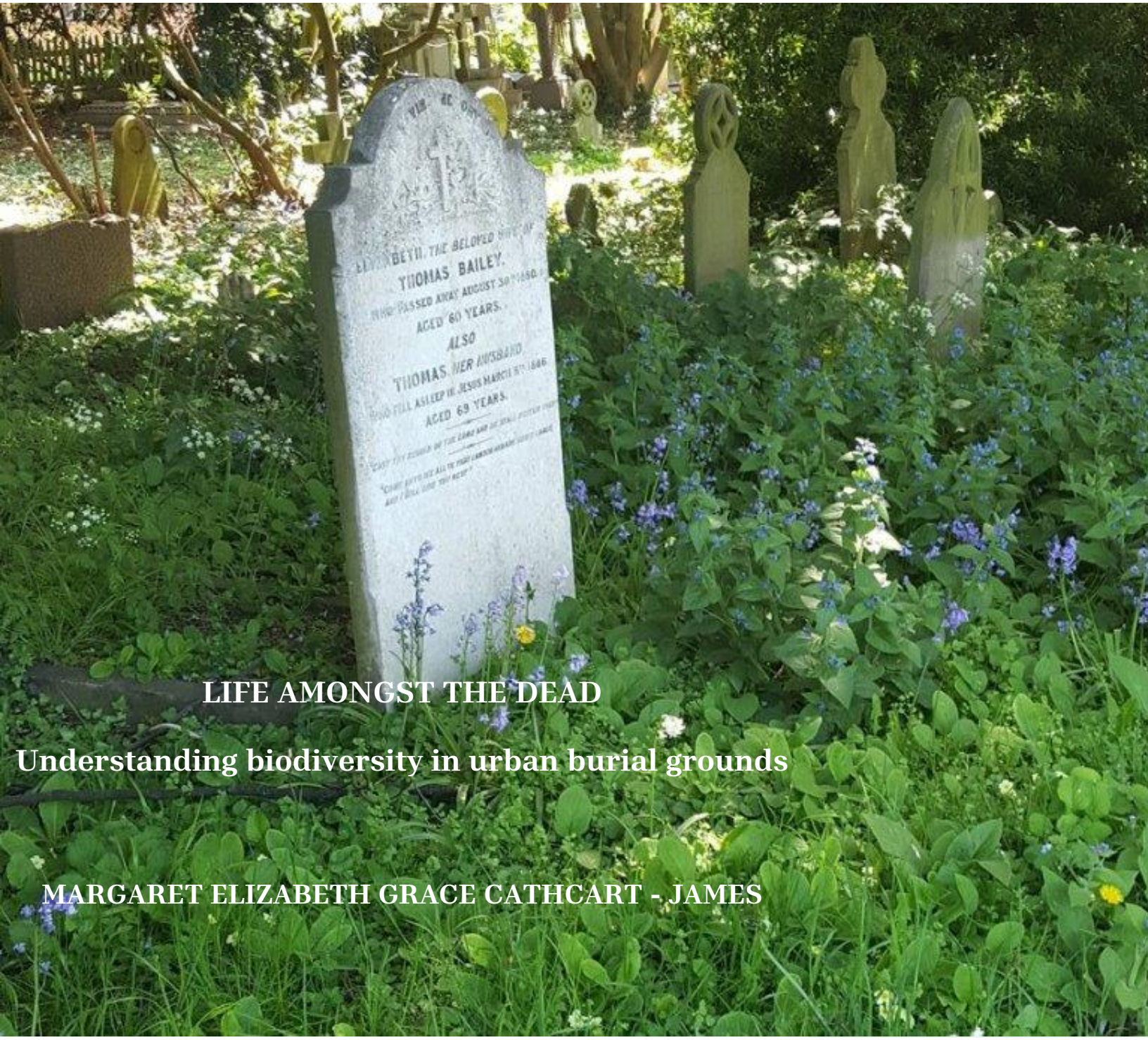

LIFE AMONGST THE DEAD

Understanding biodiversity in urban burial grounds

MARGARET ELIZABETH GRACE CATHCART - JAMES

Life Amongst the Dead:

understanding biodiversity in urban burial grounds

A thesis submitted in fulfillment of

the requirements for the degree of

Doctor of Philosophy

in the discipline of

Ecology and Evolutionary Biology

within the

School of Biological Sciences

Margaret Elizabeth Grace Cathcart-James

Submitted January 2025

Declaration

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

Margaret Cathcart-James

Dedication

This thesis is dedicated to

Tim James

March 1952 – May 2023

My staunchest supporter in staying the course, whose love and knowledge of the natural world continues to inspire me.

I did it, Dad.

"I must now stay under the old oak tree, in the midst of the long grass, with the birdsong in the air"

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Acknowledgements

This thesis is the culmination of a seven-year long adventure, and without a number of excellent people it would not have even been attempted, let alone exist now.

Although this is a space to recognise and thank those who have supported me, it isn't really enough for my supervisor Brian Pickles. A lot can happen in a person's life over the course of seven years and with every trial, curveball or terrible personal loss, every battle with imposter syndrome, every crisis of confidence or episode of just general wailing and gnashing of teeth (he has always taken my penchant for dramatics in his stride), Brian has always simply just known – *known* – that of course I can do it. Having a supervisor with that kind of easy belief in me has often tipped the scales towards me continuing the adventure. I will remain deeply grateful for his patience, good humour, advocacy, and guidance. Thank you, Brian, for fighting my corner with and for me.

Having been previously taught (and I admit, rather starstruck) by Julie Hawkins, who was the key to unlocking my love of botany, I was delighted and greatly encouraged when she became my second supervisor. My deep gratitude Julie, for the soul-healing conversations and your excellent guidance.

My sincere thanks to the members of my supervisory committee. Tijana Blanusa, you have been an inspiration since our work together before my PhD and your belief in me and forthright guidance have been so very meaningful. Jonathan Mitcheley, botanist extraordinaire and a dear colleague, I am deeply grateful for your guidance and support, and for bringing me onboard to spread the joy of plants to other students. To both of you, thank you for challenging me to make this project better, and guiding me to make it the project I wanted it to be.

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Dad – you are deeply loved and missed every day. I know you would read this thesis cover to cover; I miss the conversations about it we'll never have.

Finally, I'd like to recognise my long-suffering Mum and sister for their unerring support and cheerful refusal to let me take myself too seriously. I love you both; this is a family achievement. Go team.

Contents

Abstract

As urbanisation forges onward at pace so that the majority of the human population will be living in urban areas by 2050, the importance of urban green spaces for ecosystem functioning and our wellbeing continues to grow. Despite a significant body of research focused on urban parks, gardens and woodlands, there are almost no studies of urban burial grounds in the context of biodiversity provision and little understanding of ecosystem functioning within them.

Twenty UK burial grounds were selected as study sites from the English counties of Hampshire, Surrey, Berkshire and Buckinghamshire. These sites represented a diversity of sizes, ages and management approaches, and were distributed in more or less urban environments. A series of studies were devised to explore urban burial ground biodiversity at these sites using a range of methodological approaches.

The novel investigation of flying beetles found that larger sites were associated with greater urban population pressures, supporting lower abundances. No effect was found on flying beetle biodiversity of site age. The effects of management are presented for the first time, showing that although wildlife-friendly interventions yielded greater diversity, a horticultural landscaping approach supported higher abundances. The characterisation of urban necrosol heavy metal composition presented a varied picture, with significant differences between sites and measurements both above and below background levels. The majority of the soils were acidic, unlike typical urban soils, meaning urban necrosols may hold greater amounts of bioavailable toxic heavy metals. Sites with wildlife-friendly interventions, and those with greater surrounding coverage of trees and hedges, were associated with lower concentrations of heavy metals. Traditional pitfall trap surveys were used to study terrestrial arthropod communities, with sites under stringent management regimes found to support assemblages of greater variability and evenness than those with more sympathetic management. Large abundances of Isopoda were observed in sites under these regimes.

This study constitutes the largest-scale study of urban burial ground biodiversity undertaken to date. Common assumptions about these green spaces, such as older, undisturbed urban burial grounds being biodiversity havens with healthy soils are challenged here, and a more complex picture of their nature is presented. Crucially, for the first time, evidence of the effects of management practices on urban burial ground biodiversity are explored with practical applications of the findings considered such as soil lead concentration monitoring and increasing woody vegetation cover. Avenues for further research are a significant part of this thesis, as it is positioned as a novel foundation to be built on in the future.

Impact statement

Talk given as guest speaker at the Friends of Newtown Road Cemetery AGM – *Beetles and burial grounds.* November 2019.

Awarded a speaker slot at The Linnean Society Student Conference – *Life Amongst the Dead: biodiversity in urban burial grounds.* February 2020.

Talk given at the School of Biological Sciences (University of Reading) PhD Symposium – *The value of burial grounds as urban green spaces for biodiversity in the UK.* July 2021. Awarded Best Talk for 3rd year PhD students in the Ecology and Evolutionary Biology division.

Talk given to all staff at the Commonwealth War Graves Commission Head Office – *Understanding biodiversity in burial grounds.* November 2022.

Cathcart-James, M., Foster, C. and Pickles, B.J. (2022) 'Challenging assumptions about burial ground biodiversity using flying beetles as indicators in urban areas', *Journal of Urban Ecology*, 8(1), pp. 1–14. Available at: https://doi.org/10.1093/jue/juac024 **Chapter 2.**

Cathcart-James, M. (2023) 'Life Amongst Reading's Dead – biodiversity in Reading Old Cemetery', in Y. Dimitriadi (ed.) *Beyond the Arch.* (In press) **Appendix 0.1.**

All Saint's churchyard

Maidenhead

Berkshire

Photo credit: author's own

CHAPTER 1: How much do we know about the places where our physical remains are laid to rest?

1.1 | INTRODUCTION

Urbanisation is widely viewed as anathema to the natural environment and its wildlife. Exploration of the impacts that urban areas, natural habitats, wildlife and human populations have on each other and the complex relationships between them have generated a wide-ranging, interdisciplinary, but often disconnected body of research (Adams and Lindsey, 2011; Latta *et al.*, 2013; Kondratyeva *et al.*, 2020). With the global population estimated to rise to between 9.4 and 10.2 billion by 2050 (United Nations, 2017) and 68% of that population projected to be living in urban areas, up 13% from 2018 (United Nations, 2018) there is a growing urgency to build sustainable and resilient urban environments to improve living conditions. Research fuelling policy decisions regarding urban ecosystem health and function needs to be cross-disciplinary, comprehensive and creative to make the most of all opportunities and have greater impact.

Research across many disciplines - such as ecology, the social sciences and urban planning - into how to enhance the impacts of green infrastructure to improve human wellbeing, is crucial to the implementation of conservation measures in urban development (Chatzimentor, Apostolopoulou and Mazaris, 2020; Monteiro, Ferreira and Antunes, 2020). Defining and quantifying the contributions of urban green spaces, along with establishing which other types of green infrastructure achieve the most benefit for urban human populations, have become topics of significance. Increasing urbanisation, particularly in countries such as the UK where space is limited and population density is high, is putting heightened significance on ring-fencing, enhancing and maintaining existing urban green infrastructure, and including it in urban development (Boakes *et al.*, 2024). The need to prioritise the promotion of urban biodiversity for ecologically resilient towns and cities within urban planning and policy, is widely recognised but not widely acted upon (Oliver *et al.*, 2015; Nilon *et al.*, 2017; Kirk *et al.*, 2021).

In the context of the urban environment, ecological research is often based on the quantities and qualities of green infrastructure and the heterogenous habitat mosaics it forms in conjunction with the characteristic swathes of impervious surfaces (Wu, 2014). The nature of urban ecosystems is a severely fragmented one, made up of potentially many types of green components such as green roofs, street trees and parks – forming green infrastructure. The reader is referred to Chapter 2, section 2.1 for further discussion.

1.1.1 History of the modern UK deathscape

In the UK, methods and places of disposing of the dead have changed significantly in the last 170-200 years, shaping the 'deathscape', or burial ground geography, of modern Britain. Between the 10th and 18th centuries, in metropolitan areas, corpses were typically buried in consecrated ground within settlement limits. Hence old churchyards that were used for centuries can be found in the heart of most towns and cities (Rugg, 2000; Deering, 2012). The Industrial Revolution led to rapid population growth, particularly in London, so that urban consecrated graveyards became over-crowded and unsanitary through grave re-use leading to public health concerns about the proximity of human corpses to the living (Herman, 2010; Yarwood *et al.*, 2015a). The establishment of cemeteries (i.e. a secular burial ground on private or municipal land outside of settlement limits, such as The Rosary in Norwich which opened in 1819 (Bowdler *et al.*, 2007)), rapidly became more widespread in the following decades as a cost-effective way to push disposal of the dead out of populous areas to spacious sites on the outskirts (Rugg, 2000). Authorities were also under increasing pressure to provide non-consecrated burial grounds (Scholz, 2017). By 1841 there were seven privately-owned suburban cemeteries surrounding London (Scholz, 2017) and after the Burial Acts of 1850 and 1853 allowed for the nationalisation of cemeteries, by 1900 there were very few towns that did not have one (Bowdler *et al.*, 2007; Herman, 2010). Also by 1900, burials within the old urban churchyards were either restricted or banned altogether and they were often handed over to local authorities to be maintained (Mytum, Dunk and Rugg, 1994; Rugg, 2000). The dearth of burial space was a problem further eased by the legalisation of cremation in 1885. Whilst older cemeteries have often been overtaken by urban sprawl (Rugg, 2000), the idea of housing the dead outside of concentrated urban populations is a trend still seen in modern times, with most cemeteries and crematoria being established typically just outside a town or city.

Cremation increased in popularity between the World Wars and into the 1950's (Bowdler *et al.*, 2007; Yarwood *et al.*, 2015a) as the Victorian habit for 'showy grief' gave way to a preference for more private, often secular expressions of grief and remembrance. Thus, in the UK, religious beliefs and practices, concerns regarding public health, and fashions in funerary and mourning rituals have shaped Britain's modern deathscape. Near ubiquitous centuries-old churchyards, mostly now full and closed, sit at the ancient heart of urban areas, and much larger, secular, municipally owned cemeteries where cremations far outweigh burials (approximately 70% of burials are now of cremains (Home Office, 2004)) are found on the outskirts of urban areas.

1.1.2 UK burial ground governance and management

In the UK, the Local Authorities' Cemeteries Order of 1977 (LACO) remains the overarching legislation governing the management of burial grounds, which apart from a small number of exceptions including rules around exhumations, allows significant management discretion. Importantly, LACO only applies to local authority burial grounds, not religious or private ones, and makes no mention of ecological or wildlife considerations. In conjunction with LACO allowing for local authorities to have vastly different policies and procedures, this has allowed for inconsistent and ineffective burial ground management.

Official guidance for burial ground managers (DCA, 2005) states the importance of maintaining the burial ground environment, but that there is 'considerable room for debate' regarding the provision of 'wildlife opportunities'. It acknowledges that lawn cemeteries represent ease of maintenance and meet visitor expectations of tidiness and presents these two statements regarding the burial ground environment with no recommendation. The decision-making power is given to individual site managers, which leads to inconsistency, poor ecological practices and a lack of buy-in from managers due to perceived higher effort and cost. In the UK statutory guidance regarding ecological considerations is very limited, focusing on preventing groundwater pollution from burials and mercury emissions from crematoria (DEFRA, 2012; Environment Agency, 2018).

A public consultation on UK burial law was launched in 2004 (Home Office, 2004) during which concerns were raised regarding inconsistency of legislation and the re-development of disused burial grounds (DCA, 2006). The government's response to the consultation (Ministry of Justice, 2007) included decisions to improve burial ground maintenance through advice rather than regulation and to not develop new inspection arrangements. It concluded that rather than putting forward a bill to create a comprehensive framework, it would make smaller changes to existing legislation as needed. Overall, despite public concerns and expert advice, approaches to the governance of burial grounds have hardly changed on a national level since 1977. This is notwithstanding the comprehensive treatment of urban green spaces in modern policy, none of which consider burial grounds (e.g. Office of the Deputy Prime Minister, 2005; Department for Communities and Local Government, 2006; City of Westminster, 2018).

1.1.3 UK burial grounds as urban green spaces

In increasingly fragmented, built-up urban areas, burial grounds have been suggested to form some of the last bastions of grassland, ancient tree, deadwood and old hedgerow habitats (Kowarik et al., 2016). Their longevity is due to their social and cultural protection with ecological preservation almost as a by-product. In addition, place of worship-owned and run graveyards are protected by their private ownership from development. Council-managed burial grounds all have some form of ecologically sympathetic management, as do many private ones (CABE, 2007), however, management practices are extremely inconsistent. With greater urbanisation pressures in modern towns and cities and increased focus on ecosystem health and functioning for human wellbeing, it can be argued that ecological recognition and protection for burial grounds is ever more necessary.

There is a growing demand for burial grounds as the population increases and remaining capacity in existing burial grounds is negligible in many urban areas (Fairbairn, 2012). A better understanding of the characteristics that are of high importance for burial ground biodiversity and ecosystem service provision will inform the ecologically sound design and appropriate positioning of future cemeteries and extensions of existing ones (Bennett and Davies, 2015; Davies and Bennett, 2016).

In the UK, the responsibility for identifying, protecting and ensuring the correct care is taken of urban green spaces generally falls on local authorities (LA). Each LA is responsible for creating its own green space strategy, and these are based on the initial definition of what is classified as an urban green space. These definitions hardly vary between LAs however their treatment of burial grounds is very inconsistent; some strategies go into great detail despite a lack of guidance (GLA, 2017; SBCC, 2018), whereas others do not include them as a type of green space at all (GLA, 2016).

The sparse mentions of burial grounds in government documentation include them in the same category as parks or gardens (e.g. Natural England, 2013), which does not recognise the unique nature of burial grounds and the individual, more sensitive considerations they need to be afforded due to their profound social importance. Public cemeteries are mostly run by Bereavement Services departments; therefore, the focus is on serving the needs of mourners (CABE, 2007) rather than the treatment of cemeteries as green spaces. Overall, in the UK there is no tangible recognition of their contributions to biodiversity, ecosystem service provision or specific, consistent management in place across boroughs, counties or countries.

1.1.4 Burial ground research trends

A literature search was conducted to build a global picture of the quantity and nature of research focused on burial grounds both globally and within the UK. The level of interest in these spaces for biodiversity-related research was also examined. The search quantified the numbers of studies published in the primary literature on burial grounds within a specified timeframe and collated key information about them, followed by allocation of each study to a research topic category.

The period of interest was defined as beginning in the year 1998, one year after the publication of seminal work defining the concept of ecosystem services (Costanza *et al.*, 1997). This led to a whole new area of research that has grown into many applications of the concept in global policy (Costanza *et al.*, 2017). To address the aims of this study, the literature on ecosystem services needed to be included in the review, to ensure that important topics in modern research discourse were not omitted. Searches were conducted of published literature for every calendar year from 1998 up to and including 2020. The search engines Web of Science and Google Scholar were used.

Searches were conducted using the term 'cemetery OR graveyard OR "burial ground"', as all published research including these terms as topics, keywords or within the title were potentially of interest, for each year in the range 1998-2020. Studies were included where either the entire paper related to the search term, or it was the main focus if other subjects were included. Only papers published in the English language, in peer reviewed journals, and available online were included. Only studies related to human burial grounds were included. Author name(s), paper name, journal of publication, year of publication and country where each study was conducted were recorded.

Following assessment of suitability, each study was assigned a primary research subject category (Table 1.1). Where more than one category was addressed, that which was considered the main, or fundamental, topic according to the aims, hypotheses and conclusions were used.

Table 1.1. Topics contained in each research subject category assigned to papers included in the review.

Research subject category	Topics within each category
PRE	Prehistoric archaeology (prior to 3000 BC)
ANC	Ancient archaeology (3000 BC to 476 AD)
MED	Medieval archaeology (476 AD to 1450 AD)
EME	Early Modern Era archaeology (1450 AD to 1750 AD)
LME	Late Modern Era archaeology (1750 AD to present)
HHE	History, heritage
AET	Anthropology, ethnography, thanatology
FTD	Forensics, taphonomy, decomposition
SCU	Social, cultural
RES	Religion, spiritual
GSW	Geology, soil, water
GGL	Geography, geographical techniques, landscape
MPD	Management, planning, design
DCP	Disease, contamination, pollution
EFS	Ecosystem function, ecosystem services, green space
BHE	Biodiversity, habitat, ecology, environment

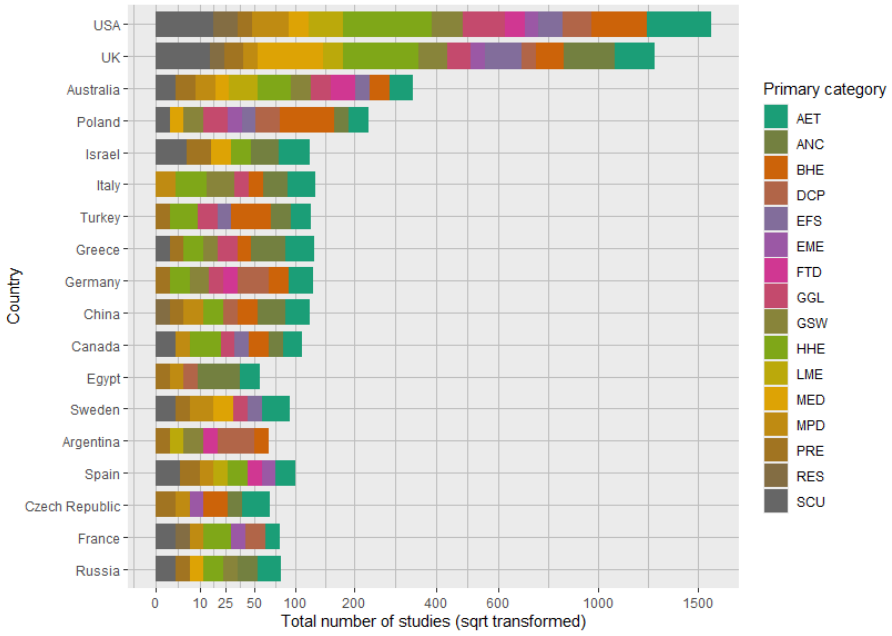
1.1.1 Global research trends

In its entirety the review found 816 papers that met the criteria for inclusion, from 100 countries across all continents except Antarctica. This included one historical study conducted in Yugoslavia which was recorded as 'Ex-Yugoslavian republics'. Palestine was included as a country where authors referenced it as such.

The United States of America produced the greatest amount of research focused on burial grounds with 137 publications (16.8%), followed by the United Kingdom with 113 published papers (13.9%). The number of studies for each country dropped considerably from this point, with the third largest bodies of research being published from Australia and Poland, consisting of 30 studies each (3.7% each).

At the other end of the scale, 75 countries published fewer than 10 studies across the whole period of interest, including 32 countries that were assigned a single study each. In terms of distribution of numbers of studies, 45% of the total number of studies came from only 7 of the 100 countries recorded. Therefore, whilst there is a wide global spread in the number of countries that have produced research on burial grounds in the 22-year period of interest, a relatively small number of countries have generated the majority of publications. The breadth of research topics differed between countries, even those with a similar number of publications; for example, Egypt and Germany had 14 and 17 publications respectively, but Germany had 8 primary research categories compared to Egypt's 4 categories (Figure 1.1).

Figure 1.1. Total number of studies (square-root transformed for visibility) published divided by research category for all countries with 12 or more published studies during the period of interest.



The number of studies within research categories showed variation over time, both in terms of total number of studies for each year and each research category (Figures 1.2 and 1.3). The most research output focused on burial grounds in the period of interest was generated in 2018, with 83 studies (10.17%), followed by 2017 with 63 studies (7.72%). Calendar years with the least amount of research output fall nearer the beginning of the period of interest, the lowest number of studies being published in 2001 (9 studies, 1.1%), followed by 1999 (14 studies, 1.72%). The number of papers published about burial grounds between 1998 and 2020 significantly increased over time ($F_{(1,21)} = 59.08$, $p = < 0.0001$, R^2 adj. = 0.73).

The number of studies published over time within each research category show both intra- and inter-category variation (Figure 1.3). No single category shows a clear trend of increasing studies over time, and some categories (EFS, FTD, GGL, GSW, EME, LME, RES) have so few studies that no trend could possibly be discerned.

Figure 1.2. Total count of studies for each year within the entire period of interest (1998-2020).

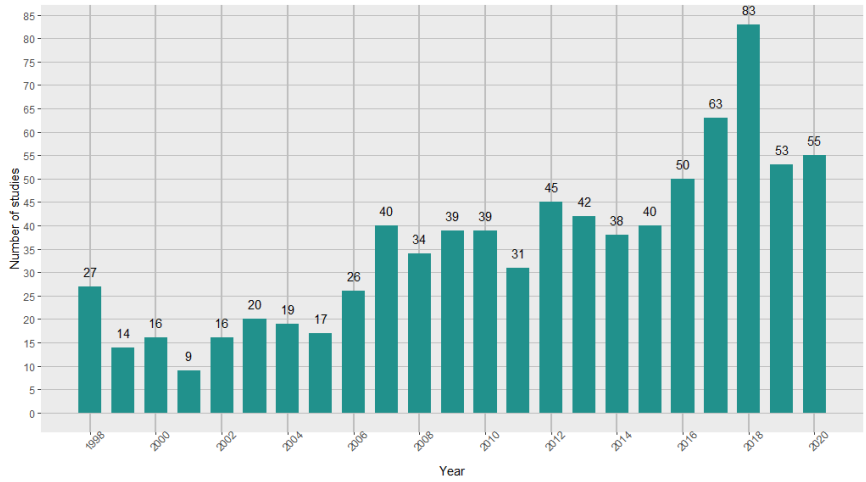
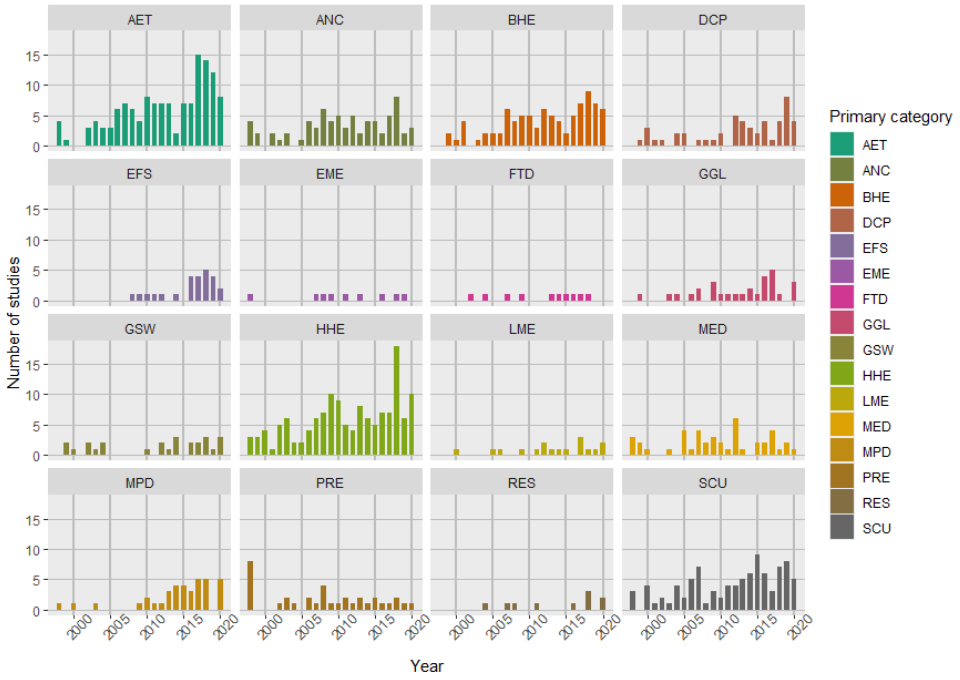
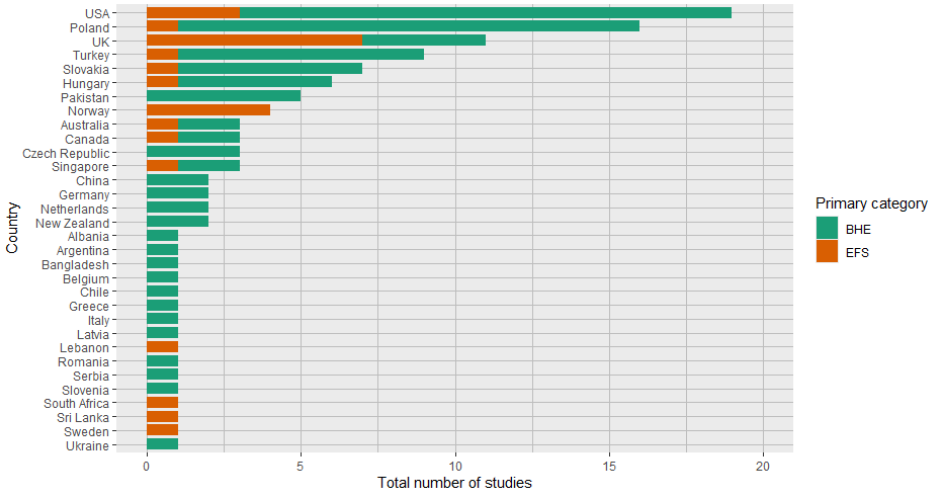


Figure 1.3. Number of studies per year within the period of interest for each research category.



The quantity of research conducted on the subjects relevant to this thesis was also explored to assess how comprehensive the body of work was in understanding biodiversity and ecosystem function in burial grounds. The 113 studies within the BHE and EFS research categories showed variation between countries of origin, both in terms of total number of studies for each country and each research category (Figure 1.4). The most research output was generated in the United States of America with 19 studies (16.8%), followed by Poland with 16 studies (14.2%). The UK produced the third highest amount of biodiversity and ecosystem function-focused research on burial grounds with 11 studies (9.7%). The number of papers published on these subjects regarding burial grounds between 1998 and 2020 significantly increased over time ($F_{(1,19)}$ = 17.51, p = 0.0005, R^2 adj. = 0.45).

Figure 1.4. Total number of studies published within the BHE and EFS research categories for each country between 1998 and 2020.

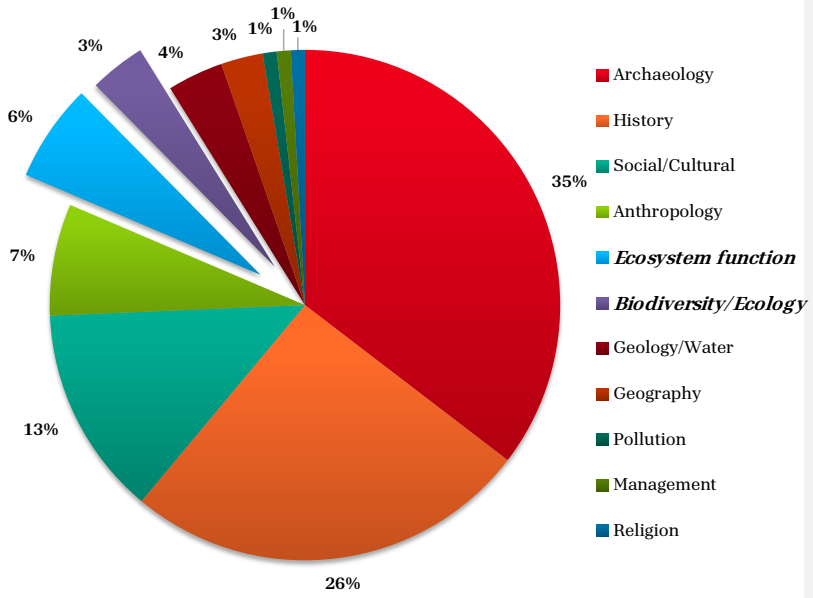


Overall, a body of research constituting 113 papers globally over a period of 22 years with the EFS category not emerging until 10 years into the period of interest (Figure 1.3), cannot constitute a contemporary, comprehensive treatment of burial grounds in an environmental or ecological context. Although there is evidence that research in this area is gaining momentum, as the number of studies globally is increasing, there remain many opportunities to build our understanding of burial grounds within environmental and ecological research disciplines.

1.1.2 UK research trends

Over the 22-year period of interest, the total body of research from the United Kingdom was composed of 113 studies focused on burial grounds (not restricted to urban areas). The majority of the work focuses on the archaeology and history associated with burial grounds, with 9% of studies related to biodiversity, ecology and ecosystems – just 11 studies (Figures 1.4 and 1.5, Table 1.2). Five studies focused on individual species or assemblages, two investigated natural burial sites and four reported on topics related to green infrastructure and cultural ecosystem services.

Figure 1.5. The distribution of studies into burial grounds across research categories for the period of interest.



Research category	Year	Author(s)	Access via	Title	Journal
BHE	2006	Paton & Sheahan	https://doi.org/10.1179/174328206X119952	*Lophocolea brookwoodiana* (Jungermanniales: Geocalycaceae), a new species in Britain	Journal of Bryology
EFS	2008	Kim *et al.*	https://doi.org/10.1080/09593330802008404	A survey of green burial sites in England and Wales and an assessment of the feasibility of a groundwater vulnerability tool	Environmental Technology
EFS	2010	Bates *et al.*	https://doi.org/10.1371/journal.pone.0023459	Changing Bee and Hoverfly Pollinator Assemblages along an Urban-Rural Gradient	PloS ONE
BHE	2011	Gardiner *et al.*	https://conservationevidencejournal.com/reference/pdf/2342	Grasshopper strips prove effective in enhancing grasshopper abundance in Rivenhall Churchyard, Essex, England	Conservation Evidence
BHE	2014	Butt *et al.*	https://www.researchgate.net/publication/281112327	Earthworms of an urban cemetery in Preston: General survey and burrowing of Lumbricus terrestris	Zeszyty Naukowe
EFS	2016	McClymont, K.	https://doi.org/10.1080/13576275.2016.1151865	'That eccentric use of land at the top of the hill': cemeteries and stories of the city	Mortality
EFS	2017	Mooers & Massman	https://doi.org/10.1016/j.scitotenv.2016.10.228	Gravestone decay and the determination of deciduous bulk canopy resistance to acid deposition	Science of the Total Environment
BHE	2018	Barclay, M.	https://www.researchgate.net/publication/324656522	Hololepta plana (Sulzer) (Histeridae) from Margravine Cemetery, West London	The Coleopterist
EFS	2018	Clayden, A.	https://doi.org/10.1016/j.ufug.2017.08.012	Cutting the lawn – Natural burial and its contribution to the delivery of ecosystem services in urban cemeteries	Urban Forestry & Urban Greening
EFS	2019	Lai *et al.*	https://doi.org/10.3390/urbansci3030072	Everyday Use of the City Cemetery: A Study of Environmental Qualities and Perceived Restorativeness in a Scottish Context	Urban Science
EFS	2020	Laia *et al.*	https://doi.org/10.1016/j.ufug.2020.126720	Are greenspace attributes associated with perceived restorativeness? A comparative study of urban cemeteries and parks in Edinburgh, Scotland	Urban Forestry & Urban Greening

Table 1.2. Details of the 11 studies published in the UK within the BHE and EFS research categories between 1998 and 2020.

1.1.5 Biodiversity of UK urban burial grounds

In a global context, biodiversity inventories for individual cemeteries or towns are most common within the limited literature, mostly based on flora (Otves, Arsene and Neacşu, 2016; De Lacy and Shackleton, 2017; Yılmaz, Kuşak and Akkemik, 2017) but with other groups such as birds and mammals investigated in a few isolated studies (Čanády and Mošanský, 2017; Gallo *et al.*, 2017; Tryjanowski *et al.*, 2017). Work has also been published in a single cemetery but taking a multi-taxon approach (Buchholz et al., 2016; Kowarik et al., 2016). These inventories do indicate habitat type and quality in burial grounds and highlight their biodiversity value which is important, however their impact and practical application is limited – for example, discussion of management intensity and type is inconsistent or absent, and the studies are isolated within cities without scope to extrapolate.

There is a significant dearth of ecologically focused research on burial grounds, whether urban or not, in the UK. A recent review of global research on burial ground biodiversity, which is often cited in recent relevant literature (Löki et al., 2019), reported just six articles published from the UK before March 2018. One of these was a report on an ecological survey undertaken in a single churchyard (Baker, 2004) focusing on flora, and there was only a single mycological exploration (Fortey, 2000). These reports were not included in the literature search reported in section 1.1.4 of this thesis as they were not published in peer-reviewed journals. Another study reported results of a grasshopper strip experiment in a rural churchyard (Gardiner, Gardiner and Cooper, 2011), the single UK animal-based study found by the review. None of the studies found by Löki et al. (2019) published from the UK addressed burial grounds in urban areas specifically. The trend found in this review was for thematic surveys and descriptive studies of single locations, which dominate the limited ecological literature on burial grounds. Although these types of study can be of restricted scope and impact, they do form a baseline of understanding, and even these are very much missing from the UK. In addition, Loki et al.'s (2019) review found a total global absence of studies looking at the direct effect of management practices on burial ground biodiversity.

Looking beyond thematic biodiversity descriptions, there is some evidence of urban cemeteries being examined as green spaces in the UK. A study from Scotland found that cemeteries play an important role as green spaces for 'perceived restorativeness' of visitors (Lai et al., 2020). Another recent study examined the potential for natural burial spaces within traditional cemeteries to enhance urban ecosystem service provision (Clayden *et al.*, 2017), which highlights the ecological importance of municipal cemeteries in the urban landscape but is largely descriptive of site layouts and is limited by a focus on only three sites across the UK. The

UK is a world leader in green or natural burials, and this is the focus of a small body of recent research (Clayden and Dixon, 2007; Powell et al., 2011; Yarwood et al., 2015). There is however a lack of quantification of biodiversity in natural burial sites in the UK, and these are mostly found outside of urban areas.

Overall, ecological research in urban burial grounds in the UK is limited to a small number of isolated studies that do not constitute an overview of their contributions to biodiversity or ecosystem functioning for service provision. In order to understand and enhance any valuable contributions by urban burial grounds in the UK, it is necessary to not only quantify the biodiversity that supports their generation, but to elucidate factors that influence it.

1.2 | THESIS AIM AND OBJECTIVES

Aim:

To investigate UK urban burial grounds as an under-explored greenspace and place them into the context of wider UK ecosystems through the exploration of novel landscape, burial ground management, arthropod biodiversity and soil data.

Objectives:

1. To assess the extent to which different factors influence the biodiversity of flying beetles focusing on human population, urban landscape variables, and local management regimes.

2. To characterise the unique soils, i.e. "necrosols", of urban ~~graveyards~~burial grounds and place~~ing~~ them in the context of wider UK urban soil properties and international pollution standards.

3. To examine the factors influencing the ground-level arthropod communities of urban ~~graveyards~~burial grounds using standard pitfall trap surveys.

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1.3 | REFERENCES

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Braywick Cemetery

Maidenhead

Berkshire

Photo credit: author's own

CHAPTER 2

This chapter represents my initial empirical exploration of biodiversity in UK urban burial grounds. In addition to producing initial insights, the chapter builds the foundation for the rest of the thesis, capturing characteristics of the sites on which this thesis is centred and the surrounding urban landscapes. This chapter is also a first attempt to quantify influences of burial ground management on biodiversity, a key theme throughout the thesis as the primary way in which stakeholders can have an impact.

Author contributions

I conceived and designed the study with contributions from Brian Pickles and Graham Holloway. I established the study sites and gained permissions, developed the sampling protocol with contributions from Graham Holloway, collected all data with the assistance of Bria Cuthbert during beetle sampling, undertook the analyses with Brian Pickles contributing to the statistical methods and data analysis, and drafted the manuscript. Brian Pickles and Chris Foster reviewed the manuscript and contributed to the revised manuscript submission.

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CHAPTER 2: Challenging assumptions about burial ground biodiversity using flying beetles as indicators in urban areas

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2.0 | ABSTRACT

Biodiversity is fundamental to the provision of ecosystem services that benefit urban communities, yet one type of green space is largely overlooked in ecological research and local governance: urban burial grounds. Their longevity, profound importance to society, and ubiquitous nature, provide unique opportunities for urban biodiversity. However, there has been little scientific exploration of their potentials.

To quantify biodiversity in urban burial grounds, a low impact methodology for the capture of flying beetles was developed and deployed at 20 sites in southern England. To the authors' knowledge this work represents the largest sampling of burial grounds in a single study. We used Generalized linear Mixed Models to examine the influence of weather, local demographic variables, urban landscape, and burial ground vegetation management on the abundance of flying beetles.

We found significant variability in beetle assemblages over time and between burial grounds. Burial ground age was not significantly associated with flying beetle abundance, challenging long-standing assumptions about older burial grounds being more valuable for biodiversity. Increasing area of domestic gardens and hedgerows in the surrounding urban landscape was positively associated with beetle abundance, whereas the most significant negative association was with burial ground size. Additionally, management of burial grounds significantly influenced beetle abundance: more stringent regimes typically resulted in lower abundance, but sites with horticultural landscaping or biodiversity-focused regimes exhibited higher abundances.

Keywords: biodiversity, abundance, flying beetles, Coleoptera, graveyard, burial ground, greenspace, indicator, management, urban

2.1 | INTRODUCTION

Urban green spaces, a form of green infrastructure, are widely acknowledged as key components of the urban environment with regards to supporting urban biodiversity, providing they are well-planned and managed (MacGregor-Fors et al., 2016; Aronson et al., 2017; Lepczyk et al., 2017; Threlfall et al., 2017). This, in turn, is what underpins the delivery of ecosystem services for urban communities, with evidence showing direct and indirect links between biodiversity and human physical and mental wellbeing (Harrison *et al.*, 2014; Ziter, 2016; Kondo *et al.*, 2018). Within the body of research exploring urban green spaces, the biodiversity therein, and their benefits to people, definitions of what types of places constitute urban green space differ between studies (Taylor and Hochuli, 2017), and many focus on just one or two types with public parks and gardens being prevalent. There is however, one type of urban green space that is often excluded from definitions in research, policy, and land management contexts, despite being globally ubiquitous out of necessity – burial grounds. Here we explore the impacts of urban landscape, human population density, and site-scale management decisions on the biodiversity of urban burial grounds, using beetles as indicator taxa.

In ecological research terrestrial invertebrates are commonly used as biodiversity indicator taxa (Gerlach, Samways and Pryke, 2013), with their diversity used to estimate the wider diversity of other taxa within a habitat to monitor how this changes over time (McGeogh, 1998). The ubiquitous insect order Coleoptera (beetles) has long been used in population, conservation, and landscape ecology studies (Hirao, Murakami and Kashizaki, 2008; Kyrö *et al.*, 2018), with carabids (ground beetles) in particular gaining status as model organisms and indicators of wider biodiversity patterns (Johan Kotze *et al.*, 2011; Koivula, 2011). Beetles meet important criteria for maximising indicator species usefulness (Noss, 1990), such as well understood biology, life history and taxonomy, being easily captured or observed in the field, and occurring in a wide range of habitat types (Pearson and Cassola, 1992; Bohac, 1999; Brin, Brustel and Jactel, 2009; Koivula, 2011). Recognised issues with using indicator taxa include: i) a lack of understanding of how well they represent other taxa, and ii) the rare reporting of statistically strong correlations (Rainio and Niemelä, 2003; Gao, Nielsen and Hedblom, 2015). However, beetles have successfully been used as biodiversity indicators in urban areas, using ground-dwelling families (Do, Lineman and Joo, 2014; Kyrö *et al.*, 2018), and in forests, using flying species (Ohsawa, 2010), and beetles are often used as proxies in the context of ecosystem service provision (Noriega et al., 2018). In addition, several ground beetle species have been identified as indicators of habitat age in urban cemeteries (Kowarik et al., 2016). Therefore, evidence suggests

that examining Coleoptera as a biodiversity indicator could produce valuable results in the context of burial grounds as urban green spaces.

Due to their unique positioning in society as places of profound cultural and historical importance, it is not possible to examine burial grounds as green spaces purely through an ecological lens. To build a comprehensive understanding of urban burial grounds as green spaces, their value for biodiversity and therefore more widely for ecosystem service generation, it is necessary to integrate historical, social changes with land management and ecological understanding. With greater urbanisation pressures in modern towns and cities, and subsequently an increased focus on ecosystem services for human health and wellbeing (Haase *et al.*, 2014; Costanza *et al.*, 2017; Hegetschweiler *et al.*, 2017), it can be argued that ecological recognition of and protection for urban burial grounds is ever more necessary.

An unresolved issue regarding burial grounds in the UK is uncertainty regarding their number and coverage. Estimates put the overall number of burial grounds (classified as Christian churchyards, official sites of burial for all other religions and cultures, and cemeteries) between 12,000 and over 25,000 (Home Office, 2004; CABE, 2007). The most comprehensive survey covering England and Wales reported 9747 sites and a total of approximately 20,000 acres (80.94 km^2) (HMCS, 2007); the true current acreage is unknown but likely to be significantly higher. Recent statistics for the UK as a whole specifically noted 'cemeteries' and 'religious grounds' as publicly accessible green spaces, forming an estimated 8.9% (18,878 acres or 76.40 km^2) and 6.7% (14,211 acres or 57.51 km^2) of the UK's total urban green space respectively (Office for National Statistics - Uk Gov, 2019). Whilst parks, gardens and playing fields dominate publicly accessible green spaces, 15.6% (133.91 km^2) is a meaningful contribution from burial grounds that merits research and policy attention. However, there is currently very little co-ordination between managers, owners, and other stakeholders of burial grounds in the UK.

From an ecological management perspective, a piecemeal legislative situation and lack of legally binding site management practices pose serious issues when considering burial grounds as green spaces. The lack of legislative ecological protection for urban burial grounds stems from a profound lack of relevant research into them (Jackson and Ormsby, 2017). Although there is a general assumption that many graveyards are unique, often ancient, and minimally managed habitats that can sustain a wealth of biodiversity, there has been little scientific exploration of this. A recent review of global research on burial ground biodiversity (Löki et al., 2019) found a total absence of studies looking at the direct effect of management practices on burial ground biodiversity and reported just six articles published from the UK before March 2018, none of which addressed burial grounds in urban areas specifically. One of these was a report on an

ecological survey undertaken in a single churchyard (Baker, 2004) focusing on flora, and there was only a single mycological exploration (Fortey, 2000). Another study reported results of a grasshopper strip experiment in a rural churchyard (Gardiner, Gardiner and Cooper, 2011), the single UK animal-based study found by the review. The trend found by Löki et al. (2019) was for thematic surveys and descriptive studies of single locations, which dominate the limited ecological literature on burial grounds. Although these types of study can be of restricted scope and impact, they do provide baseline data, and even these are very much missing from the UK.

Beyond thematic biodiversity descriptions, there is some evidence of urban cemeteries being examined as green spaces in the UK. A study from Scotland found that cemeteries play an important role as green spaces for 'perceived restorativeness' of visitors (Lai et al., 2020). Another recent study examined the potential for natural burial spaces within traditional cemeteries to enhance urban ecosystem service provision (Clayden *et al.*, 2018), which highlights the ecological importance of municipal cemeteries in the urban landscape but is largely descriptive of site layouts and is limited by a focus on only three sites across the UK.

Overall, ecological research in urban burial grounds in the UK is limited to a small number of isolated studies that do not constitute an overview of their contributions to biodiversity or their value as urban green spaces.

2.1.1 Aims and objectives

Here we examined the factors influencing biodiversity within twenty urban burial grounds in different urban areas in the south of England, using flying beetles as an indicator. The majority of ecological studies in burial grounds focus on one to five sites, so this represents a large-scale ecological investigation of these spaces. By quantifying measures of biodiversity, namely abundance and family-level diversity of the indicator and capturing a range of urban landscape and environmental variables, we set out to examine the role that urban burial grounds play as ecological units in urban landscapes and the factors that influence their value for biodiversity. To begin to address the global absence of research into the impacts of burial ground management on urban biodiversity, we further investigated whether different types of landscape management practices influenced flying beetle biodiversity.

We investigated the following research questions: 1) What is the family-level biodiversity of flying beetles in urban burial grounds, in terms of abundance and richness? 2) Is their biodiversity affected by the age or size of urban burial grounds, or by human population pressure

in the wider urban area? 3) Does the composition of the landscape surrounding urban burial grounds influence their biodiversity? 4) Does the grounds management of urban burial grounds influence their biodiversity?

2.2 | METHODS

2.2.1 Study sites

Permissions were gained to conduct sampling in 20 burial grounds in towns within the English counties of Berkshire, Hampshire, Surrey and Buckinghamshire (Table 2.1, Figure 2.1, Appendix 2.1). Population size was used as a proxy for defining 'urban', and towns with burial grounds were chosen that had a minimum population of 20,000 people; considered 'large towns' according to a popular settlement hierarchy used in UK planning policy (Doxiades, 1968). Each site was allocated to one of four management categories based on information provided by site managers (Table 2.2).

Table 2.1. Details of the 20 sample sites used for flying beetle sampling in 2018.

Site	Name	Abbreviated name	Town	Pop. by 2017 census	Population density (people/ km²)	Size (m²)	Age
1	Henley Road Cemetery	Hen.Rd	Reading	229274	4483	195640	91
2	Caversham Cemetery	Cav	Reading	229274	4483	15587	133
3	Reading Old Cemetery	Old	Reading	229274	4483	46782	175
4	Larges Lane Cemetery	Lar.Lane	Bracknell	83491	4057	11147	128
5	Worting Road Cemetery	Wor.Rd	Basingstoke	114329	3917	52617	104
6	Shaw Cemetery	Shaw	Newbury	41883	3574	49188	105
7	Newtown Road Cemetery	Newt.Rd	Newbury	41883	3574	18413	168
8	All Saints Churchyard	All.Sts	Maidenhead	67441	3862	3152	162
9	Braywick Cemetery	Bray	Maidenhead	67441	3862	32041	65
10	Slough Cemetery and Crematorium	Slo.Crem	Slough	164046	5410	139929	86
11	High Wycombe Cemetery	Wyc.Cem	High Wycombe	124073	3794	99216	163
12	Wokingham Free Church Burial Ground	Wok.FBG	Wokingham	46745	3233	4463	97
13	St Michael's Churchyard	St.Mic	Camberley	39541	2949	21430	167
14	Fleet Cemetery	Flt.Cem	Fleet	41233	3440	20746	104
15	Windsor Cemetery	Winds.Cem	Windsor	32207	4409	45843	164
16	London Road Cemetery	That.Cem	Thatcham	26217	4530	27056	129
17	Stoke Old Cemetery	Stk.Old	Guildford	85208	4104	28304	135
18	Mount Cemetery	Mount	Guildford	85208	4104	34688	162
19	Eashing Cemetery	Eash	Godalming	23410	3331	61256	118
20	Nightingale Cemetery	Ngale	Godalming	23410	3331	17576	161

Figure 2.1. Map showing locations of study sites (red circles) within the wider geographical context of the South of England.

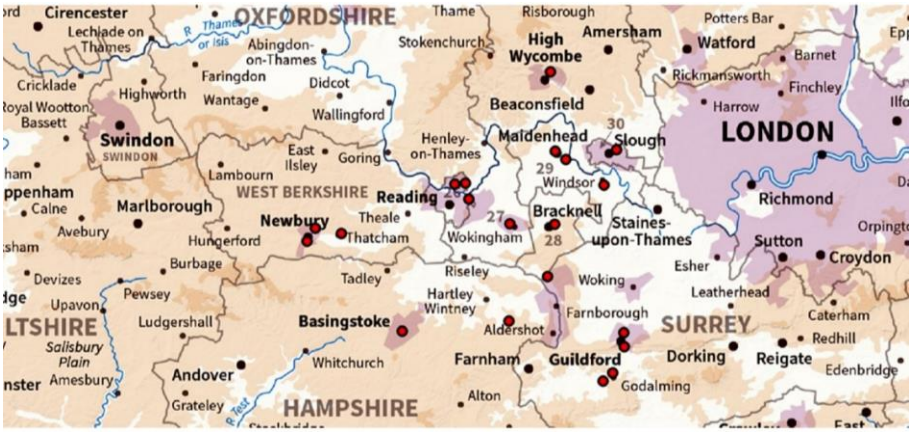

Table 2.2. Description of study site management categories and the sites allocated to each category.

Management category	Description	Sites allocated
Clear	Usage: in use Horticultural design elements: few/none Trees and hedges: sparse, heavily pruned Lawn: ubiquitous, close-cropped Mowing/strimming: non-discriminatory, 2-4 per month Free growing areas: None Biodiversity management: None	6. Shaw 9. Braywick 12. Wokingham Free 14. Fleet 15. Windsor 19. Eashing 20. Nightingale
Scape	Usage: in use Horticultural design elements: present, well-kept (e.g. planted flower/shrub arrangements) Trees and hedges: present, well-kept Lawn: present Mowing/strimming: 1-3 per month Free growing areas: None to very few Biodiversity management: None	1. Henley Road 5. Worting Road 10. Slough 11. High Wycombe 16. London Road
Wild	Usage: full or in use Horticultural design elements: few Trees and hedges: present, no or minimal pruning Lawn: present Mowing/strimming: minimal to none Free growing areas: set-aside for grassland/wildflowers Biodiversity management: Present, part or whole	4. Larges Lane 7. Newtown Road 8. All Saints 17. Stoke Old 18. Mount
Min	Usage: full except family plots, no to few interments Horticultural design elements: few/none Trees and hedges: present, safety management only Lawn: Not present (patches of grassland) Mowing/strimming: once per year (late summer) Free growing areas: present (safety management only) Biodiversity management: Present but unintentional (safety management only)	2. Caversham 3. Reading Old 13. St Michael's

2.2.2 Flying beetle sampling development

Pitfall trapping has long been a widely accepted, convenient technique for sampling ground-dwelling arthropods (Greenslade, 1964; Johan Kotze et al., 2011; Montgomery et al., 2021). However, for this project the profound social and sacred importance attached to the actual ground in graveyards meant that a less invasive methodology needed to be employed. This was at the behest of site managers, due to concerns about public perceptions.

Light traps have also been used successfully to capture beetles (Hébert *et al.*, 2000; Hirao, Murakami and Kashizaki, 2008) and are much less invasive, however safety considerations of working in urban areas and site managers' concerns over public perceptions precluded this method from being used here. Therefore, whilst beetles are the focus of this study's sampling effort based on their demonstrable value in previous ecological research, neither carabids specifically nor light traps were deemed suitable. Hence, an alternative minimally invasive survey method was developed for the capture of flying beetles, to be used as a proxy measure of biodiversity.

2.2.3 Sampling protocol

The final apparatus used was a white, UK standard single size (180 x 260 cm) bedsheet affixed to two tent poles (or alternatively, affixed to the poles at the top end and pegged into the ground at the bottom) held upright by guy ropes pegged into the ground with small diameter metal pegs (see Appendix 2.2). It was important to ensure the sheet was as taut as possible to prevent movement or snapping in a breeze so as not to divert or dislodge insects, and this was achieved by using adjustable height poles and tethering them to the ground with guy ropes in a tripod fashion for stability a suitable distance apart.

In addition, another identical white sheet was placed flat on the ground as a further sampling area, as it was unknown whether flying beetles would preferentially land on the ground or sampling would be more successful when intercepting them in the air. The design of this sheet trap meant that upon its removal, only 4 small peg holes would be left in the ground (which due to grass cover would be unnoticeable) and the surrounding grass flattened by footsteps, which would recover.

Sampling took place between the 19th of April and 7th of September 2018. Four samples were conducted within each site; a randomised list of sites was created for each replicate using the 'rand( )' function in Excel 2016. Samples were conducted in this randomised order, during

daylight hours on days when climatic conditions were considered suitable for beetles to take wing i.e., when warm enough (min. 18°C) (Caprio and Grafius, 1990; Cox, Wakefield and Jacob, 2007; Gaylord *et al.*, 2008) with low wind speed (max. 7 mph) (Blau and Stinner, 1983; Vanwoerkom, Turpin and Barrett, 1983). Placement of the sheet trap within the site for each replicate was decided upon arrival, as it was necessary to ensure that it was set up away from any visitors present and not encroaching on graves.

Each sample was conducted for a 2-hour period, whereby a pooter was used to capture beetles landing on both the upright and ground sheets (both sides of the upright sheet were used). An anemometer was used to record ambient temperature at the start and finish of each sample, initial wind speed and relative humidity. An approximation by eye was made by the sampler of the percentage cloud cover at the start of each sample. Collected Coleoptera samples were kept in the collection tubes and frozen at -20°C for a minimum of 24 hours. They were then identified to the family level and preserved in 70% (v/v) ethanol at the Health and Life Sciences Building, University of Reading, Berkshire, UK.

2.2.4 Land category data

Data was obtained on the positioning of each burial ground in relation to other land use types within their urban landscapes. As this data was to be used in investigations of beetle abundance and diversity, a suitable area around the sample sites needed to be established. Other studies sampling Coleoptera in urban areas to understand community dynamics obtained landscape data for a maximum buffer area of 400 metres around each sample site (S. Braaker, J. Ghazoul, 2014a; Kyrö *et al.*, 2018), and based on this a maximum radial buffer of 400 metres was used here.

Ordnance Survey map, topography and satellite image data for each site and its immediate surrounding area were obtained from the EDINA Digimap Ordnance Survey Service. These files were loaded into and manipulated using ArcGIS version 10.5.1 to create maps with the site at the centre and radial buffers around it at intervals of 50, 100, 200 and 400 metres (Figure 2.2). Where polygons had not been assigned a land type, the satellite image was used to determine their nature and then a land type was manually assigned. Land types were assigned to five categories (Table 2.3), and the total area in m^2 for each category was calculated for each buffer interval.

Figure 2.2 Map of Reading Old Cemetery (Site 3) and surrounding 50, 100, 200 and 400 metre radial buffers, created using the OS MasterMap™ Topography Layer in EDINA Digimap Ordnance Survey Service.

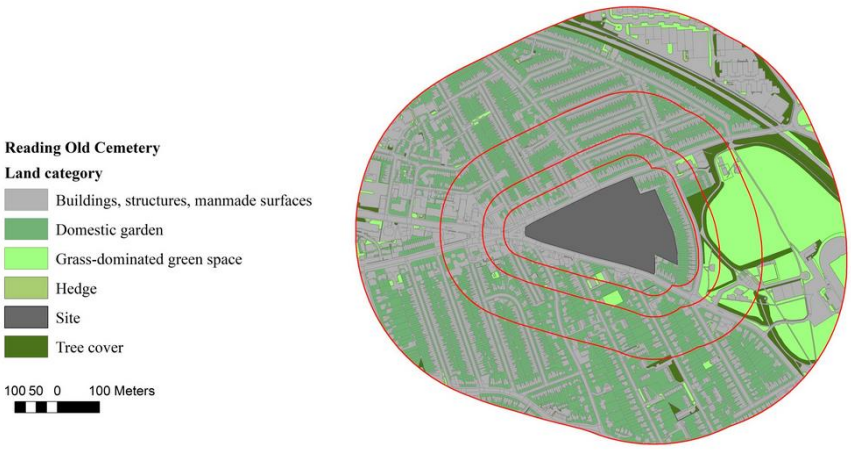

Table 2.1. Land categories assigned to the OS MasterMap™ Topography Layer polygons within radial buffers around each study site.

Code	Land category	ArcGIS Topography land types assigned
BSMS	Buildings, Structures and Manmade Surfaces	Building, Structure, Path, Road or Track, Car park, Rail
GDGS	Grass-Dominated Green Space	Amenity grassland, Allotment, Green roundabout, Agric grass, Golf course, Nature reserve, Parkland, Park, Graveyard (other than site)
Hdg	Hedge	Hedge
Gdn	Domestic Garden	Garden
TC	Tree Cover	Broad tree cover, Conifer tree cover, Scattered tree cover, Mixed tree cover

2.2.5 Statistical analysis

Indicator species analyses (IA) was performed for the multivariate beetle family dataset using Monte Carlo significance testing with 999 randomisations (Dufrêne and Legendre, 1997) in PC-Ord 5.0 (Wild Blueberry Media LLC, Corvallis, Oregon, USA) to examine whether specific beetle families were significant indicators of Site, Replicate, or Management type. All other statistical analyses were conducted in R version 4.0.3 (R Core Team, 2020) using R Studio Version 1.3.959.

Predictor variables were first screened for multicollinearity using pairwise correlation matrices. Landscape variables (Table 2.3) within the 50, 100, 200 and 400 m buffer zones (Figure 2) were strongly and positively correlated with each other ($0.95 \leq r \leq 0.60$), with the sole exception of hedges (Hdg) inside the 400-metre buffer ($r < 0.20$). Hence, in further analyses only one buffer level (200m) was used for each land category. A significant positive correlation was found between total town population and both (i) population density ($r = 0.63$), and (ii) the area of buildings and impervious surfaces ($r = 0.54$; see BSMS in Table 3). Lastly, a moderate but significant negative correlation was found between average temperature and relative humidity recorded at the time of sampling ($r = -0.45$). All variables were scaled and centred to allow for meaningful comparison.

To address our research questions regarding whether total beetle abundance was affected by (i) environmental conditions at the time of sampling, (ii) urban landscape and population factors, or (iii) site management, we used additive and interactive generalised linear

mixed models (GLMMs). Based on the collection of count data, a Poisson error structure was initially used to model the response, but the residuals of all such models were found to be overdispersed. To account for this, we instead used GLMMs with a negative binomial error structure. All models used sampling replicate as a random effect and we confirmed the lack of multicollinearity using tests of variance-inflation factors (VIF). Relative humidity showed consistently high VIF values and was therefore removed prior to further analyses.

Due to the large number of potential explanatory variables, we explored all combinations of predictor variables using the dredge function in MuMIn package (Bartoń, 2020). We then applied a multi-model averaging approach to the set of potentially informative candidate models (all models with ΔAICc < 7, as suggested by Burnham *et al*. (Burnham, Anderson and Huyvaert, 2011)) to assess which of the multiple predictors (weather, human population, landscape) were most strongly related to beetle abundance. GLMMs were constructed with R package "lme4" (Bates *et al.*, 2015) using a negative binomial error structure (log link). Multi-model averaging was conducted using R package "MuMIn" (Bartoń, 2020). Model validation, including tests of singularity, variance inflation factors (VIF), and model fit was assessed using R package "performance" (Lüdecke *et al.*, 2021). Importance values were calculated for each predictor and the significance of predictor variables was assessed using the 95% confidence intervals of their coefficients. These analyses were conducted on total abundance across all beetle families, and for individual families with sufficient abundance ($n \geq 50$).

2.3 | RESULTS

2.3.1 Overall abundance, diversity, and temporal change

The sheet trap surveys captured a total of 884 individuals within 24 Coleopteran families, with Nitidulidae (sap beetles), Chrysomelidae (leaf beetles), and Curculionidae (true weevils) making up 48.2%, 25.9%, and 7.8% of the total capture, respectively.

Across all sites the total observed beetle community changed significantly over time during the sampling period (19th April to 7th September 2018) (Appendix 2.3 and Appendix 2.4a). Jaccard coefficients were calculated as a measure of taxonomic family similarity between samples, and show that replicates 1, 2 and 3 are very similar in terms of community composition, sharing between 44% and 56% of families. Replicate 4 was relatively distinct from all previous replicates, sharing between 35% and 37.5% of families (Appendix 2.5a). Both Shannon and

Simpson diversity indices showed that Replicate 1 had the highest beetle family diversity, followed by Replicates 2, 4 and 3 respectively (Appendix 2.4a).

Indicator analyses show that certain families were significantly associated with a particular temporal replicate, based on abundance and incidence(Table2.4). Apionidae (seed weevils) were significantly associated with Replicate 1 (p=0.003), Nitidulidae with Replicate 3 (p=0.001) and both Chrysomelidae and Latridiidae (minute brown scavenger beetles) with Replicate 4 (p=0.001 and 0.031, respectively). In addition to these changes in family composition over time, total beetle abundance showed distinct inter-site variation (Figure 2.3).

Figure 2.3. Boxplot of total beetle abundance (square root transformed) grouped by management category for each sample site.

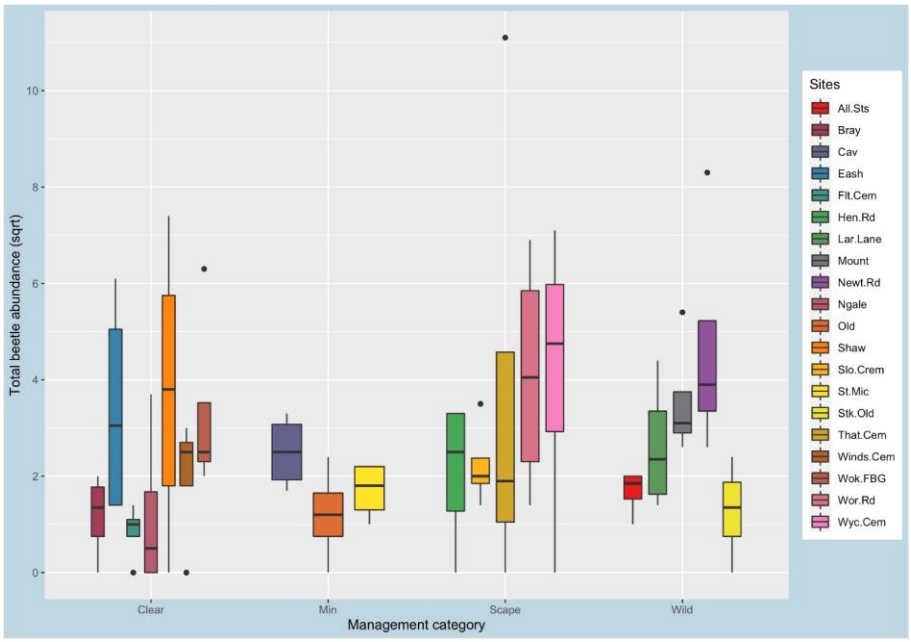

Table 2.4. Indicator analysis for all beetle families between temporal replicates (1), and for families with significantly higher abundance/incidence between management categories within temporal replicates (2).

Beetle family	Group	Observed indicator value	Monte-Carlo Mean	Monte-Carlo SD	P-value*
1. Replicate					
Apionidae	1	32.6	12.1	4.55	0.003
Cryptophagidae	1	15.8	9.4	4.53	0.099
Staphylinidae	1	21.8	13.4	5.09	0.074
Nitidulidae	3	57.3	22.8	6.65	0.001
Chrysomelidae	4	62.9	25.5	5.94	0.001
Coccinellidae	4	23.4	16.8	5.28	0.113
Endomychidae	1	15.0	6.1	3.68	0.055
Curculionidae	1	16.4	19.2	5.51	0.644
Carabidae	1	12.4	7.4	4.13	0.134
Elateridae	1	4.3	6.3	3.84	0.614
Oedemeridae	2	11.4	8.1	3.89	0.176
Scraptiidae	1	6.2	6.1	3.66	0.563
Erotylidae	1	5.0	5.8	0.67	1
Dasytidae	1	5.0	5.8	0.67	1
Ptinidae	2	6.7	5.8	0.67	0.236
Melyridae	2	6.7	5.8	0.66	0.194
Dermestidae	3	12.5	5.3	3.52	0.105
Cerambycidae	3	6.2	5.8	0.67	0.485
Tetratomidae	2	6.7	5.8	0.67	0.218
Byturidae	2	6.7	5.8	0.67	0.217
Ptilidae	4	5.6	5.8	0.68	0.685
Latridiidae	4	16.7	6.2	3.61	0.031
Corylophidae	4	5.6	5.8	0.67	0.721
Melandryidae	4	11.1	5.5	3.2	0.148
2. Management (Replicate)					
Apionidae	Scape (R3)	50.0	25.1	15.10	0.051
Chrysomelidae	Clear (R4)	56.3	41.1	8.32	0.042

*Proportion of 999 randomized trials with indicator value equal to or exceeding the observed indicator value. P = (1 + number of randomized runs >= observed)/(1 + number of randomized runs).

2.3.2 Influence of size, age, and local human population factors

Site size was, *a priori*, predicted to positively influence biodiversity. Using multi-model inferencing, from the set of all plausible models (Appendix 2.6a), we found that site size had a significant negative influence on total beetle abundance in the AICc "best" model (Appendix 2.6b). Site size was the 5th most important factor in the multi-model inferencing analysis, with a negative effect on abundance, but this was not found to be statistically significant (RI = 0.39, p=0.286; Table 2.5). Burial ground age was also predicted to have a positive influence on biodiversity. However, age did not appear as a significant influencing factor based on relative importance values (Tables 2.5 and 2.6) and was not included in any of the "best" models for total abundance or abundance of individual beetle families (Appendices 2.6 to 2.9). Increasing population pressure was predicted to have a negative influence on biodiversity. We found that population density was negatively associated with total beetle abundance and ranked 4th in terms of relative importance (Table 2.5). However, in both the AICc "best" model including management (Appendix 2.6b) and the multi-model inferencing (Table 2.5), this association did not constitute a significant effect. Similarly, total town population was included in the AICc "best" model (Appendix 2.6c) and was negatively associated with beetle abundance, but this effect was not statistically significant (Appendix 2.6c). Using multi-model inferencing town population was ranked 6th in terms of relative importance.

Table 2.5. Model-averaged coefficients for factors influencing total abundance based on multi-model inference ordered by relative importance value (RI). Bold indicates significance based on 95% CI.

Factor	Coef	Adj. SE	95% CI	Z value	P value	RI
Domestic garden	0.022	0.0102	(0.0021, 0.0426)	2.162	0.031	0.72
Hedge	0.017	0.0085	(0.0002, 0.0338)	1.984	0.047	0.65
Average temperature	0.012	0.0073	(-0.0027, 0.0265)	1.600	0.110	0.50
Population density	-0.014	0.0134	(-0.0402, 0.0127)	1.018	0.309	0.40
Site size	-0.018	0.0164	(-0.0500, 0.0148)	1.067	0.286	0.39
Town population	-0.010	0.0148	(-0.0391, 0.0192)	0.668	0.504	0.36
Tree cover	-0.011	0.0094	(-0.0301, 0.0075)	1.179	0.239	0.36
Grass-dominated green space	0.011	0.0130	(-0.0144, 0.0371)	0.864	0.388	0.33
Management category	NA	NA	NA	NA	NA	0.32
Min	-0.003	0.0134	(-0.0297, 0.0233)	0.235	0.815	NA
Scape	0.032	0.0161	(0.0002, 0.0638)	1.975	0.048	NA
Wild	0.008	0.0111	(-0.0141, 0.0300)	0.708	0.479	NA
Cloud cover	0.008	0.0083	(-0.0083, 0.0249)	0.979	0.328	0.31
Buildings, structures and man-made surfaces	-0.007	0.0104	(-0.0275, 0.0138)	0.646	0.518	0.30
Site age	0.000	0.0103	(-0.0201, 0.0209)	0.038	0.970	0.24
Wind speed	-0.001	0.0083	(-0.0172, 0.0156)	0.097	0.923	0.24

Table 2.6. Model-averaged coefficients for factors influencing Nitidulidae abundance based on multi-model inference ordered by relative importance value (RI). Bold indicates significance based on 95% CI.

Factor	Coef	Adj. SE	95% CI	Z value	P value	RI
Domestic garden	0.070	0.0210	(0.0285, 0.1108)	3.316	>0.001	0.98
Hedge	0.054	0.0186	(0.0171, 0.0899)	2.881	0.004	0.93
Site size	-0.038	0.0245	(-0.0865, 0.0096)	1.570	0.116	0.46
Management category	NA	NA	NA	NA	NA	0.37
Min	0.016	0.0193	(-0.0217, 0.0541)	0.840	0.401	NA
Scape	-0.006	0.0292	(-0.0628, 0.0517)	0.190	0.850	NA
Wild	0.041	0.0162	(0.0090, 0.0727)	2.515	0.012	NA
Buildings, structures and man-made surfaces	-0.023	0.0178	(-0.0576, 0.0123)	1.269	0.204	0.36
Site age	0.018	0.0216	(-0.0243, 0.0603)	0.834	0.405	0.30
Tree cover	-0.017	0.0202	(-0.0568, 0.0225)	0.849	0.396	0.29
Average temperature	0.014	0.0177	(-0.0208, 0.0487)	0.788	0.431	0.28
Grass-dominated green space	0.006	0.0231	(-0.0392, 0.0515)	0.265	0.791	0.27
Population density	0.010	0.0205	(-0.0298, 0.0505)	0.506	0.613	0.25
Cloud cover	0.011	0.0177	(-0.0237, 0.0456)	0.621	0.535	0.25
Town population	-0.001	0.0227	(-0.0451, 0.0437)	0.031	0.975	0.23
Wind speed	-0.002	0.0158	(-0.0329, 0.0289)	0.126	0.900	0.22

2.3.3 Influence of the surrounding urban landscape

The total abundance of flying beetles was positively influenced by the area of grass dominated green space (p=0.049) and domestic gardens (p=0.045) within 200 metres in the AICc "best" model including management (Appendix 2.6b). Relative importance values from the multi-model inferencing supported the cover of domestic gardens (RI = 0.72) and hedges (RI = 0.65) as the two most important, and only statistically significant, surrounding landscape factors influencing total abundance, with grass dominated green space showing a weakly positive association and tree cover weakly negative (Table 2.5).

The abundance of the Nitidulidae family was also positively influenced by the area of domestic gardens (p=0.001) and hedges (p=0.006) in the AICc "best" model including management (Appendix 2.7b), which were also ranked as the most important of the explanatory variables modelled (RI = 0.98 and 0.93, respectively) using multi-model inferencing (Table 2.6).

2.3.4 Influence of site management

Burial grounds under "Clear" management (the strictest regime) exhibited lower total beetle abundances than those with less intensive management. However, analysis of estimated marginal means using the AICc "best" model (Appendix 2.6b) showed no significant difference in total beetle abundance between pairwise combinations of "Clear", "Wild", and "Min" management categories. The second most intensive management category, "Scape", had a significantly higher total beetle abundance than "Clear" (p=0.011) and "Min" (p=0.033).

A priori it was hypothesised that burial grounds with the least intensive management would exhibit greater family-level diversity. However, as with total abundance, diversity did not exhibit the hypothesised trend. The results of diversity analyses are presented here with acknowledgement that groupings are unbalanced, as different numbers of sites were assigned to each management category. Categorisation was performed retrospectively after site visits and speaking to site managers, so the imbalance was not known in advance.

Both Shannon and Simpson diversity indices show that the "Wild" management category had the highest beetle family diversity, followed by "Clear", "Min" and "Scape" in that order, although the Simpson index values for "Clear" and "Min" are the same (Appendix 2.4b). Pairwise Jaccard coefficients were calculated as a measure of taxonomic family similarity between management categories and produced a varied picture (Appendix 2.5b). The "Clear" category showed the highest levels of similarity overall, to "Scape" and "Wild" with 59% and 55% family

similarity respectively. The "Wild" category showed the most dissimilarity to other categories; "Scape" and "Min" at 47% and 43% respectively. When the most and least intensive management categories were compared, "Clear" and "Min", 45% family similarity was observed.

Some beetle families were only found in one of the four management types. Beetles from two families (Erotylidae, Cerambycidae) were only found at sites considered to be under "Clear" management (15 families in total). Three families (Dasytidae, Byturidae, Ptilidae) were only found at sites under "Min" management (14 families in total). No families were only found at sites with "Scape" management (12 families in total, highest abundance). Four families (Ptinidae, Melyridae, Tetratomidae, Corylophidae) were only found at sites with "Wild" management (16 families in total). Using indicator analyses Chrysomelidae were associated with management type "Clear" during Replicate 4 ($p=0.042$), and Apionidae were strongly associated with management type "Scape" during Replicate 3 although this was not statistically significant ($p=0.051$).

2.3.5 Summary of factors influencing the total abundance of flying beetles

Model averaging revealed that surrounding domestic gardens, hedges, and the "Scape" management category (see Table 2.2) all exhibited significant positive influences on the total abundance of flying beetles (Table 2.5). From the set of plausible models (Appendix 2.6a), the AICc "best" model that included management indicated positive effects of grass-dominated green space, domestic garden, and "Scape" management, and negative effects of population density and site size (Appendix 2.6b). The AICc "best" model that did not include management indicated positive effects of domestic gardens and hedges, and a negative effect of town population (Appendix 2.6c).

When model fit was assessed, the global maximal model (model including all potential explanatory variables), which is the basis for model averaging, had marginal $R^2 = 0.370$ and conditional $R^2 = 0.422$ (Nakagawa R^2) with no singularity. For the total abundance of flying beetles there was strong support across all statistical modelling techniques for positive influences of the area of domestic gardens and other green spaces in the immediate urban surroundings of the burial grounds, positive influences of management focused on horticultural design, and weaker support for negative effects of burial ground size and total population or population density of the surrounding town.

2.3.6 Summary of factors influencing the abundance of specific beetle families

Each beetle family with abundance $\geq$ 50 was examined separately to assess the factors impacting these distinct groups. These were the Nitidulidae, Chrysomelidae and Curculionidae families.

Model averaging revealed that surrounding domestic gardens, hedges, and the "Wild" management category (see Table 2.2) all exhibited positive influences on the abundance of Nitidulidae based on model averaging results (Table 2.6). When model fit was assessed, the global maximal model had marginal R^2 = 0.341 and conditional R^2 = 0.776 (Nakagawa R^2) with no singularity. From the set of plausible models (Appendix 2.7a), the AICc "best" model that included management indicated positive effects of domestic gardens, hedges, and "Wild" management (Appendix 2.7b). The AICc "best" model that did not include management (Appendix 2.7c) indicated positive effects of domestic gardens and hedges, and a negative effect of site size.

None of the measured weather, human population, or landscape factors significantly influenced the abundance of Chrysomelidae based on model averaging results (data not shown). The global model for Chrysomelidae abundance had marginal R^2 = 0.220 and conditional R^2 = 0.700 (using Nakagawa R^2). From the set of plausible models (Appendix 2.8), the AICc "best" model for Chrysomelidae was the null model (intercept only, no predictor variables included).

None of the measured weather, human population, or landscape factors significantly influenced the abundance of Curculionidae based on model averaging results (data not shown). The global model for Curculionidae abundance indicated the random effect of temporal replicate did not improve model fit (both marginal and conditional Nakagawa R^2 = 0.425) suggesting, in agreement with indicator analysis, that there was little temporal change. From the set of plausible models (Appendix 2.9), the AICc "best" model for Curculionidae was the null model (intercept only, no predictor variables included).

2.4 | DISCUSSION

Flying beetle communities recorded in the 20 urban burial grounds studied here changed over time in terms of family-level composition, richness, and abundance, and showed distinct inter-burial ground variation. Burial ground age (the number of years since the first recorded interment) did not exert a significant influence on total flying beetle abundance. Larger burial grounds yielded lower flying beetle abundances and we note that site size was positively correlated with the urban population, which was in turn positively correlated with the presence

of man-made structures and surfaces in the surrounding urban landscape. The greater the amount of green space, public and private, surrounding the study burial grounds, the greater the abundance of flying beetles found within them.

The management regimes employed at the study burial grounds had significant effects on flying beetle abundance and diversity, however the expected trend of higher abundance and greater diversity with the least intensive management was not found. Rather, horticultural landscaping practices appear to promote greater flying beetle biodiversity than the most minimal management approaches. In addition, ground management practices to encourage biodiversity, and the most rigorous mowing and pruning regimes, resulted in greater flying beetle diversity than leaving a burial ground almost completely alone. Nine families were found only in one specific management type; two associated with the lightest touch management regimes are frequent flower visitors, with the remaining seven known to affiliate with deadwood, dead fungi and decaying organic matter (Duff and Schmidt, 2012).

2.4.1 Research question 1: overall abundance, diversity, and indicator analyses

Our results indicate clear variation in the abundance and diversity of flying beetles at the family level. The flying beetle communities found within urban burial grounds were generally dominated by three families (Nitidulidae, Chrysomelidae, Curculionidae), however family-level similarity and community diversity between replicates exhibited meaningful differences. The highest level of family diversity was found earlier in the sampling period, whereas the last temporal sampling replicate showed the most distinctive community. Observed variations in abundance and diversity are reflective of the ecology of the beetle families. For example, chrysomelids were found both earlier and later in the year, with the late appearance identified as an indicator; many species within this family overwinter as adults and lay eggs in the spring, followed by a new generation of adults emerging in the autumn. Beetles of the family Nitidulidae were found in the greatest numbers in high summer when flower pollen availability is highest, and indicator analyses supported this association.

This establishes that not all urban burial grounds included in this study are equal in terms of the biodiversity they support, and that abundance and family diversity change over time. Whilst relevant research discourse generally identifies burial grounds, particularly in urban areas, as places of potentially high biodiversity value (Barrett and Barrett, 2001; Löki et al., 2019), the current study illustrates that some may be of relatively low value for taxa of interest.

2.4.12 Nitidulidae, Chrysomelidae and Curculionidae

Most species within the family Nitidulidae are flower visitors that feed on pollen, and so greater floral resources are required to support larger populations (Frearson *et al.*, 2005). Domestic garden and hedge coverage in the urban landscape surrounding the burial grounds were the two most important factors affecting Nitidulidae abundance and had a positive effect, as did burial grounds under the Wild management category. These factors could increase floral resources both within and surrounding the burial grounds, boosting Nitidulidae population sizes and potentially attracting beetles on the wing into the area, making them more likely to be sampled.

The family Chrysomelidae is large and diverse, with members feeding on leaves of a wide range of host plants. Some species could feasibly benefit from any of the management types, so it could be expected that no one variable predicts their abundance. The family Curculionidae is similarly diverse with specific host plant associations; however, they typically feed on different parts of the plant to chrysomelids, namely the stems and roots. Based on their resource requirements, we predicted that the same factors that were important for Nitidulidae would be so for these other abundant beetle families, as an increase in green space coverage and wildlife-focused management practices such as pruning and mowing reductions may increase vegetative biomass in addition to floral resources. However, our study found that none of the measured variables explained the abundances of these two taxonomic families.

2.4.2 Research question 2: burial ground size, age, and local human population factors

Burial grounds are often positioned as the last remnants of natural habitats in urban areas, with the longevity of their land use within these dynamic, transformed landscapes viewed as fundamental to their value for biodiversity (Barrett and Barrett, 2001; Buchholz et al., 2016; Löki et al., 2019). Studies have found that older urban burial grounds harbour considerable biological richness, however these mainly focus on vascular plants, sometimes lichens, mosses, bats and birds, with invertebrates either excluded or reduced to ground-dwelling groups such as ground beetles or spiders (Buchholz et al., 2016; Kowarik et al., 2016; Löki et al., 2020). Our findings based on a novel taxonomic group challenge these assumptions, as burial ground age was not found to have a significant effect on flying beetle biodiversity.

A key aspect of older burial grounds may be the presence of older vegetation and greater tree cover, and in those burial grounds that are minimally managed due to being closed to new interments, a greater quantity of deadwood. Therefore, in newer burial grounds older vegetation

cover and deadwood habitats may be largely replaced by younger shrubs and trees as part of modern horticultural installations and flower displays; the most abundant flying beetle families we found are associated with pollen, leaves and developing stems, hence newer vegetative resources and floral resource availability may be more important for these taxa, meaning the age of a burial ground would not have the expected impact. Burial ground size did appear to exert a significant influence on beetle abundance, but not in the predicted direction. It was hypothesised that larger sites, by virtue of having greater surface area (and hence more green space), would support higher levels of biodiversity. Previous studies produce a mixed but limited picture of the importance of urban burial ground size; it was not found to be significant for Turkish orchid taxa (Löki *et al.*, 2015) or birds in Chile despite expectations that it would be important (Villaseñor and Escobar, 2019), however a positive correlation was found between size and vascular plant species richness in Poland, although it was the least important explanatory variable (Nowińska, Czarna and Kozłowska, 2020). Studies examining urban green spaces more generally have found patch area to be one of the most important positive influences on biodiversity of multiple taxonomic groups (Beninde, Veith and Hochkirch, 2015; Callaghan *et al.*, 2018); however these findings are discussed in the context of green spaces and their various attributes such as tree cover and distance to water, rather than the investigation of specific green space land use types.

The current study provides some evidence of a negative effect of larger burial grounds on total flying beetle abundance, potentially because they are associated with urban areas of higher population size and density, which also have negative impacts on beetle abundance. Larger burial grounds are required in more populous urban communities to support the higher number of deaths, and urban areas with greater human pressure by necessity have more man-made infrastructure; a more impermeable, hostile landscape surrounding larger burial grounds has a negative impact on the abundance of flying beetles. Similar results regarding the surrounding landscape have been found for native birds (Villaseñor and Escobar, 2019), although the limited number of sites was thought to obscure any influence of burial ground size. Previous studies that sampled invertebrates were either conducted in a single burial ground (Orstan and Kosemen, 2009; Gardiner, Gardiner and Cooper, 2011b; Atay, Jansson and Gürkan, 2012; Tan, 2012; Buchholz et al., 2016; Kowarik et al., 2016), so that size could not be examined as an explanatory variable, or otherwise did not include it as a variable of interest (J. Hartley et al., 2007; Matteson, Grace and Minor, 2013; Tan et al., 2013). Future research building on the relationships observed here between urban populations and burial ground biodiversity could be beneficial, for example

the exploration of links between ecological and social values or pressures within a human-ecological functional model (sensu Tan 2017).

2.4.3 Research question 3: the surrounding urban landscape

Analyses show statistically strong and consistent effects of different land use types in the immediate surroundings on flying beetle abundances (total and Nitidulidae) in burial grounds. Variables associated with green infrastructure in the urban landscape surrounding the study burial grounds were prominent in both the modelling and relative importance analyses. This strongly suggests that increased coverage of green infrastructure in an urban landscape can have significant, positive impacts on the biodiversity within urban burial grounds. Specifically, increasing area of domestic gardens and hedges were associated with total abundance of flying beetles and the abundance of Nitidulidae, and there was some evidence for the importance of grass dominated green space for total abundance of flying beetles.

The influence of wider land use in urban areas on biodiversity within a green space is a topic of research interest at different scales. For example, within 1 kilometre of cemeteries (Villaseñor and Escobar, 2019) found an important positive impact of surrounding vegetation cover on native bird diversity but did not break this down into specific green infrastructure types. An investigation of vegetation cover influence on flower-visiting insects within urban green spaces found that smaller spatial scales (30m) were more explanatory than larger ones (200-500m) (Matteson, Grace and Minor, 2013). By contrast, from the perspective of beetle dispersal distances, our study found that green infrastructure within a 200m buffer had significant effects on flying beetles. There is evidence that local-scale, rather than landscape-scale, habitat area and connectivity are more important for supporting higher levels of biodiversity (Philpott et al., 2014; Beninde, Veith and Hochkirch, 2015; Callaghan et al., 2018), although explicit definitions of 'landscape-scale' and delineations of the extent of an urban landscape often either differ or are not provided. The buffer intervals used in our study were found to be strongly colinear, meaning that they were all as explanatory as each other. Therefore, green infrastructure coverage within up to a 400m radius of urban burial grounds could be considered important for the biodiversity of flying beetles within them.

The significant positive effect of domestic gardens and hedges on flying beetle abundances indicates that management and retention of garden space by individual households can play a significant role in the maintenance of urban biodiversity, which could be especially important in large, densely populated towns and cities. Our results are supported by prior work

on the biodiversity value of urban gardens, which consistently finds them to be an important type of green space for enhancing and retaining biodiversity of multiple taxonomic groups (Davies *et al.*, 2009; Goddard, Dougill and Benton, 2010; Cameron *et al.*, 2012; Belaire, Whelan and Minor, 2014).

The increased presence of Nitidulidae beetles specifically, whose ecology shows a strong affinity with flowering plants, may indicate that the enhancement and elongation of the flowering period within gardens is especially important for the maintenance of, at least, flying beetle abundances.

2.4.4 Research question 4: site management

Our analysis shows that caretakers of burial grounds in urban areas directly influence biodiversity through management practices. More specifically, our results show that a hands-off approach (the "Min" category) yields higher richness and uniqueness of beetle families, more so than purposeful ecologically sensitive initiatives such as cultivating areas of wildflower meadow and a 'light touch' pruning regime (the "Wild" category). In terms of the size of flying beetle communities, our results suggest that the second most intensive management type, "Scape", generated higher overall abundances, but of fewer families. A priori it was expected that more intense management would negatively affect biodiversity, however a small degree of management and horticultural installations as characterised by the "Scape" category were found here to generate higher beetle abundance than no management at all (the "Min" category). Flying carabid beetles have been found to fly more in graveyards than other grassland habitats, possibly allowing for more effective dispersal due to increased topsoil disturbance from digging and trampling (J. Hartley *et al.*, 2007a). This could contribute to in-use, actively managed graveyards such as those in the "Scape" category supporting higher abundances of generalist flying beetles such as the family Nitidulidae.

Any of these approaches result in higher beetle abundance than the most intensive management (the "Clear" category). This is not necessarily to say that urban burial grounds under these stringent management regimes are not valuable for flying beetles; the family Chrysomelidae was identified as an indicator during late-Summer sampling in the Clear management type.

The burial grounds allocated to the management category "Wild" were associated with higher flying beetle diversity in addition to greater Nitidulidae abundance. Four beetle families

known to be deadwood affiliates were found only in burial grounds within this category. Along with the greater abundance of flower visitors, this suggests that active management for deadwood retention is more important than the presence of incidental deadwood due to tree age in older burial grounds, as supported by our results showing that burial ground age was not an important influence.

A previous study investigating the effect of management intensity on the biodiversity of urban cemeteries used a single management technique, the uprooting of tree saplings, to represent management effort (Kowarik et al., 2016) and found that although spiders responded negatively to increasing management pressure, there was no significant effect on ground beetles. Our study incorporates entire management regimes, not just a single practice, and the impacts on the biodiversity of flying beetles demonstrated here suggests that flying and ground-dwelling invertebrate communities may respond differently to management practices in urban burial grounds. Research conducted on the biodiversity of arthropods in other green space types found little impact of management intensity on highly mobile taxa, but a negative impact on those with low mobility (Sattler et al., 2010), although again only a single practice was used to represent site management. Further work is needed to better understand the effects of grounds management regimes on different functional invertebrate groups in urban burial grounds.

2.4.5 Sampling method

This study presents a beetle capture methodology suitable for deployment in environments where high mobility and preservation of the ground are key considerations. The use of this low-invasive sampling method has translated into positive working relationships for future projects, providing opportunities for further sensitive investigation of biodiversity in burial grounds.

2.4.6 Conclusions

Our study of flying beetles challenges assumptions about biodiversity in urban burial grounds. Larger, older sites were not found to contain a higher abundance of flying beetle families and had a negative influence on beetle abundance that may have been related to larger urban populations. We found that an increase in the green space surrounding an urban burial ground, particularly gardens and hedges, had the most significant positive impact on abundance of flying beetles within the burial grounds.

Perhaps most importantly, our study provides the first insights into the effects of site management on urban burial ground biodiversity, showing that expensive and high intensity maintenance practices appear to be detrimental. A positive outcome of this work is that burial grounds managed as horticultural public garden landscapes can support high abundances of wild taxa similar to those that are managed, at least in part, as wildlife refuges or not actively managed at all; an arguably rare situation in which public perception and demand correlate with benefits to nature. However, ecologically sensitive management practices in urban burial grounds are shown here for the first time to promote higher level of diversity and provide opportunities for specialist species to persist in ever-changing urban landscapes.

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Nightingale Cemetery

Godalming

Surrey

Photo credit: author's own

CHAPTER 3

Having begun in the air with flying beetles, this chapter brings the study down to the ground. The importance of soil health for sustaining biodiversity is a prominent research focus, but is not understood in burial grounds. Moreover, heavy metal pollution of soil is a well-known problem for both ecosystem and human health, particularly in urban areas, but again burial grounds have been excluded as distinct ecological units in research exploring this timely and significant issue. Many urban burial grounds have existed for a long time, particularly those at the historical centre of a town or city which can be over 100 years old and will exist for many more years to come. Their unique longevity, due to especial social and cultural importance as resting places for the revered dead, mean that their soils – recently classed as necrosols – have existed under this single type of land use since their inception, which with increased urbanisation and rejuvenation of towns and cities is a rarity. There is reason to think that burial grounds may be particularly susceptible to heavy metal pollution by virtue of varying trends in interment fashions, for example an historical preference for lead-lined coffins.

This chapter aims to provide a platform for research into urban necrosols and their bearing on biodiversity, specifically heavy metal contamination. The interment of human remains and accompanying materials represent unique sources of heavy metals compared to any other urban land use, and the longevity of urban necrosols means they have been exposed to sources of urban pollution, for instance vehicle exhausts, for a particularly long time; so is heavy metal pollution of urban necrosols due to 'cars or coffins'? Having shown in Chapter 2 that management of urban burial grounds appears to affect aspects of above-ground biodiversity, does it also affect heavy metal levels in the soil?

CHAPTER 3: Cars or coffins? An investigation into sources of heavy metal pollution in UK urban necrosols and potential implications for biodiversity

3.1 | INTRODUCTION

The functional ability of the below-ground component of terrestrial ecosystems is of fundamental importance to sustaining biodiversity, ecosystem service provision and human health (Haygarth and Ritz, 2009; Bünemann *et al.*, 2018; Li *et al.*, 2018; Sun *et al.*, 2023). The study of soil ecosystem health in all its complexity has become a significant and vitally relevant research focus in areas such as agriculture, flood management, combatting climate change through carbon storage, nutrient cycling, pathogen management and the support of biodiversity both above and below ground (Oliver, 1997; Maikhuri, 2012; Bünemann *et al.*, 2018; O'Riordan *et al.*, 2021). In particular, the study of soil health is a significant research focus with regards to urban areas as over half of the global population live in towns and cities (UN Department of Economic and Social Affairs, 2018). Therefore, it is important to build an understanding of the effects of urban pollution on soils and the consequent impacts on urban communities. The accumulation of heavy metals is of especial concern as this can have wide-ranging detrimental impacts, affecting human health via urban agriculture, health of green infrastructure, and delivery of ecosystem services (Wiseman, Zereini and Püttmann, 2013; Pan et al., 2018; Crispo et al., 2021).

3.1.1 Urban soil heavy metal pollution

Extensive urbanisation and industrialisation cause the emission of pollutants into urban ecosystems (Li *et al.*, 2018; Pan *et al.*, 2018), with vehicle exhausts, tyre and brake wear, oil leakages, waste disposal, coal combustion, and industrial activities such as construction, releasing, amongst other pollutants, a number of toxic heavy metals (Werkenthin, Kluge and Wessolek, 2014; Binner et al., 2023). Soils are known to accumulate elevated concentrations of these heavy metals, including lead, cadmium, zinc, chromium, nickel, copper, and arsenic, as they are accumulated and transported via atmospheric deposition and runoff, and can persist for a long time (Li *et al.*, 2018; Binner *et al.*, 2023). Where these heavy metals, in toxic concentrations, exist or speciate into mobile forms they can have high bioavailability for uptake by soil organisms and plants resulting in severe damage to human health if contaminated soil or plant materials are ingested or inhaled (Li *et al.*, 2018; Crispo *et al.*, 2021; Q. Li *et al.*, 2022;

Monib *et al.*, 2024). For example, soils in a number of urban sites in China were found to contain levels of chromium and nickel that present a high risk of cancer in children (Tong *et al.*, 2020), and exposure to even low concentrations of cadmium are known to cause a number of severe illnesses including cancers, chronic obstructive pulmonary disease, and itai-itai disease (Suhani et al., 2021).

The accumulation of heavy metals in urban soils also contributes to severe declines in soil health, including the harm of soil organisms such as bacteria, fungi, and invertebrates, resulting in poor ecosystem function which is of ever-increasing importance in urban areas (O'Riordan *et al.*, 2021; Binner *et al.*, 2023; Tóth, Dombos and Hornung, 2023a). The ability of ecosystems to provide crucial services for the large and ever-growing human populations that reside in urban areas is dependent on biodiversity (Pulleman *et al.*, 2012; Tibbett, Fraser and Duddigan, 2020), the success of which is dependent in turn on soil health; therefore, heavy metal pollution of urban soils is of great importance and concern.

3.1.2 Impacts on biodiversity

When exploring the abundance, diversity, and dynamics of living organisms in any given habitat, it is necessary to understand the nature of the soil's health as it is the foundation upon which all is built. In urban areas, with the pressures exerted on ecosystems by human activity, an understanding of the impacts of heavy metal pollution is key to the exploration of the nature of urban biodiversity and how to enhance it. Soil health, by means of soil biodiversity, is increasingly being explored using biological indicators such as nematodes, earthworms and springtails as their biodiversity is affected by pollutants including heavy metals (Gutiérrez et al., 2016; Saberi Pour et al., 2023; Tóth, Dombos and Hornung, 2023). Where soil biodiversity is negatively affected and soil health declines, the ability of the soil to sustain above-ground biodiversity is diminished; with regards to heavy metals, they can bioaccumulate in living organisms and travel upwards through trophic levels disrupting ecosystem function and biodiversity further (Ali, Khan and Ilahi, 2019; Ghannem et al., 2023; Adewumi and Ogundele, 2024).

Whilst the study of urban soils, their biodiversity and function, and the effects of heavy metal pollution are often positioned in green spaces, many studies either do not define green space types or omit one particular type of green space that is ubiquitous in urban areas: burial grounds (O'Riordan et al., 2021; Sun et al., 2023; Luo et al., 2024).

3.1.3 Urban necrosols

The soils of burial grounds are only recently becoming recognised as a distinct anthropogenic soil type, known as necrosols (Sobocka, 2004). These are characterised by soil horizon perturbation and the presence of human corpses, resulting in enrichment with organic matter, phosphorus, calcium, nitrates, and associated micronutrients and metals (Burghardt, 1994; Hart, 2005; Greinert and Kostecki, 2024). The body of research on necrosols focuses heavily on concerns regarding human burials as a source of various type of contamination of both soils and groundwater (known as "necroleachates") such as mercury from dental amalgam, harmful microbes, drugs, formaldehyde, plastics, and products from coffins such as wood varnishes and metals including lead, zinc and copper (Spongberg and Becks, 2000; Hart, 2005; Guttman, Watson and Miller, 2009; Amuno, 2013; Aruomero and Afolabi, 2014; Fiedler, Dame and Graw, 2018; van Allemann, Dippenaar and Olivier, 2019; Martin *et al.*, 2021). There is limited literature on the ecosystem function and biodiversity associated with this unique soil type (Pawlett *et al.*, 2024), with the focus tending to be on ecosystem service delivery of burial grounds themselves and how they function as green spaces rather than focusing on their soils (Sallay et al., 2023; Säumel, Butenschön and Kreibig, 2023; Itescu and Jeschke, 2024).

In an urban context, necrosols are starting to be considered in urban planning and human health (Dent and Knight, 1998; Quinton and Duinker, 2019; Andrzej Greinert and Kostecki, 2024), however as a soil type urban necrosols remain significantly under-researched. Little is known about their composition and how this changes over time due to human decomposition and funereal practices, and the resulting impacts on soil health and biodiversity in burial grounds. With heavy metal pollution of urban soils at the forefront of concerns for environmental and human health, and necrosols being a recognised source, it is important to understand the nature of heavy metals more fully in urban necrosols, particularly as burial grounds are important components of urban green space for ecosystem service delivery and biodiversity.

At the time of writing, to the author's knowledge, there has never been an in-depth exploration of geochemical properties or the heavy metal burden of urban necrosols in the UK. To understand the nature of urban burial grounds as green spaces these fundamental aspects of their soils require characterisation, and the factors influencing their characteristics need to be explored. This will provide vital information for the further study of biodiversity, soil health and ecosystem functioning in these notably under-researched spaces.

3.1.4 Research questions and hypotheses

1. Are there differences in heavy metal concentrations in urban necrosols when compared to background levels present in UK soils? I hypothesised that lead and other heavy metals would be elevated compared to background urban soil levels.

2. Is there significant variation in the heavy metal content of urban necrosols between burial grounds, and if so, can drivers of this variation be identified such as the interment of human remains or other known sources of urban pollution? I hypothesised that the time since interment (a proxy for changes in human remains and burial materials) and proximity to roads with differing levels of traffic would be key drivers of variation.

3. Is there any evidence of a relationship between soil qualities and heavy metal concentrations in necrosols and the management of urban burial grounds? I hypothesised that more intensive management would lead to increased heavy metal concentrations due to more opportunities for metals to be incorporated into the upper soil layers.

3.2 | METHODS

Study site selection, management category allocations and land category mapping methodologies are described in Cathcart-James, Foster and Pickles (2022). The two locations in Guildford, Surrey, had to be omitted from the present study due to there being no records of the number of burials; these records were destroyed by a fire before digitisation. Management category descriptions are included here for ease of reference, amended to remove the Guildford locations (Table 3.1).

Table 3.1. Description of study site management categories and the sites allocated to each category, amended from Cathcart-James et al. (2022).

Management category	Description	Sites allocated
Clear	Usage: in use Horticultural design elements: few/none Trees and hedges: sparse, heavily pruned Lawn: ubiquitous, close-cropped Mowing/strimming: non-discriminatory, 2-4 per month Free growing areas: None Biodiversity management: None	6. Shaw 9. Braywick 12. Wokingham Free Burial Ground 14. Fleet 15. Windsor 17. Easching 18. Nightingale
Scape	Usage: in use Horticultural design elements: present, well-kept (e.g. planted flower/shrub arrangements) Trees and hedges: present, well-kept Lawn: present Mowing/strimming: 1-3 per month Free growing areas: None to very few Biodiversity management: None	1. Henley Road 5. Worting Road 10. Slough 11. High Wycombe 16. London Road
Wild	Usage: full or in use Horticultural design elements: few Trees and hedges: present, no or minimal pruning Lawn: present Mowing/strimming: minimal to none Free growing areas: set-aside for grassland/wildflowers Biodiversity management: Present, part or whole	4. Larges Lane 7. Newtown Road 8. All Saints
Min	Usage: full except family plots, no to few interments Horticultural design elements: few/none Trees and hedges: present, safety management only Lawn: Not present (patches of grassland) Mowing/strimming: once per year (late summer) Free growing areas: present (safety management only) Biodiversity management: Present but unintentional (safety management only)	2. Caversham 3. Reading Old 13. St Michael's

3.2.1 Sample collection

Site maps were created to establish sample locations. Ordnance Survey map, topography and satellite image data for each site and its immediate surrounding area were obtained from the EDINA Digimap Ordnance Survey Service. These files were loaded into and manipulated using ArcGIS version 10.5.1. Once each site was identified, if a polygon existed for it then this was checked for accuracy and edited if necessary; if a polygon did not exist, one was created. The 'Create random points' tool was then utilised to add an overlay of random point features to each site map (Figure 3.1). The exact coordinates of each point were recorded.

Figure 3.1. Site map showing satellite image and random point feature overlays for Slough Cemetery, Berkshire, UK. Point features were edited to be large to aid in finding the right area in the field.

All soil samples were collected between the 1st and 12th of July 2019. Site managers were provided with a map of sample locations and were asked to share with grounds staff, to ensure they were aware of the reason for small areas of disturbed ground.

When on-site the large red point features on printed site maps were used to navigate close to the coordinates by eye, and a Garmin eTrex® 30 GPS handheld navigator was then used to pinpoint the precise coordinates. If the exact coordinates of a random point fell on an impervious surface or directly on top of a grave, the nearest suitable location was used instead. In addition, at site managers' behest, children's interment areas and memorial gardens were excluded. Exact coordinates for each sample point were recorded using the Garmin eTrex® 30.

Once the location of a sample was established, the distance to the nearest grave and the year of death on the grave marker were recorded. If there were multiple interments within a grave, the latest date was taken. The vegetation immediately surrounding each sample point was assessed and allocated to a vegetation type category (Table 3.2). A 7-centimetre diameter open-head combination soil auger was used to extract samples. Samples were placed directly into sealed plastic bags and delivered to cold storage on the day of collection. Samples were then stored in cold storage at 3°C in the Ecology and Evolutionary Biology Laboratory, University of Reading, Berkshire UK, before further processing and analysis.

Table 3.2. Vegetation type categories allocated to each soil sample location.

Vegetation category	Description
OMG	Mown grassland
OUG	Unmown grassland
WDA	Wooded area
HED	Hedgerow

3.2.2 Urban traffic variables

Variables regarding proximity and intensity of urban traffic were measured and categorised to provide indications of local emissions from vehicle activity. The maps created for sample collection were loaded into ArcGIS Pro 2.7 and the Distance tools used to measure the distance in metres from each sample point to the nearest road. The classification of the nearest road was recorded (Table 3.3) as a measure of road use, and annual average daily traffic flow figures from the most recent manual count, rather than years where estimates were calculated, were recorded from the nearest count point to each site (Department for Transport 2023).

Table 3.3. Road type category allocated to the nearest road to each soil sample location.

Road type category	Description
STR	Residential street (generally below 30 miles per hour, built up with residential and local facilities)
ARO	A-road (major connecting route)
BRO	B-road (feed traffic between A-roads and smaller roads)
DCA	Dual carriageway (two lanes for each direction of travel with a central reservation)

3.2.3 Soil reference values

Reference values commonly used in pedological research for the heavy metals measured in this study were collated with the aim of using them as benchmarks to place the measured concentrations into a wider context (Table 3.4).

Table 3.4. Benchmark heavy metal values used in UK and worldwide pedologic research to place concentrations of elements of interest into context.

Heavy metal	Dutch pollutant standard intervention value (ppm) [1]	UK normal background concentration (urban domain) (ppm)[2]	England UKSHS mean concentration in urban soils (ppm)[4]	England UKSHS mean ambient concentration (ppm)[5]
Arsenic	76.0	32[3]	14.6	13.9
Cadmium	13.0	2.1	0.53	0.43
Chromium	78.0	-	27.8	33.4
Copper	190.0	190.0	51.0	19.8
Nickel	100.0	42.0	23.3	19.5
Lead	530.0	820.0	137.0	62.0
Zinc	720.0	-	142.2	95.0

1. Value at which functional properties of soil for life are seriously impaired or threatened (Ministry of Infrastructure and Water Management (NL), 2013)
2. Technical guidance sheets developed from (Ander E L *et al.*, 2011) by DEFRA (2012b, 2012a, 2012e, 2012c, 2012d)
3. Value is for the Principal Domain which contains England's urban areas, as urban and industrial activities are not classified as being significant controls on the distribution of these elements
4. UK Soil and Herbage Pollutant Survey (UKSHS): Environmental concentrations of heavy metals in UK soil and herbage (Ross S M *et al.*, 2007)
5. UK Soil and Herbage Pollutant Survey (UKSHS): Introduction and summary (Barraclough, 2007)

3.2.4 Processing and analysis of soil properties

Prior to analysis, the 100 samples were air-dried in a glasshouse at the Crop and Environment Laboratory, University of Reading. They were then put through a 2-millimetre sieve. All subsequent analyses were conducted in the School of Archaeology, Geography and Environmental Science at the University of Reading.

3.2.4.1 Measuring pH

Three replicates per soil sample were prepared by using a 2-decimal place top balance to weigh 10 grams of soil into a 50-millilitre centrifuge tube, followed by the addition of 25 millilitres of deionised water. Samples were centrifuged in an Eppendorf benchfuge at 4500 xg for 5 minutes, then allowed to settle for a further 5 minutes.

Following calibration, a pH meter was then used to measure the pH of the solution above the soil in each prepared sample. The average pH of the 3 replicates was recorded as the final value for each sample.

3.2.4.2 Ball milling

The analytical technique for measuring heavy metals required the soil to first be ground into fine particles. Milling was carried out in a Pulverisette 5 Classic Line planetary ball mill using agate 80-millilitre bowls and five 20-millimetre diameter balls per bowl (composition 99.9% SiO_2, density 2.65cm^3). Six grams of soil was added to each bowl using a glass fibre nylon spatula. The samples were then milled at 300 revolutions per minute for 3 minutes. The resulting subsamples were stored at room temperature.

3.2.4.3 Measuring heavy metals

The following methodology is based on US-EPA Method 3051A – Microwave assisted acid digestion of sediment, sludges, soils and oils. Ball-milled soil from the 100 samples was used. In addition to the samples, blanks and standard reference materials were also processed for quality assurance.

Samples were first prepared for digestion in a MARS 6 microwave. In a fume cupboard, 0.5g of each sample was weighed into a MARSXpress digestion tube along with 9ml of Trace Element Grade concentrated nitric acid and 3ml of Trace Element Grade hydrochloric acid. After standing for 15 minutes to allow for predigestion the tubes were secured in the MARS 6 microwave and the 'USEPA 3051' programme was run. This programme ramped the tubes up to 175°C for 5 minutes and 30 seconds and held them at that temperature for a further 4 minutes and 30 seconds, followed by a 15-minute cooldown.

For sample filtration, empty acid-washed 50ml centrifuge tubes were weighed and Whatman 42 filter papers pre-washed with 10% nitric acid solution were placed in acid-washed

funnels on top of each tube. Once the MARSXpress digestion tubes were safely opened in a fume cupboard, the digestates were filtered into the 50ml centrifuge tubes using ultra-pure water, ensuring each digestion tube was thoroughly rinsed. The used filter papers containing sediment were disposed of. The centrifuge tubes were weighed again, and ultra-pure water was added until each sample weighed 50g more than the weight of the empty tube.

Dilution for ICP-OES analysis was carried out immediately. For each sample, 9.5ml of ultra-pure water was added to a new acid-washed 50ml centrifuge tube, followed by 0.5ml of the digested sample. Both the digested samples and ICP-OES dilutions were stored in a refrigerator at 4°C. Concentrations of As, Cd, Cr, Cu, Ni, Pb and Zn were determined by ICP-OES analysis, using internal standard solutions, matrix matched with the MARS 6 reverse aqua regia digestion described above. The results are reported as mg/kg (or ppm) for direct comparison with standardised values.

3.2.4.4 Soil moisture

For each of the 100 samples, the weight of an empty crucible was measured on a four-point balance. Ten grams of air-dried, sieved soil was then weighed into the crucible, and the total weight recorded. All crucibles were placed in an oven at 105°C and left overnight. Once removed, the crucibles were placed in a desiccator to cool for a minimum of 30 minutes. The total weight of each crucible was recorded, then subtracted from the original total weight of crucible and soil sample. The remaining value was recorded as the soil moisture content, expressed originally as grams H_2O per 100 grams of oven-dry soil, then converted to a percentage.

3.2.4.5 Soil organic matter

The crucibles containing the oven-dried soil were placed in a muffle furnace at 500°C overnight. They were left to cool in the furnace for 4 hours before being moved to a desiccator to cool further to room temperature. The crucible and ignited soil were weighed again, the value subtracted from the original total weight of crucible and oven-dried soil sample and the remaining value recorded as the soil organic matter content. Values were expressed originally as grams per 100 grams of oven-dried soil, then converted to a percentage.

3.2.5 Statistical analysis

All data analyses were conducted using R 4.3.1 (R Core Team 2023) in the R Studio environment 2023.06.1. Basic differences between burial grounds in the concentration of different elements were examined using ANOVA. Boxplots with embedded ANOVA results were created using the "ggplot2" package (Wickham 2016). To explore differences in necrosol heavy metal concentrations the data were analysed using generalised linear models incorporating the explanatory variables of interest; namely, those associated with the interment of human remains (burial number and density, date of most recent interment, distance to the nearest grave), other intra-site variables (management and vegetation types, site size and age), soil qualities (pH, moisture and organic matter content) and those associated with the wider urban landscape and pollution (nearest road type, land use category coverage, traffic intensity). However, due to multicollinearity issues that were revealed as part of the modelling process, this was not considered to be sufficiently robust (Vatcheva and Lee, 2016; Kalnins, 2018). This was due to potential explanatory variables correlating with each other, causing variance inflation whereby the model appears to be explaining more of the variance than in reality. Collinearity checks on the models showed high variance inflation, even with the removal and re-running of the models with different combinations of variables.

Principal component analysis (PCA) was then applied as it is considered to be an effective statistical method where there are many explanatory variables that display multicollinearity; the so-called curse of dimensionality (Kuo and Sloan, 2005). To address the research questions, it was most informative to investigate any evidence of clustering of heavy metal concentrations based on the explanatory variables of interest and PCA allows the use of all response (heavy metal concentrations) and explanatory variables at the same time. PCA was conducted using the "prcomp" function in the stats package of base R (R Core Team 2023), including all numerical variables based on a correlation matrix where all variables were scaled. Correlations were then examined between the PCA axes and the measured heavy metals, incorporating both explanatory variable vectors and spatial positioning of the individual soil samples. The visualisations were created using the "factoextra" package (Kassambara 2016).

3.3 | RESULTS

3.3.1 Necrosol overview and comparison with key indicator values

The statistical summary and plots that follow (Table 3.5, Figures 3.2-8) aim to place the heavy metal concentrations measured for this study into a wider context by comparing them to national and international values used in pedological research (Table 3.4).

Table 3.5. Statistical summary of heavy metal concentrations measured during the study and difference between reference values (Table 4) and the mean concentration of each heavy metal (ppm). Negative values indicate that concentrations were so low as to be negligible, and not able to be accurately measured during analysis. All concentrations are presented as ppm.

Heavy metal	Min	Max	Median	Mean	SD	SE	Dutch standard intervention value	UK normal background	England UKSHS mean urban	England UKSHS mean ambient
Arsenic	-3.7	73.4	16.2	16.1	12.2	1.2	-59.9	-15.9	1.5	2.2
Cadmium	-1.7	1.9	-0.3	-0.3	0.8	0.08	-13.3	-2.4	-0.83	-0.73
Chromium	0.7	54.6	21.3	23.0	11.5	1.2	-55.0	-	-4.8	-10.4
Copper	0.5	251.6	12.8	18.4	36.1	3.6	-171.6	-171.6	-171.6	-1.4
Nickel	1.6	52.6	16.6	18.7	11.2	1.1	-81.3	-23.3	-4.6	-0.8
Lead	8.4	591.0	69.1	91.3	170.7	17.1	-438.7	-728.7	-45.7	29.3
Zinc	9.5	199.0	62.9	67.8	105.5	10.6	-652.2	-	-74.4	-27.2

The levels of each heavy metal measured for the 18 study sites are presented below (Figures 3.2 - 3.8) and include the p-value and significance level results obtained from simple ANOVAs performed to compare the concentration of each heavy metal between burial grounds. Confidence intervals at the 95% level are also included (Tables 3.6 – 3.12). Management categories (Table 3.1) are visualised to allow for any initial observations on associations between heavy metal levels and the approaches taken to managing the study sites. To place the measured heavy metal levels into a wider context, three key values are overlaid; the value in red is the Dutch pollutant standard intervention value which is indicative of contamination levels potentially damaging to people and ecosystems (Swartjes, 1999). The other two overlaid values are taken from the UK Soil and Herbage Pollutant Survey which established a set of baseline values for soil pollutant levels in the UK; the value in blue is the estimated ambient concentration in England which accounts for both the degradation of the parent rock (background concentration) and input from human activity (Barraclough, 2007). The value in green is the mean concentration measured in 42 towns and cities in England, providing a comparable value for urban soils only (Ross et al., 2007).

3.3.11 Arsenic

Arsenic levels in fifteen of the eighteen sites were measured, at least in part, as higher than both ambient and urban concentrations previously established in England (Figure 3.2). The ANOVA revealed statistically significant differences in arsenic concentrations between sites ($F_{(17, 72)}$ = 3.42, p = 0.0001, R^2 adj. = 0.32). Table 3.6 details the 95% confidence intervals for the mean arsenic values of each site. The base mean arsenic concentration is higher than both the ambient and urban thresholds for England. Concentrations of arsenic in All Saints churchyard (Wild management category) and Eashing cemetery (Clear management category) were significantly higher compared to all sites. Arsenic concentrations in these two sites and Old Cemetery (Min management category), Shaw Cemetery (Clear management category), and Thatcham Cemetery (Scape management category) were entirely elevated above ambient and urban levels for England.

Concentrations of arsenic in Fleet Cemetery (Clear), St Michael's churchyard in Camberley (Min), Slough Cemetery (Scape) and High Wycombe Cemetery (Scape) were significantly lower compared to all sites. With the exclusion of Slough, these sites measured entirely below the English ambient and urban thresholds.

There was one notable outlying measurement from Old Cemetery of 73.4 ppm which is close to the Dutch intervention value of 76 ppm.

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Figure 3.2. Concentrations of arsenic (ppm) measured from 18 urban burial grounds with management category visualised, ANOVA results (p-value with asterisks indicating sites with significant differences in mean concentration: **** p<0.0001, ***p<0.001, **p<0.01, *p<0.05) and overlaid lines for the base mean (dashed), Dutch pollutant standard intervention value (red), estimated ambient background value for England (blue) and mean value in urban soils for England (green). Negative values indicate that concentrations were so low as to be negligible, and not able to be accurately measured during analysis.

The midline of each box represents the median concentration, with the upper and lower limits of the box representing the 75th and 25th percentiles respectively of the inter-quartile range. The upper and lower whiskers extend to the highest and lowest concentrations at no more than 1.5* the IQR from the respective limit. Data points beyond the whiskers are denoted as outliers.

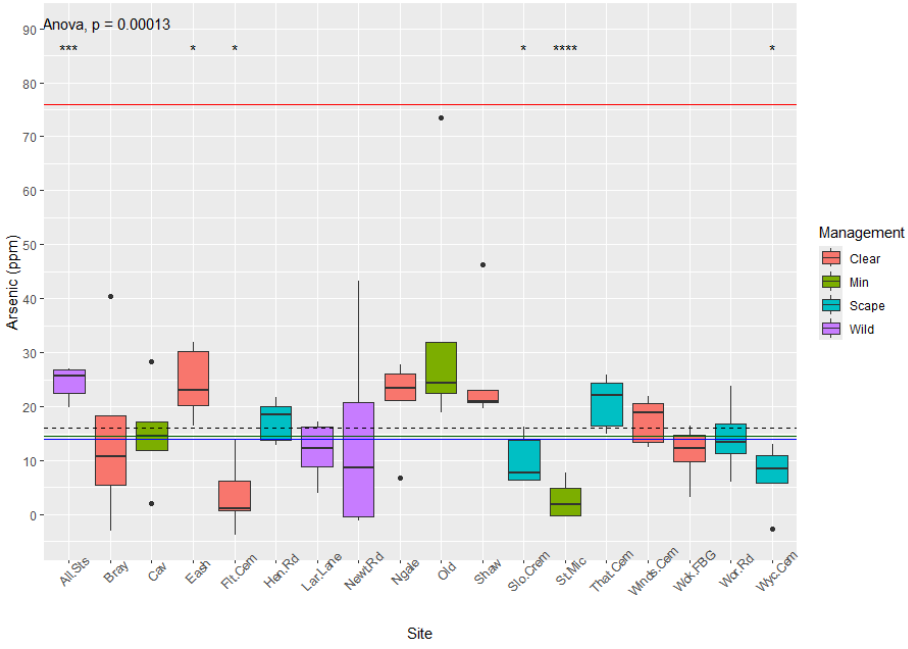


Table 3.6. 95% confidence intervals for mean arsenic concentrations in all sites.

Site	95% CI	
All.Sts	15.620957	33.099846
Bray	-22.340637	2.3782458
Cav	-21.958681	2.7602018
Eash	-12.35778	12.361103
Flt.Cem	-33.036574	-8.317691
Hen.Rd	-19.366974	5.3519091
lar.Lane	-25.016456	-0.2975736
Newt.Rd	-22.485859	2.2330232
Ngale	-15.703776	9.0151068
Old	-2.489056	22.229827
Shaw	-10.571363	14.14752
Slo.Crem	-26.631998	-1.9131154
St.Mic	-33.913862	-9.194979
That.Cem	-15.962825	8.756058
Winds.Cem	-19.303762	5.4151208
Wok.FBG	-25.447431	-0.7285486
Wor.Rd	-22.453741	2.2651416
Wyc.Cem	-29.617487	-4.8986043

3.3.12 Cadmium

All measured concentrations of cadmium were substantially below the Dutch intervention value of 13 ppm, with the highest concentration obtained being 1.9 ppm in Worting Road Cemetery (Scape) (Figure 3.3). The ANOVA revealed statistically significant differences in cadmium concentrations between sites ($F_{(17, 72)} = 14.23$, $p = <0.0001$, R^2 adj. = 0.72). Table 3.7 details the 95% confidence intervals for the mean cadmium values of each site.

The base mean is below zero and concentrations in ten study sites were all measured below zero, indicating negligible levels that could not be accurately measured during analysis. Only six out of the eighteen study sites had all measurements above zero, with Braywick Cemetery (Clear), Nightingale Cemetery (Clear), St Michael's churchyard (Min), Windsor Cemetery (Clear) and High Wycombe Cemetery (Scape) having significantly higher cadmium concentrations compared to all sites.

Braywick, Nightingale, Worting Road (Scape) and High Wycombe cemeteries had cadmium concentrations measured above the estimated ambient and mean urban concentration thresholds. Of the other sites, Henley Road Cemetery in Reading (Scape) and Windsor Cemetery (Clear) both had a single outlying measurement (1.6 ppm and 0.8 ppm respectively) above these thresholds.

Figure 3.3. Concentrations of cadmium (ppm) measured from 18 urban burial grounds with management category visualised, ANOVA results and overlaid lines for the base mean (dashed), Dutch pollutant standard intervention value (red), estimated ambient background value for England (blue) and mean value in urban soils for England (green). Negative values indicate that concentrations were so low as to be negligible, and not able to be accurately measured during analysis.

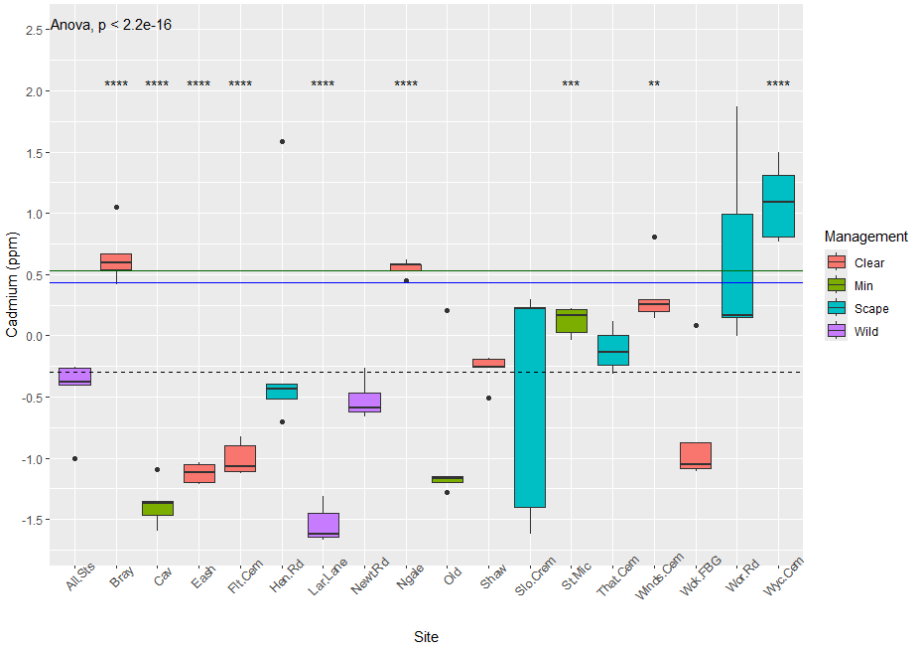


Table 3.7. 95% confidence intervals for mean cadmium concentrations in all sites.

Site	95% CI	
All.Sts	-0.86278675	-0.06364162
Bray	0.55325236	1.68341424
Cav	-1.47651846	-0.34635659
Eash	-1.22679159	-0.09662971
Flt.Cem	-1.10640162	0.02376026
Hen.Rd	-0.19405992	0.93610196
lar.Lane	-1.64128756	-0.51112568
Newt.Rd	-0.62107719	0.50908469
Ngale	0.4487546	1.57891648
Old	-1.02018801	0.10997387
Shaw	-0.38195251	0.74820936
Slo.Crem	-0.55837424	0.57178764
St.Mic	0.01592385	1.14608573
That.Cem	-0.21477043	0.91539145
Winds.Cem	0.23826713	1.36842901
Wok.FBG	-0.90896581	0.22119607
Wor.Rd	0.53219121	1.66235308
Wyc.Cem	0.99277953	2.12294141

3.3.13 Chromium

All measured concentrations of chromium were below the Dutch intervention value of 78 ppm, with the highest concentration obtained being 54.6 ppm in Worting Road Cemetery (Scape) (Figure 3.4). The ANOVA revealed statistically significant differences in chromium concentrations between sites ($F_{(17, 72)} = 20.1$, $p = < 0.0001$, R^2 adj. = 0.79). Table 3.8 details the 95% confidence intervals for the mean chromium values of each site. The base mean chromium concentration is lower than both the ambient and urban thresholds for England. Concentrations of chromium in Eashing (Clear), Nightingale (Clear), Windsor (Clear) and Worting Road (Scape) cemeteries were significantly higher compared to all sites. These sites and additionally Wokingham Free Burial Ground (Clear) had chromium concentrations above the ambient and urban thresholds. A further three sites had measured levels above the urban threshold: Caversham (Min), Henley Road (Scape) and Thatcham (Scape) cemeteries.

Concentrations of chromium in Braywick (Clear), Fleet (Clear), Larges Lane (Wild), Newtown Road (Wild), High Wycombe (Scape) cemeteries and St Michael's churchyard (Min) were significantly lower compared to all sites. Chromium levels for these sites and All Saints (Wild) and St Michael's (Min) churchyards, Caversham (Min), Old (Min), Shaw (Clear), Slough (Scape), High Wycombe (Scape) cemeteries were also fully measured below the ambient and urban thresholds.

Figure 3.4. Concentrations of chromium (ppm) measured from 18 urban burial grounds with management category visualised, ANOVA results and overlaid lines for the base mean (dashed), Dutch pollutant standard intervention value (red), estimated ambient background value for England (blue) and mean value in urban soils for England (green).

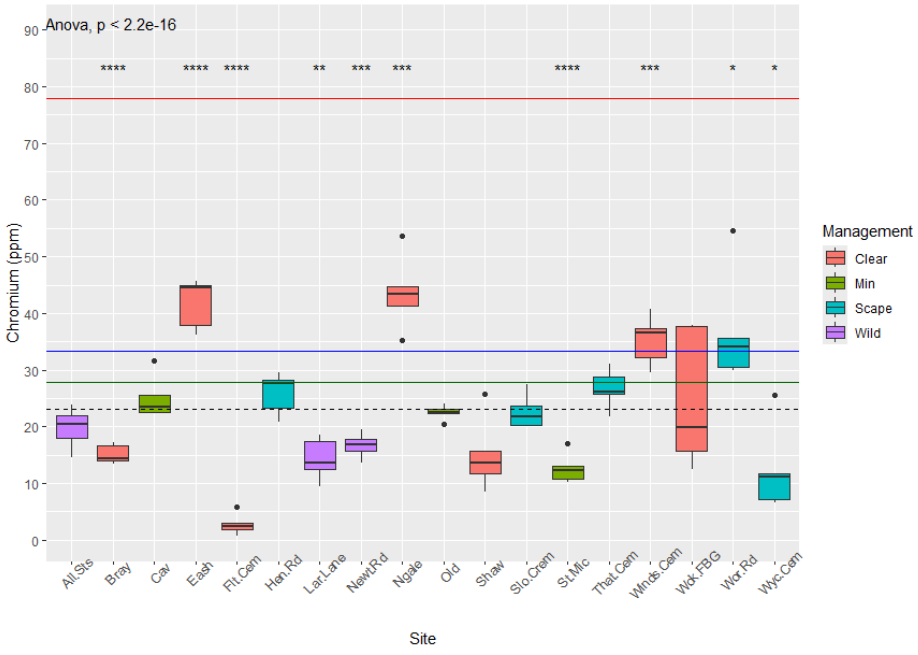


Table 3.8. 95% confidence intervals for mean chromium concentrations in all sites.

Site	95% CI	
All.Sts	14.890202	24.617987
Bray	-11.504967	2.2521978
Cav	-1.5502545	12.206911
Eash	15.207011	28.964176
Flt.Cem	-23.867738	-10.110573
Hen.Rd	-0.7491687	13.007996
lar.Lane	-12.375077	1.3820879
Newt.Rd	-9.9415077	3.8156573
Ngale	17.003431	30.760597
Old	-4.1431656	9.6139995
Shaw	-11.527468	2.2296967
Slo.Crem	-4.0174453	9.7397198
St.Mic	-13.990401	-0.2332363
That.Cem	0.0929141	13.850079
Winds.Cem	8.6220637	22.379229
Wok.FBG	-1.879237	11.877928
Wor.Rd	10.293719	24.050885
Wyc.Cem	-14.204193	-0.4470278

3.3.14 Copper

Measurements of copper were below urban levels, with nine sites having all measured levels below the ambient threshold (Figure 3.5), with two notable outliers. One measurement in Newtown Road Cemetery (Wild), (137.7 ppm), was substantially above the ambient and urban thresholds but still below the Dutch intervention value of 190 ppm. One measurement in Worting Road Cemetery (Scape) was substantially above the Dutch intervention value at 251.7 ppm.

The ANOVA revealed statistically significant differences in copper concentrations between sites ($F_{(17,72)} = 2.16$, $p = 0.0123$, R^2 adj. = 0.18). Table 3.9 details the 95% confidence intervals for the mean copper values of each site. The base mean copper concentration is lower than both the ambient and urban thresholds for England. Copper levels for St Michael's churchyard (Min) and Braywick, Eashing, Fleet, Nightingale, Shaw (all Clear), Larges Lane (Wild), and Thatcham (Scape) cemeteries were significantly lower compared to all sites.

Figure 3.5. Concentrations of copper (ppm) measured from 18 urban burial grounds with management category visualised, ANOVA results and overlaid lines for the base mean (dashed), Dutch pollutant standard intervention value (red), estimated ambient background value for England (blue) and mean value in urban soils for England (green).

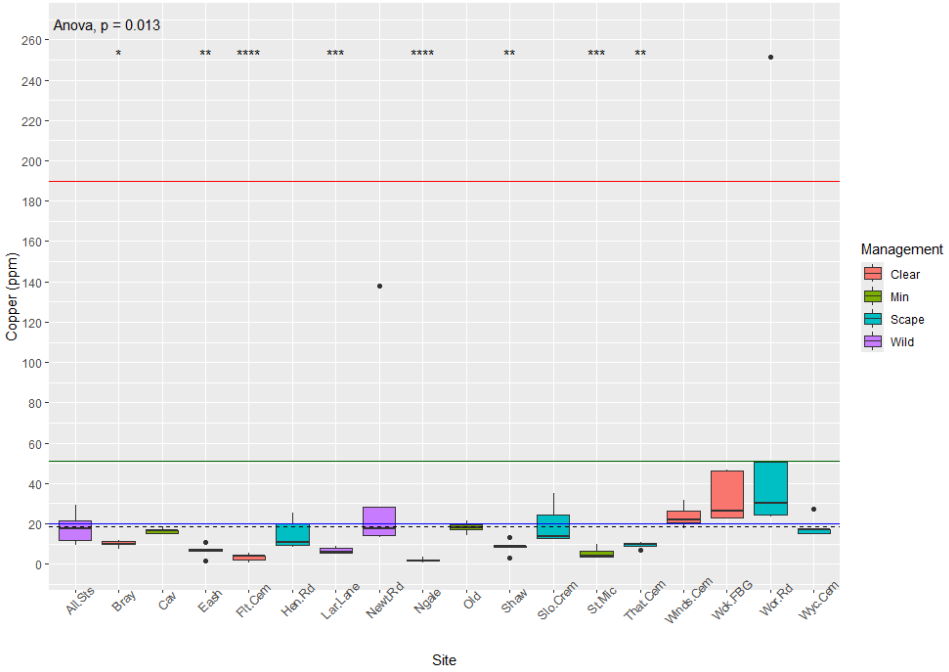


Table 3.9. 95% confidence intervals for mean copper concentrations in all sites.

Site	95% CI	
All.Sts	-6.202639	41.93778
Bray	-41.80318	26.27765
Cav	-35.59712	32.48371
Eash	-45.413969	22.66686
Flt.Cem	-48.755594	19.32524
Hen.Rd	-37.121766	30.95906
lar.Lane	-45.161921	22.91891
Newt.Rd	-9.720842	58.35999
Ngale	-50.030109	18.05072
Old	-33.886001	34.19483
Shaw	-43.494202	24.58663
Slo.Crem	-32.157257	35.92357
St.Mic	-46.481883	21.59895
That.Cem	-42.633006	25.44783
Winds.Cem	-28.35117	39.72966
Wok.FBG	-19.057556	49.02327
Wor.Rd	24.148875	92.22971
Wyc.Cem	-33.657645	34.42319

3.3.15 Nickel

Measurements of nickel for eight sites were below both ambient and urban concentrations in their entirety. Nickel concentrations for five sites were all above ambient and urban thresholds, most notably Eashing Cemetery (Clear) where all bar one measurement ranged from 46.7 ppm to 53 ppm, the highest concentrations of this metal that were recorded. All measurements were substantially below the Dutch intervention value of 100 ppm.

The ANOVA revealed statistically significant differences in nickel concentrations between sites ($F_{(17,72)} = 24.31$, $p = <0.0001$, R^2 adj. = 0.82). Table 3.10 details the 95% confidence intervals for the mean nickel values of each site. The base mean concentration of nickel is lower than both the ambient and urban background levels for England. Concentrations of nickel in Caversham (Min), Eashing (Clear), Nightingale (Clear), Old (Min), Windsor (Clear) and Worting Road (Scape) cemeteries were significantly higher compared to all sites. All measurements for these sites were above the ambient and urban background nickel levels with the exception of Caversham which contained nickel measurements below the urban threshold.

Nickel concentrations for All Saints (Wild) and St Michael's (Min) churchyards, and Braywick (Clear), Fleet (Clear), Larges Lane (Wild), Newtown Road (Wild), Shaw (Clear) and Thatcham (Scape) cemeteries were significantly lower compared to all sites.

Figure 3.6. Concentrations of nickel (ppm) measured from 18 urban burial grounds with management category visualised, ANOVA results and overlaid lines for the base mean (dashed), Dutch pollutant standard intervention value (red), estimated ambient background value for England (blue) and mean value in urban soils for England (green).

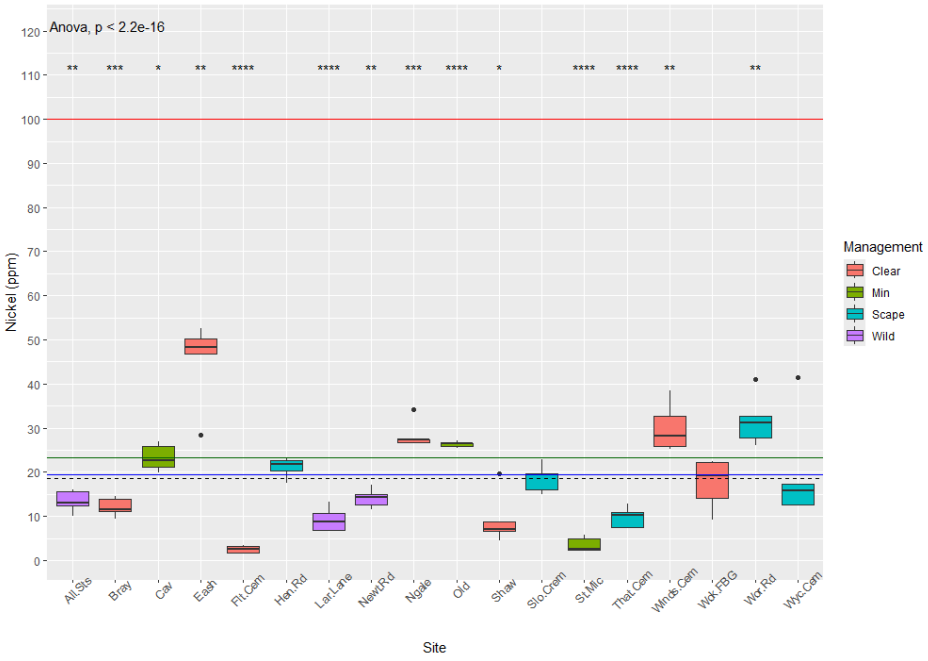


Table 3.10. 95% confidence intervals for mean nickel concentrations in all sites.

Site	95% CI	
All.Sts	9.0041386	17.834759
Bray	-7.5019042	4.986478
Cav	3.6099018	16.098284
Eash	25.567657	38.05604
Flt.Cem	-17.135669	-4.647286
Hen.Rd	1.4563685	13.944751
lar.Lane	-10.429211	2.059171
Newt.Rd	-5.5880121	6.90037
Ngale	8.8556753	21.344058
Old	6.6281743	19.116557
Shaw	-10.352943	2.13544
Slo.Crem	-1.0777423	11.41064
St.Mic	-16.091728	-3.603346
That.Cem	-9.907036	2.581346
Winds.Cem	10.421905	22.910287
Wok.FBG	-2.2204606	10.267922
Wor.Rd	12.082984	24.571367
Wyc.Cem	0.2398716	12.728254

3.3.16 Lead

Concentrations of lead measured predominantly between or below the ambient and urban thresholds (Figure 3.7), however eight sites contained measurements above the urban threshold with two higher outliers; one just below the Dutch intervention value of 530 ppm at 523.8 ppm, and one above this value at 590.9 ppm: Caversham Cemetery (Min) and Newtown Road Cemetery in Newbury (Wild) respectively.

The ANOVA revealed statistically significant differences in lead concentrations between sites ($F_{(17,72)} = 2.319$, $p = 0.0072$, R^2 adj. = 0.2). Table 3.11 details the 95% confidence intervals for the mean lead values of each site. The base mean lead concentration is lower than the urban threshold for England, but higher than the ambient background threshold. Neither Caversham nor Newtown Road cemeteries, the two sites with singular outliers, showed overall significant differences in lead concentrations to any other sites. Levels of lead in High Wycombe Cemetery (Scape) were significantly higher compared to all sites, and those in Eashing (Clear), Fleet (Clear), Henley Road (Scape), Shaw (Clear) and Thatcham (Scape) cemeteries were significantly lower. Lead concentrations in these sites fell entirely below the lower ambient threshold.

Figure 3.7. Concentrations of lead (ppm) measured from 18 urban burial grounds with management category visualised, ANOVA results and overlaid lines for the base mean (dashed), Dutch pollutant standard intervention value (red), estimated ambient background value for England (blue) and mean value in urban soils for England (green).

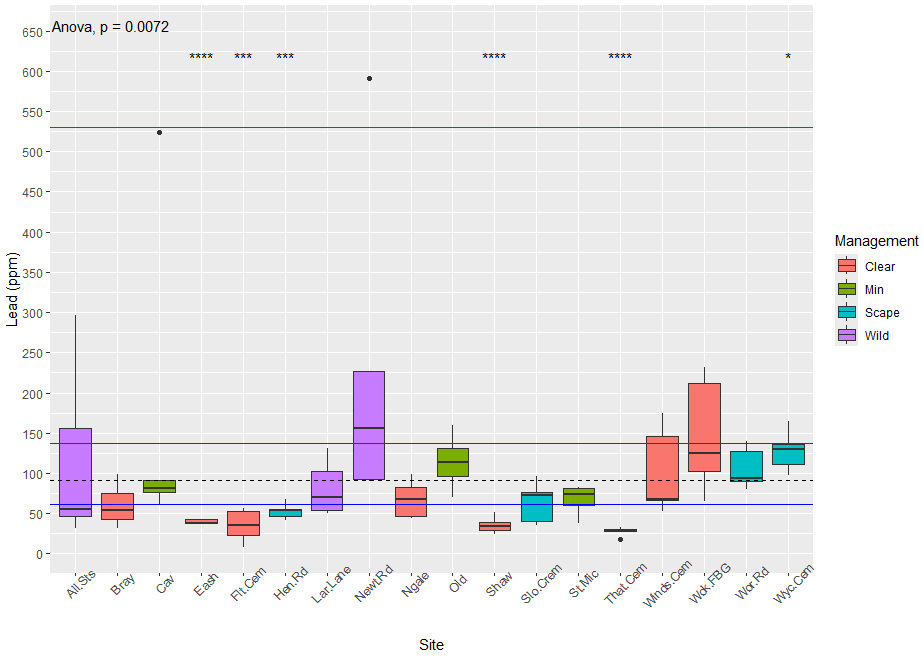


Table 3.11. 95% confidence intervals for mean lead concentrations in all sites.

Site	95% CI	
All.Sts	47.14899	187.0893
Bray	-155.56099	42.344496
Cav	-49.563	148.34249
Eash	-176.68185	21.223634
Flt.Cem	-180.70913	17.196356
Hen.Rd	-162.83104	35.074445
lar.Lane	-134.61522	63.290258
Newt.Rd	15.0089	212.91438
Ngale	-148.20598	49.6995
Old	-101.99868	95.906804
Shaw	-180.782	17.123487
Slo.Crem	-151.77607	46.129412
St.Mic	-148.9517	48.953787
That.Cem	-188.66337	9.242109
Winds.Cem	-114.50108	83.404399
Wok.FBG	-69.05521	128.85027
Wor.Rd	-109.81843	88.087054
Wyc.Cem	-87.96681	109.93867

3.3.17 Zinc

All measured concentrations of zinc were substantially below the Dutch intervention value of 720 ppm, with the highest concentration obtained being 199 ppm in Newtown Road (Wild), which is above both the ambient and urban background thresholds (Figure 3.8). Only one other site had zinc concentrations measured above both thresholds: Worting Road Cemetery (Scape).

The ANOVA revealed statistically significant differences in zinc concentrations between sites ($F_{(17,72)} = 4.793$, $p = <0.0001$, R^2 adj. = 0.42). Table 3.12 details the 95% confidence intervals for the mean zinc values of each site. The base mean zinc concentration is lower than both the ambient and urban thresholds for England, and all measurements for 13 sites were measured below these thresholds. Concentrations of zinc in Old (Min) and Worting Road (Scape) cemeteries were significantly higher compared to all sites. Zinc concentrations measured in Braywick (Clear), Eashing (Clear) and Nightingale (Clear) cemeteries, and St Michael's churchyard (Min) were significantly lower compared to all sites.

Figure 3.8. Concentrations of zinc (ppm) measured from 18 urban burial grounds with management category visualised, ANOVA results and overlaid lines for the base mean (dashed), estimated ambient background value for England (blue) and mean value in urban soils for England (green). The Dutch intervention value for zinc is 720 ppm and is not included for visibility of the plot as the value is far higher than all other values.

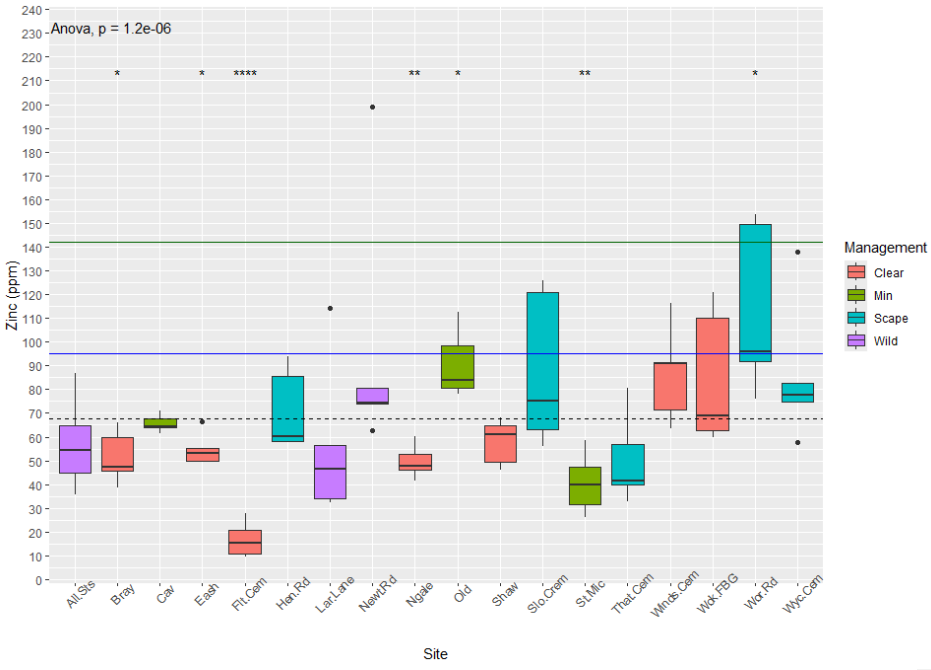


Table 3.12. 95% confidence intervals for mean zinc concentrations in all sites.

Site	95% CI	
All.Sts	35.6767234	79.081227
Bray	-36.5745221	24.808716
Cav	-22.2649288	39.118309
Eash	-33.1743014	28.208936
Flt.Cem	-71.170395	-9.787157
Hen.Rd	-17.0090652	44.374173
lar.Lane	-31.323243	30.059995
Newt.Rd	10.0884428	71.471681
Ngale	-38.4070704	22.976167
Old	2.6321774	64.015415
Shaw	-30.2143395	31.168898
Slo.Crem	0.1666947	61.549932
St.Mic	-47.2897214	14.093516
That.Cem	-37.7527664	23.630471
Winds.Cem	-1.2927624	60.090475
Wok.FBG	-3.5270904	57.856147
Wor.Rd	25.3859659	86.769204
Wyc.Cem	-1.9251857	59.458052

3.3.18 Other soil characteristics

The pH, moisture content and organic matter content of the sample soils are presented below (Table 3.13).

	pH						Moisture content (%)						Soil organic matter (%)					
Site	Min	Max	Median	Mean	SD	SE	Min	Max	Median	Mean	SD	SE	Min	Max	Median	Mean	SD	SE
All.Sts	4.92	6.8	5.34	5.6	0.72	0.32	0.82	1.6	1.24	1.2	0.3	0.13	3.9	7.4	5.9	5.61	1.5	0.7
Bray	5.14	5.73	5.3	5.34	0.23	0.1	1.1	1.23	1.2	1.2	0.06	0.03	5.5	6.73	6.0	6.0	0.5	0.21
Cav	5.04	6.54	5.7	5.7	0.54	0.24	1.23	2.23	1.74	1.73	0.4	0.16	4.44	8.43	5.91	6.2	1.5	0.7
Eash	5.2	5.8	5.3	5.4	0.26	0.12	1.02	1.27	1.2	1.14	0.11	0.05	4.2	4.84	4.32	4.42	0.27	0.12
Flt.Cem	4.15	5.61	4.63	4.73	0.55	0.23	0.34	1.39	0.78	0.8	0.4	0.18	4.21	12.81	6.7	7.6	3.21	1.44
Hen.Rd	5.36	6.6	5.64	5.9	0.51	0.23	1.22	1.83	1.6	1.6	0.22	0.1	4.6	8.02	6.6	6.42	1.27	0.6
Lar.Lane	4.3	5.54	5.2	5.09	0.48	0.21	1.09	1.53	1.5	1.41	0.18	0.08	5.0	8.4	6.2	6.64	1.38	0.62
Newt.Rd	4.2	6.9	5.8	5.63	0.98	0.44	1.1	2.04	1.7	1.57	0.36	0.16	5.9	10.6	9.32	8.7	1.83	0.82
Ngale	5.21	5.5	5.46	5.41	0.12	0.05	0.84	1.01	0.98	0.94	0.09	0.04	4.02	5.0	4.54	4.47	0.34	0.15
Old	5.57	7.4	7.17	6.74	0.8	0.34	1.2	1.9	1.7	1.6	0.3	0.11	6.51	8.4	7.5	7.4	0.8	0.34
Shaw	5.6	7.1	5.81	6.3	0.71	0.32	1.0	2.7	1.81	1.83	0.62	0.28	5.43	10.1	7.22	7.72	2.0	0.9
Slo.Crem	5.33	6.8	5.9	6.0	0.6	0.26	1.35	2.0	1.64	1.62	0.22	0.1	4.8	6.71	5.9	5.86	0.74	0.33
St.Mic	4.5	5.2	4.9	4.9	0.27	0.12	0.94	1.62	1.12	1.2	0.3	0.12	5.6	11.6	6.2	7.11	1.5	1.12
That.Cem	5.37	5.81	5.57	5.61	0.19	0.08	1.11	2.8	2.26	2.03	0.71	0.32	4.66	14.0	9.5	9.1	3.7	1.64
Winds.Cem	6.05	6.99	6.76	6.63	0.37	0.16	3.63	4.34	3.92	3.95	0.26	0.11	12.1	13.92	13.0	12.93	0.7	0.31
Wok.FBG	5.1	5.42	5.31	5.3	0.15	0.1	1.2	1.42	1.3	1.29	0.1	0.11	6.04	7.71	6.74	6.84	0.61	0.27
Wor.Rd	5.6	7.24	6.2	6.44	0.72	0.32	1.7	2.62	2.33	2.3	0.34	0.15	6.52	9.5	8.75	8.18	1.31	0.6
Wyc.Cem	7.4	737	7.56	7.6	0.11	0.05	1.7	2.4	2.13	2.11	0.26	0.12	9.02	12.0	10.16	10.23	1.16	0.52

Table 3.13. Statistical summary for soil characteristics measured for the 18 study sites.

3.3.2 Principal component analysis (PCA)

The scree plot (Figure 3.9) shows that eight components explained more than one variable's worth of information as indicated by the red line and should therefore be included in further analysis. The amount of variance explained by the ninth component sits on or very near to the red line, so could potentially be included. The eigenvalues provide a more detailed view of the variance explained by the top ten components (Table 3.14) and when applying Kaiser's Criterion whereby components with an eigenvalue <1 should be included in further analysis, the ninth component met this criterion. The top nine components in the PCA explained 80.5% of the variance, with PC1 and PC2 accounting for 34.7%.

Figure 3.9. Scree plot showing the percentage of variance explained by each component of the principal component analysis. The red line is positioned on the y-axis at the value for the variance that would be explained by a principal component if it only contained one variable.

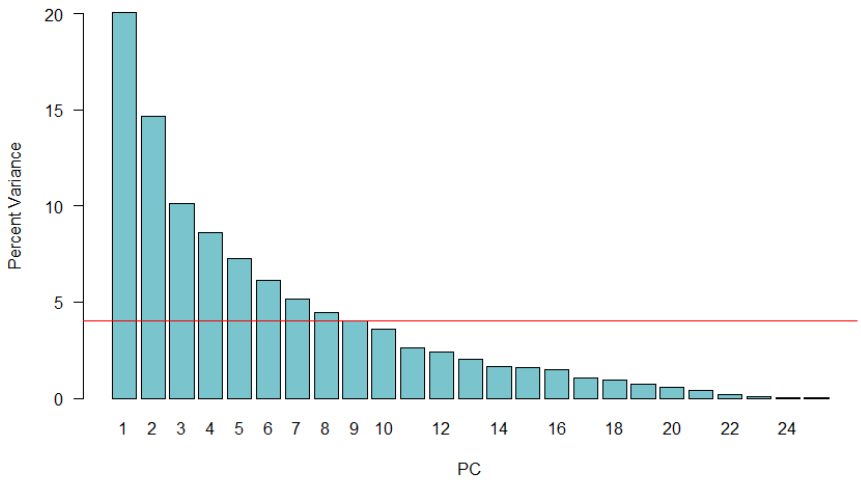


Table 3.14. Eigenvalues and the percentages of the variance explained for the first ten components both individually and cumulative.

Principal component	Eigenvalue	Variance explained (%)	Cumulative variance explained (%)
1	5.01232248	20.04928993	20.04929
2	3.66076881	14.64307525	34.69237
3	2.52644263	10.10577052	44.79814
4	2.1605561	8.6422244	53.44036
5	1.81706835	7.26827338	60.70863
6	1.52711465	6.1084586	66.81709
7	1.29552411	5.18209646	71.99919
8	1.10878949	4.43515796	76.43435
9	1.01188772	4.04755088	80.4819
10	0.90368722	3.61474888	84.09665

Variables correlated with the first two principal components are considered the most important in explaining variability. Balancing ease of interpretation with detailed analysis as the third component explains an additional 10.1% of the variance, PC1, PC2 and PC3 were explored further.

The extent to which each of the variables contributed to a component provides further detail as to which were most important in explaining variability within a PCA. The contributions of the number of burials (15.5%), size of the site (12%), soil pH (11%), the coverage of manmade structures and surfaces (8.3%), and population density (8.1%) accounted for over half of the variance explained by PC1 (Figure 3.10). Zinc and nickel were the only heavy metals that contributed by more than the expected value to PC1 (7% and 5% respectively).

The contributions to PC2 indicate further important variables in the explanation of variance within the PCA (Figure 3.11). The age of the site (16.2%), the date of death of the most recent deceased interred in a grave (13%), burial density (12%), distance to the nearest road (9.4%) and levels of lead measured in the soil (8.4%) accounted for 59% of the variance explained by PC2. Lead was the only heavy metal that contributed by more than the expected value to PC2.

Further variables of importance contribute to PC3 (Figure 3.12). The area of tree coverage surrounding the site (15.3%), concentrations of nickel and chromium (13.1% and 12%

respectively), annual average daily flow of traffic the vicinity (11.4%) and the area of hedgerow coverage surrounding the site (11%) account for 62.8% of the explained variance in PC3. Nickel, chromium, arsenic (8%) and cadmium (4.2) contribute to the component above the expected value.

Figure 3.10. Contributions of variables to the first principal component. The red dashed line is the percentage contribution expected if all contributions were equal.

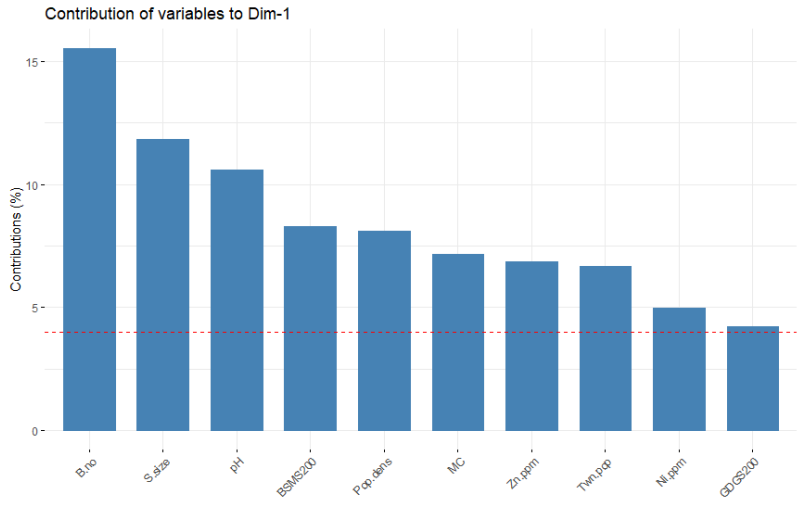


Figure 3.11. Contributions of variables to the second principal component. The red dashed line is the percentage contribution expected if all contributions were equal.

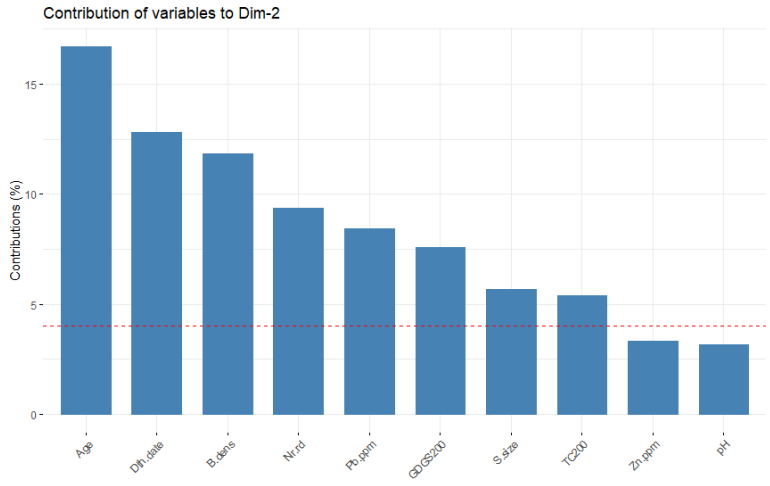
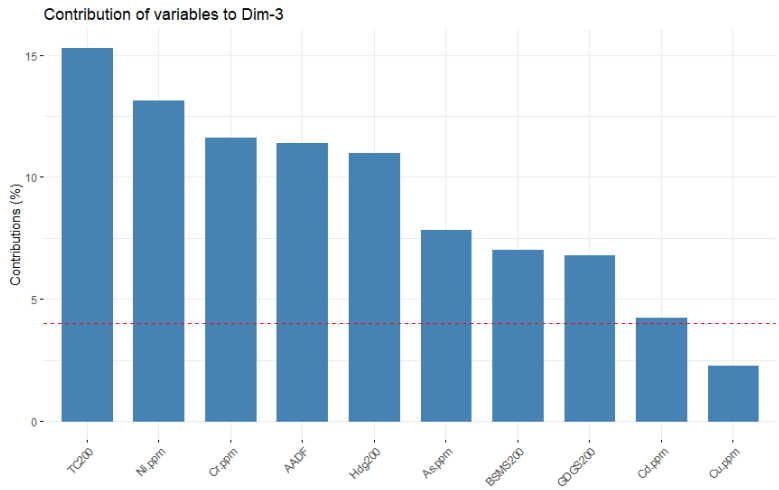


Figure 3.12. Contributions of variables to the third principal component. The red dashed line is the percentage contribution expected if all contributions were equal.



In addition to the contributions of variables to the principal components, the strength of their representation was plotted along with how the soil sample points were positioned within the components (Figure 3.13 and 3.14).

Figure 3.13. Biplot of the quality of representation (cos2) for variables included in the PCA and positioning of sample points within the **first** and **second** principal components. The longer the arrow for a variable or further away a sample point is from the centre, the stronger the representation.

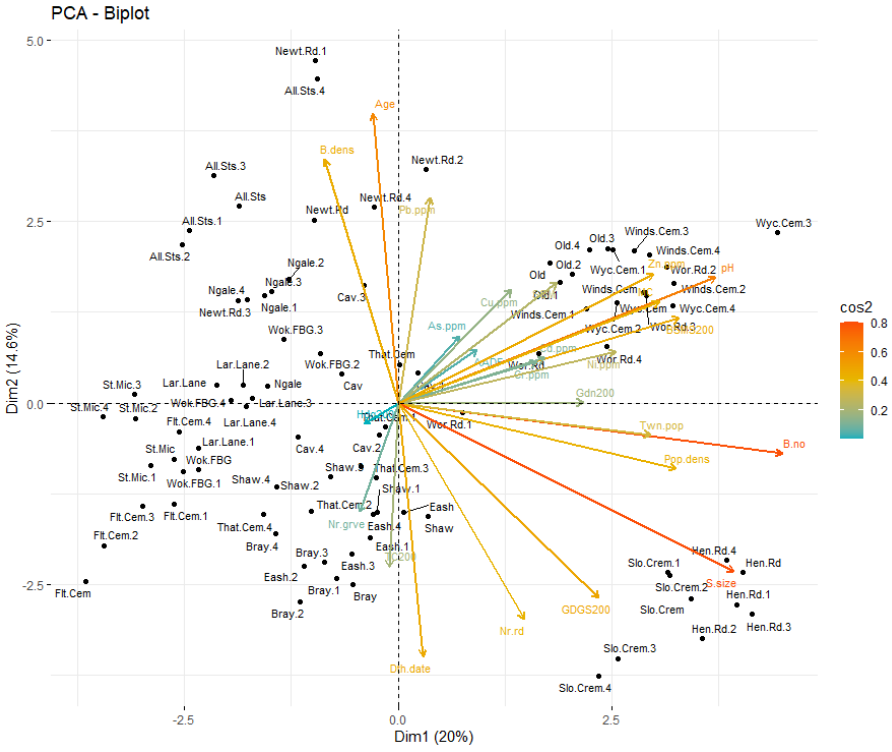
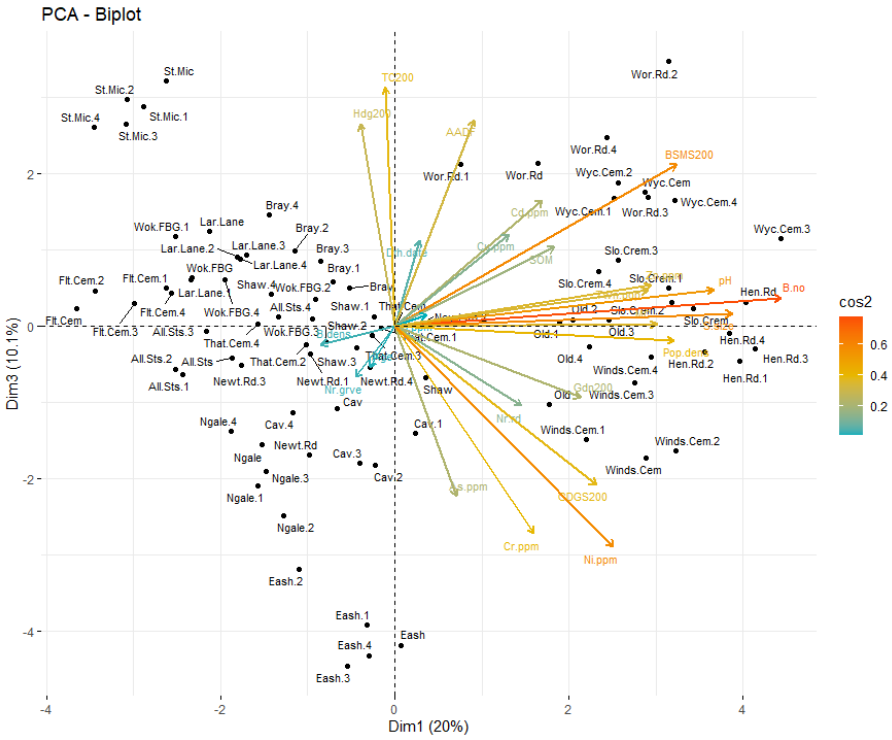


Figure 3.14. Biplot of the quality of representation (cos2) for variables included in the PCA and positioning of sample points within the **first** and **third** principal components. The longer the arrow for a variable or further away a sample point is from the centre, the stronger the representation.

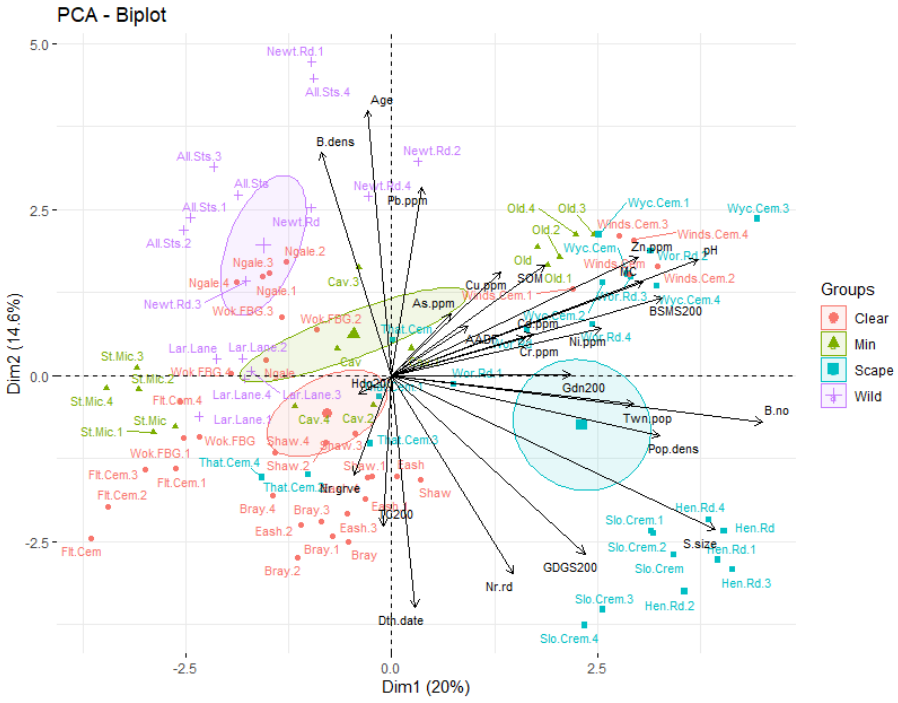


To investigate influences of potentially important categorical variables, further plots with 95% confidence ellipses were created where sample points were categorised by management type (Figure 3.15), vegetation type (Figure 3.16), and nearest road type (Figure 3.17).

The 95% confidence ellipses for management categories (Figure 3.15) indicate that the positions where 95% of data points from each category would be expected to fall with repeated sampling are all distinctly separate from each other. Examining the location of sample points on the biplot allocated to each category, the Min and Wild categories appear to correspond well to the respective ellipse positions; there may be multiple groupings for Clear and Scape. The size and shape of the ellipses reflect the dispersion of the data points; the ellipse for the Scape

management category, for example, is the largest and indicates there is more variability along the principal components. The Scape category ellipse is positioned opposite the ellipses for Wild and Min categories on PC1 and PC2, however the Min category ellipse is positioned across both axes. The ellipses for Min and Clear categories are both positioned close to the centre, indicating weaker representation within the PCA.

Figure 3.15. Biplot for the first and second principal components with sample points categorised by management type and 95% confidence ellipses.

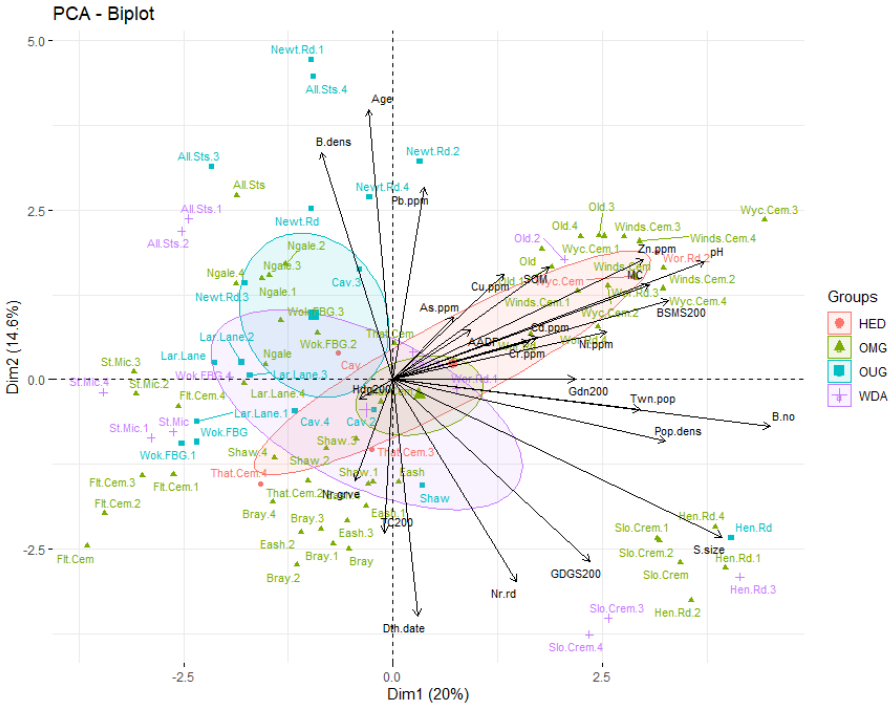


The 95% confidence ellipses for WDA (wooded area) and HED (hedgerow) vegetation types overlap with all other types (Figure 3.16) indicating a weaker influence of vegetation type on sample point locations on the principal components. The size of confidence ellipses can be

affected by sample size, which is relatively small for HED and WDA compared to the other two types; these ellipses have the largest area which contributes to the level of overlap.

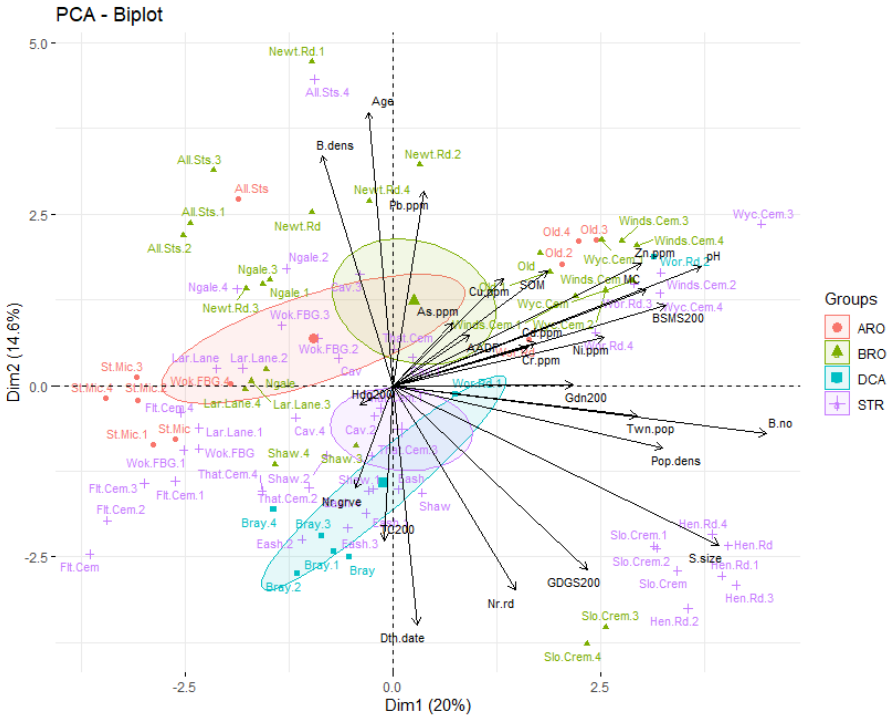
The confidence ellipses for OMG (open mown grassland) and OUG (open unmown grassland) are positioned adjacent to each other but do not overlap, indicating different positioning of sample points along the principal components assigned to those two vegetation types.

Figure 3.16. Biplot for the first and second principal components with sample points categorised by vegetation type and 95% confidence ellipses.



The 95% confidence ellipses for ARO (A-roads) and BRO (B-roads) overlap, with a small sample size for ARO contributing to a larger ellipse (Figure 3.17). The ellipses for these road types are positioned on the components opposite DCA (dual carriageways) and STR (residential street), indicating opposing influences. The sample point locations for DCA correspond well with the ellipse, however, there appear to be multiple groupings for BRO and STR.

Figure 3.17. Biplot for the first and second principal components with sample points categorised by nearest road type and 95% confidence ellipses.



3.4 | DISCUSSION

The heavy metal composition of necrosols measured in this study of 18 burial grounds exhibits significant differences between sites and compared to expected UK ambient and urban background levels (Table 3.5, Figures 3.2-3.8). For every metal tested, at least one measurement was below these levels, with some arsenic and cadmium concentrations so negligible as to not be accurately measured in analysis. For two of the burial grounds examined here (Fleet Cemetery and St Michael's churchyard) all measurements were below urban background concentrations for the seven heavy metals, indicating lower contamination levels than the wider urban environment; including other types of green space which were included in developing these background concentrations.

There were however a small number of measurements recorded for all heavy metals that were above the expected urban background levels. Although most sites do not appear to have consistently high levels of heavy metals, all measured concentrations of arsenic, chromium, and nickel in Eashing and Nightingale cemeteries, both in Godalming, Surrey UK, were elevated compared to expected urban concentrations (Figures 3.2, 3.4 and 3.6). Other sites yielded total concentrations above expected levels; arsenic and nickel in Reading Old cemetery (Figures 3.2 and 3.6), chromium and nickel in Windsor and Worting Road (Basingstoke) cemeteries (Figures 3.4 and 3.6), and cadmium in High Wycombe cemetery (Figure 3.3). Individual arsenic, lead, and copper concentrations were measured that were very close to or above the Dutch intervention value (Reading Old cemetery, Caversham and Newtown Road (Newbury) cemeteries, Worting Road (Basingstoke) cemetery, respectively) indicating levels of contamination that are considered dangerous to life (Figures 3.2, 3.5 and 3.7). These are worthy of further investigation due to the potential risks to biodiversity and human health.

After establishing heavy metal concentrations in the study burial grounds, and initially exploring comparisons to expected urban background levels, the further aims of this study were to investigate how heavy metal pollutants relate to factors i) within the wider urban landscape and ii) within the burial grounds themselves. In this way, potential drivers of variation in heavy metal concentrations were examined from among the following factors: site size and age, most recent interment in the nearest grave, number and density of interments, management, pH, soil organic matter and moisture and land types in the surrounding urban landscape.

3.4.1 Site size

The size of a burial ground contributes to PC1 and PC2 of the PCA and is well-represented on the components (Figures 3.10, 3.11, 3.13). There is little evidence here that the size of the study burial grounds influenced soil heavy metal concentrations. Zinc and nickel both contributed to PC1 for which site size was the second largest contributor (Figure 3.10), and lead contributed to PC2, with site size having a weaker contribution (Figure 3.11). Site size did not appear to be correlated with any heavy metals based on the Principal Component Analysis (Figure 3.13).

All of the samples collected from the two largest sites in the study, Henley Road in Reading and Slough Cemetery, which are both municipal cemeteries on the outskirts of their respective towns, were strongly clustered together (positively along axis 1 and negatively along axis 2) and away from all other samples. Sample points positioned in the opposite quadrant (positively along axis 2, negatively along axis 1) were generally the smaller sites in the dataset. In addition to being the largest sites, Henley Road and Slough had further similarities in that they were both in the Scape management category (Table 3.1, Figure 3.15) and their sample points were all closest to residential streets (Figure 3.17). This reflects the planning philosophy of these two burial grounds, as the current approach to the positioning and design of modern cemeteries in urban areas is to transform larger pieces of land in the suburban vicinity, where there is more space than the urban centre and more residential streets, to accommodate larger populations and therefore more interments (Rugg, 2006; McClymont and Sinnett, 2021). Modern tastes in landscaping for municipal cemeteries, and public green spaces more generally, call for horticultural design elements incorporating trees, shrubs, and lawns that are kept well-maintained (Swensen, 2018; Quinton and Duinker, 2019).

As there were no clear correlations between site size and any heavy metal concentrations, and measured concentrations of nickel, lead and zinc for Henley Road and Slough cemeteries fell below expected background concentrations (Figures 3.6, 3.7, 3.8 respectively), this indicates that at least these large contemporary cemeteries, particularly by virtue of their size, appear to not contain elevated heavy metal concentrations. This may be because the soil has been under this type of land use for a relatively short time period (Slough opened 86 years ago, Henley Road 91 years ago; only one cemetery is 'younger' at 65 (Table 3.1) and site age had almost the opposite relationship to site size, being positively associated with axis 2 of the PCA (Figure 3.13). There is evidence that the management approach to urban burial grounds exhibited in the Scape category can be beneficial for biodiversity (specifically abundance of flying beetles; Cathcart-James, Foster and Pickles, 2022), the success of which may be compounded by lower soil heavy metal concentrations.

3.4.2 Site age

The age of the study burial grounds is the largest contributing variable to PC2 (Figure 3.11) and is also strongly represented on the component (Figure 3.13). There is some evidence that concentrations of lead measured in soils were positively correlated with site age, along with burial density, as these factors were all positively associated with PC2 and separated from other factors (Figure 3.13). Site size appeared to have the opposite effect to date of death of the most recent interment in terms of its influence on necrosol composition. This rather appropriately suggests, that i.) older burial grounds hold older interments, and ii.) smaller sites tend to be older and have a higher intensity of interment activity, likely due to historical pressures on burial grounds that originated in the centre of urbanised areas. As older urban burial grounds are mostly located in or near the centre of towns and cities their soils have also been subjected to urban pollution pressures for longer time periods, including vehicular emissions which are a leading cause of lead pollution in urban soils (Li, Poon and Liu, 2001; Ona *et al.*, 2006; Guagliardi *et al.*, 2015). The positioning of lead concentrations on the principle components, and evidence that the older sites in the study generally have higher lead concentrations (including Newtown Road cemetery in Newbury, which is the second oldest site and sixth smallest, and contained one measurement of lead above the Dutch intervention value; Figure 3.7), indicates that the older an urban burial ground is, the higher the lead concentrations are likely to be.

The sample points positioned positively on PC2 in alignment with site age show other similarities. The majority are in the Wild management category (Table 3.1, Figure 3.15), situated in open unmown grassland areas (Figure 3.16). It may be that older sites which are managed at least in part with wildlife in mind, typically by incorporating areas of unmown grassland, are buffered from further lead pollution by these interventions. These samples were also mostly located nearest to B-roads except for one point in All Saint's which was closest to a residential street (Figure 3.17), benefiting in this case by being surrounded by quieter roads, albeit for a longer period of time, and accepting few to no interments due to the sites' ages and being at capacity. Further investigation is needed, but it may be that despite long-term lead pollution, wildlife-sympathetic and remedial management in older urban burial grounds can still yield positive results for biodiversity (Tosini et al., 2023; Ojija, 2024).

3.4.3 Most recent interment in nearest grave

The date of death for the most recent interment nearest to each sample point is the second largest contributor to PC2 behind site age (Figure 3.11) and is well-represented on the

component (Figure 3.13). This variable was captured as a measure of potential leachate load in the soil surrounding the nearest grave, as substances identified as leachates, including heavy metals from full body interments, have previously been measured in topsoil (Spongberg and Becks, 2000; Aruomero and Afolabi, 2014; van Allemann, Dippenaar and Olivier, 2019).

There is some evidence here to suggest that how recently a burial has been undertaken closest to a sampling point is associated with soil concentrations of lead, the only heavy metal to contribute to PC2 (Figures 3.11 and 3.13). When examining these variables they respond in opposite ways, suggesting a negative correlation; the more recently an interment had been undertaken in the nearest grave, the lower the concentration of lead measured.

The distance to the nearest grave from sample points did not contribute to the first three principal components above the expected value for explaining variation in a single variable, and although there was some suggestion of association with the date of death, this factor was weakly represented in the first two components (Figure 3.13). This suggests that the timing of interments is more important than proximity for levels of lead in the soil. This may be attributed to the length of time required for lead to undergo adsorption and become mobile, which is dependent on the stability of the form it takes (Hettiarachchi and Pierzynski, 2004; Wuana and Okieimen, 2011). As discussed in the previous section, lead is also positively correlated with site age and burial density indicating that older sites, which by their nature have older interments and at greater density, exhibit higher levels of lead in the soil closest to older burials. Higher concentrations of lead in soil have been shown to have detrimental effects on soil-dwelling and above-ground organisms, thereby threatening soil health, wider biodiversity and ecosystem function (Hernández and Pastor, 2008; Ghannem et al., 2023). It could therefore be important for managers of older urban burial grounds to understand the different forms of lead, and assess their concentrations, when planning for biodiversity enhancements and measuring their success.

Several sample points aligned with the vector for the most recent interment from Eashing, Shaw, and Thatcham cemeteries (Figure 3.13), although they are weakly represented in the PCA. These sample points did share some similarities, namely the Clear management category and being mostly situated in open mown grassland, which is characteristic of that management type. The nearest type of road to all of these sample points was residential street, inferring less traffic, and indicating that intra-site factors were likely to be more important in explaining concentrations of lead than vehicle exhausts at these points. The 95% confidence ellipse for the residential street road type overlaps with that of dual carriageway showing a lack of statistically significant differences (Figure 3.17). However, there were far fewer sample points closest to dual carriageways, making this road type a less reliable grouping, and samples closest

to residential streets tended to be aligned with the date of most recent interment (i.e. these locations were recently disturbed).

3.4.4 Number of interments

The number of interments in the study sites was the largest contributing factor to the first principal component, which itself explained 20% of the total variance (Figure 3.10), and this factor was very strongly represented on the component (Figure 3.13). Number of interments was closely aligned with the population size and density of the town or city the study burial grounds are located within, showing as expected *a priori* that the larger and more densely populated the town or city, the greater the number of deaths and therefore interments in their burial grounds. Sample points within the Scape management category tend to be pulled out positively along PC1, indicating they are associated with a greater number of burials. In addition, PC1 is associated with increases in soil pH, suggesting soils in sites with higher burial numbers appear to be more alkaline than those with fewer burials.

3.4.5 Management

Management categories for the study burial grounds (Table 3.1) were overlaid on the original biplot of the PCA to examine any relationships between soils collected under a specific type of site management and the factors contributing to the first two principale components (Figure 3.15). The ANOVA analyses performed for each of the heavy metals measured here revealed significant differences between sites (Figures 3.2 – 3.8), and some insight can be gained from comparing the management categories of sites exhibiting those differences in conjunction with the PCA.

The 95% confidence ellipses indicate distinct groupings of sites according to management type, particularly Scape and Wild as they are positioned opposite each other on the principal components and further away from the centre of the ordination, indicating stronger separation along PC1 than the other two management categories. Sites under the Wild management category are particularly well-grouped together on the components (mostly negative along PC1 and mostly positive along PC2) and were found to have significantly lower concentrations of several heavy metals measured here; namely chromium in Newtown Road and Larges Lane cemeteries, nickel in all three sites in this management category (Newtown Road, Larges Lane, and All Saint's churchyard), and copper in Larges Lane. However, levels of arsenic

were significantly higher in All Saint's churchyard, and Newtown Road cemetery had two outlying high measurements for copper and lead. These results indicate that further research is needed to investigate whether aspects of site management from the Wild category are maintaining lower levels of chromium, nickel, and copper, and whether the high levels of arsenic, copper, and lead are indicative of problematic contamination. In Chapter 2, the Wild management category was found to support the highest diversity of flying beetle families (Cathcart-James, Foster and Pickles 2022); it may be that lower contamination levels of some heavy metals contribute to biodiversity support in these sites, but additional investigation, particularly of ground-dwelling organisms is needed to understand this further.

Heavy metal concentrations found in sites under the Scape management category presented a varied picture. Significantly higher levels of cadmium and lead were measured in High Wycombe cemetery, along with chromium, nickel, and zinc in Worting Road cemetery. However, significantly lower levels of all heavy metals except cadmium were found in other sites under the Scape management category. These results present further research opportunities into the effects of Scape category-specific management activities on levels of different heavy metals in the soils. This management category was found to support higher abundances of flying beetles (Cathcart-James, Foster and Pickles 2022), to which lower levels of heavy metals may be a contributing factor. Further investigation will help to build a clearer picture of why the Scape and Wild management categories exhibit statistically significant differences in soil heavy metal concentrations.

3.4.6 pH

The pH of the soil samples is the third largest contributing factor to PC1 behind the number of interments and site size (Figure 3.10) and is also well represented on the component (Figure 3.13), showing that pH is important in explaining variation in the PCA. The vector on the biplot is overlaid by that for soil moisture content indicating a strongly positive correlation whereby less acidic soils hold more water. Pedological research has determined that the solubility of many heavy metals is negatively correlated with pH, and that pH is often one of, if not the most important determining factor in their solubility and adsorption (Chuan, Shu and Liu, 1996; Kupka et al., 2021; Kicińska, Pomykała and Izquierdo-Diaz, 2022). Zinc, cadmium, chromium, and nickel concentrations were positively associated with pH in the PCA, indicating that concentrations of these heavy metals increase as the soil pH becomes more alkaline. Potentially this corresponds to retention of heavy metals in more alkaline soils. However, in real terms, only

17 of the 90 soil samples had a pH measured above 7, meaning the majority were acidic or neutral; most urban soils are characterised as having an alkaline pH (Tóth, Dombos and Hornung, 2023). Therefore, these heavy metals are likely to be more soluble and have a higher mobility in urban burial grounds, meaning they are more available for uptake by plants and other organisms.

Several soil samples from High Wycombe, Windsor, and Worting Road (Basingstoke) cemeteries were associated with pH. The pH for soil samples across the three sites were measured between 5.55 and 7.7 with a mean of 6.9 and median of 7, indicating that on average the soils were weakly acidic. These soils exhibited several similarities in that all bar two, which were situated in hedgerows, were collected in open mown grassland (Figure 3.16), and High Wycombe and Worting Road were in the Scape management category with Windsor in the Clear category (Figure 3.15). Larger areas of mown grassland are characteristic of both these management approaches. The sample point randomly located in a hedgerow at Worting Road was closest to a dual carriageway running the length of one side of the cemetery, whereas the other sample points for the three cemeteries were closest to B-roads and residential streets (Figure 3.17).

The Worting Road Cemetery hedgerow soil had a recorded pH of 7.12, the highest recorded in the site. The hedgerow is mature and tall, including trees, and boundaries of this nature have been shown to play a role in buffering pollution from traffic (Gromke, Jamarkattel and Ruck, 2016; Blanusa *et al.*, 2019; Vitaliano, Cascone and D'Urso, 2024), which could explain a higher pH than expected for soils in that location. However, there is another sample point in this site located closest to a dual carriageway but located in a woodland area (Figure 3.16) with pH measured at 5.55, the most acidic sample recorded in High Wycombe, Windsor, and Worting Road cemeteries. The woodland is the most likely cause of this elevated acidity, however it is an anomaly that is worth investigating further.

The evidence here indicates that urban necrosols are generally acidic, with less acidic soils accumulating greater concentrations of four ecologically important heavy metals, particularly in burial grounds with more intensive management and mown grassland.

3.4.7 Soil organic matter

Organic matter content of the soil samples did not contribute meaningfully to the first three components of the PCA (Figures 3.13 and 3.14), indicating that this element of soil composition is

not a strong explanatory factor for variance in the PCA. On examination of representation via the biplot for the first and third components (Figure 3.14) the vector is positioned similarly to those for copper and cadmium concentrations; these contribute to the third principal component (Figure 3.12), although copper is below the value expected for contribution to more than one variable, and representation on the component is relatively weak.

The organic matter content of soils is recognised as being a key factor in the accumulation and immobilisation of heavy metals due to stable complexes forming between them, with some metals exhibiting particular affinities such as copper, nickel, lead and zinc (Kwiatkowska-Malina, 2018; Li et al., 2022). *A priori* a more significant influence of soil organic matter on heavy metal concentrations was expected, however urban necrosols have not previously been researched in this manner and other factors discussed here were found to have greater influence.

3.4.8 Buildings, structures and manmade surfaces including roads

The area covered within a 200-metre radius of the study sites by buildings, structures and manmade surfaces (BSMS) contributes to both the first and third component of the PCA and is strongly represented on the components (Figures 3.10, 3.12, 3.14). BSMS appeared somewhat associated with cadmium and copper in the PCA suggesting a positive correlation, however these heavy metals were not strongly represented and contributed to PC3 to a far lesser degree (Figure 3.12). In addition, the third component explains half the variation of PC1, therefore limiting interpretation of the potential influence of BSMS on cadmium and copper.

Deposits of technogenic materials are expected in urban soils from building construction, infrastructure installation, ground levelling, and road building, all of which are expected to be greater where BSMS covers more area; however, detection of these materials may require deep soil sampling and, in this study, only topsoil was analysed. Therefore, any influence of technogenic materials on soil heavy metal content would be limited in this study. Urban cemeteries created in more modern times can constitute a change in land use, and they are more likely to be located on the foundations of old buildings, built over pipelines, and contain previous construction debris. By contrast, older, more central burial grounds have been under this type of land use for longer and, due to their long-standing social importance, are rarely disturbed by further urbanisation, so they are not subject to the same technogenic deposits. More broadly, new material is generally not introduced into burial grounds other than compost, wood chippings, and new topsoil through horticultural activities and families tending to graves; this

further limits any impact of construction activity on the soil. Backfilling graves following interments and exhumations use the same soil as was removed, or rarely spare soil will be used from another burial ground, so whilst soil is disturbed it does not often introduce new material that may be contaminated.

BSMS can also be examined as a proxy for urban population pressures via vehicle and machinery use in more built-up areas, therefore leading to deposition of heavy metals via particulate matter or surface runoff into the topsoil of the urban burial grounds studied. Whilst cadmium and copper are known constituents of urban emissions, if BSMS as a proxy was of importance in determining the levels of heavy metals found in this study then evidence of a relationship with concentrations of lead would also be expected as it is a significant contributor to lead deposition; however, no evidence has been found here of any meaningful influence of BSMS on lead concentrations in burial ground soils.

3.4.9 Tree cover

The area covered by trees in a 200-metre radius of each study site contributed modestly to PC2 but was the largest contributor to PC3, accounting for 15% of the variation explained by the component, and was well represented (Figures 3.11, 3.12 and 3.14). There was a positive correlation with hedge cover, indicating that these two types of green infrastructure in vicinity of the study burial grounds may influence soil structure in a similar way. With regards to heavy metals, the vectors for displayed the opposite pattern to both tree and hedge coverage, suggesting that as green infrastructure coverage increases, concentrations of these heavy metals decrease (Figure 3.14). Arsenic, chromium and nickel all contributed strongly to PC3 in addition to tree and hedge coverage (Figure 3.12) and were well-represented. Although PC3 overall had a weaker contribution to explaining variation within the soil data there was evidence of potentially important relationships between two types of green infrastructure and three important heavy metals found within the study burial grounds. There is a significant body of research related to the heavy metal mitigation potential of urban tree and hedge species, particularly looking at the mechanisms of leaf deposition and bioaccumulation (Grote *et al.*, 2016; Blanusa *et al.*, 2019; Ozdemir, 2019). With greater coverage in the immediate surroundings of the study sites may come greater buffering of intra-site pollution and any associated negative impacts on biodiversity.

There is evidence of a negative correlation between hedge and tree coverage surrounding the study sites, and grass-dominated green space (GDGS) (Figure 3.14). It is logical for places

with a greater area of GDGS to contain fewer trees and hedgerows, however, these two types of urban green infrastructure have been previously shown to have beneficial effects on pollution mitigation, and there is some evidence here of benefits to urban burial grounds which are of particular social importance to communities. Therefore, the incorporation of hedges and trees into existing GDGS, and planning of new GDGS with these features, could be beneficial for the health of urban populations and biodiversity.

3.4.10 Conclusions

The evidence presented here provides an initial exploration of intra-site and wider urban influences on the heavy metal content of urban burial ground soils. Initially it was expected that the major drivers of heavy metal content in urban burial grounds would be either "Cars or coffins?", based on traffic pollution or funeral fashions as primary sources of these pollutants. However, exploration of potential contributing factors to necrosol composition, and whether these originate within the burial grounds or from the surrounding urban landscape, reveals that answer is not as clear cut as was anticipated.

The influences on urban soil heavy metal content are varied and complex. In this study, the complexity of heavy metal sources was recognised and taken even further by examining a unique land use: the interment of human bodies, cremated remains, and accompanying materials. This practice directly impacts the soil and gives it a special designation: "necrosol". Several site-related factors associated with the history and planning of urban burial grounds appear to have some utility in explaining necrosol concentrations of lead, namely the size and age of the sites, the date of the most recent interment, and the management approaches. Older, smaller burial grounds situated in the original urban centre with a higher interment density and older interments tended towards higher lead concentrations. Further investigation is needed to discern whether this increase in lead could be due to longer exposure to sources of urban pollution or leaching from older interments, although it may well represent a combination of these processes.

The approaches to management for sites of different ages and sizes, depending on whether they are currently in use and contemporary landscaping preferences, show similarities in terms of heavy metal concentrations. This provides initial evidence from which to conduct further investigation into the short- and long-term effects of management practices on soil heavy metals in urban burial grounds. From a biodiversity enhancement point of view, this type of research could provide examples of how management could be employed to protect soil health.

One aspect of future burial ground planning, or retrospective implementation in existing burial grounds, that is evidenced here as being potentially valuable for lowering heavy metal concentrations, is the amount of tree and hedge cover. This study found that with greater coverage of trees and hedges in the surrounding urban area, lower concentrations of arsenic, chromium and nickel were present within the burial ground soils. This is likely due to the uptake of heavy metals by woody vegetation (Luo *et al.*, 2016), and this would benefit from future research.

Perhaps the most notable factor influencing heavy metal concentrations was the soil pH. The necrosols studied here were found to be mostly acidic, in contrast to urban soils which are known to have generally more alkaline pH due to the weathering of technogenic materials which release calcium. Here, concentrations of zinc, cadmium, chromium, and nickel were observed to increase as pH decreases, and as most samples were acidic this means there are likely to be higher levels of soluble forms of these heavy metals in the topsoil of urban burial grounds. This has implications for uptake by plants and micro-organisms, thereby leading to heavy metals entering the ecosystem; further investigation into heavy metal content of organisms in urban burial grounds is needed to further explore impacts on biodiversity. The results here suggest low acid neutralisation capacity of urban necrosols, meaning they are more vulnerable to enhanced leaching of heavy metals.

This study has found differences between expected urban background concentrations of heavy metals and those observed in urban burial grounds, with some isolated samples having extremely elevated levels. Statistically significant variation in heavy metal concentrations was observed between the study burial grounds, with evidence that site features (size, age, date of most recent interments) could potentially influence necrosol heavy metal concentrations, particularly lead. By contrast, the number of interments and proximity to interments did not have strong influences on heavy metal concentrations, nor did measures of wider urban pollution related to industrial activity, ~~and~~ vehicle activity and emissions. However, there was evidence of differences in heavy metal concentrations between sites under different management regimes. Ultimately, this study forms a baseline for future research into the nature of urban necrosols.

3.5 | REFERENCES

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High Wycombe Cemetery

High Wycombe

Buckinghamshire

Photo credit: author's own

CHAPTER 4

This chapter builds upon the previous two, bringing together all the characteristics of the burial grounds studied here to achieve a deeper, fundamental understanding of their nature as urban green spaces. Remaining on the ground, having gained knowledge about urban necrosols, this chapter applies everything explored thus far to investigate potential influences on terrestrial invertebrate assemblages. Invertebrates, more specifically arthropod communities, are prime candidates for a more comprehensive analysis of urban burial grounds as ecological units as they are widely seen as the 'backbone' – as it were – of understanding how influences on ecosystem health, including soil health, affect biodiversity.

CHAPTER 4: A deeper investigation of biodiversity in urban burial grounds utilising arthropod assemblages

4.1 | INTRODUCTION

4.1.1 Importance of arthropod biodiversity

Arthropoda, the largest animal phylum, exhibits great diversity accounting for over 80% of all known species (Sollai *et al.*, 2024). Assemblages of its terrestrial members form crucial features of ecosystems on whose functioning all animal life relies for survival (Prather *et al.*, 2013; Sollai *et al.*, 2024). Due to their ubiquitous nature, they occupy many important trophic niches and are recognised as playing important roles in ecosystem service provision, for example pollination, pest control, soil creation, and food sources for higher trophic levels (Yang and Gratton, 2014; Noriega et al., 2018b; Eisenhauer, Bonn and Guerra, 2019; Sollai et al., 2024). The varied and vital roles of arthropods in natural systems are recognised and increasingly understood, particularly with respect to their interactions with many trophic groups. A focus of recent arthropod research is on monitoring their biodiversity with relation to changes in ecosystem function and ecosystem service provision due to disturbances such as climate change, pollution, agricultural practices, and habitat loss (Marta *et al.*, 2021; Sohlström *et al.*, 2022; Sollai *et al.*, 2024).

4.1.2 Urban arthropod biodiversity

As most of the global human population reside in urban areas, understanding the impacts of human activity on urban ecosystems is of great importance (Grimm *et al.*, 2008; Kowarik, 2023). Studies show that overall, biodiversity in urban areas is at serious risk due to industrial activities, expansion and intensification of construction, and an increase in vehicular emissions, which ultimately lead to habitat degradation and loss (Oliver *et al.*, 2015; Piano *et al.*, 2020; G. Li *et al.*, 2022). In efforts to understand the impacts of these human activities on the function and health of vital ecosystems in urban areas, arthropods in all their biomass, abundance, and diversity are often utilised (Sattler *et al.*, 2010b; Kaiser and Resasco, 2023; Lewthwaite *et al.*, 2024). Changes in, and detriments to, arthropod biodiversity in urban habitats are seen as indicative of changes in wider ecosystem function and thereby ecosystem service provision due to their sensitivity to environmental change (Braaker & Ghazoul, 2014; Fenoglio, Rossetti and Videla, 2020; Lewthwaite et al., 2024). For example, arthropod assemblages were sampled in

Turin, Italy to investigate the effects of impervious surface area, urban heat island effect, and habitat fragmentation on their biodiversity (Piano, Bona and Isaia, 2020). The study found that a multi-taxonomic approach elucidated impacts of temperature and impervious surface coverage on different taxonomic groups. More recently in (Cabon *et al.*, 2024), the functional traits of spider species were examined to study the impacts of habitat and temperature-related variables on community composition, showing that short vegetation and urban heat island effect contributed to a decline in larger, more heat-sensitive species.

4.1.3 Arthropod pitfall trap sampling

The inimitable variety and complexity of arthropod biodiversity, along with its fundamental importance to ecosystem functioning on a range of scales has led to researchers developing many ways to effectively capture it. High-throughput methods such as metabarcoding of bulk arthropod samples (Yu *et al.*, 2012) and the use of eDNA and mapping (Allen *et al.*, 2023; Li *et al.*, 2024) aim to speed up the identification process and bypass the need for human expertise. Although the immediacy of the world's environmental issues calls for identification methods such as these, high throughput DNA sequencing does not effectively capture abundance of individuals (Iwaszkiewicz-Eggebrecht *et al.*, 2023); hence, conventional terrestrial arthropod collection methods such as pitfall trapping remain vital and relevant as efficient and versatile ways to gain insight into arthropod abundance as well as their diversity, with their potential biases and disadvantages well-understood (Ahmed *et al.*, 2023; Bertoia *et al.*, 2023). Pitfall traps remain one of the most common methods of sampling terrestrial arthropod assemblages, having first been deployed soon after the Second World War (Greenslade, 1964; Boetzl et al., 2018). Efforts have been made to evaluate different approaches and standardise method design to aid comparisons between studies (Brown and Matthews, 2016; Hohbein and Conway, 2018).

Pitfall trapping has been used to measure arthropod communities in many environments, enabling research through many lenses (Brown and Matthews, 2016; Hohbein and Conway, 2018; Bertoia *et al.*, 2023). Research in urban environments has focused on how urbanisation affects arthropod, and therefore wider, biodiversity and the subsequent impacts on ecosystem function (Gibb and Hochuli, 2002; Norton et al., 2014; Philpott et al., 2014; Piano, Bona and Isaia, 2020). Studies have been conducted in several different urban spaces including heathland, woodland, brownfield, public parks and domestic gardens, however at the time of writing no studies could be found whereby pitfall traps were deployed in urban burial grounds for the purpose of investigating biodiversity.

4.1.4 Arthropods in urban burial grounds

In the context of human burials, the utility of arthropod biodiversity sustains entire fields of study, providing crucial context and evidence in the endeavour to understand the nature and timing of the burial of human corpses for forensic advantage (Rai *et al.*, 2020; Byrd and Sutton, 2023) and archaeological investigations (Magni, Harvey and Guareschi, 2023). However, the limited body of research into designated urban burial grounds for the purpose of legally disposing of the dead reveals a paucity of research into the biodiversity of these spaces using arthropod communities (Hartley et al., 2007; Buchholz et al., 2016; Kowarik et al., 2016; Cathcart-James, Foster and Pickles, 2022; Monzón et al., 2024). It is striking that we know far more about the arthropods associated with ancient archaeological finds and murder victims than we do about those inhabiting the places where our dead are laid to rest, places of great personal importance to today's society. This research gap is a key theme of this thesis whereby burial grounds are typically omitted from definitions of urban green spaces; hence, any role they may play in urban biodiversity provision, and therefore urban ecosystem function and related services, is not understood because it is so rarely considered or investigated.

4.1.5 Research questions

1. Do different burial grounds contain different assemblages of arthropods or is there any evidence of a "burial ground community"?

2. Are there specific orders of arthropods that show greater or lower variation between burial grounds?

3. Is there any evidence that soil, vegetation, management or urban landscape variables influence the composition of arthropod communities in urban burial grounds?

4. If so, which factors appear to have the strongest impact and are these similar to drivers of arthropod diversity identified in other ecosystems?

4.2 | METHODS

4.2.1 Sampling methodology

Study site selection, management category allocations and land category mapping methodologies are described in Cathcart-James, Foster and Pickles (2022b). Sample location methodologies are described in Chapter 3. In addition to soil collection, permission was also obtained from site management to install pitfall traps in the resulting holes. Once soil samples were removed (methodology described in Chapter 3), two stacked 7-ounce plastic drinking cups were placed in the hole and filled to the halfway mark with a 50% (v/v) antifreeze : water mix. A label explaining the research purpose of the trap was affixed to a plastic cover measuring 17.5 x 12-centimetres using adhesive clear vinyl. The cover was then screwed into the ground over the pitfall trap using 5 x 100-millimetre screws, leaving 2-3 centimetres clearance. The pitfall trap was therefore made visible and more protected whilst still allowing invertebrates to travel freely on the ground.

Three samples per pitfall trap were collected; the first collection took place between the 15th and 26th of July 2019, the second between the 29th of July and the 8th of August 2019, and the final collection between the 12th and the 23rd of August 2019. For each collection, once the cover was removed the contents of the trap were decanted into a sampling pot and the second stacked cup was refilled with the same antifreeze solution before replacing. The first stacked cup was left in the ground to maintain the integrity of the trap. The cover was then reinstalled. On multiple occasions, the traps had been destroyed by mowing, strimming or interference from members of the public; in these instances, the trap was fully reinstalled with new equipment apart from during the final replicate. The samples were transferred into further sampling pots with a 70% (v/v) ethanol in water solution for preservation.

Of an anticipated 300 samples, due to the destruction of 46 traps over the sampling period a total of 254 samples were collected. The sampling effort for two burial grounds were particularly affected; Fleet Cemetery, where only 2 of 15 samples were successfully collected, and Slough Cemetery where 7 out of 15 samples were intact. These sites are not included in the dataset due to a paucity of sample data and potential influences on subsequent statistical analysis. As in Chapter 3 the two locations in Guildford, Surrey, had to be omitted due to there being no records of the number of burials; these records were destroyed by a fire before digitisation.

4.2.2 Arthropod identification

Due to practical constraints all arthropods were identified to Order level except for ants (Order Hymenoptera, family Formicidae), which were identified to species level. Due to time constraints only the first replicate was identified. Identification initially took place at the University of Reading Entomology laboratory; the remaining samples were sent to FlyEvidence (Pentrefoelas, Wales) for identification.

4.2.3 Statistical analysis

All data analyses were conducted using R 4.3.1 (R Core Team 2023) and the "vegan" package (Oksanen *et al.* 2025) in the R Studio environment 2023.06.1. Shannon and inverse Simpson indices were calculated as measures of diversity (variability), references to "alpha diversity" are in fact capturing order-level richness (i.e. the observed number of arthropod orders within each site), and Pielou's evenness index was calculated as a measure of relative abundance evenness between orders. Indicator analysis was also performed to examine whether specific arthropod orders were significant indicators of sites or management type. PERMANOVA analysis was conducted to examine the statistical significance of the management categories.

Having measured richness and abundances on a local, or intra-site scale, Bray-Curtis dissimilarity indices were then calculated as a measure of beta diversity (at the order level) to assess any differences in arthropod community composition between sites (Anderson *et al.*, 2011). Rarefaction was also examined to evaluate the success of the sampling effort and therefore our confidence in any conclusions to be drawn from the results of analyses.

Finally, non-metric multidimensional scaling (NMDS), a type of unconstrained ordination, was undertaken to investigate how similar or different the arthropod communities of the sites were to each other at the order level (Smith and Mather, 2012). Management type was used as a grouping variable to explore the extent to which any clustering of sites was influenced by this factor. Environmental variables were then overlain as a biplot to determine their relationships to the ordination axes.

4.3 | RESULTS

4.3.1 Abundances and alpha diversity

A total of 20,208 individuals from 15 invertebrate orders, with ants separated from other members of Hymenoptera, were captured during the first replicate from 67 pitfall traps installed in 16 study sites (Tables 4.1 and 4.2). The three orders with the highest abundances, woodlice (Isopoda), ants (Hymenoptera, family Formicidae) and mites (Acari), made up 73.15%, 8.33% and 6.01% respectively of the total number of individuals caught.

Both Shannon and inverse Simpson diversity indices showed that Henley Road Cemetery had the highest arthropod order variability, followed by Shaw and Windsor cemeteries respectively (Table 4.1). These indices also showed that Caversham Cemetery had the lowest arthropod order variability, with values substantially lower than the next highest-ranking site, Reading Old Cemetery (Table 4.1). The values obtained for Pielou's evenness index (Table 4.1) indicate that the arthropod communities within the three sites with highest variability in the orders sampled were also the most balanced with the most even distributions of orders, whereas Caversham Cemetery had the lowest index value indicating a far less even distribution where the community may be dominated by a small number of more numerous orders. On examination of the abundances for each order within the sites (Table 4.2), Caversham Cemetery yielded 7,260 individuals within the Isopoda order, namely woodlice, which in the context of all other sample abundances is significantly larger and would explain the site having the lowest diversity and evenness indices. Total arthropod abundance showed distinct inter-site variation (Table 4.1, Figure 4.1).

Diversity and evenness indices were also calculated for arthropod communities within each management category (Table 4.3). These show that the Clear management category (the strictest regime) had the highest arthropod order variability and most evenly distributed orders within the community, followed by Wild, Scape and then Min having the lowest. Total arthropod abundances for different management categories showed variation (Figure 4.1). The Wild category tends to have moderate or high abundance, the Min category has the highest abundances but a wider range, whilst Scape tends to show moderate abundance and the Clear category, although mostly showing moderate abundance, also shows the lowest abundances.

Table 4.1. Summary of abundances and richness with diversity and evenness indices for all sample sites.

Site	(n)	Order richness	Shannon's diversity index	Pielou's evenness index	Inverse Simpson's index	Raw abundance
All.Sts	4	11	1.6049446	0.66931390	3.230494	510
Bray	3	12	1.3120761	0.52801828	2.562028	772
Cav	4	11	0.2048528	0.08543024	1.070625	7513
Eash	5	11	1.6321229	0.68064813	3.787759	791
Hen.Rd	3	12	2.0597064	0.82888683	6.773580	235
Lar.Lane	3	12	1.3949929	0.56138644	2.637094	759
Newt.Rd	5	11	1.1678203	0.48701890	2.320423	2617
Ngale	4	8	1.0455081	0.50278310	1.939737	129
Old	5	12	0.7612053	0.30633156	1.417093	1628
Shaw	5	10	1.8312132	0.79528577	4.865251	302
St.Mic	5	13	1.2668018	0.49388959	2.243647	420
That.Cem	5	12	1.6433164	0.66131916	3.691667	241
Winds.Cem	2	8	1.6740159	0.80503147	4.342237	153
Wok.FBG	5	11	1.6177079	0.67463659	3.904801	453
Wor.Rd	5	10	0.8003682	0.34759550	1.541394	2892
Wyc.Cem	4	12	0.7622743	0.30676175	1.454380	793
Total	67					20208

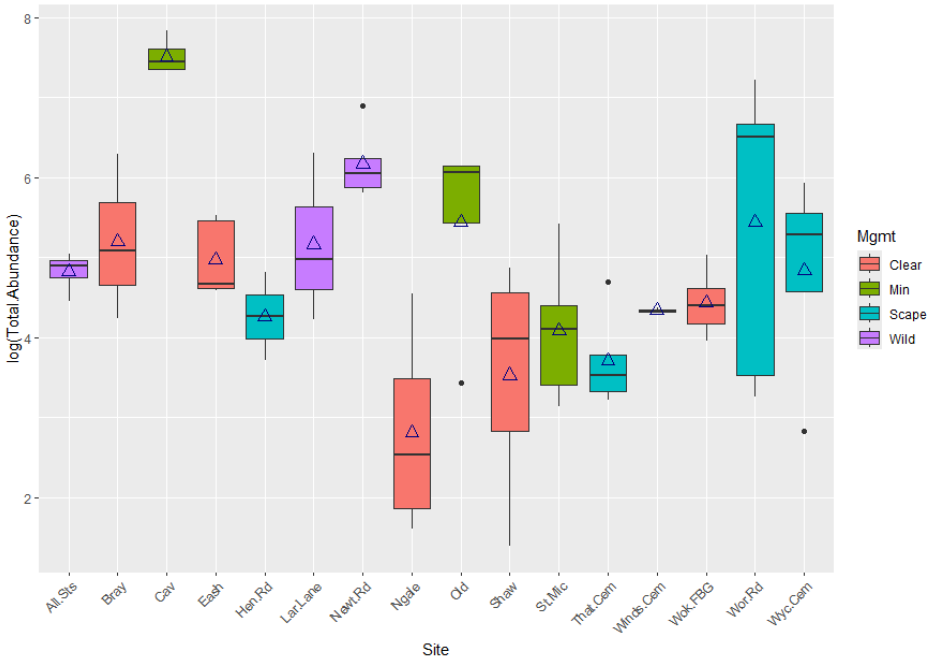
Table 4.2. Total counts of individuals collected from all pitfall trap samples during the first collection which took place between the 15th and 26th of July 2019 for each arthropod order, broken down by Site.

Site	Ants	Othr. hymen	Opilio	Araneae	Coleop	Hemip	Isopoda	Diptera	Collemb	Acari	Lepido	Dermap	Thysan	Psocop	Orthop	Miriap
All. Sts	48	17	0	64	54	28	264	9	18	4	0	2	0	0	0	2
Bray	425	21	2	10	27	12	223	25	4	12	4	7	0	0	0	0
Cav	76	4	8	68	50	4	7260	33	5	3	0	0	0	0	0	2
Eash	0	14	3	112	111	56	108	26	1	353	2	0	0	0	0	5
Hen.Rd	37	5	0	34	39	12	37	11	6	49	3	0	0	0	1	1
Lar.Lane	423	18	11	15	29	14	192	24	14	12	1	6	0	0	0	0
Newt.Rd	204	11	0	111	35	13	1588	30	5	611	5	0	0	0	0	4
Ngale	0	0	0	9	19	1	90	1	3	0	5	1	0	0	0	0
Old	52	12	10	43	15	11	1363	33	7	79	1	0	0	0	0	2
Shaw	68	16	0	46	23	17	103	12	0	13	1	3	0	0	0	0
St. Mic	1	1	3	25	24	14	270	2	8	65	2	0	0	1	0	4
That.Cem	0	10	2	41	43	14	108	15	2	2	2	1	0	0	0	1
Wind.Cem	0	8	0	54	12	9	38	27	0	3	0	0	0	0	0	2
Wok.FBG	1	11	0	83	45	94	185	19	9	2	3	0	1	0	0	0
Wor.Rd	348	18	9	43	43	62	2301	44	21	3	0	0	0	0	0	0
Wyc.Cem	1	5	0	54	16	9	654	34	2	15	1	1	0	0	0	1
Total	**1684**	**171**	**48**	**812**	**585**	**370**	**14784**	**345**	**105**	**1226**	**30**	**21**	**1**	**1**	**1**	**24**

Table 4.3. Diversity and evenness indices for each management category.

Management category	Shannon's diversity index	Pielou's evenness index	Inverse Simpson's index
Clear	1.9680518	0.7457405	5.843050
Scape	1.0494699	0.3976685	1.760256
Wild	1.4632414	0.5704758	2.968284
Min	0.3934711	0.1534031	1.154831

Figure 4.1. Boxplot of total arthropod abundance (log-transformed) for all sample sites colour-coded by management category with mean abundance denoted by Δ.



Initial analyses of order-level diversity and abundances show there is significant variability in the diversity, distribution, and abundances of arthropod communities between the study sites and the different management categories. The analyses that follow aimed to quantify how statistically significant the variation between arthropod communities was, and whether any drivers of that variation could be identified.

4.3.11 Indicator analysis

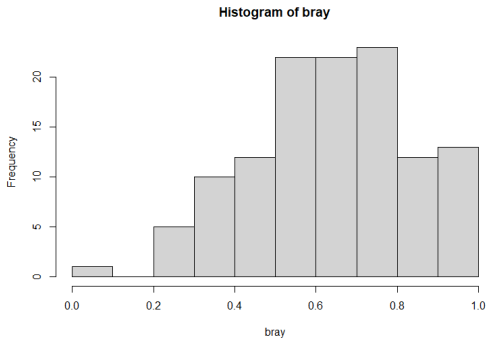
Indicator analyses did not reveal any statistically significant indicator arthropod orders for site or management category. Previous indicator analysis performed in Chapter 2 (Table 2.4) produced several beetle family indicators, and it is probable that key patterns are more likely to be found at higher taxonomic levels such as family, genus or species than order level, such as the arthropod communities analysed here. It may require a more granular level of detail within the analysis and could be gleaned from the dataset presented here at order level by future researchers.

Due to the extremely high abundances of Isopoda, the remaining analyses for this chapter were run for both the entire dataset including Isopoda and again with Isopoda removed (data not shown) to ascertain if these high abundances may be masking any trends involving the rest of the dataset. No such masking was detected, so the results presented here were calculated using the entire dataset.

4.3.2 Community composition dissimilarity

Having examined alpha diversity and abundances of the arthropod communities, analyses were performed to examine differences in community composition between the study sites. Bray-Curtis dissimilarity indices were calculated for all possible pairings of the 16 sites and overall the majority of pairings had an index value over 0.5, indicating a higher proportion of dissimilar pairs (Figure 4.2). This indicates larger variation in arthropod order composition across the sites.

Figure 4.2. Histogram to show frequency of Bray-Curtis dissimilarity index values occurring between site pairs.



Ten sites were over 90% dissimilar in terms of community composition compared to Caversham Cemetery (Table 4.4). This is perhaps attributable to the large abundance of Isopoda captured in this site. There are however other site pairings with extremely high dissimilarity such as Nightingale and Windsor cemeteries with Worting Road Cemetery. In total, 92 out of 120 site pairings had a Bray-Curtis index over 0.5 (77%).

Table 4.4. Top 10% of site pairings for dissimilarity.

Site 1	Site 2	Bray-Curtis index
Ngale	Cav	0.97
Winds.Cem	Cav	0.96
Hen.Rd	Cav	0.95
That.Cem	Cav	0.94
Eash	Cav	0.94
Shaw	Cav	0.93
Wor.Rd	Ngale	0.92
Wok.FBG	Cav	0.92
St.Mic	Cav	0.91
Lar.Lane	Cav	0.91
Cav	Bray	0.91
Wor.Rd	Winds.Cem	0.91

At the other end of the scale, the most similar order composition pairings were those for Larges Lane and Braywick cemeteries, with 95% similarity (Table 4.5). Worting Road, Shaw, Henley Road, Thatcham, Nightingale and Larges Lane cemeteries, Wokingham Free Burial Ground and St Michael's churchyard all appear in both the most and least similar site pairings, indicating that a number of strong similarities and differences exist between the arthropod communities in these sites compared to others.

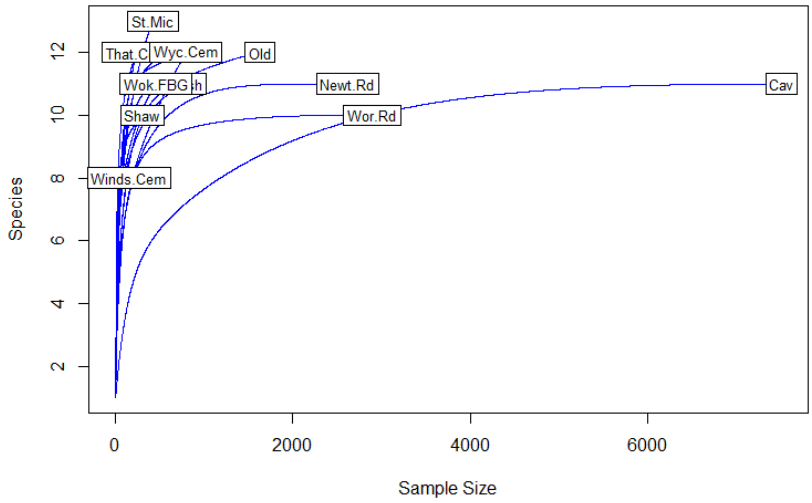
Table 4.5. Bottom 10% of site pairings for dissimilarity.

Site 1	Site 2	Bray-Curtis index
Wyc.Cem	Old	0.36
Shaw	Hen.Rd	0.36
Shaw	All.Sts	0.34
That.Cem	Ngale	0.32
Wok.FBG	That.Cem	0.32
Wor.Rd	Old	0.32
Wor.Rd	Newt.Rd	0.30
Wok.FBG	All.Sts	0.26
St.Mic	All.Sts	0.26
Old	Newt.Rd	0.24
That.Cem	Shaw	0.24
Lar.Lane	Bray	0.05

4.3.3 Rarefaction

Rarefaction analysis was conducted to assess the strength of the sampling effort. Figure 4.4 shows that the rarefaction curves for Caversham, Newtown Road and Worting Road cemeteries reached a plateau, indicating that with further sampling there would be a limited gain of new orders captured in these sites. Old Cemetery appears to be approaching a plateau, however for the other study sites the curves indicate that with further sampling effort, more orders could be captured and therefore a more accurate representation of their arthropod communities. This needed to be taken into account when drawing conclusions from the analyses described here.

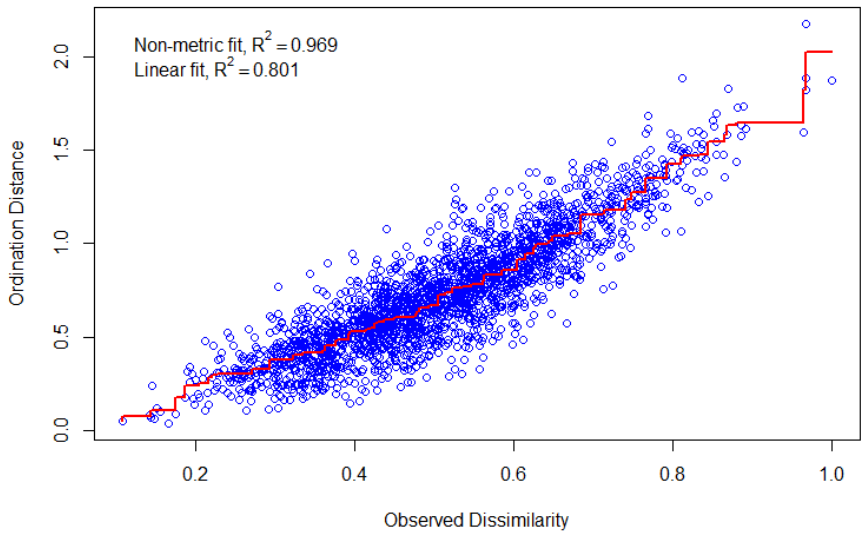
Figure 4.3. Rarefaction curves for each site.



4.3.4 Non-metric multidimensional scaling (NMDS)

NMDS analysis was performed with the 'metaMDS' function from the 'vegan' package using a distance matrix composed of the Bray-Curtis distance and order abundances. The data underwent a square-root transformation and Wisconsin double standardisation, which prevents large sample sizes (such as Isopoda in Caversham Cemetery, Table 4.2) from being dominant. Three dimensions were used to minimise stress, with 999 iterations and a maximum of 500 restarts. The stress value obtained was 0.176 which indicates a satisfactory goodness of fit and low risk of false interpretation. In addition to the rarefaction results, this should be considered when evaluating the strength of any conclusions drawn. The stress plot produced from the results of the NMDS analysis displays how closely the ordination fits the observed dissimilarities, and the high R-squared values indicate that a strong reliance can be placed on interpretation of the NMDS results (Figure 4.4).

Figure 4.4. Stress plot to show how closely the NMDS ordination represents community dissimilarities.



Having performed the ordination, the environmental variables of interest were plotted onto it as a biplot and the scores were extracted along with measures of their contributions to the dimensions (Table 4.6). Town population density, soil moisture content and management category were found to have statistically significant contributions of 17.9%, 13.2% and 10.4% respectively. Whilst vegetation type, soil organic matter, pH and GDGS200 (grass-dominated green space coverage within a 200-metre radius of the site; see Chapter 2, Table 2.3) all had similar contributions to management type, these were not statistically significant.

Table 4.6. Extracted variable and factor scores, R^2 and p-values from the NMDS ordination for the three dimensions.

Environmental variable	NMDS1 score	NMDS2 score	NMDS3 score	R^2	p-value
Nr.grve	0.276296	0.827227	0.489241	0.0213	0.709
Dth.date	-0.44541	0.127807	-0.88616	0.0128	0.846
Age	0.892681	-0.03086	0.449631	0.0476	0.368
Pop.dens	0.175929	-0.96928	-0.17188	0.1793	***0.007***
B.no	-0.00463	-0.24831	0.96867	0.0738	0.175
B.dens	-0.22132	-0.97507	0.016024	0.0732	0.186
S.size	-0.14011	0.107699	0.984262	0.0652	0.24
Gdn200	-0.27841	0.374919	0.884265	0.0647	0.223
BSMS200	-0.10741	-0.78645	-0.60824	0.0366	0.507
Hdg200	0.049386	0.047876	-0.99763	0.0661	0.221
TC200	0.253315	0.555785	-0.79179	0.0438	0.457
GDGS200	0.089968	0.094427	0.991458	0.1102	0.061
pH	0.502413	-0.84918	0.162736	0.0962	0.088
MC	0.582767	-0.7911	0.185846	0.1323	***0.029***
SOM	0.581388	-0.78154	0.226223	0.1095	0.066
As.ppm	0.863626	0.377402	-0.33424	0.0038	0.961
Cd.ppm	-0.31542	0.913709	-0.25622	0.0392	0.482
Cr.ppm	-0.49381	0.793001	0.356793	0.0407	0.443
Cu.ppm	-0.02864	-0.5055	-0.86235	0.0400	0.454
Ni.ppm	-0.0368	0.005171	0.999309	0.0269	0.62
Pb.ppm	0.388946	-0.22481	-0.89341	0.0311	0.589
Zn.ppm	0.137225	-0.93818	0.31779	0.0635	0.24
Mgmt (factor)				0.1038	***0.011***
Veg.type (factor)				0.1167	0.326

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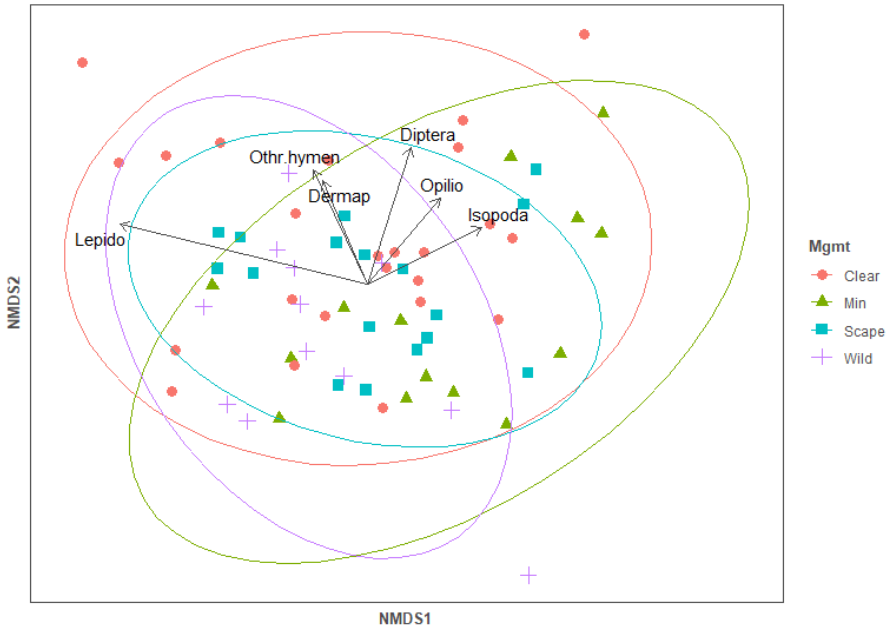
The ordination process was followed by a rotation via principal components analysis to ensure the axes reflect descending sources of variation in terms of importance; therefore, axes 1 and 2 are the focus of further exploration here as they are the principal sources of variation.

When the sample points were plotted for axes 1 and 2 no strong clustering was observed by management type (Figure 4.5). Management type 95% confidence ellipses overlapped, although some degree of separation can be discerned (Figure 4.5). Samples within the Scape management category showed relatively little spread from the centre of the ordination, whilst those within the Wild category were generally located within the ordination space defined by negative values of axes 1 and 2. For both the Scape and Wild categories, the sample points were mainly positioned closer in ordination space to members of the same category indicating more similarity within those groups. Sample points within the Clear and Min categories showed a subtle difference in positioning, with Clear being positioned further towards the positive end of axis 2 and Min towards the positive end of axis 1. However, both these categories displayed substantial spread of samples within ordination space, indicating greater differences between some samples within the same management category, leading to large confidence ellipses and contributing to their overlap.

A PERMANOVA test followed by a post-hoc test of pairwise differences using the Bonferroni correction was conducted to analyse any significant difference between management categories, to ascertain whether any of the visualised groupings on the NMDS ordination were significant. The analysis revealed a significant difference in arthropod community structure between the management categories (pseudo-$F = {}_{2.74}$, $p = 0.002$, $R^2 = 0.12$) based on Bray-Curtis dissimilarity. The post-hoc test revealed significant pairwise differences between the Min and Clear categories ($F = {}_{4.801}$, $p = 0.006$, $R^2 = 0.12$) and the Clear and Wild categories ($F = {}_{3.33}$, $p = 0.024$, $R^2 = 0.09$). Management type as a grouping factor was therefore significantly associated with the clustering of sample points but only explains ~10% of the variance, which is why it is not particularly clear in the NMDS plot.

There were six arthropod orders with statistically significant contributions to the first two axes of the ordination and vectors were added to the plot to indicate the directions of greatest change for these orders (Figure 4.5). Isopoda and Lepidoptera increased in opposite directions, suggesting a negative correlation, whereas Dermaptera and Hymenoptera (excluding ants) appeared to be strongly positively correlated with each other, and unrelated to Isopoda.

Figure 4.5. NMDS ordination of arthropod orders data illustrating community differences between management categories. Each data point is an individual sample. 95% confidence ellipses are overlaid for each management category and vectors indicating direction of increase in contributions to community dissimilarity by orders with p-value <= 0.05.



In addition to arthropod orders, environmental variables of interest that were captured in the previous chapters were visualised as vectors on the first three NMDS axes (Figures 4.6 and 4.7). pH, soil organic matter (SOM), and soil moisture content (MC) were all positively associated with axis 1 and negatively associated with axis 2 (Table 4.6) suggesting positive correlations with each other. Several sample points within the Min, Wild, and Scape management categories were separated positively along axis 1 and negatively along axis 2 indicating that they may be associated with increases of these soil qualities.

Concentrations of soil cadmium and chromium were positioned in the opposite direction to those for pH, SOM and MC (i.e. negatively associated with axis 1 and positively with axis 2), suggesting a negative correlation. Several sample points from the Clear and Scape management categories, along with one sample from the Wild category, were separated in the direction of increase for cadmium and chromium, likely indicating an association with increases in these soil heavy metals, and decreases in pH, SOM and MC.

Town population density was found to have a significant negative association with axis 2 (Table 4.6). When this variable was examined in ordination space it appeared to be the most significant measured factor associated with variation along this axis (Figures 4.6 and 4.7). Sample points from all management categories were distributed across axis 2 of the ordination, hence there appeared to be a significant influence of population density on community variability regardless of management category.

The area covered by grass-dominated green space within a 200-metre radius of each study site (GDGS200) was found to have a strong positive association with axis 3, with no apparent association with axes 1 and 2 (Figure 4.7, Table 4.6). The area covered by hedges in the same radius (Hdg200) was positioned in the opposite direction, suggesting a negative correlation although this was not statistically significant (Figure 4.7).

Figure 4.6. NMDS ordination of arthropod orders data illustrating the direction of increase for the environmental variables of interest and separation of individual sample points along the first and second axes.

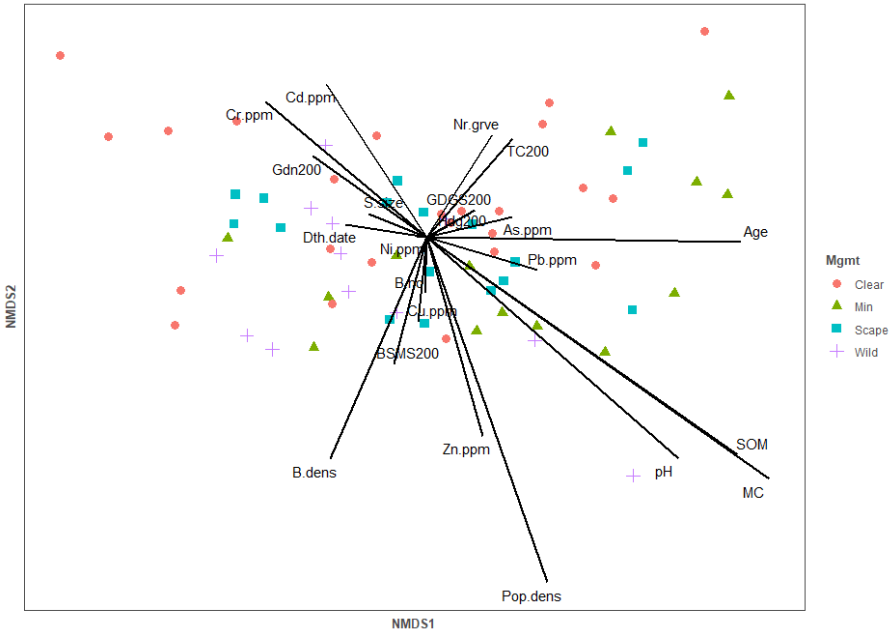
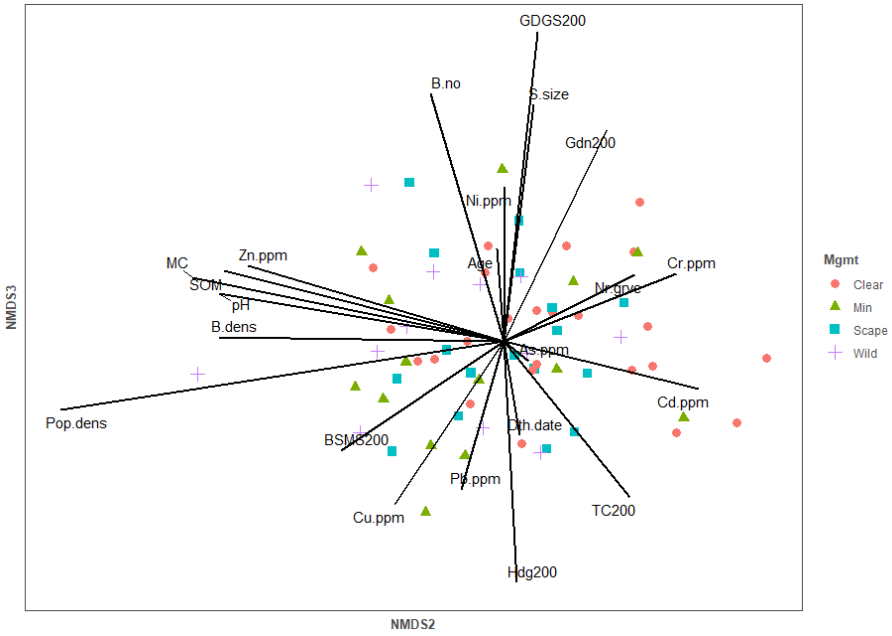


Figure 4.7. NMDS ordination of arthropod orders data illustrating the direction of increase for the environmental variables of interest and separation of individual sample points along the second and third axes.



4.4 | DISCUSSION

This study has shown variation in the diversity, evenness and abundances of arthropod communities between sites and management categories. Measures of alpha and beta diversity at the order level revealed generally high levels of dissimilarity, and ordination analysis provided initial insights into the importance of a variety of environmental variables in contributing to the observed variation. The results presented here show for the first time significant differences between arthropod communities in urban burial grounds under different management regimes.

4.4.1 Arthropod community similarities and differences

Diversity analyses showed variation in the biodiversity of the arthropod communities between sites, with 77% of pairwise comparisons showing that over half of the arthropod orders were different between communities. This level of dissimilarity between sites could be interpreted as an absence of any typical 'burial ground arthropod community' and suggests there are other influences affecting the arthropod communities within urban burial grounds in different ways. In addition, indicator analyses did not reveal any specific arthropod orders with meaningful differences in incidence or abundance that would suggest any affinity with particular aspects of the sites that have been quantified.

Although a large degree of dissimilarity in arthropod communities was observed, there were some consistent patterns for particular orders in all sites. It is worth noting that there was a substantial presence of Isopoda, which were in the top three most abundant orders at every study site and constituted over 70% of the total abundance of all arthropods captured across the study sites. Caversham Cemetery demonstrated a substantial over-abundance with 96.6% of the >7500 individual arthropods belonging to Isopoda (Table 4.2). Many terrestrial isopods exhibit a dependence on the presence of leaf litter (Pitzalis *et al.*, 2005), and as Caversham Cemetery is under the Min management category there is little to no removal of leaf litter and other organic debris, hence this could account for their high abundance. Future research could benefit from a more detailed understanding of the vegetation structure within urban burial grounds, for example the number and canopy areas of deciduous trees. In addition, isopod biodiversity has been shown to decrease in intensively managed landscapes due to the effects of management practices such as pesticide applications (Paoletti and Hassall, 1999). Again, the extremely light-touch approach to managing sites in the Min category could be supporting the success of isopods.

In terms of other consistent presences, Araneae (spiders), Coleoptera (beetles), Hemiptera (true bugs), Diptera (flies) and Hymenopterans other than ants were present in all sites. Apart from the Hymenopterans, these five orders had the highest total abundances of all orders identified with the exception of ants which were absent in four sites (Table 4.2).

Given the total abundance of ants being ranked second behind Isopoda, it is possible that they are also responding to the presence of dead organic material, including carrion and its associated invertebrates such as fly maggots (Nooten *et al.*, 2022). The three sites with the highest ant abundances were Worting Road (Scape), Larges Lane (Wild), and Braywick (Clear) cemeteries, and isopods were captured in these sites in similar or greater numbers (Table 4.1). It is possible in sites in the Scape category, with horticultural features, that leaf litter and other suitable habitats could be present and would also be a key feature of the Wild category. In Braywick Cemetery it may be that a nest was sampled, skewing the observed abundance (King and Porter, 2005; Baccaro and Ferraz, 2013).

These results indicate that despite a lack of similarity in the overall arthropod community composition between the sites, there is some evidence that a number of orders may be consistently present within urban burial grounds.

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4.4.2 Influence of site management regimes

There was variation reported in total arthropod abundances between management categories (Figure 4.1), and significant differences were found in arthropod community composition between the Min and Wild categories, and the Clear category. Management category accounted for a modest but statistically significant amount of the variability in arthropod abundance and diversity of 10.4%. In the initial exploration into the effects of urban burial ground management on biodiversity undertaken in Chapter 2, sites in the Min and Wild categories supported greater diversity of flying beetles than those in the Clear category (Cathcart-James, Foster and Pickles, 2022). In the case of terrestrial arthropods, the evidence suggests the opposite. Sites under Clear management show the most variability, meaning that in a small sample individual arthropods are more likely to belong to different orders. These sites also had higher evenness index values (Table 4.1), indicating that specific orders do not dominate in terms of abundance. In the case of the significant difference between sites in the Clear and Min categories - representing opposite ends of management intensity - Clear sites exhibit greater arthropod order variability and evenness whilst Min sites exhibit the least (Table 4.3). This may be explained by the high abundances of Isopoda which would affect the diversity and evenness indices, perhaps in

conjunction with sites in the Clear category having fewer individuals captured overall (Table 4.1).

Adding yet more complexity, Henley Road Cemetery in the Scape management category was the site with the highest diversity index values, but a comparatively low total abundance (Table 4.1). This meant that in any given sample there was a greater likelihood of capturing a higher number of orders from fewer individuals. Rarefaction analysis showed that greater sampling effort would have been likely to capture more orders from the majority of sites, including Henley Road (Figure 4.3), so it is possible that greater diversity could be found in sites in the Scape management category. In Chapter 2, sites under this regime produced higher overall abundances of flying beetles, but of fewer families. As with the significant differences between Min and Wild, and Clear categories, this is the opposite of what was found here with terrestrial arthropod communities.

Statistically meaningful and somewhat opposing results have been reported in Chapters 2 and 4. Direct comparisons may be misleading as Chapter 2 dealt with members of a single arthropod order (Coleoptera) and only those able to fly, taking an indicator approach; this chapter has applied an ordination approach to samples from the broader terrestrial arthropod communities present. Further insights into the effects of management regimes on urban burial ground diversity could be gained by quantifying in more detail the habitats present within the grounds as a result of those regimes; for example, leaf litter cover (Ober and DeGroote, 2011; Ashford *et al.*, 2013), vegetation structure (Randlkofer *et al.*, 2010; van Schalkwyk *et al.*, 2021) and quantity of edge habitat (Wimp and Murphy, 2021), all of which have been shown to affect arthropod biodiversity.

4.4.3 Influence of vegetation type

The vegetation type at the sample points had an 11.7% contribution to the variability of arthropod communities captured in the NMDS ordination (Table 4.6), but this was not found to be statistically significant. As stated above, the structure of vegetation in a habitat has been shown to be important for arthropod biodiversity; there are other aspects of vegetation that could also be of importance here such as plant diversity (Ebeling *et al.*, 2018; Nighswander *et al.*, 2021), plant biomass (Francoeur *et al.*, 2021; Proske, Lokatis and Rolff, 2022), native and non-native plant species (Philpott *et al.*, 2023) and lawn management (Francoeur *et al.*, 2021; Proske, Lokatis and Rolff, 2022) which would be valuable to explore.

With regards to plant species in urban burial grounds, it may be that sites with more light-touch management such as those in the Wild and Min categories have a greater presence of invasive species, which has been shown to increase arthropod abundance and homogenisation (Jesse *et al.*, 2020). This could be a contributing factor to the high abundances of Isopoda found in sites within these categories, particularly Caversham Cemetery (Table 4.2).

Future research into arthropod biodiversity in urban burial grounds would benefit from recording aspects of their vegetation in more detail than was undertaken here.

4.4.4 Influence of soil characteristics

Whilst soil pH, organic matter and moisture content exhibited correlation with the ordination axes (Figures 4.6 and 4.7), only moisture content was found to have a statistically significant contribution of 13.2% (Table 4.6). On the first and second axes, several sample points from sites in the Min and Wild management categories were located positively along axis1 and negatively along axis 2, which were the directions of increase for pH, SOM, and moisture content (Figure 4.6). This suggests a relationship between variation in arthropod biodiversity in at least some of the samples with these management regimes and soil characteristics, particularly moisture content. Soil moisture has been shown to have significant impacts on arthropod communities (Chikoski, Ferguson and Meyer, 2006; Kirichenko-Babko *et al.*, 2020; Qin *et al.*, 2024), and members of the orders found to have significant effects on community dissimilarity (Figure 4.5) are characteristic of typically moist habitats such as leaf litter, soil, deadwood and dense foliage (Menta and Remelli, 2020).

Although the second and third axes of the NMDS have less explanatory power, they do pull out some observations of interest when plotted together (Figure 4.7). Sample points within the Min management category were separated in the direction of the overlaid vector for increases in copper concentrations in the soil. There were notable abundances of Isopoda in sites in the Min category described above, and members of this order are known to bioaccumulate a range of heavy metals, with copper being most well established (Weißenburg and Zimmer, 2003; Golobič *et al.*, 2012). Previous research has investigated isopod species as potential soil contaminant indicators with promising results (Pastorino *et al.*, 2011; Panza *et al.*, 2024), and the evidence here suggests they may be usefully studied in urban burial grounds in this context.

On the second and third axes of the ordination, a number of sample points in the Clear management category were separated in the direction of increases in soil cadmium levels (Figure

4.7). Sources of cadmium contamination of urban soils are well-documented (Li *et al.*, 2014; Hanfi and Yarmoshenko, 2020; Yang *et al.*, 2022), and there is some limited evidence of elevated levels in burial grounds, attributed tentatively to paints and wood treatments from coffins (Jonker and Olivier, 2012; Aruomero and Afolabi, 2014). Understanding the sources of cadmium in the soils of urban burial grounds in sites from the Clear category would be worth exploring; three sites from this category had cadmium levels measured around or above expected urban background levels (Chapter 3, Figure 3.3).

4.4.5 Influences from the surrounding urban landscape

Turning attention to variables from outside the sites themselves, there was limited evidence found here of significant influences of the wider urban landscape. The urban population density was the only variable with a statistically significant contribution to explaining variation in the NMDS, which at 18% was also the highest contribution of all variables (Table 4.6). Throughout this thesis, population density has been included as a proxy for urban pressures on ecosystems due to human activity such as the use of vehicles, industry, and construction. It was not found to have a significant influence on flying beetle diversity (Table 2.5) but was a contributing factor to variability in soil heavy metal concentrations (Figure 3.10). In the PCA analysis of necrosols for Chapter 3, town population density appeared to be correlated with the number of burials in each site (Figure 3.13); in the visualisation of the NMDS for arthropod communities, these two factors appear to be positively correlated once again (Figure 4.6). As previously discussed, any positive correlation between town population metrics and burial numbers makes sense; the larger the community the more deaths take place, and therefore there will be more interments within the limited allocated space.

The evidence for an effect on arthropod biodiversity suggests there may be a link with towns and cities with greater interment of deceased pressures, and subsequent effects on soil quality. As soil quality, and particularly heavy metal pollution, has been shown to affect terrestrial arthropod biodiversity (Tóth, Dombos and Hornung, 2023), the connections made throughout this thesis provide some evidence to suggest that the arthropod communities that urban burial grounds host could be in part dependent on how populous the urban area is.

4.4.6 Conclusions

The results here show a lack of similarity in the composition of arthropod communities in the study sites, with diversity and evenness indices indicating differences in order variability and evenness of order distribution; overall, a varied picture that does not indicate a specific "burial ground community". However, there was evidence of certain arthropod orders with a consistent presence within urban burial grounds, including woodlice (at surprisingly high abundance), ants, and spiders.

This chapter represents an important step forward in understanding the influence of management on urban burial ground biodiversity. Significant differences were revealed between arthropod communities under different regimes, constituting evidence of management influencing their composition. Developing a finer resolution approach to distinguishing between management regimes in future research could help to bring out the key drivers at work here. A related variable thought *a priori* to demonstrate influence was the type of vegetation each sample was located within; however, there was no statistically significant effect found based on the categories devised here. Recommendations for future research into the impact of management activities and vegetation, based on a perceived need for exploration on a finer scale, were presented.

Evidence was found of a significant influence of increasing soil moisture content on the arthropod communities of sites within the Min and Wild categories. Monitoring changes in and managing soil moisture could be key in sustaining arthropod communities in sites with either little active management, or those with specific wildlife-friendly interventions.

There was limited but significant evidence of urban population density affecting arthropod biodiversity. As a variable, this has been utilised throughout the thesis as a proxy for human activity-related pressures in the urban environment and may have an indirect effect on arthropod communities through influences on soil quality, for which evidence was provided in Chapter 3.

Analyses have shown here that management, urban population density, and soil moisture content have the strongest impact on order level arthropod community composition in urban burial grounds. The evidence discussed here shows that these are similar to influences on arthropod communities in other ecosystems.

4.5 | REFERENCES

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St Michael's churchyard

Camberley

Surrey

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CHAPTER 5: Building knowledge

Table 5.1. Summary of the main findings from Chapters 1-4 of this thesis.

Thesis chapter	Main findings
Chapter 1: Burial ground research trends	• In the period 1998 – 2020, the USA produced the greatest amount of burial ground-focused research, followed by the UK, with 45% of the 816 papers published from just 7 out of a total of 100 countries • 113 studies were found worldwide on burial ground biodiversity and ecosystem function, with the most research output being again from the USA, followed by Poland then the UK, which produced just 11 studies • Both globally and within the UK, the number of studies do not constitute a comprehensive body of research, and the ecosystem function catengory does not appear in research until 10 years into the period of interest
Chapter 2: Challenging assumptions about burial ground biodiversity using flying beetles as indicators in urban areas	• Increase in burial ground size had a significant, negative influence on total flying beetle abundance, with some evidence to indicate this could be due to larger sites being associated with urban areas of higher population size and density to accommodate the higher number of interments required • The age of the study burial grounds was not found to have a significant effect on flying beetle biodiversity at the family level • Significant positive effects on total and Nitidulidae abundances of increased coverage in the urban surroundings of domestic gardens and hedges • Effects of management on urban burial ground biodiversity presented for the first time – sites with some wildlife-friendly interventions found to have the highest flying beetle family diversity • Sites with purposeful horticultural landscaping were found to support higher abundances than those with either next to no management interventions or very stringent management practices

Chapter 3: Cars or coffins? An investigation into sources of heavy metal pollution in UK urban necrosols and potential implications for biodiversity	• Heavy metal composition of urban necrosols exhibited significant differences between sites and when compared to expected UK ambient and urban background levels, with some isolated, extremely elevated measurements • Majority of the urban necrosols studied were acidic, whereas most urban soils are characterised as having an alkaline pH • Zinc, cadmium, chromium and nickel concentrations were positively associated with pH, and acidic soil conditions contribute to higher heavy metal bioavailability meaning urban necrosols may be more vulnerable to heavy metal leaching with low acid neutralisation capacity • Sites with wildlife-friendly interventions were found to have significantly lower concentrations of chromium, nickel and copper, but with some high measurements of arsenic, copper and lead • Greater coverage in the urban surroundings of trees and hedges was associated with lower concentrations of arsenic, chromium and nickel, possibly due to their uptake by woody vegetation – this could be of importance in future burial ground planning • Some evidence that older sites with older interments at a greater density were found to have higher lead concentrations, possibly related to the time needed for lead to adsorb within the soil – potentially valuable for managers of older sites to understand lead levels within the soils • Measures of wider urban pollution related to industrial activity or vehicle emissions were not found to have significant impacts on urban necrosol heavy metal concentrations
Chapter 4: A deeper investigation of biodiversity in urban burial grounds utilising arthropod assemblages	• Community composition was found to be significantly different between Min and Wild, and Clear management categories but with opposite effects on ground-dwelling arthropods compared to flying beetles studied in Chapter 2 – communities in Clear sites found to have the most variability and higher evenness • Lower measures of alpha diversity for sites within the Min category could be attributed to the over-abundances of Isopoda, possibly due to the lack of organic debris removal • Isopoda species are known to bioaccumulate a range of heavy metals, and have been utilised as soil contaminant indicators – they may usefully be studied in urban burial grounds in this context, considering the results of Chapter 3 whereby urban necrosols may contain more mobile forms of heavy metals

Our recognition and understanding of burial grounds as urban green spaces in the UK is still in early development, and the work presented here forms part of an initial exploration. By focusing on fundamental aspects such as soil characteristics, management regimes, and surrounding landscape factors, this study contributes to building understanding of UK urban burial ground biodiversity. The focus on using arthropods, in both indicator and community analyses, provides a glimpse at some of the key players that support higher trophic levels. The multitude of various, and sometimes conflicting, potential influences on biodiversity discovered here reflect the challenges of quantifying urban biodiversity, compounded by the unique type of land use.

The lack of knowledge of UK burial grounds as urban green spaces is despite an increase globally in research interest of biodiversity in burial grounds in recent years. Since the original literature search was undertaken for Chapter 1, which included research up to and including the year 2020, published research in the primary literature on the subjects of biodiversity or ecosystem functioning in urban burial grounds has grown. It appears that recognition of the role of urban burial grounds as green spaces, and their value for biodiversity, is increasing, although many draw conclusions regarding the latter from the same small number of pre-2020 studies (e.g. McClymont and Sinnett, 2021; Długoński, Dushkova and Haase, 2022; Franco et al., 2022; Säumel, Butenschön and Kreibig, 2023). Of this recently published research, only two papers could be found from the UK; one being the publication described in Chapter 2 of this thesis (Cathcart-James, Foster and Pickles, 2022), and another which discussed the contributions of urban cemeteries to green infrastructure (GI) and ecosystem services (McClymont and Sinnett, 2021). This second study described incidental observations of wildlife and biodiversity interventions in urban cemeteries and recommended that GI strategies include proposals to enhance biodiversity (McClymont and Sinnett, 2021). There is a long way to go in building our understanding of how urban burial grounds function as green spaces in UK towns and cities for biodiversity provision.

At the outset of this project, the lack of empirical research into the biodiversity of urban burial grounds, and the assumptions made about them as undisturbed wildlife refugia, provided the impetus to devise studies to confirm or refute these assumptions and begin to build a more informed picture of the nature of these unique spaces.

In Cathcart-James, Foster and Pickles (2022) we were able to provide initial evidence challenging the assumptions that larger, older sites would be greater reservoirs of biodiversity; increasing site size was found to have a negative influence on flying beetle abundance, perhaps due to their association with larger urban populations, as greater capacity would be needed to inter the deceased. This constitutes an initial finding on the influences of urban populations on

their burial grounds. In addition, the age of the burial grounds was not found to have a significant effect on flying beetle diversity or abundance. However, in Chapter 3, increasing site age and burial density were found to be associated with increased concentrations of lead in the soil. This further challenges assumptions that older or larger burial grounds are necessarily more beneficial for biodiversity, as variables related to human interments, such as burial number and density, and recency of interments, may result in increased heavy metal pollution leading to novel dynamics that are not found in other urban green spaces.

5.1 | IMPACTS OF MANAGEMENT

The management of urban green spaces has been recognised as a complex concept, being that it is the subject of much inter-disciplinary research with many aspects of importance, including biodiversity provision (Jansson and Lindgren, 2012). Amongst the challenges of developing effective management strategies for urban green space biodiversity is the issue of inadequate data regarding amounts of green space and managers' understanding of its qualities and potential benefits, resulting in failures to effectively plan and manage (Feltynowski *et al.*, 2018).

Recent work on the enhancement of urban biodiversity in green spaces has often been focused on urban planning, ensuring connectivity, and how urban biodiversity affects human health (Douglas, Lennon and Scott, 2017; Reyes-Riveros *et al.*, 2021). What is understood has been gleaned mostly at a wider landscape level, or within social experiments into perceptions of urban biodiversity (Reyes-Riveros *et al.*, 2021; Belaire *et al.*, 2022). Whilst there is growing research interest in encouraging communities to engage in wildlife-friendly practices within their own spheres of control (Mattijssen *et al.*, 2017), there is a lack of site-level investigations into the effect of practical management activities, such as mowing regimes, chemical use, planting choices and habitat creation, on biodiversity in public green spaces (Aronson et al., 2017).

The approach taken in this thesis to understand the impacts of green space management on urban biodiversity is at the site scale, looking at differences in biodiversity between categories of differing intensities of practical management tasks. This approach to studying burial grounds has been established as absent from primary literature; Loki et al.'s (2019) review found a complete lack of studies looking at the direct effect of management practices on burial ground biodiversity. Despite this, there is a narrative around wildlife-friendly management practices and recognition of the value of burial grounds focused on raising awareness and community involvement in data gathering (e.g. Caring for God's Acre 2023, NBN Atlas Partnership 2021).

Encouragingly, a report designed to assist local authorities in England in managing burial grounds for biodiversity promotion was released in 2023, which demonstrates an increasing awareness at government level of burial grounds as green spaces (Priestley, 2023) The management activities proposed by the report, such as replacing fences with hedgerows, less mowing, planting of native species and installing bird or bat boxes are aimed re-naturalising and providing wildlife refuges. Establishing whether management specific to urban burial grounds as opposed to other green spaces is necessary relies on focused research, such as that presented in this thesis. Working from the assumption that what is done elsewhere, is best done in burial grounds, may limit the effectiveness of management activities.

Chapter 2 of this thesis showed that taking a hands-off approach to managing entire urban burial grounds, those in the minimal ("Min") management category, provided the greatest beetle family richness, more so than those in the Wild category with ecologically sensitive interventions such as those posited in the recent report for LAs (Priestley, 2023). However, in Chapter 3 these sites were found to have significantly lower concentrations of chromium, nickel, and copper, indicating that this management approach may be contributing to better soil health. Sites in the landscaping ("Scape") category were found to support greater abundances of flying beetle families than those in the Min category, indicating that horticultural design and landscaping may have a beneficial effect on abundances of some insects, but not on their diversity. This result challenges the assumption that modern landscaping preferences in urban burial grounds are not as effective for biodiversity generation, supported by the findings in Chapter 4 that sites in the "Clear" management category evidenced the most variability in arthropod order composition, and the single site with the greatest variability was Henley Road Cemetery which is in the Scape category.

5.2 | FUTURE WORK

Throughout this thesis, opportunities for future researchers to take our understanding of urban burial ground biodiversity even further have been posited, based on what has been found here. In addition, there are research opportunities that I believe would be valuable, were they possible, for developing our understanding of whether biodiversity is affected by the interment of human remains in urban burial grounds.

5.2.1 Management

A significant finding from the research presented here is that meaningful differences were found within arthropod communities between different management regimes. In addition, these regimes exhibited significant differences in soil heavy metal concentrations as described in Chapter 3. However, developing the management categories devised here to a more granular level, investigating impacts of more specific practices on urban burial ground diversity, would not only build understanding within these specific spaces but also urban green spaces more generally. As outlined above, research discourse on urban biodiversity lacks an understanding of front-line management practices.

Future research into the effects of management on urban burial ground biodiversity could further our understanding of how those responsible for their care may be able to bring burial grounds into the fold of urban green spaces, building on the growing governmental recognition of their potential contributions. This thesis has presented evidence to suggest that how urban burial grounds are managed does not always translate into expected results based on knowledge of how management of other types of green space influence biodiversity. Additional research would be beneficial for exploring the longer-term effects of specific practices, for example by categorising tasks such as mowing and pruning regimes, timings of chemical use and planting choices and consistently sampling a range of taxonomic groups over the course of at least two years. Incorporating all seasons including winter, which is typically the most intense period for funerals taking place, would be a useful contribution. The key to understanding how management practices influence biodiversity in these spaces may be in tracking their effects over extended periods of time, as they have existed for decades and in some cases for over a century. This project looked at the differences in flying beetle biodiversity over the course of the summer months in one year, but in general little research has been conducted using consistent sampling or documentation of management tasks over a significant time period. In doing so, future researchers may be able to bring out the key management practices that affect the biodiversity of multiple taxa.

To build much larger datasets than could be accomplished here, and in the spirit of utilising community science for strong research outcomes, regular 'bioblitz' activities could be conducted within urban burial grounds whereby experts and the local communities come together to record as many species as possible in a single day. Not only could this grow large datasets over time, it would promote the importance of urban burial grounds and raise awareness so that more of the urban population are aware of, and can benefit from, what they can provide.

It might be tempting to take an experimental approach and install various management regimes into urban burial grounds, in conjunction with biodiversity sampling, however, taking into account their unique nature and longevity, this may lead to results of limited usefulness unless the experiment were to be conducted over a significant period of time. In aiming to understand whether the interment of human remains, along with management practices influence biodiversity, considerations may need to be made regarding evaluating interactions between decomposition processes and management practices. This type of land use sets burial grounds apart from other urban green spaces, and further research is needed to build on what has been described here to more fully elucidate the potentially unique nature of biodiversity dynamics.

5.2.2 Vegetation

There are many potential avenues for further research into the vegetation within urban burial grounds and its impact on biodiversity. The vegetation structure and habitats present are dependent on site planning and management, and studies incorporating a deeper exploration of vegetation with management approaches could be valuable not only from a research point of view but also from an applied one, whereby practical approaches to enhance biodiversity could be communicated to managers.

As the main above-ground components of habitats, vegetation is commonly measured in terms of its type, height and coverage, so that structural drivers of biodiversity can be elucidated (Cross *et al.*, 2016; Mitchell *et al.*, 2016; Guo *et al.*, 2017; Melin *et al.*, 2018). The vegetation structure of urban burial grounds has not been characterised and presents an opportunity to gain a deeper understanding of how habitat structure in these spaces influences their biodiversity. To achieve this level of detail on a large-scale, data from LiDAR could be used, a type of remote sensing technology that can measure vegetation structure in 3D using pulses to form point clouds. Remotely sensed data is increasingly used to map and monitor vegetation fragmentation in urban areas (Kowe, Mutanga and Dube, 2021) but also on a finer scale to provide a more detailed picture of vegetation structure within a specific urban green space (Caynes *et al.*, 2016) which could be applied to burial grounds. The diversity and abundance of a range of taxa in relation to vegetation characteristics could be explored including birds (Clawges *et al.*, 2008), reptiles (Shokirov *et al.*, 2024) and arthropods (Acebes, Lillo and Jaime-González, 2021; Li *et al.*, 2024).

Research of this nature could aid in evidence-based management decisions in urban burial grounds being made regarding planting choices, landscaping and tree management to support biodiversity. Differences in the taxa focused on here were observed between management regimes and a more detailed understanding of the vegetation structures those regimes produce would better our understanding of how site-level management practices influence habitats.

In addition to the structure of vegetation in urban burial grounds, explorations of woody plant species coverage and diversity could also be valuable. In Chapter 3 of this thesis greater coverage of trees and hedges surrounding the study sites was associated with lower soil heavy metal concentrations; more in-depth surveys of shrubs, hedges and trees within sites, including tests on leaves, bark and roots, would enable a clearer picture to be built of the pathways heavy metals take in the urban burial ground ecosystem. The capabilities of plant species to bioaccumulate heavy metals from soils are increasingly well-documented (Dadea *et al.*, 2017; Günthardt-Goerg *et al.*, 2019; Bhat *et al.*, 2022) as are the potential risks of heavy metals in food from urban areas such as allotments (Antisari *et al.*, 2015; Augustsson *et al.*, 2015; Laidlaw *et al.*, 2018). The soil heavy metal study reported in this thesis found evidence of higher concentrations of lead in older burial grounds and increasing zinc, cadmium, chromium and nickel levels as the soils became more acidic, likely raising their bioavailability for uptake by plants (Weber *et al.*, 2019); it may be safest for anyone walking through an urban graveyard or cemetery to think twice before eating any blackberries they may find.

5.2.3 Necrosols and isopods

In addition to plants, heavy metals in soils are known to bioaccumulate in a number of animal species, notably isopods (woodlice) (Costa *et al.*, 2013; Ghemari *et al.*, 2017). Woodlice have been found to accumulate copper, zinc, lead and cadmium (Paoletti and Hassall, 1999), and have been used as bioindicators of urban pollution for over 30 years (Paoletti and Hassall, 1999; Pastorino *et al.*, 2021). Woodlice can be exposed to heavy metals from many sources and routes of exposure are likely determined by the level of bioavailability of the metal (Van Gestel, Loureiro and Zidar, 2018). There has however not been any research discourse on the potential for heavy metals from the interment of human remains to result in bioaccumulation in woodlice, and heavy metals proposed to be from this source have been found previously in burial ground topsoils (Amuno, 2013; Madden *et al.*, 2022) where woodlice reside.

In Chapter 4, woodlice made up over 70% of all arthropods sampled and with necrosols shown in Chapter 3 to be generally acidic, the potential for heavy metals to accrue in these animals is greater as they are more likely to be in mobile, more bioavailable forms (ref). This could lead to organisms at multiple trophic levels in urban burial grounds being vulnerable to the negative effects of heavy metal contamination such as (refs), thereby affecting the biodiversity within these green spaces. Woodlice have been found in their highest densities in calcareous rather than acid soils, likely due to their calcium requirement for growing the exoskeleton (Paoletti and Hassall, 1999). However, Antonović *et. al.* (2012) found their species richness to be unexpectedly high in an acidic peat bog and not significantly different from an adjacent forest, concluding that an important factor was vegetation succession. This makes the study of vegetation structure in urban burial grounds, as discussed above, even more valuable for understanding the dynamics of heavy metals in plants, soils and invertebrates.

Future work could build knowledge of the movement and accumulation of heavy metals in the fauna of urban burial grounds by undertaking tests on isopod communities to measure their heavy metal content, along with soil analyses, and comparing them with other types of urban green space. It would be valuable for managers of urban burial grounds to understand any differences in the impacts of heavy metal pollution stemming from the soil to other spaces such as parks, for site-specific risk management, phytoremediation and biodiversity interventions.

5.2.4 Grand ambitions

In order to build knowledge of the impacts burials and cremated remains interments have on urban burial ground diversity, long-term studies could be devised that require stringent ethics considerations and permissions. However, assuming these requirements could be satisfied, there are projects that could be embarked upon to gain valuable insights into how the decomposition processes of both human remains and the accompanying burial materials affect biodiversity – both above and below ground – in the short, medium and long term. To build on research utilising deceased pigs to study mites associated with human decomposition (Perotti and Braig, 2009; Rai, Pickles and Perotti, 2022), rather than laying the pigs directly into the ground they would be interred in urban areas at the legally designated depth for a full burial (a depth of 2 feet and 6 inches of soil must be above the interment) into coffins used for human interments

custom-made to the pigs' dimensions and including the customary linings, nameplates and handles. Clothing and shoes constructed of manmade and natural materials could accompany the interments, and items made of materials similar to those that may be found in burials such as average amounts of dental amalgam, gold and silver jewellery and stuffed toys. The deceased pigs could also be injected with common drugs associated with end-of-life care such as morphine to evaluate the effect of pharmaceuticals. Soil and above-ground flora and fauna could be sampled above, below and around the burials over an extended period of time, allowing for a range of weather conditions and tracking decomposition to skeletonisation and beyond. This could provide holistic, long-term evidence of the effects of burials on urban biodiversity, assuming an appropriate burial density reflecting spacing of grave plots in burial grounds.

Rather than attempting to replicate the impacts of human interments, actual full burials of deceased humans could be studied in the same way as described above within the ethically stringent confines of a body farm, a facility for the study of forensic science which is common in the USA but yet to be authorised in the UK.

5.3 | THOUGHTS FROM A FUNERAL DIRECTOR

I have been in the funeral industry for four and a half years as of submission, firstly as a Funeral Service Operative (undertaker) then later a Funeral Director. I have found that my work in caring for the deceased and their families, and my work on the biodiversity of urban burial grounds in which I have spent much of my time and whose stakeholder communities I have been immersed in, have informed and complemented each other.

In working alongside managers of churchyards and cemeteries, I have found that teams are very small and under a lot of pressure in urban areas as populations are ever-growing, and as demand for funerals increases, teams do not get any bigger. This means that often there is little time, money or person-power to afford much engagement in environmental activities in the grounds they are responsible for. This is not necessarily through a lack of interest, but a lack of education and priority from dioceses and councils. I have seen positive and negative opinions from families about wildlife interventions in burial grounds – some do not like the wild areas in cemeteries, but they are appreciated in churchyards as there is a perception of peace and nature attached to history. My personal opinion of sites in the Clear management category, such as Eashing and Nightingale cemeteries, as being rather desolate, uniform places is not mirrored by families – extremely clean, tidy spaces denote care and reverence. Particularly when young people and babies have passed away, whom I have had the solemn privilege of looking after, I

cannot see in the contemporary public cemeteries a widespread acceptance of extensive wildlife-friendly interventions such as overgrown areas, the leaving of deadwood, very relaxed mowing regimes – children's graves and interment areas are kept particularly immaculate, and the sense of ownership is particularly strong.

The reverence shown and the perceived sacrosanct nature of burial grounds is not reserved for churchyards or religious areas of cemeteries. Although there is a move towards secular funerals, or quite commonly 'hybrid' funerals where the religion aspect is light-touch, this move away from traditional religious services does not translate into moving away from the sanctity of churchyards. I read papers and wrote myself about society's emotional attachment to burial grounds before I had witnessed it personally – it is more profound than I had thought, and perhaps more than other authors have experienced. Entire communities have their family and friends buried in the local churchyards and cemeteries; families have multiple generations resting there and often point out to me other plots where extended family rest, or their friends, or their friend's parents, their neighbours. Children and young adults attending funerals know this, and that attachment is set for generations to come. I regularly make funeral arrangements with clients who have long since moved away from the area but wish for their older relatives to be laid to rest where they came from in the same burial grounds as previous generations. Mourning families often see the entire burial ground as the place where their loved ones are resting, not just the grave, and feel a sense of belonging and ownership for the entire space.

The importance of burial grounds to communities cannot be extricated from understanding these places as urban green spaces whose ecosystem functioning and biodiversity need to be enhanced, protected and maintained. In no other type of green space is stakeholder involvement more fundamental. There is growing awareness of the impacts funerals can have on the environment, and natural burial grounds are becoming more popular across generations. I have guided families through ecologically impactful decisions such as clothing choices, coffin choices and native seasonal floral tributes, and these are often considerations for families having a cremation rather than a burial. There is also a common theme of families not wanting to be wasteful - many of the older generations (the elderly passing now were born in 1930s and 1940s) had frugal attitudes themselves, and as the cost-of-living increases so too does the cost of dying.

As cremations grow ever more popular, in the context of this thesis' interests there are real-life impacts of interring significant quantities of cremated remains, or cremains. The ways in which cremains can be memorialised are myriad and increasing all the time in terms of commercial ventures, from jewellery and paperweights to shooting them into space; having a

cremation allows for the splitting of a loved one's remains for various types of memorialisation, and many families choose some form of scattering. A common practice in cemeteries is the scattering of ashes in designated areas including public health cremations where no family has been found, which constitutes large depositions of potash in grassland and woodland habitats; I can only hypothesise that these depositions would have an impact on the biodiversity these areas can sustain. The interment of cremains in a burial ground is still a very popular option, although this is increasingly seen as traditional rather than the modern norm. The interment of cremains and planting over them of rosebushes is a common choice, and cemetery managers are reporting problems with keeping those rosebushes alive due to the cremains causing sterility of the soil. Other planting choices have been explored with species that are more resistant to high levels of potash, such as fuschias, although there is minimal uptake due to families preferring the traditional rose. As cremation's popularity continues to dominate, I think the challenges associated with the disposal of cremains in urban burial grounds where populations are most dense and anticipated to become even more so, will become of increasing importance. If I was to say to you, as a mourning family member that an interment accompanied by a rosebush was not possible in the long-term, how would that impact you and your family?

Through my research for this thesis, I have found there is a level of concern about the impact of embalming fluids on soil and groundwater, with research generated in countries where embalming is common practice, for example the USA and South American countries. In the UK we have seen a drop in popularity of this practice, and in conversations about embalming of the deceased with families I often find that due to extensive medical interventions at the end of life, families do not wish for any more invasive procedures on their person. With funerals generally taking place within 3 to 5 weeks of passing, families can still visit their loved one in the chapel of rest without this level of preservation and families often do not see the point if they are having a cremation, which is overwhelmingly popular. Soil and water pollution from embalming fluids is likely to not be a serious issue in this country, especially as burials are becoming practically less possible, especially in urban areas where there is dwindling burial space, and certainly more expensive.

On the subject of burial space, there will be significant issues in the near future with the chronic lack of it already recognised by the government. I have already seen LAs searching for additional land to buy and considering either closing public cemeteries or stopping full burials as ashes interments occupy far less space. The social ramifications for this approach are significant, particularly in cultures where burial is the only acceptable form of body disposal; Muslim communities, for example. In Stoke Cemetery, Guildford, the LA recently suggested exhuming

historical burials and re-interring all remains at the ends of rows to free up space; this resulted in public outcry, even when Guildford's communities today have no ties to the deceased in question. If the mass exhumation approach is not adopted and urban cemeteries stop full burials, people will not be able to bury loved ones in the town or city where they lived; this risks personal connections with burial grounds in urban areas starting to fade within communities. This could have implications for how urban burial grounds are governed, managed and protected in the future. It would be a difficult communicative tightrope to walk, promoting the wildlife-friendly approach and family-orientated focus to urban burial grounds when the perspective of the latter is that the most important aspect of site management is stringent landscaping.

Whether I am wearing my top hat and frock coat or t-shirt and walking boots, carrying a coffin or a clipboard, my feelings when in an urban burial ground are those of belonging, of care, a desire to understand and protect them; yes, for my own academic curiosity, but more so for the sheer amount of life – be it human or otherwise – that relies on them.

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APPENDICES

Appendix 0.1

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Introduction

When considering burial grounds and wildlife, it is easy to reach for the common assumption that they are biodiversity hotspots; an image could be conjured of a quaint churchyard full of ancient trees, wildflower glades, gravestones covered in lichens with the sounds of birds and flying insects all around, people visiting to reflect and speak to each other in hushed tones. It is a lovely image, and a true one in many instances; there are thousands of old, 'closed' churchyards in the UK that resemble it. However, to think of burial grounds in our highly populated towns and cities that assumption can no longer hold due to influences from human activities, and we must dig (sometimes literally) to explore their true nature.

The typical geography of urban burial grounds is older, full churchyards in the historical centre of a town with larger, newer municipal cemeteries towards or beyond the town limits where there is more space. Reading conforms to this general 'deathscape', with old, closed graveyards such Old and Caversham cemeteries in the centre, and the currently in use Henley Road Cemetery on the edge of town. With burial grounds of different ages, sizes, management and number of interments, from an ecologist's point of view it would be incredibly unusual if all of Reading's burial grounds housed the same abundances and diversity of plants and wildlife.

Reading Borough Council's latest Biodiversity Action Plan (BAP) published in 2021 is a local framework for biodiversity enhancement and conservation. The BAP defines habitat types, explains the nature conservation designations within the area and centres around 'themes for action'. There is a significant focus on water courses, road verges and woodlands. Reading Old Cemetery is bullet-pointed under 'historic parks and gardens' and is mentioned as being designated a Local Wildlife Site (LWS), a conservation designation which forms one of the themes for action. However, if one looks at the most current LWS list published in 2023, the cemetery is absent. Several BAP objectives could be applied to the cemetery, such as those focused on tree, hedgerows and grasslands, however the cemetery slips through the cracks of the BAP as a unique green space of urban Reading, leaving it with little recognition or protection.

Reading Old Cemetery as an urban green space is mostly subject to the same pressures from human disturbances as others such as parks, gardens, roundabouts, road verges, for example air and noise pollution. Therefore, biodiversity faces similar challenges and requires our protection. Why? For the physical and spiritual benefits it brings to our communities, and for species' own intrinsic value. Soil microorganisms, plants, lichens, invertebrates and the species they support are the building blocks which ultimately form ecosystems, the functioning of which are needed for human health. There are many stakeholders involved in the cemetery, from the council to interest groups to the public to nature itself, so how it is managed and used to suit all is extremely challenging.

So, an important question to ask is – can nature flourish in Reading Old Cemetery?

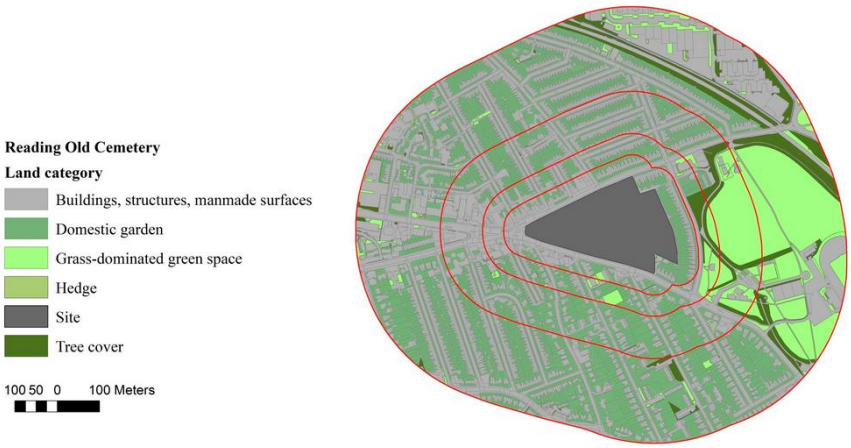
Reading Old Cemetery within the urban landscape

To understand the nature of biodiversity in the cemetery (why what species are there, are there), it helps to place the site into the wider urban context; viewing any green space of interest in isolation can lead to important influences being missed.

There are many likely drivers of, or influences on, biodiversity in the cemetery – both good and bad. Pollution (vehicle exhausts, litter, noise), human disturbance (gravedigging, trampling, vandalism, hunting), sympathetic interventions such as a hay-making mowing regime, minimal pruning and non-use of chemicals, the types of land use in the immediate surroundings, soil type and quality, planting choices – are all examples of these drivers, both within and outside the cemetery. The extent to which these drivers influence the abundance and diversity of species, the positive working to counteract the negative, ultimately determines the biodiversity of the cemetery.

As you can see from the map below, the cemetery is surrounded in close proximity by busy roads, residential streets and domestic gardens, with a large urban park at the rear. There is a distinct lack of mature trees in the area. So, the wider urban context of the cemetery is a lot of manmade, impermeable, hostile surface (road, pavements, driveways, buildings) and fragmented areas of habitat all managed in different ways. This type of urban mosaic typically creates a fragmented green space situation, which limits species' ability to travel around the landscape in order to find resources and mate; thus affecting their resilience. High levels of disturbance and fragmentation can also make it very difficult for sensitive, often rarer, species to establish and thrive, reducing diversity. As mentioned previously, ecosystems are built on biodiversity and

their healthy functioning is needed for human health – a fragmented, highly disturbed urban landscape surrounding the cemetery presents risks for the resilience of the ecosystems within the cemetery.



Map of Reading Old Cemetery in the surrounding urban landscape of Reading (Cathcart-James et al. 2022)

A study published in 2022 by myself and colleagues which included Reading Old Cemetery, found that land use type in the surroundings of urban cemeteries was an important influence on cemetery biodiversity. We found that an increased area of domestic gardens and hedges were beneficial – a situation where people who live near the cemetery are in a position to benefit its biodiversity from home, which highlights how important our contributions to nature can be no matter how small we may think they are.

Invertebrates in Reading Old cemetery

Invertebrate biodiversity plays crucial roles in the ecosystem function and resilience within urban green spaces. They are vital components of natural processes such as food webs, decomposition and pollination. Invertebrates are often used as indicators for wider biodiversity and ecosystem health by researchers as their presence or absence, abundance and diversity can tell us a lot about the nature of the biodiversity a green space can support when we combine this information with measurements of potential influences with statistics.

Flying beetles (Order: *Coleoptera*)

Beetles are a taxonomic order of insects that have characteristically hardened forewings which form a protective case. Beetles have huge abundance and diversity as an order; in the UK alone, there are over 4000 species. These insects perform many important functions within ecosystems as they are successful in different types of habitats. Whilst many are predators of other invertebrates, other species will feed on plants, fungi, dung and decaying organic matter. Understanding beetle biodiversity in Reading Old Cemetery can give an insight into the functioning of its ecosystems and the types of habitats present.

Information box 1 with accompanying example species illustration:

Leaf beetles (*Chrysomelidae*)

- Mostly flea beetles (Family: *Alticinae*, genus mostly *Longitarsus*)
- Characteristic enlarged back legs, so named for their hopping behaviour – if you disturb one, they jump so fast it's like they just disappear! Fun to try and catch….
- Herbivorous, species usually have a preferred plant species or family

Information box 2 with accompanying example species illustration:

True weevils (*Curculionidae*)

- Distinctive rostrum ("nose")
- Mostly broad-nosed weevils (Family: *Entiminae*)
- Herbivorous, can feed on a wide range of plant species which contributes to their success
- They lay eggs in the soil and larvae then develop underground

Information box 3 with accompanying example species illustration:

Seed weevils (*Brentidae,* sub-family *Apioninae*)

- All of genus *Protapion*, clover weevils
- Pear-shaped with prominent rostrum
- Herbivorous, feed on clover species, especially white clover
- Lay their eggs in the flowers, emerging larvae then eat the seeds

Ants (Order: *Hymenoptera*, Family: *Formicidae*)

Ants are part of the same order as bees, wasps and sawflies, *Hymenoptera,* which means 'membranous wing'. Like bees and wasps, ants have a characteristic 'hourglass' shape, with a distinct waist separating the abdomen and thorax. Although we would typically think of ants as ground-dwelling, most ant species will grow wings to swarm for the 'nuptial flight' and to form new colonies, whereby populations will take flight to find a mate. In the UK there are 51 native species, the most common being present in great numbers. Due to their building of colony nests, they are referred to as 'ecosystem engineers', having many ecological impacts such as improving soil quality through tunnelling, spreading seeds, 'farming' butterflies and aphids and preying on other invertebrates. They also form an important food source for birds and mammals.

During sampling for our study, a total of 462 ants were found - 397 of them (86%) from 2 sampling spots – one in plot 80, the other in plot 67 which incidentally are both in the eastern extension of the cemetery. The other three spots were in plots 21, 41 and 29.

[Image of the cemetery with plot numbers – not yet produced]

Information box 4 with accompanying example species illustration:

Common red ant – *Myrmica rubra*

- Two segments at the waist, mainly red in colour with darker head
- Commonly found under walls, stones, deadwood, long grass
- Colonies are built under soil or moss
- Can deliver a painful sting

Information box 5 with accompanying example species illustration:

Yellow meadow ant – *Lasius flavus*

- All *Lasius* species have one segment at the waist
- Yellowish-brown in colour
- Create characteristic anthills in meadows and lawns
- Feed on insects and woodlice that live in grass

Woodlice (Order: *Isopoda,* sub-order: *Oniscidea*)

Woodlice are crustaceans, related to crabs and lobsters, and are the only crustacean to have successfully colonised dry land. They have seven pairs of legs and a shell that moults, with characteristic external 'book lungs' on their underside, evolved from gills. So that the lungs do not dry out, woodlice are nocturnal and stay protected in damp areas such as under wood or stones during the day. Woodlice play an important role in nutrient recycling as they are detritivores, feeding on decaying vegetation which makes material more accessible to fungi and bacteria, so it is broken down faster.

A total of 1448 woodlice were found from the same sampling spots as the ants. Six individuals were from plot 80 (0.4%), 279 from plot 67 (19%), with the rest being fairly evenly

divided between the other three sample spots – quite opposite to the distribution of ants, a trend we have seen in general across the dataset from other cemeteries as well.

Information box 6 with accompanying example species illustration:

Striped woodlouse - *Philoscia muscorum*

- Yellowish-brown with characteristic dark stripe down the back and a black head
- Fast moving when disturbed, can tolerate drier conditions
- Commonly found in grassland

Information box 7 with accompanying example species illustration:

Common pill woodlouse – *Aramadillidium vulgare*

- Uniform slate colouration, can develop lighter patches
- Rolls into a tight ball for defence, hence the name
- Can tolerate drier conditions and found in a wide variety of habitats, from walls to leaf litter and under stones or deadwood

Lichens in urban burial grounds

Lichens are not a single organism; rather, a lichen is a symbiosis formed of two organisms, a fungus and an algae or cyanobacteria. The fungus provides the body of the lichen, or 'thallus', which is a protective home for the photosynthesising algae or cyanobacteria which provides the food for both organisms. In general, lichens have three types of growth – crustose, where the thallus is very closely attached to the substrate, foliose, where the lichen looks like a cluster of lobed leaves, and fruticose, whereby the thallus attaches at the base and forms a branched, bushy shape. Lichens are very slow growing, sometimes only less than a millimetre a year. They have been used for many years to measure air pollution levels; growth rates and the absence or presence of species with different pollution tolerances can tell us a lot about air quality. Lichens receive all their requirements from the air, and so absorb heavy metals in urban areas where there is no escape from them – more pollution-tolerant species are therefore found in town and

city centres. In addition, lichens play important roles in an ecosystem such as a source of food, bird nest material and invertebrate habitat.

Lichens have long been associated with burial grounds, primarily due to the concentration of stone substrates which are often undisturbed and have been there for a long period of time. There is a distinct lack of natural rock in urban areas so gravestones, boundary walls, chapels, statues provide habitat for saxicolous (stone or rock-dwelling) lichens. However, as gravestones can be cleaned with chemicals and lawn areas treated with pesticide or herbicide sprays, there are significant risks to lichen diversity, as many species are sensitive to pollutants.

Lichen species are also able to tolerate different levels of moisture and sunlight levels; shaded and sunny sides of gravestones, walls, trees and other substrates can host different species of lichens. The type of substrate is also important for which lichen species can establish; different stone types, due to how acidic or basic they are, will host different suites of species. Gravestone fashions and preferences over time play an important part here, not only in stone type but also finish – polished stone provides fewer micro-habitats and nooks or crannies for lichens to take hold and establish from. In addition to saxicolous lichens, other species are described as lignicolous, or wood-dwelling. Further species can be found on undisturbed wooden surfaces such as long-living trees and shrubs, deadwood, benches, fences and wooden grave markers. Some of the more common lichens can be found on both stone and wood if the conditions are favourable.

Captions for proposed illustration panel of common urban gravestone lichens:

- ***Caloplaca flavescens***
    - Crustose, middle part often missing so it forms a ring, likes sunny limestone (basic)
- ***Psilolechia lucida***
    - Crustose, powdery appearance, distinctive yellow-green colour, quite pollution-tolerant, grows on dry, shaded acid stones (high silica content, e.g. granite, sandstone)
- *Parmelia saxatilis*
    - Foliose, pollution-tolerant, grows on acid stones and acid-barked trees (larch, pines, birch and oak less so)
- *Xanthoria parietina*
    - Foliose, very pollution-tolerant, goes from orange if growing in the sun to green/grey if shaded, likes nutrient-rich basic substrates (concrete stones, alkaline-barked trees such as sycamore, elder, aspen) so often seen where birds perch such as the tops of gravestones and branches where bird droppings would fall

Conclusion

Nature likes a mess, but in burial grounds there is a perception that 'untidy' can equate to 'not cared for' – referencing back to the many different stakeholders in burial grounds, there are diametrically opposed influences on how cemetery grounds are managed as green spaces. There is however some good news from our study of which Reading Old cemetery was a part – there is evidence that some level of landscaping is beneficial for wildlife species diversity, so there is the possibility that requirements for nature and expectations of local communities can both be met. The key for promoting urban biodiversity is heterogeneity and connectivity – both within the cemetery and in the surrounding area. Perhaps the first step in protecting and enhancing Reading Old's biodiversity is to gain an understanding of the species living within it, and those that could make it home – in the words of Baba Dioum, "In the end, we will conserve only what

we love; we will love only what we understand and we will understand only what we are taught".

References of interest

- Cathcart-James, M., Foster, C., Pickles, B.J. (2022) *Challenging assumptions about burial ground biodiversity using flying beetles as indicators in urban areas.* Journal of Urban Ecology, 8(1)
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- Thames Valley Environmental Records Centre (2023) *Local Wildlife Sites in Reading – 2023.* [Accessed 07.11.2023] Available from: https://www.tverc.org/cms/sites/tverc/files/documents/Reading_list_2023.pdf

Appendix 2.1

Demographic information for each of the towns within which sampling was conducted (Office for National Statistics 2011, 2020).

Town	Local authority	Town area (km^2)	Average number of public green spaces[1] within 1km radius	Average distance to nearest public green space[2] (m)	Number of households with at least one usual resident[3]	Population declared as having a religion (%)[4]	Average total annual income (£) for financial year 2017-18 (local authority level)	Population aged 65 or older (%)[5]	Number of registered deaths in 2020 (local authority level)[6,7]
Reading	Reading	83.7	4.46	355.09	126,086	65	52,839	13.4	1381
Bracknell	Bracknell Forest	20.6	4.76	331.78	32,181	63.8	56,767	11.8	850
Basingstoke	Basingstoke and Deane	29.2	3.94	400.46	44,544	60.7	57,186	12.3	1607
Newbury	West Berkshire	11.7	4.36	437.05	16,757	63.3	56,868	16.1	1466
Maidenhead	Windsor and Maidenhead	18.5	4.41	354.35	25,935	70.8	59,744	16.2	1419
Slough	Slough	34.1	4.14	315.75	60,203	80.9	47,521	10.6	949
High Wycombe	Buckinghamshire	39.2	3.8	408.6	52,011	68.9	55,812	14.7	4952
Wokingham	Wokingham	14.5	4.27	359.96	17,184	65.7	66,825	16.8	1367
Camberley	Surrey Heath	13.4	3.39	370.22	14,823	68	61,467	16.7	957
Fleet	Hart	12	3.64	365.65	15,428	66.7	63,409	16.7	736
Windsor	Windsor and Maidenhead	8.1	4.41	354.35	13,855	70.4	59,744	16	1419
Thatcham	West Berkshire	5.8	4.36	437.05	10,321	64.3	56,868	11.9	1466
Guildford	Guildford	20.8	4.76	372.69	29,889	61.9	58,778	13.2	1192
Godalming	Waverley	7.2	3.93	374.25	9219	63.8	57,329	17.2	1381

[1,2] Public green spaces are defined as parks, public gardens and playing fields.

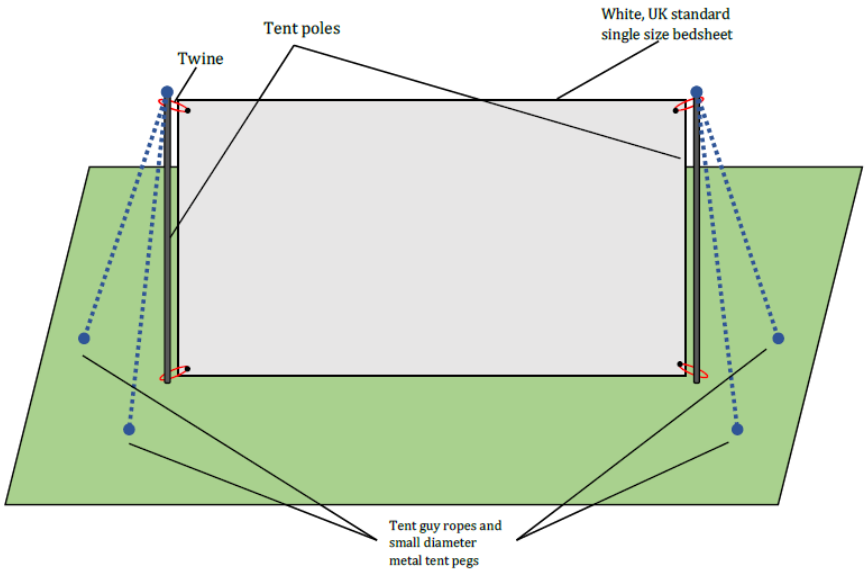
[3,4] Taken from the 2011 Census as the 2021 Census has not been published at this level of detail yet.

[5] This is the earliest year that data is available at the local authority level rather than the regional level. Inflation due to the COVID-19 pandemic means these figures may not accurately reflect historic levels, which tend to remain stable.

[6] High Wycombe District Council was abolished in 2020 so registered death data is only available for the entire county.

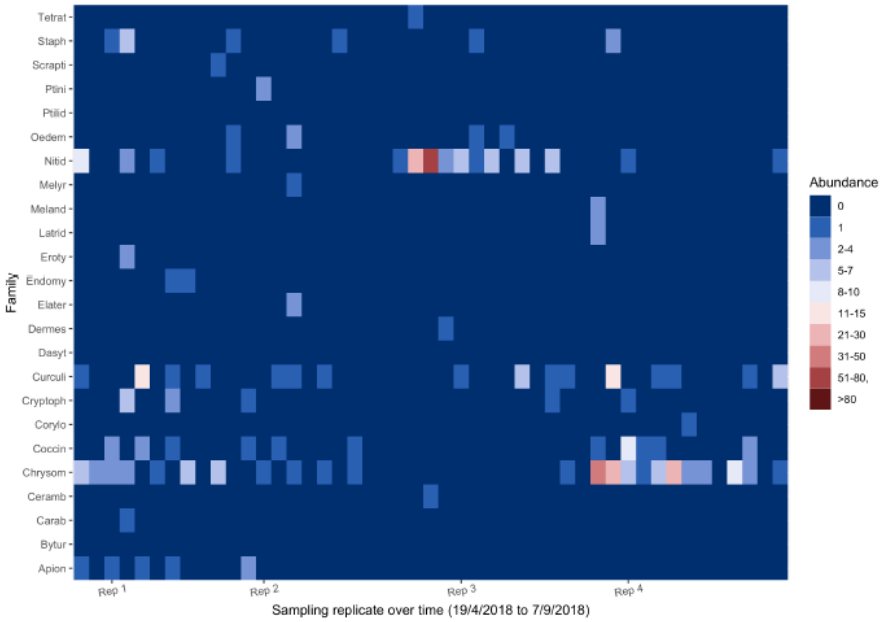
Appendix 2.2

Diagram of the novel beetle collection setup that was developed for this study, specifically the upright sheet setup.



Appendix 2.3

Heatmap to illustrate flying beetle family abundances over time (the x-axis range is the full sampling period demarcated by the first date of each replicate).



Appendix 2.4

Family level diversity indices for (a) the four sample replicates and (b) the four management categories.

a. Temporal replicate

	Rep 1	Rep 2	Rep 3	Rep 4
No. of families	14	13	12	10
No. of individuals	193	119	359	213
Shannon H	2.1	1.26	0.75	1.08
Simpson 1-D	0.85	0.48	0.3	0.47

b. Management category

	Clear	Scape	Wild	Min
No. of families	15	12	16	14
No. of individuals	257	361	217	49
Shannon H	2.71	2.48	2.77	2.64
Simpson 1-D	0.93	0.92	0.94	0.93

Appendix 2.5

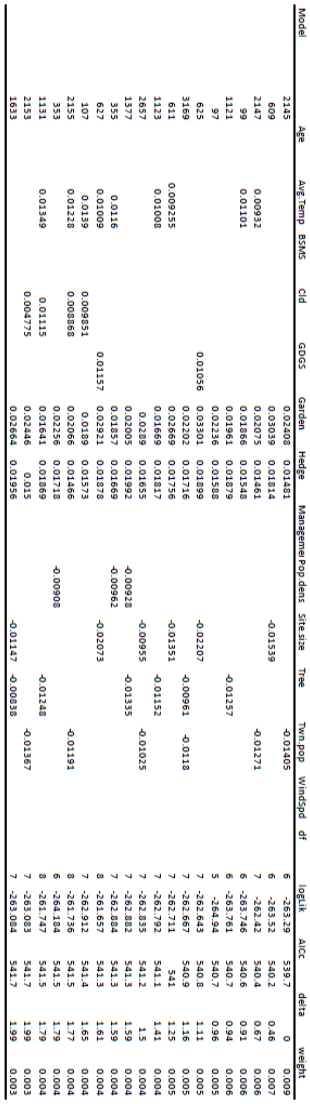
Jaccard similarity index and distance values for pairwise comparisons of (a) sample replicates and (b) management categories.

a. Temporal replicate pair	Jaccard Similarity Index (JSI)	Jaccard Distance (1 - JSI)
2_1	0.444	0.556
3_1	0.563	0.438
4_1	0.353	0.647
3_2	0.471	0.529
4_2	0.353	0.647
4_3	0.375	0.625

b. Management category pair		
Scape-Clear	0.588	0.412
Wild-Clear	0.55	0.45
Min-Clear	0.45	0.55
Wild-Scape	0.474	0.526
Min-Scape	0.529	0.471
Min-Wild	0.429	0.571

Appendix 2.6

(a) Set of negative binomial GLMMs with ΔAICc<2 for total beetle abundance where all continuous variables were centred and scaled and replicate was used as a random term.



Model	Age	AvgTemp	BSMS	Cld	GDGS	Garden	Hedge	Management	Pop dens	Site size	Tree	Twn pop	WindSpd	df	logLik	AICc	delta	weight
2145						0.02408	0.01481					-0.01405		6	-263.29	539.7	0	0.009
609						0.03039	0.01814			-0.01539				6	-263.52	540.2	0.46	0.007
2147		0.00932				0.02075	0.01461					-0.01271		7	-262.42	540.4	0.67	0.006
99		0.01101				0.01866	0.01548							6	-263.746	540.6	0.91	0.006
1121						0.01961	0.01879				-0.01257			6	-263.761	540.7	0.94	0.006
97						0.02236	0.01588							5	-264.94	540.7	0.96	0.005
625					0.01056	0.03301	0.01899			-0.02207				7	-262.643	540.8	1.11	0.005
3169						0.02202	0.01716				-0.00961	-0.0118		7	-262.667	540.9	1.16	0.005
611		0.008255				0.02669	0.01756			-0.01351				7	-262.711	541	1.25	0.005
1123		0.01008				0.01669	0.01817				-0.01152			7	-262.792	541.1	1.41	0.004
2657						0.0289	0.01655		-0.00928	-0.00955		-0.01025		7	-262.835	541.2	1.5	0.004
1377						0.02005	0.01992				-0.01335			7	-262.882	541.3	1.59	0.004
355		0.0116				0.01857	0.01669		-0.00962					7	-262.884	541.3	1.59	0.004
627		0.01009			0.01157	0.02921	0.01878							8	-261.657	541.3	1.61	0.004
107		0.0139		0.009851		0.0189	0.01573			-0.02073				7	-262.912	541.4	1.65	0.004
2155		0.01228		0.008868		0.02066	0.01466					-0.01191		8	-261.736	541.5	1.77	0.004
353						0.02256	0.01718		-0.00908					6	-264.184	541.5	1.79	0.004
1131		0.01349		0.01115		0.01641	0.01869				-0.01248			8	-261.747	541.5	1.79	0.004
2153				0.004775		0.02446	0.015					-0.01367		7	-263.083	541.7	1.99	0.003
1633						0.02664	0.01956			-0.01147	-0.00838			7	-263.084	541.7	1.99	0.003

(b) AICc "Best" model including Management

Covariate	Estimate	Std. Error	Z-value	P-value	$R^2_{(M)}$	$R^2_{(C)}$	df	logLik	AICc	delta	weight
(Intercept)	1.533	0.359	4.273	**<0.0001**	0.274	0.340	10	-259.419	542	2.3	0.003
Grass-dominated green space (m^2)	0.432	0.219	1.972	**0.049**							
Domestic garden (m^2)	0.377	0.188	2.009	**0.045**							
Population density (people/km^2)	-0.355	0.210	-1.694	0.090							
Site size (m^2)	-0.660	0.274	-2.410	**0.016**							
Min (management)^2	0.228	0.602	0.379	0.705							
Scape (management)^2	1.765	0.574	3.073	**0.002**							
Wild (management)^2	0.577	0.450	1.283	0.200							

(c) AICc "Best" model

Covariate	Estimate	Std. Error	Z-value	P-value	$R^*_{(M)}$	$R^*_{(C)}$
(Intercept)	2.219	0.202	10.971	**<0.0001**	0.197	0.260
Domestic garden (m^2)	0.444	0.165	2.694	**0.007**		
Hedges (m^2)	0.280	0.136	2.063	**0.039**		
Town population	-0.270	0.153	-1.763	0.078		

Appendix 2.7

(a) Set of negative binomial GLMMs with ΔAICc < 2 for Nitidulidae abundance where all continuous variables were centred and scaled and replicate was used as a random term.

Model	Age	Avg.Temp	BSMS	Cld	GDGS	Garden	Hedge	Manageme	Pop.dens	Site.size	Tree	Twn.pop	WindSpd	df	logLik	AICc	delta	weight
609						0.076	0.045			-0.040				6	-139.462	292.100	0.000	0.020
225						0.074	0.061	+						8	-137.108	292.200	0.170	0.018
229			-0.025			0.076	0.065	+						9	-136.167	292.900	0.830	0.013
865						0.082	0.046							7	-138.943	293.400	1.370	0.010
611		0.016				0.071	0.048		0.018	-0.052				7	-138.996	293.500	1.470	0.010
613			-0.015			0.080	0.052			-0.040				7	-139.075	293.700	1.630	0.009
241					0.019	0.077	0.066	+		-0.038				9	-138.577	293.700	1.650	0.009
98	0.028					0.052	0.044							6	-140.321	293.800	1.720	0.008
610	0.014					0.071	0.046			-0.032				7	-139.177	293.900	1.830	0.008
102	0.032		-0.025			0.059	0.057							7	-139.203	294.000	1.890	0.008
1633						0.071	0.047			-0.034	-0.012			7	-139.239	294.000	1.960	0.008

(b) AICc "Best" model including Management

Covariate	Estimate	Std. Error	Z-value	P-value	$R^2_{(M)}$	$R^2_{(C)}$	df	logLik	AICc	delta	weight
(Intercept)	-0.26	1.023	-0.254	0.799	0.244	0.749	8	-137.108	292.200	0.170	0.018
Domestic garden (m^2)	1.252	0.376	3.333	**0.001**							
Hedge (m^2)	1.025	0.374	2.743	**0.006**							
Min (management)^2	0.597	0.958	0.623	0.533							
Scape (management)^2	-0.604	0.946	-0.639	0.523							
Wild (management)^2	1.456	0.675	2.156	**0.031**							

(c) AICc "Best" model

Covariate	Estimate	Std. Error	Z-value	P-value	$R^2_{(M)}$	$R^2_{(C)}$
(Intercept)	0.213	0.855	0.249	0.804	0.229	0.701
Domestic garden (m^2)	1.286	0.334	3.852	<0.001		
Hedges (m^2)	0.759	0.263	2.881	0.004		
Site size (m^2)	-0.687	-2.159	-2.159	0.031		

Appendix 2.8

Set of negative binomial GLMMs with ΔAICc < 2 for Chrysomelidae abundance where all continuous variables were centred and scaled and replicate was used as a random term.

Model	Age	Avg.Temp	Cld	GDGS	Garden	Hedge	Management	Pop.dens	Site.size	Tree	WindSpd	df	logLik	AICc	delta	weight
1 (Null)												3	-149.001	304.3	0	0.021
3		0.03747								-0.0434		4	-148.141	304.8	0.5	0.016
513						0.03959				-0.05949		4	-148.21	305	0.64	0.015
545		0.03739								-0.04346		5	-147.3	305.4	1.09	0.012
515						0.02372						5	-147.352	305.5	1.2	0.011
33				0.02996								4	-148.622	305.8	1.46	0.01
11		0.04602		0.01891								5	-147.53	305.9	1.55	0.01
9								-0.01789				4	-148.751	306	1.72	0.009
129												4	-148.815	306.2	1.85	0.008

Appendix 2.9

Set of negative binomial GLMMs with ΔAICc < 2 for Curculionidae abundance where all continuous variables were centred and scaled and replicate was used as a random term.

Model	Age	Avg.Temp	GDGS	Garden	Hedge	Management	Pop.dens	Site.size	WindSpd	df	logLik	AICc	delta	weight
1 (Null)										3	-95.042	196.4	0	0.043
2	0.1198									4	-94.442	197.4	1.02	0.026
9				0.1116						4	-94.642	197.8	1.42	0.021
130	0.2234							0.2133		5	-93.515	197.8	1.44	0.021
6	0.1974		0.1459							5	-93.538	197.9	1.49	0.021
194	0.2332						-0.1917	0.3815		6	-92.414	198	1.58	0.02
65							-0.07164			4	-94.733	198	1.6	0.019
5			0.07355							4	-94.777	198.1	1.69	0.019
3		0.07383								4	-94.853	198.2	1.84	0.017
129								0.07757		4	-94.879	198.3	1.89	0.017
17					-0.05502					4	-94.931	198.4	1.99	0.016