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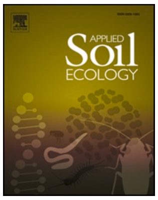

Review Article

The contribution of natural burials to soil ecosystem services: Review and emergent research questions

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ABSTRACT

The modern funeral industry faces many environmental risks and challenges, such as the use of sustainable materials for coffins, the release of potentially damaging materials and organisms to the soil and groundwater, and reduced space available for cemeteries. “Natural burial” proposes an alternative and more sustainable funeral practice, omitting the use of preservatives that inhibit body decomposition, thus proposing to reduce environmental degradation and benefit soil ecosystem services. This study conducted a literature review to identify proposed risks and benefits of “natural” compared to “traditional” burial practices, identifies knowledge gaps, and proposes further research questions. The approach was multidisciplinary, including literature from soil, environmental, forensic, and archaeological sciences, and the Humanities. Results identified that here are some clear environmental benefits to natural burial, such as habitat creation and aboveground biodiversity. However, there is a substantial deficit of research that compares the unseen risks and benefits of natural burial practice. Multiple potential risk factors include: (i) groundwater contaminated with biochemical products of decomposition, pathogens, and pharmaceutical products, (ii) atmospheric emissions, including greenhouse gases (CO_2, CH_4, N_2O). There is also a deficit of information related to the release of cadaver decomposition products to soil ecological processes. More detailed scientific research is required to identify the risks and benefits of funeral options, thus develop fit for purpose regulations and legislation and to describe the cultural incentives for natural burial. This paper identifies key areas of research required to understand and mitigate the potential environmental and cultural implications of human burial practices.

1. Introduction

In modern western society, conceptions of death and burial lead to routinely laying the deceased to rest within cemeteries. However, the burial industry today faces many challenges in terms of its environmental impact. Materials used for the embalming process have the potential to cause environmental harm. For example, formaldehyde is the main chemical routinely used for modern embalming and is a potential carcinogen (IARC, 2006). It is estimated that >30 million litres of formaldehyde are buried annually with the interned cadaver in the USA (Chiappelli and Chiappelli, 2008). Other potentially toxic substances, such as arsenic, zinc, copper, lead, and iron from metal coffins and coffin fittings, as well as varnishes, sealers and wood preservatives can leach from wood caskets (Spongberg and Becks, 2000) and may contaminate groundwater. Materials used for a coffin may be sourced unsustainably, for example the use of mahogany for coffins. In addition, many cemeteries are reaching or have reached capacity, with permissions for new locations facing challenges such as underlying geology (connectivity to the water table) and land price (Cohen, 2019). Land scarcity provides problems if the death rate increases, such as disease outbreak (e.g., COVID-19 pandemic), a natural disaster causing many fatalities or war.

Natural Burial offers an alternative funerary practice with an identity of sustainability, proposing to reduce ecological impacts and promoting biodiversity and habitat creation. The term “Natural burial” refers to the internment of the deceased in the ground with the intention of recycling nutrients back to the soil; hence it omits the use of preservatives that would impede natural decomposition processes and often reduces grave depth so is proposed to increase connectivity with biological components of the soil. Natural burials also omit the use of grave markers, and use biodegradable materials sustainably produced as burial containers.

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The term is a modern western construct, as some religious groups have always buried following its philosophy e.g., Islam and Judaism where cremation is prohibited. Other terms are often used (sometimes interchangeably) to describe this type of burial practice, including "green", "woodland" and "conservation" burial, however the latter is less popular in the scientific literature (Fig. 1). "Woodland burial" was used until 2012 but hasn't been used much since, and the terms "green" and "natural" burial have been used at similar frequency. For the purposes of this manuscript, the term "natural burial" will be used.

Unlike traditional burial grounds, natural burial gives people comfort in the thought that their bodies will be recycled to nature, rather than be preserved in a highly manicured way prior to burial (Yarwood et al., 2015). Cemeteries offering natural burials first occurred in 1993 (UK: Carlisle) (Yarwood et al., 2015); others followed later, such as Ramsey Creek Preserve in the USA (Westminster South Carolina) in 1998. Natural burial is growing. In the UK the Natural Death Centre estimated that in 2016 there were 270 grounds practicing this type of burial (Inman-Cook, 2016); whilst in the USA were approximately 162 providers in 2017 (Coutts et al., 2018). Many countries globally (e.g., Germany, Sweden, China, Canada) now recognise natural burials, each with different concepts, rituals, philosophy, and novel practices, e.g., integrating with Virtual Reality (Lau et al., 2020a, 2020b). Identifying precise numbers of natural burial grounds is difficult, as often there is a lack of regulations and imprecise definitions. The popularity of natural burial is possibly driven by the proposed reduced environmental impact, an increasing ageing population combined with lack of burial space in the urban environment (Lau et al., 2020a, 2020b), ethical issues associated with grave re-use (Rugg and Holland, 2017), but also changes in people's attitudes towards death and burial (Yarwood et al., 2015). Unlike European cities where burial sites are often recycled, UK government has restricted the disturbance of burial sites since the mid-18th century, creating deficits in burial spaces in urban settings. Natural burials have the potential to extend the working life of a cemetery, increasing the capacity for burial in urban cemeteries by accessing marginal land and grave space not suitable for traditional burial. It can also transform traditional cemetery landscapes, reducing maintenance costs and creating a richer habitat and more spatially complex landscape with a distinct identity (Clayden et al., 2018).

Despite the growing number of natural burials, academic research (Fig. 1) and subsequently environmental risks and benefits remain poorly described. As the body is not embalmed in preservatives, nutrients (for example nitrogen and phosphorus) within the decomposing body will be returned to the natural environment at greater rates. These bioavailable nutrients may benefit flora and fauna within the local habitat through increased nutrient acquisition; however, there is also a risk that the nutrients enter the groundwater as a source of diffuse pollution (Kim et al., 2008). There are also risks of environmental contamination from human pathogens and pharmaceuticals, although there has been little research into these risks. With the COVID pandemic, for example, there is uncertainty regarding virus survival outside the human host. A review by van Wyk et al. (2022) suggests that "the groundwater table will not be significantly impacted by contamination from SARS-CoV-2"; however further research is required to fully understand risks. Enveloped viruses (SARS-CoV-2 and other coronaviruses, influenza, Ebola, HIV) are less stable in the environment compared to non-enveloped viruses (Tegally et al., 2020). However, other microorganisms (e.g., *Bacillus anthracis*, *variola* virus, and *Clostridium* spp.) are longer lived and may survive in soil profiles or groundwater systems (Bition and Harvey, 1992). The risks associated with pathogen transport in the soil are substantial. An outbreak of foot and mouth and avian influenza in the Republic of Korea during 2010–2014 resulted in the burial of millions of cattle, swine, and poultry carcasses. A subsequent nationwide study of groundwater contamination identified subsequent contamination with faecal coliforms and *E. coli* in groundwater (Kwon et al., 2017). Concerns regarding borehole protection have led to increased guidance by the UK government to organisations wishing to plan new or develop existing cemeteries to prevent the contamination of vulnerable groundwater (Ministry of Justice, 2009).

Fears of groundwater contamination associated with natural burial practice are often used for objections at the planning stage (Yarwood et al., 2015). Regulation and legislation of burial practice is country specific. The natural burials industry is largely unregulated; landowners need to follow local rules and hence there is considerable difference between sites as to how they are managed. The law, in England and Wales stipulates that no standing water should be present at the bottom of a grave when first dug, that the grave should not be within 250 m of a

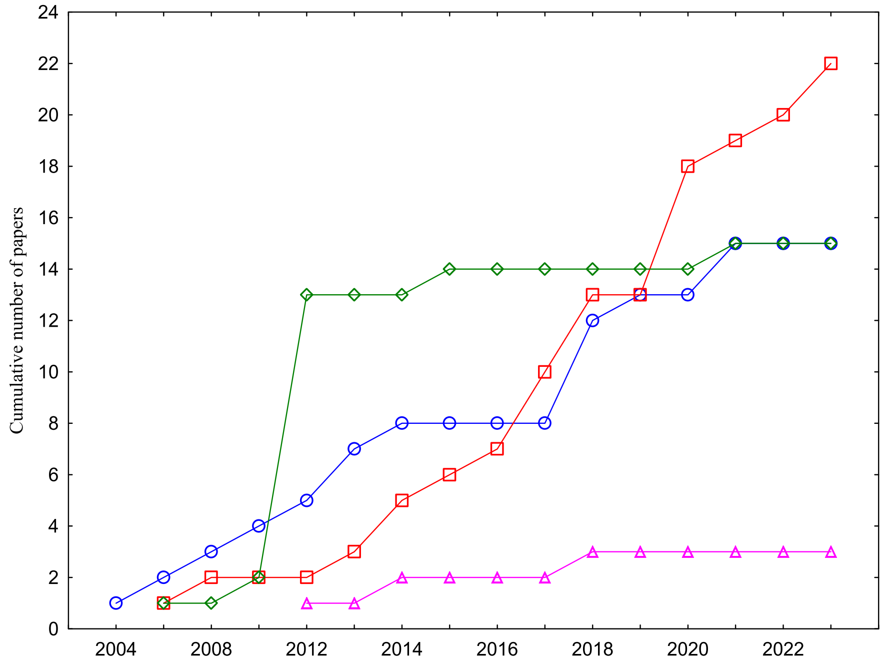

Fig. 1. Number of papers per annum (2004 to 2023: Cumulative) that refer to the terms "Natural Burial" (blue), "Green burial" (red), "woodland burial" (green) or "conservation burial" (pink) in their titles, abstract or keywords and then filtered for subject specificity (Data from Scopus).

spring or well used for drinking water or 50 m of any other spring or borehole, and that the depth should be 0.92 m (3 ft) "unless soil is considered to be of suitable character", when the depth can be 0.61 m (2 ft) (Ministry of Justice, 2009). However, there is little information in respect of what constitutes soil of suitable character to prevent environmental degradation. In the USA the lack of regulations in Colorado led to an investigation after a putrid smell from a "green burial" funeral home was reported to the police, the smell was then found to be due to the mishandling of 189 bodies (Planas, 2023). In addition, other things regulation should consider include whether shallow burials are at risk of disturbance from factors including scavenging animals, such as badgers and foxes.

In addition to the environmental risk, there is also a lack of understanding regarding the sociological drivers (and barriers) which influence the trend in natural burials in modern western society (Rugg, 2000). Some barriers identified in the USA include lack of public awareness, fear and misguided assumptions associated with the deceased, opposition by the funeral industry, fragmented access to eco-funeral options and potential "greenwashing" in the industry (Slominski, 2023).

United Nation statistics (United Nations, 2022) suggests that the world population is expected to reach 9.8 billion by 2050, two thirds which will reside in cities, and that the death rate will reach 121.7 million/year by 2099. In 2002 the funeral industry in the USA was estimated to generate more than $13 billion per year (Harrington and Krynski, 2002). Given the global trend towards urbanisation more attention is now being placed on ecosystem service delivery in urban spaces. Research has largely centred on ecosystem functions provided in the green spaces within towns and cities, with parks, community and residential gardens, allotments, and woodlands being the most studied, and considerably less attention has been given to spiritual spaces such as cemeteries and natural burial grounds (Clayden et al., 2018; Evans et al., 2022). This paper aims to review our current understanding of the environmental consequences of natural burial and identify key knowledge gaps. It is envisaged that the information presented here will increase our awareness of the risks and benefits that natural burial may have on soil ecological processes and services, which is needed for effective legislation, regulation, and public confidence.

2. Products of cadaver decomposition

The human body is comprised of organic (17 % w/w protein; 17 % w/w fat and 6%w/w carbohydrate) and inorganic (65 % w/w oxygen; 18.5 % w/w carbon; 9.5 % hydrogen; 3.2 % w/w nitrogen and the remaining 4 % w/w consists of 26 other elements) substances (Tortora and Grabowski, 1999). A body of a 70 kg adult has approximately 50 L of H_2O (71 %), 16 kg C, 1.8 kg N, 0.5 kg P, 0.14 kg K and a range of other elements such as S, Mg, Zn, Fe, Mn and Na (Rushbrook and Ucisik, 1998). In addition to the chemical elements, the human body harbours many bacteria specific to bodily location, the greatest concentration being in the gastro-intestinal tract at 10^{13}–10^{14} bacteria while other organs are considered essentially sterile (e.g. upper stomach and respiratory tract) (Dash and Das, 2020).

The process of decomposition is often described to follow the six stages of (i) Fresh, (ii) Bloat, (iii) Active Decay, (iv) Advanced Decay, (v) Dry and (vi) Skeletal Remains (Payne, 1965; Micozzi, 1991). Numerous by-products of these processes have been extensively described elsewhere (e.g., Carter et al., 2007; Dent et al., 2004). Briefly, in the absence of embalmment aerobic decomposition quickly depletes oxygen levels in the body resulting in anaerobic decomposition (autolysis) and putrefaction within 48–72 h, thus leading to liquefaction and disintegration. Autolysis occurs as oxygen becomes depleted, respiration fails and subsequently oxidative phosphorylation and so ATP production stops. Metabolism switches to anaerobic glycolysis and ultimately cell death through the action of enzymes within the cell. Purification shortly follows as opportunistic microorganisms benefit from nutrients generated from the autolysis process. Ultimately the decomposition processes lead to the redistribution of body constituents into the environment in various forms, many of which are bioavailable and so may be taken up by plants and/or soil organisms, some as leachates, and others as gaseous by-products. For example, proteins breakdown to ammonium (NH_4^+) through proteolysis, the nitrogen then is converted to nitrate (NO_3^-) and nitrite (NO_2^-); these forms of nitrogen are available for plant and microbial uptake thus promoting plant growth but can contribute to groundwater pollution (Kim et al., 2008; Yarwood et al., 2015). Proteolysis may also produce gaseous N as ammonia-N (NH_3), with potential to imbalance soil pH and for volatilization and contribution to atmospheric N pollution. In acidic soils ammoniacal-N (NH_3) converts to ammonium ions (NH_4^+); in alkaline conditions ammonium ions in the soil may revert to ammonia and undergo volatilization. Hypoxic cadaver decomposition also produces other greenhouse gases, including carbon dioxide (CO_2), methane (CH_4) (Santarsiero et al., 2000).

3. Burial containers

One of the main purposes of burial containers is to support the soil and so prevent subsidence (called "coffin-collapse"). Containers also encapsulate the body so preventing the leakage of fluids during funerals and preserve the body in the soil. The materials used to entomb the body varies considerably historically and between cultures, coffins and burial shrouds being common. The choice of material will affect the severity and rate of interactions of the decaying cadaver with the environment, and so the rate of release of decomposition by-products into the environment. Hard coffins are common as they are less susceptible to coffin collapse, they are also less permeable than softer materials thus limiting fluxes between the coffin and the environment and persist in the soil for many years. However, coffins constructed from wood, such as oak, pine, elm, yew, and mahogany, may not be sourced sustainably. Wood coffins are also often preserved with creosote, with the potential to release dioxins, furans, and polycyclic aromatic hydrocarbons to the environment (Mininni et al., 2007). Lead has been used historically to seal the vault and preserve the contents, this is now only used for specific burials e.g., British monarchy. Often composite materials such as chipboard and MDF are used as cheaper coffins, sometimes with hardwood (oak, mahogany) veneers or wrapped in decorative vinyl plastic for aesthetics. However composite materials contain synthetic resins and formaldehyde, which may enter the environment when the coffin breaks down after burial thus damaging local ecology.

In keeping with the philosophy of sustainability, materials used for natural burials should be naturally sourced or from recycled biodegradable materials. Wicker coffins are often the material of choice for Natural burial in UK, other innovative materials used include bamboo, willow, cardboard, banana leaf, wool, seagrass, papier-mâché (Rumble, 2010) and hemp. These materials are likely to degrade quicker in the environment, thereby offering less protection and so the process of decomposition will be faster than the harder materials.

Coffin liners and packaging materials, used routinely to prevent seepage prior to burial, are also an important consideration for sustainability as they are commonly constructed from plastic and are thereby a potential source of plastic pollution with inevitable damage to biodiversity as microplastics. Biodegradable materials, such as cardboard, paper, and natural calico cotton, are often sought to replace plastic coffin liners. An alternative to using liners is the use of absorbent materials such as shellfish waste (Dutkiewicz, 2002). However there has been little research regarding the risks and benefits of different liner/absorbent material types to the soil and wider environment.

Biodegradable burial shrouds (e.g., wool, cotton) are often used as an alternative to coffins, whereby the body is wrapped in cloth without the need of a coffin. As biodegradable shrouds are permeable, it is likely that their use will increase the connectivity of the decomposing cadaver with the soil's natural ecology and improve gaseous fluxes, thus speeding up decomposition processes. Historically wool was used in UK, driven by the Acts for "Burying in Woollen" 1666–80, non-compliance which resulted in a £5 fine (enforced to 1814). Wool is beneficial for its absorptive properties, and it was readily available. Modern burial shrouds also include other materials, such as cotton, linen, muslin, hemp, and silk. The consequences that the material from which the burial shroud is constructed has on cadaver decomposition processes and their persistence in the environment is largely unknown, however research has been conducted in respect of material decay in the soil. For example, cotton is comprised of up to 97 % cellulose, and as such is prone to decomposition (hydrolysis) by cellulolytic enzymes that are present in the soil. The diversity and abundance of cellulolytic microorganisms in soil is vast, and includes Genus such as *Pedobacter, Mucilaginibacter,* and *Luteibacter*; their presence and gene expression (function) are likely to be dependent on local environmental factors (López-Mondéjar et al., 2016; Peralta-Videa et al., 2011). The main component of wool is keratin, which is subject to hydrolysis from keratinase enzymes produced by numerous bacteria and fungi such as *Bacillus subtills* and *Streptomyces albidoflavus* (Lange et al., 2016). *Pseudomonas aeruginosa* is the main causative microorganism causing fleece rot, is pathogenic to plants and animals but can also occur in soil (Deredjian et al., 2014; Kingsford and Raadsma, 1997). However, there is a deficit of research into the implications of burial material on cadaver decomposition processes.

The protection offered to the cadaver from exposure to its environment is likely to be specific to the material used for the coffin, the burial shroud, and liner designs. The persistence of materials and presence of indigenous microorganisms capable of degrading the materials in the soil environment is likely to be dependent on local environmental factors such as pH, moisture content, and soil texture. Within a sealed grave, oxygen quickly becomes depleted leading to anaerobic decomposition. Materials used for burial have different gas diffusion coefficients, thus this will affect the rate of oxygen infiltration into the coffin space and decomposition rates (Dent et al., 2004). Buried cadavers can remain intact for many years in anaerobic conditions, for example bodies buried in peat bogs can survive for hundreds of years (Van der Sanden, 1996).

Innovative grave design is rarely considered within the funeral industry. Yet it offers opportunity to manipulate rate of decomposition. For example, the incorporation of permeable grave or shroud materials (such as wool), and/or engineering grave designs may improve gaseous exchange. While designs such as impregnating materials with fungi mycelia can be used to speed up decomposition in the so-called "infinity suit" (designed by Jae Rhim Lee of the company Coeio). However, speeding up decomposition may inadvertently promote faster release of environmental pollutants including leachable products (e.g., NH_4^+) into the groundwater and gaseous by-products. It may be more desirable to release products of decomposition in a slow controlled way through using materials that naturally decompose slowly or contain antimicrobial compounds, thereby preventing a flush of nutrients leaving the grave.

4. Interactions of the decomposing cadaver with the soil environment

The rate at which biochemical products of cadaver autolysis and putrefaction (for example organic acids, nitrogen, phenolics) are decomposed and released to the environment will depend on various soil characteristics, including temperature, moisture, pH (Dent et al., 2004), porosity and texture (Pawlett et al., 2018). These compounds can significantly impact soil processes, for example the generation of greenhouse gases, through priming of the microbial community (Girkin et al., 2018). In the absence of a protective grave, cadaver decomposition in the soil generally lasts between 20 and 200 days for a 68 kg human depending on environmental factors within the soil (Benninger et al., 2008). Products are released to the soil as a pulse in early-stage decomposition, resulting in nutrient hot spots that may contribute to landscape heterogeneity, biodiversity, and terrestrial biogeochemical cycling (Carter and Tibbett, 2008). Where buried with a protective covering, these early-stage biochemical products may be released at a slower rate depending on the porosity of the materials.

Soil texture, water logging and gas diffusivity affect cadaver decomposition processes. Course (sandy) soils have greater gaseous diffusivity and permeability compared to clays and hence greater decomposition rates (Carter et al., 2007) and improved interactions with indigenous aerobic microflora (Pawlett et al., 2018). However, cemetery managers usually avoid sandy soils to mitigate the potential release of nutrients to the groundwater. Decomposition in low permeability soils that are easily waterlogged and become anaerobic can be increased to decades (Fiedler et al., 2012; Santarsiero et al., 2000), but conversely may prevent leaching of nutrients to groundwater. Tumer et al. (2013) compared decomposition rates in loamy, sandy, clay and organic soils. They found decomposition was fastest in loamy and organic soils compared to clay and sandy; they did not offer a rational for the texture effect but likely the different conclusions of the studies are due to idiosyncratic responses of soil microorganisms with soil physicochemical parameters.

Where soils are anaerobic fat hydrolysis leads to the production of adipocere (waxy organic material formed from saponification comprising of saturated and some unsaturated fatty acids). *Clostridium perfringens* plays a key role in the formation of fatty-acids post-mortem through the production of lecithinases (O'Brien and Kuehner, 2007). Although it is generally accepted that adipocere formation occurs in wet oxygen limited environments, there remains many unknowns as more recently adipocere was identified as forming in an arid dry environment, probably due to the remains being wrapped in leather which preserved bodily fluids and promoted anaerobic decay (O'Brien and Kuehner, 2007). Waterlogging also promotes denitrification, whereby ammonia will denitrify to nitrogen gas and N_2O. The resultant high ammonium (and low nitrate) arising from cadaver decomposition denitrification reduces the pH of grave soil (Hopkins et al., 2000; Pawlett et al., 2018). In addition, a range of organic acids are produced (Dent et al., 2004) which would also reduce soil pH.

Burial depth is also a key factor that will affect the rate at which decomposition processes occur. Kim et al., (2008) identified that the mean depth over 49 natural burial graves was 1.45 m compared to burial depth ranges between 1.8 m and 4.6 m for other burial practices. The reduction of burial depth in natural burial compared to standard practice may increase gaseous exchange and increase connectivity of the decomposing cadaver to surface biology. A reduced burial depth will increase the depth of sub-surface layers beneath the body thus potentially mitigating against pollution to underlying soil parent materials and the groundwater, but conversely may speed up decomposition processes and hence the release of gaseous and leachable products of decomposition to the environment.

Some of the biochemical consequences of cadaver decomposition have been understood for a long time; for example, in the presence of iron, hydrogen sulphide gas released from anaerobic decomposition will produce a black precipitate of ferrous sulphide (Starkey, 1934). Since then, our understanding has increased as analysis and monitoring procedure advance. Products of cadaver decomposition can accumulate in the grave soil depending on their bioavailability. In a field experiment (Cobaugh et al., 2015) four human carcasses were buried over a period of 200 days and soil samples were collected at different stages of decomposition. They found that total organic carbon and total nitrogen increased from 0.31 to 4.92 mg C gdw^{-1} and 0.05 to 2.08 mg N gdw^{-1} respectively ranging from initial to advanced stages of decomposition. In an archaeological study of prehistorical graveyard in the Czech Republic from ca 2800–2500 BCE (Asare et al., 2020) researchers found that increased total C content only occurred near to the bones; they suggest that this was due to mineralization and leaching of body C in the sandy soils of the site.

Studies of mass graves from WWII have identified greater quantities of P, Ca and Na in the soil (Żychowski, 2021). Few studies have been conducted to identify elevated elements within cemetery soils, however (Holden and McDonald-Madden, 2018) identified elevated levels of Fe, Pb, Mn, Cr, Cu, Zn, with higher levels of accumulation in clay compared to sandy soils. Chemical signatures of cadaver decomposition can persist for many years (Hopkins et al., 2000). Phosphorus is one of the most comprehensively documented minerals, which accumulates in grave soil due to its presence in bone (Benninger et al., 2008). The bioavailability of phosphorus depends on soil chemistry (inorganic P can complex with Ca and Mg depending on pH thus biologically unavailable) but has the potential to accumulate in leachates and cause environmental damage. In addition to the nutrients from the body, medical interventions may degrade and accumulate in soils, such as Hg and Au from teeth fillings (Fiedler et al., 2012).

Implications of human decomposition processes on below-ground soil ecology are largely unknown. Bioavailable products of decomposition may be utilised by the surrounding ecology, including plant roots and soil biology. Nutrient cycling processes in soil are driven by the native soil biology, however, there remains little empirical evidence regarding the contribution that cadaver decomposition has on soil microbiology and ecological functional processes (Cobaugh et al., 2015; Singh et al., 2018). At a functional level, it has been hypothesized that localised biological hotspots may affect the wider ecosystem and influence pedogenesis, e.g., the formation of *Terra preta* soils (Graham et al., 2017; Graham et al., 2016). Anthropogenic soils formed from decomposing cadavers at cemeteries was named *Necrosol* by (Graf, 1986).

Existing research observing implications of cadaver decomposition processes on soil microbiology has focused on the response of bacteria. For example, Procopio et al. (2019) identified that the presence of bacteria of the genus *Proteobacteria*, *Firmicutes*, *Bacteroidetes*, and *Acidobacteria* in grave soil may assist with Post-mortem Interval (PMI: time since death) investigations. However, research has largely omitted the response of fungi and archaea (Singh et al., 2018). Procopio et al. (2020) aimed to address this knowledge gap by identifying specific fungal communities associated with PMI, although this study was inconclusive as they found very few taxa specifically associated with carrion decomposition. Fungi are almost exclusively obligate heterotrophic anaerobes, and hence survival may be limited in anaerobic graves and with limited accessible carbon to sustain long-term communities. However, graves do go through wet/dry cycles depending on the environmental and climatic conditions; hence fungi could play an important role in cadaver decomposition processes as fungi and prokaryote communities (and possibly functional traits) are affected by cycles of drying and re-wetting (Meisner et al., 2018). Moreover, the role of archaea in cadaver decomposition processes is yet to be explored.

In addition to the indigenous soil microorganisms, the human body harbours an extensive microbiome. Numerous papers that have investigated the human microbiome of a healthy person, but very few have investigated fates after death. Those published relate to survival of microorganisms (e.g. *Streptococcus, Pseudomonas, Firmicutes, Bacteroidetes, Lactobacillus*) within the body after death to estimate PMI for forensic science purposes (Dash and Das, 2020; Finley et al., 2016; Handke et al., 2017; Javan et al., 2016; Procopio et al., 2019). Soil microorganisms can colonise body orifices, this is known as the thanatomicrobiome (Javan et al., 2016). However, little is known regarding the interactions of the human with the soil microbiome post-mortem and whether their survival has implications for microbial community structure.

Cemetery management practices may affect the rate of cadaver decomposition through changing the soil environment, and thus affecting the rate and intensity at which products of decomposition are released. The disruption of the soil profile upon soil excavation for graves will provide a major disturbance of the soil's physical characteristics and re-distribute nutrient and biology within the soil profile. Haploidization (i.e., the mixing of soil horizons) often takes place when soil is replaced back into the grave, redistributing nutrients and biological components. In addition, the digging process will affect soil physical properties, such as bulk density, soil pore connectivity, porosity, permeability, all of which will affect the capacity of the soil to infiltrate and retain moisture. Innovative cemetery managers may remove the earth in layers, which are subsequently backfilled in sequence, thus retaining the horizons of the original soil profile, however the benefits of this process have not been described. The inclusion of compostable organic material in the grave or burial shroud, such as straws, are likely to affect the microclimate with increased temperature, microbially derived processes through altering C/N ratios and affecting pore space, and so affect cadaver decomposition rates and influence the distribution of decomposition products into the environment.

5. Wider implications for ecosystem services

5.1. Site selection

The extent to which natural burial grounds provide ecosystem functions may, in part, be governed by their location. Natural burials tend to be situated in urban cemeteries, although not exclusively as some may be in woodlands or grasslands. In contrast to the grey infrastructure of the built landscape, cemeteries exhibit a relatively high level of vegetation. Indeed, cemeteries provide about 4 % of accessible greenspace (McClymont and Sinnett, 2021). As a result, cemeteries represent urban refugia, with the space (and thus capacity) to provide a wide range of ecosystem services including recreation, human health and wellbeing, stormwater management, microclimate regulation, and aesthetics (Grabalov and Nordh, 2022). However, some researchers have questioned whether this capacity for ecosystem delivery is, or can ever be, realized, given the increasing levels of 'cemetery management' being practiced since World War Two (Rugg, 2006). For instance, (Clayden et al., 2018) highlights that the regular levelling of earth mounds, regular lawn cutting, and application of pesticides and fertilisers may constrain ecosystem service delivery, while others have suggested that maintaining land as single-use lawn-parks is not environmentally sustainable (Coutts et al., 2018). By contrast, natural burials, which are based on a more reciprocal relationship with nature, often require less maintenance than traditional options (Schade, 2011). There remains a lack of information comparing practice to describe risks and benefits to ecosystem services, for example carbon lost due to intensive mowing compared to less intensively mowed Natural Burial cemeteries, what are the implications to flood management and air quality. The critical question is whether introducing natural burials within pre-existing cemeteries can enhance ecosystem service delivery.

The combination of natural burial grounds within pre-existing cemeteries has given rise to the term 'hybrid cemeteries". These may provide opportunities to restore, conserve, and enhance habitats and biodiversity, therefore expanding the capacity for ecosystem service delivery. One example of this comes from what was the first hybrid cemetery established in the UK. In Carlisle, natural burials were introduced as part of a vision to transform what was rough grassland around its perimeter into native woodland; instead of erecting headstones, families would plant oak trees (Clayden et al., 2018). The return of native woodland directly enhanced biodiversity, and this would have promoted other associated ecosystem services, such as microclimate regulation.

Within the built urban landscape, 'hybrid cemeteries' represent key opportunities for introducing green infrastructure into grey space and ensuring the provision of ecosystem services. However, natural burial grounds can also be found beyond the urban environment. Clayden et al. (2018) suggest that the concept of the hybrid cemetery was challenged because other, more rural habitats – wildflower meadows, woodland groves, mature woodlands, orchards – set fewer constraints than the traditional space-confined cemetery. There is a diverse catalogue of rural and wilderness spaces in which natural burials have taken place, such as among tree roots in the Peruvian Amazon (Shepard, 2002), or within the bush in Tanzania (Kopytoff, 1971), although research into ecosystem service delivery among these is meagre. However, some of the rural cemeteries established in the USA during a period known as the 'rural cemetery movement' in the 19th century (Coutts et al., 2018) have seen the introduction of natural burials, and some research into their ecosystem functions exists. For example, the Honey Creek Woodlands cemetery in Georgia is not a conventional lawn cemetery, but permits natural burial (Mathis, 2016). Integrated within woodlands, the cemetery has been observed to deliver multiple cultural services (e.g., immersive experience in nature, sense of place, contemplation) and regulating services (e.g. plant diversity, pollinator habitats). In the same study, Mathis (2016) also examines Greenhaven Preserve, a natural burial cemetery twenty miles outside Columbia, South Carolina. This cemetery is set within 360-acres of pine forests and wildlife corridors, where multiple supporting, regulating, and cultural ecosystem services are delivered. The potential of cemeteries to improve connectivity between habitats and ecosystems (particularly in the urban environment) was observed by Scalenghe and Pantani (2020) who proposed the idea of "green belt communalities", which are essentially green corridors containing natural burial cemeteries.

5.2. Biodiversity

The ability of sacred spaces to support and enhance biodiversity and benefit threatened species has been researched, however there remains knowledge gaps in respect of the management of biodiversity within cemeteries (Löki et al., 2020). For example, in a review of the flora and fauna found in cemeteries and churchyards across five continents, Löki et al. (2019) reported that these sacred spaces held 140 protected taxa. Botanical surveys of 991 cemeteries in Hungary (Löki et al., 2020) identified that 56 % contained protected plant species. This is supported by a raft of studies focusing on the presence of rare and endangered species within urban spaces. These range from macro-fungi (Brown et al., 2006) lichens and bryophytes (Buchholz et al., 2016), orchids (Löki et al., 2015), vascular plants (Czarna, 2016), and nesting birds and bats (Trewhella et al., 2005). Despite these surveys, Löki et al. (2019) noted in their review that many of these are conducted only once in a year. Natural systems follow cycles (e.g. circadian, annual), therefore, it is possible that these studies have underestimated biodiversity in sacred spaces. Flowering plants are easier to identify, but different species may bloom at different times of the year, migratory species and those in hibernation at the time the survey is conducted may not be counted, rare species may not be observed, the activity of soil microorganisms is affected by temperature, moisture and plant feedback mechanisms.

Beyond cemeteries and churchyards, studies have evaluated the biodiversity at other sacred sites. For example, Bhagwat and Rutte (2006) found relict populations of threatened tree species in the sacred groves of Karnataka state, India. They concluded that the protection afforded to sacred groves means that they inevitably act as shelters, safeguarding a high diversity of flora in so-called "biodiversity islands". A study in Nigeria (Ejikeme and Okonkwo, 2022) identified that sacred groves have exceptional value for eco-tourism due to biodiversity gain. However, this does not necessarily imply that sacred groves need to be positioned in protected wilderness spaces exclusively. In fact, some work has found that sacred groves in cultivated landscapes can provide unique habitats and important wildlife corridors (Bhagwat et al., 2005).

The assertion that sacred sites are naturally strong at supporting biodiversity because they are protected from high intensity land use has some merit. There is also evidence to suggest that the careful management of these spaces to deliver other ecosystem services can still maintain biodiversity. Planting native plant species is a relatively simple measure to foster biodiversity. However, bereaved families may request the planting of non-native trees and plants in memory of the deceased but with the risk of potential harm to the native ecology if species become invasive, in addition deep rooting species may promote potential diffuse pollution through speeding up infiltration. Selecting the right plant for the environment may mitigate pollution, especially if the species utilises the products of decomposition for plant biomass. Selective mowing can also provide clear access for visitors to experience cultural services (Clayden et al., 2018) and the mown grass can also be used for fodder as a provisioning service. Similarly, selective coppicing in woodland burial sites can enhance access and provide fuel, whilst still maintaining tree-dwelling species and enhancing carbon sequestration potential.

The contribution of natural burials per se to support and enhance biodiversity has been less researched, and key knowledge gaps remain. For example, the impact of burial depth on both below- and above-ground biodiversity has not been comprehensively researched on natural burial sites. However, it could be hypothesized that the depth from the surface is not the sole influencing factor; the connectivity between the surface and the point of burial is also important. Positioning the burial so that it is sufficiently connected to the surface to enhance biodiversity requires evidence which, in part, must be sought after and collected by soil scientists.

5.3. Impacts of management on ecosystem services

Precise methods of management can have a substantial impact on ecosystem services. Natural burial sites are variously managed as wildflower meadows, coppiced and mature woodlands, orchards, and low intensity pasture. This is likely to affect soil ecosystem functioning ranging from the degree of interception of stormwater by soils and vegetation (Kowarik et al., 2016), to the production and emissions of greenhouse gases (GHGs). In some instances, specific management practices may even provide provisioning ecosystem services. For example, it is common practice to plant a memorial tree on or near a grave site. Extensive literature is available on the management of coppiced woodland, and the wider interactions and benefits from trees in their interactions with the soil. Benefits from this practice can include increased carbon sequestration, reduced soil erosion (compared to agricultural sites), and a more diverse soil microbial community. However, limited information is available on how different types of vegetation can affect decomposition processes. We can surmise that the presence of tree roots is likely to grow nearer to decomposing cadavers, as a significant source of nutrients, particularly nitrogen (i.e., cadaver decomposition islands). Such effects have even been proposed to enable the identification of clandestine graves (Brabazon et al., 2020). Many natural burial sites are also managed through grazing. While providing benefits through managing sward height, and returning some nutrients to the soil, this is also likely to have significant impact on soil-cadaver interactions, as manure, urine inputs and localised compaction will influence nutrient cycling processes and local ecology. The inclusion of sheep or cattle may also be a localised source of GHG emissions, particularly N_2O and CH_4, through deposition of urine and manure (Somers et al., 2019), although such impacts may be mitigated through careful grazing management (Allard et al., 2007). Alongside this, decomposing organic remains will also be an important localised GHG source, albeit one which cannot easily be regulated.

While the importance of ecosystem services for human well-being are well-established, specific management practices can also result in a range of potential issues and loss of function, i.e., ecosystem disservices. Natural burials have the potential to have fewer and less intensive negative impacts on ecosystems compared to many conventionally managed cemeteries (Lyytimäki and Sipilä, 2009). Examples of such impacts in urban cemeteries include contamination of soils through inputs of preservatives (for example formaldehyde), as well as regular inputs of pesticides and fertilisers to maintain turf health, both of which may contribute to diffuse pollution. While natural burial sites do not have substantial inputs of fertilisers, or chemical preservatives, contamination of groundwater due to leaching is a possibility and is thus controlled under currently legislation in UK. This also mitigates risks from pathogens entering water bodies.

6. Cultural implications of burial practice

Implications of changes to funeral practice on culture and society are important considerations (Scalenghe and Pantani, 2020), however meta-analysis of urban ecosystem service valuation studies found that <2 % of assessments focused on spiritual services (Haase et al., 2014). There are many religious and cultural differences in approaches. For example, it is common for Muslims to follow a form of natural burial, whilst the Greek orthodox church prohibits cremation resulting in problems related to space. Subsequently in Greece bones are commonly exhumed after 3–5 years, with the inevitable distress on the bereaved. In some countries (UK, USA) the public appear to be attracted to natural burial, potentially through its proposed sustainability credentials (e.g., Lau et al., 2020a, 2020b). Nevertheless, environmental concerns are not the only factor affecting choice, with many individualised reasons (Yarwood et al., 2015) related to emotions, culture, and beliefs. Indeed, the concept of Natural Burials can initially be attractive to some bereaved families, who later decide against this practice likely as there are no permanent fixtures such as headstones and religious symbols which limits mourners their expression of grief (Balonier et al., 2019). Also, it is likely that the public are not aware of the environmental risks and benefits associated with different funeral approaches. In part this may be due to substantial knowledge gaps in the peer-reviewed literature. There have been very few studies on Natural Burial per se and so consequently few studies that have compared different methods. A brief report (Niziolomski et al., 2016) summarises some environmental implications of cremation and shallow burial (for natural burial) on soil properties, but the report is brief and does not go into detail of risks and benefits. This information is critical if the public are to make informed decisions regarding laying their bodies to rest.

Although the potential for natural burial sites to promote cultural services has been under-researched, there is evidence to suggest that urban green “sacred” spaces (places associated with religious worship) as can improve mental wellbeing, reduce stress, enhance social interaction, boost a sense of place, and expand environmental knowledge (de Lacy and Shackleton, 2017). This was attributed to the feeling that the garden space was necessary to enhance their overall spiritual and religious experience. Interestingly in their study neither the size of the space nor the number of years that the person visits the space affected the overall experience. Whether these services can be facilitated by natural burial grounds is less known, although some authors have found that recreation, often a service delivered in parks and gardens, is an important service provided by cemeteries. Nordh et al. (2022) identified cultural differences between locations as “physical activity and experiencing nature” were the primary recreation activities in Copenhagen cemeteries, while “social interaction spirituality and tranquility” were the most common activities in Helsinki cemeteries.

Researchers investigating sacred spaces (cemeteries, burial groves, churchyards) have concluded that that sacred sites have the capacity to deliver a unique suite of ‘spiritual’ ecosystem services that wouldn't otherwise be provided so abundantly in other green spaces. For example, the monuments and inscriptions, typically found in more traditional cemeteries, hold great cultural and historical value, and may provide visitors with an enhanced sense of cultural identity. A study in England found that individuals valued green spaces more when they contained a variety of natural and structural elements (e.g., gravestones, monuments, benches) than open featureless grassland (Burgess et al., 1988). This may have implications for some natural burial grounds, particularly those situated in rural meadows and woodlands, where monuments are typically not erected in favour of allowing native species to thrive without fragmentation. This demonstrate the need for more research so that the importance and value of urban sacred sites can be communicated to urban planners.

7. Emergent research questions

We are proposing a series of questions that must be answered to ensure the long-term sustainability of the funeral industry in general. The focus is towards understanding whether Natural Burials would mitigate identified risks of burial practice, while also understanding risks associated with this burial practice. A framework of risks and benefits are identified in Table 1; however, it is important to understand that this is conceptual as empirical evidence is lacking in this area.

Research Questions: Through our synthesis of the available data on the benefits and trade-offs from the adoption of natural burials, we propose the following research questions as key priorities for the wider environmental, archaeological, forensics, and social science communities to address:

Table 1
Conceptual Risk Benefit analysis of natural burial compared to more traditional burial using hardwood graves and embalming products.

	Potential risk	Potential benefit
Natural Burial	• **Pathogen:** virus (non-enveloped) and bacteria release to environment • **Groundwater:** contamination from biochemical products of decomposition (e.g., NH_4^+, NO_3^-), pharmaceuticals. • **GHG emissions:** CO_2, CH_4 and N_2O (in anaerobic decomposition) released from decomposition. Shallow burial depth may elevate GHG emissions. • **Scavenging animals** may be problematic for shallow burial. • **Coffin collapse/ subsidence:** in the absence of the supporting coffin • **Society acceptance:** largely unknown but is common practice for some groups.	• **Materials:** sourced sustainably and biodegradable, e.g., linen shroud, wool • **Faster decomposition**: Greater connectivity with biology speeds up decomposition. Biochemical products of decomposition more readily available for fauna and flora acquisition • **Biodiversity and habitat creation:** Aboveground and belowground biodiversity enhanced. • **Working life of a cemetery:** potential to extend if graves can be re-used. • **Reduced maintenance costs:** vegetation requires little attention. • **Cultural services:** largely unknown but may benefit mental health and wellbeing through increased connectivity with nature (especially in urban space). • **Contribution to pedogenesis:** promotion of *necrosol* formation • **Carbon sequestration:** unquantified but potential benefit to soil carbon.
Traditional Burial	• **Groundwater:** contamination from biochemical products of decomposition, but also from toxic embalming (e.g., formaldehyde) and coffin (e.g., wood preservatives) materials • **Land scarcity**: slow land-use turnover due to slow cadaver decomposition. Cadavers can remain intact for many years in anaerobic environments. • **Use of unsustainable materials** for example mahogany coffin and plastic coffin liners; materials used (concrete for headstones, casket, and vault materials) often have a high carbon footprint	• **Pathogen:** rate of virus and bacteria release to the environment still a risk but likely to be reduced due to slower decomposition. • **GHG emissions** still a risk but likely a reduced rate of emissions due to slower decomposition, greater burial depth and fluxes to the environment limited by hard coffins. • **Coffin collapse** reduced due to hard coffin. • **Cultural services and society acceptance**: accepted in western culture.

- *Can existing evidence from theoretically comparable ecosystems (*e.g., *grasslands and woodlands) be applied to Natural Burial cemeteries to understand the contribution to ecosystem services?* Preliminary evidence suggests many broad similarities but certain key differences (for example local and national regulations and legislation, site specific alterations in management practice, and individual burial wishes) are likely to have profound implications for ecosystem processes.
- *Is there a preferred ecosystem type to mitigate risks and enhance benefits to sustainable management practice in cemeteries?* Woodland burials are common, but would it be better to utilise grasslands (pasture, species rich meadow) or even as a practice to restore the health of degraded agricultural soils? However, implications of burials on adjacent agricultural land are unexplored: would groundwater contamination (e.g., pathogens, pharmaceuticals) affect food quality, would it be socially acceptable to use agricultural soils for burial. Could Natural Burial be a way for farmers to diversify through “hybrid” management strategies that combine Rewilding with Natural Burial? Would the inclusion of Natural Burials in wildlife trust sites in UK be feasible; currently in US burials are used to conserve threatened species.

- *Can existing knowledge of soil properties and decomposition be related to cadaver decomposition processes?* Carcasses decay much faster in early stages of decay compared to plant matter due to its low C:N (5:1 to 8:1), high water content and a diverse supply of labile nutrients (Cobaugh et al., 2015). In addition, soil properties such as texture may be important as decomposition in well aerated sandy soils is likely to be faster than in waterlogged soils such as clays (Pawlett et al., 2018).

- *Are there carbon sequestration benefits to burial?* The average 70 kg adult has approximately16 kg carbon (Rushbrook and Ucisik, 1998). The global annual death rate is expected to reach 121.7 million/year by 2099 (United Nations, 2022), which represents 1.95 million tonnes C per year. If the body were cremated much of this carbon would be emitted as CO_2, but natural burial would promote the sequestration of carbon from the buried body to the soil. The bioavailability of the carbon is likely to vary depending on the stage of decomposition, with early-stage decomposition releasing labile carbon and then more recalcitrant forms in latter stages. Implications of this in the wider ecology are unknown.
- *What are the comparative GHG implications of the funeral industry?* Currently there is no comprehensive LCA to understand the consequences of different approaches and material use to GHG emissions and limited available data to undertake such an assessment.

- *What are the legacy effects of natural burial?* There are clear legacy implications for soil chemistry; after 4500 years “hotspots” of elevated elements (carbon, phosphorus, Mn, Cu, As, Pb and especially Zn) have been identified in grave soils (Asare et al., 2020). However, little is known regarding the persistence of biotic shifts beyond that of Singh et al. (2018) who identified bacterial community changes that persisted for >2 years. This knowledge may benefit research of *necrosols*, particularly in urban ecosystems, and their contribution to key soil ecosystem service questions such as resilience to climate change, long-term contribution to biodiversity and ecosystem functioning.

- *What are the implications of burial practice on resultant risks and benefits?* Various questions arise within this, including: (i) the implications of burial depth (does shallow burial increase connectivity to soil biology), (ii) implications of the material (coffin vs shroud) on decomposition processes, and soil gas and leachate release to the environment, (iii) can innovations mitigate the release of GHGs and leachable nutrients? (iv) are current regulations sufficient in respect of isolating products of decomposition from the environment. Regulations in UK do not consider the underlying parent materials and soil type.

- *What are the hidden risks associated with burial practice?* Bodies buried may contain a range of medicines and pharmaceuticals, some of which may be detrimental to the environment if they are distributed, for example chemotherapy drugs, antibiotics and the rise of antimicrobial resistance, steroids. A small-scale study (Yuan et al., 2013) identified that cattle burial resulted in higher levels of steroid hormones and veterinary pharmaceuticals in leachates than were found in comparable leachates from other major sources of effluent. Bacterial pathogens identified in *necrosol* include *Enterococcus* spp., *Bacillus* spp., and *E. coli*; *Penicillium* spp. and *Aspergillus* spp. fungi. were also isolated (Ca et al., 2015) thus emphasising the potential release of human pathogens to the environment.

- *What are the environmental risks and benefits of accelerating decomposition process?* Increasing the rate of decomposition may be possible through strategies such as lining the grave with topsoil and altering the C/N ratio of the graves soil (for example using straw) and encouraging gas flows to prevent anoxic conditions. This may benefit the public as they may take comfort with that knowledge that their bodies have returned to nature within a short timeframe. This may free up land for subsequent burials; in the absence of a body would society consider re-using grave space? In Greece the bones are disinterred, sometimes after only 3 years. However, speeding up decomposition may also speed up the rate of release of products of environmental concern, e.g., nitrogen in the groundwater and GHG emissions. Would lining graves with clay mitigate the potential of leachable nutrients to the environment?

- *What are the sociological drivers of choice?* Drivers related to public decision-making process are unclear; are decisions driven by economics and business rather than environmental, ethics and society? We do know some are seeking sustainable options to end-of-life choices to benefit the natural world. The central question of the public is often “how can we lay our bodies to rest in ways that help the living and the earth”, this demonstrates the need for evidence based environmental research and innovative communication strategies to the public, for example storytelling for education.

8. Conclusions

Cemeteries are historically integral to the development of human settlements. With the expansion of urbanisation, and concurrent threats to the environment such as the climate change and the biodiversity crisis, understanding the potential ecosystem benefits of sustainable funeral practice to mitigate detrimental effects of urban expansion is critical. This is especially important given global challenges of space available for burial. Despite the growing global population, burial practice has remarkably few changes and innovations to mitigate issues related to sustainable burial practice. Much of the peer-reviewed research in this area is conceptual and often assumes that eco-funerals benefit the environment. Companies in US and UK are now investigating innovative eco-funeral solutions such as human composting; however, such practices remain fringe and provide unique challenges in terms of the regulatory framework and risk/benefit analysis. Gained knowledge is also critical to formulate effective strategies for mass death events, such as disease outbreak (does the pathogen survive in the deceased and contaminate groundwater) and war. Traditions, religion, and spirituality are embedded within sociological challenges; perhaps changing the mindset of society such that the deceased becomes a valuable resource rather than a waste is required.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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