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Predicting the preservation of cultural artefacts and buried materials in soil

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HIGHLIGHTS

- The preservation in soils of different materials and of stratigraphic evidence is reviewed.
- A predictive framework for the preservation of materials in soil is proposed.
- Preservation of materials and stratigraphic evidence in soils of the EU is predicted.
- Soil performs an important cultural service by preserving anthropogenic artefacts.

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ABSTRACT

This study identifies factors affecting the fate of buried objects in soil and develops a method for assessing where preservation of different materials and stratigraphic evidence is more or less likely in the landscape. The results inform the extent of the cultural service that soil supports by preserving artefacts from and information about past societies. They are also relevant to predicting the state of existing and planned buried infrastructure and the persistence of materials spread on land. Soils are variable and preserve different materials and stratigraphic evidence differently. This study identifies the material and soil properties that affect preservation and relates these to soil types; it assesses their preservation capacities for bones, teeth and shells, organic materials, metals (Au, Ag, Cu, Fe, Pb and bronze), ceramics, glass and stratigraphic evidence. Preservation of Au, Pb and ceramics, glass and phytoliths is good in most soils but degradation rates of other materials (e.g. Fe and organic materials) is strongly influenced by soil type. A method is proposed for using data on the distribution of soil types to map the variable preservation capacities of soil for different materials. This is applied at a continental scale across the EU for bones, teeth and shells, organic materials, metals (Cu, bronze and Fe) and stratigraphic evidence. The maps produced demonstrate how soil provides an extensive but variable preservation of buried objects.

1. Introduction

1.1. Background

Soil contributes to a series of ecosystem services through its functions. Assessment and maintenance of these functions are central to the EU's thematic strategy for soil protection (European Commission, 2006a,b). Storage of buried heritage and providing a platform for the built environment are the main soil functions identified in the strategy and further assessments are required to characterise these and describe their spatial variability. A wide range of archaeological and cultural heritage and buried infrastructure is preserved in the soil environment and in landscape features that are formed from soil. Knowledge about which soils preserve which materials is valuable for the management of heritage and buried infrastructure and may also inform assessments of the longer-term impact on soil of spreading of wastes to land. The range of buried objects is wide and includes: artefacts made from a variety of materials e.g., stone, ceramics, bone, metals, wood and other plant materials, skins and hides, glass and plastics; burial mounds, cultivation terraces, and other earthworks; stratigraphic evidence of past environments (Harris, 1989), land management and human activities; and contemporary distribution and communication infrastructure. The spatial distribution of archaeological artefacts and landscape features reflects past occupation patterns and land uses and the actual presence of buried objects in soil and earthworks depends on many factors other than the soil type and its potential to preserve materials (Holden et al., 2006; Lillie and Smith, 2007). It is useful, however, to assess the preservation service that soils may or may not provide if objects are buried in them; such an assessment has potential to provide information for valuing the cultural and other

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ecosystem services provided by soils and to inform decisions about the management of buried resources. The survival and condition of buried objects and stratigraphic evidence depend both on the particular soil environment in which they are buried and the material from which they are formed (Cronyn, 1990) and, for anthropogenic artefacts, the nature of their manufacture. This study investigates the preservation of buried objects in soil, how this is affected by their material nature and soil type and how information about the distribution of soils can be used to assess preservation capacities spatially. It builds on existing guidance about which soil properties are important for the preservation of buried objects (Davidson and Wilson, 2006; Crow, 2008; English Heritage, 2008, 2011) and provides a commentary on the fate of different materials for different soil types defined according to standard taxonomic classification. It describes how soil mapping data can be used to systematically map the preservation of different materials by soil and applies this to predict this potential for soils across the European Union (EU).

1.2. Bones, teeth and shells

Human and animal bones and teeth are made of hydroxyapatite ($CaCO_3$) and smaller amounts of protein (collagen) fibres. Bones that still retain collagen have some elasticity but become more brittle with age as collagen degrades. The circumstances of burial and the immediate post-burial environment influence the longer-term fate of buried bones (Baxter, 2004; Jans et al., 2004). Relevant factors are the burial location, depth and any containment. In the early phases of bone burial, biological action affects the ageing process which may continue for decades. Colonisation is initially dominated by bacteria followed by fungi (Child, 1995; Jans, 2008). Biological degradation continues until nitrogen (N) derived from collagen is exhausted; in parallel and subsequently, physical degradation and chemical alteration and degradation occur. The solubility of hydroxyapatite rises with increasing acidity and the survival of bone and teeth correlates with the pH of soil and groundwater. Dissolution of bone results in a lower density material with more and larger pores and this progressively increases the bone area being actively dissolved and the rate of degradation. Alongside dissolution, ions in the soil solution can be incorporated into new minerals. Avian and mollusc shells are formed from calcite ($CaCO_3$) which dissolves more readily in moist acid conditions than hydroxyapatite in bones and their fate is similar but accelerated compared to bone and teeth.

The dry conditions present in soils in arid and semi-arid regions preserve bones and teeth and shells. Bones and teeth and shells are preserved better in alkaline soil, while their degradation and eventual destruction are quite rapid where the soil water is acidic and unsaturated, as in acid soils that are wet and free draining and formed on sands and acidic parent material in higher precipitation zones. Bones, teeth and shells are preserved better in soils that are permanently waterlogged by stagnant alkaline groundwater, as occurs in some lowland peat soils. Static pressures and surface loading to the soil e.g., during cultivation and by vehicles (Dain-Owens et al., 2013) may cause physical damage to buried bone material as may soil movement resulting from wetting and drying cycles in soils that contain expansive clay minerals.

1.3. Ceramics, glass and phytoliths

Many types of ceramics are preserved in soil, including tiles and bricks as well as figures, pots and other domestic items. Ceramic artefacts can survive in the buried environment for very long periods and a ceramic figurine dated to 16,000 years before present (Vandiver and Vasil'ev, 2002) has been found. This longevity reflects the resistance of ceramics to biological and chemical degradation processes. The material properties of ceramics vary depending on the clay and other materials used for their manufacture, e.g., carbonaceous or non-carbonaceous clay, with or without addition of calcite (Fabbri et al., 2014). Firing temperature affects robustness: higher firing temperatures produce stiffer objects that resist mechanical and other stresses better. Objects fired at lower temperature tend to have a more open pore structure allowing water to enter and cause degradation, including by subsequent frost-shattering.

Glass is a relatively durable material in the buried environment (Jackson et al., 2012) and the morphology of solid glass objects and fragments often remain intact. However, surface corrosion of glass occurs in moist and wet soils leading to a loss of transparency and the formation of a surface crust rich in silica and depleted of basic ions. This process weakens the glass and this may accelerate shattering of thinner objects (Huisman et al., 2008). The rate of surface degradation in soil is strongly affected by the glass composition and not easily predicted (Van Giffen, 2014). The alkali type and content is critical: Roman and other ancient glass is generally more resistant to chemical attack than glass from the mediaeval period when wood ash containing potassium (K) replaced soda ash in its manufacture. Under acidic conditions and moderately alkaline conditions ($pH < 9$) alkali ions are leached from the glass matrix, while under more alkaline conditions hydroxyl ions disrupt silicon–oxygen bonds within the silica structure (Melcher et al., 2010). At more alkaline pH, laminar surface layers are more likely to form (Roemich et al., 2003) which may be iridescent. In all but the driest soils, surface coatings and other decoration on glass are expected to degrade quite quickly (<100 y). The strong dependence of corrosion rates of glass objects on material composition and manufacture leads to uncertainty in any prediction of the relative rates of surface degradation in different soils: corrosion is expected to be least in very dry soils; rates of corrosion may be moderated in well-drained and neutral soils in drier regions; highly alkaline soils are anticipated to be the most corrosive.

While both ceramic and to a lesser extent glass materials are preserved well in soil, they tend to shatter and the resulting shards may then become dispersed. Physical damage to ceramics and glass buried in soil can arise from static and dynamic forces. Static forces increase with depth and dynamic forces from the treading action of animals and people and vehicle movements (Dain-Owens et al., 2013) may propagate in to subsoil. Where expansive clay minerals are present, these will create potentially destructive mechanical forces during wetting-drying cycles. Soil stiffness, which is a measure of resistance to deformation, will affect the likelihood that brittle objects will be fractured. For example, a dry clay soil will be more resistant to deformation and better protect objects from shattering than will a wet sandy soil. For most soils, however, the dominant factor determining shattering is likely to be land use and management rather than soil type.

Opaline silica is deposited as phytoliths in plants that vary in form between species and can provide evidence of past vegetative cover; they are highly resistant to degradation in soil and will be preserved in most soils, a possible exception being very wet and strongly alkaline soils.

1.4. Organic materials

Organic materials buried in soil include plant material (e.g., wood, fibres, fruits, seeds, and pollen), fungal spores, insects and their larvae, parasite eggs and the remains of animals and humans (e.g., skin, soft tissues). Immediately following their burial, organic materials may be recovered or at least disturbed by soil fauna, ranging from macrofauna including burrowing rodents to arthropods and their larvae. Subsequently, the main degradation process for organic material is biological oxidation by the soil ecosystem and this usually leads to its complete destruction where aerobic and moist soil conditions prevail, whereas soil conditions that are anaerobic are preserving, although not completely (Bjordal et al., 1999; Douterelo et al., 2010). In very dry soils microbial activity is restricted and this preserves organic materials. The least preserving hydrological conditions are expected to be those where soil is seasonally wet but dries in summer as this cycling of soil moisture levels encourages ‘flushes’ of more intense microbial activity as the soil wets up. Any activity that disturbs the soil and redistributes and releases soil organic matter, including tillage, is also likely to accelerate aerobic degradation. The rate of biological degradation of organic materials in soil is affected by their molecular structure because this determines the net energetic gain to the soil ecosystem of using one organic material as an energy substrate compared to another. Starch and other polysaccharides yield a higher net energy than more intractable components; for example, cellulose is utilised preferentially over lignin and other poly-phenols present in wood. Acidity influences the soil ecology and the ratio of fungal to bacterial population sizes increases as pH decreases while rates of organic matter degradation are generally reduced by increasing soil acidity. Where the soil solution is high in dissolved organic matter this can react with buried organic material and this process may confer resistance to biological degradation, as in the natural 'tanning' process that occurs when skin and soft tissues are deposited in waterlogged peat. Organic material may also be protected by absorption and occlusion in the soil matrix and this is more likely in fine textured clay soils than coarse sandy ones. Nutrient levels may affect the survival of organic materials; for example where intensive agriculture introduces higher levels of nutrients releasing microbial activity that has been limited by nutrient availability.

1.5. Metals

The degree of preservation of metals in soil is specific to the type of metal. Au objects are resistant to corrosion and indefinitely preserved in the buried environment, although more fragile ones may be damaged by static and dynamic pressures. Ag is less resistant to corrosion than Au but more so than Cu while Zn corrodes still faster. Cu artefacts may contain As and this element is also commonly a minor constituent of bronze (an alloy of Cu and Sn which is more resistant to corrosion than pure Cu). Fe is much more easily corroded than Cu, while Pb is resistant to corrosion in most ambient aqueous environments. Al forms a protective surface oxide coating that gives it some resistance to oxidative corrosion.

The soil factors that affect the survival of buried metal objects have been studied (Tylecote, 1979; Johnson and Francis, 1980; Gerwin and Baumhauer, 2000; Nord et al., 2005; Neff et al., 2006; Réguer et al., 2007). In an aerobic, oxygenated aqueous environment, oxidation of metal and resulting corrosion is favoured thermodynamically and becomes more so with increasing acidity. The presence of chloride increases the rate of oxidation and resulting corrosion, especially of Fe. Depending on the metal type and the solutes present, initial corrosion processes may create a protective layer that slows corrosion further: these layers may include oxides (e.g., Al_2O_3), phosphates (e.g., $FePO_4$) and carbonates (e.g., $CuCO_3$). Under reducing conditions, biological activity may encourage the formation of sulphides that slow corrosion that is already being inhibited by a lack of free oxygen.

Metals are preserved in the dry conditions present in arid climates. In moist climates preservation is worst in free-draining soils that have oxygenated water flowing through the soil profile. In these climates, fine-textured clay soils with permanent or seasonal waterlogging are more preserving than those with coarse sandy textures. Corrosion is slowed in peats and other waterlogged soils that are permanently anaerobic, especially of the groundwater is alkaline. Preservation in alkaline soils formed from calcareous parent materials may be augmented by protective carbonate coatings. The presence of chloride (e.g., in naturally saline soils or from tidal flooding, marine-affected atmospheric deposition, irrigation with saline water or spreading of salt) increases the corrosion rate of Fe. Soil formed mainly by human action can be a strongly corrosive environment where derived from wastes that contain chloride and sulphur. Strongly acidic soils in which corrosion of metals is rapid result when sulphide is oxidised, such when marine sediments are drained.

1.6. Stone and plaster

Buried stone artefacts include flint artefacts, figures, stone hand tools and mortars and building materials. These are resistant to physical, chemical and biological degradation in soil. Flints and igneous and metamorphic rock-derived minerals are expected to be more resistant (Karkanas, 2010) than some sedimentary rock material e.g., sandstones and chalk, especially in wet environments and where there are active freeze–thaw cycles. Plaster and mortar can be likened to a weakly structured sedimentary rock material that loses its structural integrity when wet, containing carbonates and sulphates that are solubilised under acid conditions.

1.7. Stratigraphy

Stratigraphy describes archaeological contexts that are interpretable from the chronological succession of layers of deposited material in soil (Harris, 1989). It supports the collection and interpretation of information about the burial context of buried objects and materials, such as their relation to other objects, age and the environmental conditions that prevailed in the burial period. Where the depth of the soil profile is being increased, stratigraphic evidence will be better preserved than where soil is being eroded. Evidence is likely to be better preserved in soils that are receiving continuing inputs of parent material such as sediments during flood events. Therefore soils that form in alluvial floodplains or that have gained colluvium material should preserve evidence better than those that are on slopes and those that have properties that make them easily eroded. Soil hydrology and changes in water regime will affect the preservation of stratigraphic evidence. Wet anaerobic conditions will preserve organic remnants that distinguish strata from each other. Drainage of wetland soils causes oxidation of organic material and in the case of peat soils it can dramatically reduce the depth of the soil profile, destroying stratigraphic evidence. Soils are living systems and biological activity within them can perturb stratigraphic evidence. Lighter texture soils are favoured by mammals and birds that burrow in them, disturbing the soil profile. Worm activity mixes the soil, sometimes to considerable depth, and worm casts left on the soil surface gradually alter the apparent height of the soil surface so that objects appear to sink in to the soil profile. Worm type and behaviour as well as population size varies between soil types. Soil that is well-drained but moist and rich in fresh organic material is more favourable for worms than waterlogged or very dry soil with low inputs of organic material, while neutral soil is more favourable to worms than is acid soil.

1.8. Relevant soil properties

Soil properties that influence the preservation of buried materials are as follows.

1. Hydrology (e.g., drainage), as affected by texture and profile type and the combined influences of climate and landscape features and position, because this affects the levels of dissolved oxygen in the soil solution and the potential for dissolution of bones, teeth and shells, the corrosion of metals and the biological oxidation of organic materials.
2. Acidity and alkalinity, because these affect the rates of bone, teeth and shell dissolution, metal corrosion, oxidative degradation of organic material and the corrosion of glass.
3. Solute types and concentrations, because these affect secondary mineral formation within bones, the formation of protective coatings on metals and corrosion of glass.
4. Levels of dissolved organic matter in the soil solution because this can protect organic materials.
5. Vulnerability to erosion, because this affects the likelihood of surface exposure and loss of stratigraphic evidence.
6. Stiffness because this affects the physical protection of brittle objects from fracture, with texture being the main determining factor.
7. Factors that favour preservation of stratigraphic evidence include continuing inputs of soil forming materials and an absence of erosion, together with wetness as this assists the preservation of organic evidence and is less favourable to perturbing fauna.

Table 1
Properties relevant to preservation capacities of soils and their ranges and range descriptions.

Property	Ranges (and range descriptions)				
Drainage	Free drainage	Some restriction	Seasonal or permanent waterlogging of at least subsoil		
Wetness	Dry	Moist	Wet		
Organic matter	>2% (high)	<2 and >0.5% (medium)	<0.5% (low)		
Base saturation	>50% (high)	<50% (low)			
pH	>7.5 (alkaline)	<7.5 and >6.0 (neutral)	<6.0 (acidic)		
Chloride	Below (low) or above (high) background concentration				
Stiffness	(Low)	(Medium)	(High)		
Vulnerability to erosion	(Low)	(Medium)	(High)		
Climate zone in which soil occurs (IPPC definitions)	Warm temperate dry	Warm temperate moist	Cool temperate dry	Cool temperate moist	Boreal moist

Note: other relevant soil properties to be considered (in particular in relation to the preservation of stratigraphy) are the degree of biological perturbation and the presence of swelling and shrinking due to the presence of expansive clay minerals and wetting and drying cycles.

Table 1 summarises the key soil properties that affect the preservation service of soil and the ranges over which these properties need to be considered when assessing the service level provided. It includes the climate zone in which the soil occurs as this influences the annual cycle of soil wetness and temperature which in turn affects material preservation.

2. Materials and methods

2.1. Definition of soil types

Taxonomic definitions within the Soil Geographical Database of Eurasia (SGDBE) (European Commission, 2003) were used to identify soil types (Soil Typological Units (STUs)). The SGDBE contains a list of STUs defined using the legend for the Soil Map of the World (FAO, 1998). Tóth et al. (2008) provide a commentary on the STUs, their extent in Europe and a table correlating them to the key used by IUSS Working Group WRB (2006); additional information on the STUs is given in the Soil Atlas of Europe (European Commission, 2006a). For this study, STUs were identified to the second taxonomic level (Reference Soil Group and prefix).

2.2. Assignment of Soil Typological Units (STUs) to 'preservation categories'

The cultural value of objects buried in soil is reduced as they degrade and if the object is destroyed this value is lost. Whereas some materials (bones, teeth, shells; copper, bronze and iron; organic materials) are destroyed in soil, albeit sometimes over very long periods, other materials (ceramics, glass, gold) may be degraded but are not generally destroyed even after as long as 5×10^3 y. We develop a qualitative narrative describing how different STUs may affect those materials that are not destroyed. For those materials that are destroyed, however, we develop a more quantitative analytical approach as follows. We define destruction as being where the object no longer has any recognisable morphology and its material has dispersed, at which time its cultural value has been lost. The time after burial at which destruction is complete represents the endpoint of a process of degradation. As degradation proceeds its rate changes and in many cases will reduce progressively as less resistant material is removed. We assume that the degradation rate decays exponentially and that the percentage of remaining material versus log time ($\log_{10} t$) can be represented by a linear relationship, as in Fig. 1.

We then define preservation categories for materials in relation to endpoints of (i.e., complete destruction) within 10^2 y (poor), after 10^2 and before 2000 y ($10^{3.3}$ y) (fair) and after $10^{3.3}$ y (good). For example, if we estimate that a metal object in a well-drained and moist soil will be destroyed within 10^2 y then we would assign that soil to the category (poor) for preservation of this metal, or, if we estimate that an object made of organic material buried in a soil with permanently waterlogged subsoil will not be destroyed within $10^{3.3}$ y, we would assign that soil to the category 'good' for preservation of organic materials. Numeric values were assigned to each preservation category (poor = 1, fair = 2, good = 3). These values were assigned by relating the STU description (e.g., soil profile, diagnostic horizons and soil properties) to soil properties that drive material destruction (e.g., hydrology and associated redox conditions, pH, base saturation, soil organic matter content, chloride levels).

2.3. Mapping the preservation service of soils for buried materials

SGDBE consists of (1) a geometric dataset at scale 1:1,000,000 and (2) a semantic dataset containing attribute files. The geometrical component of the database are polygons that form soil mapping units (SMUs) (EC, 2003). SMUs contain one or more STUs that form a discrete landscape unit with shared characteristics. The semantic dataset of the

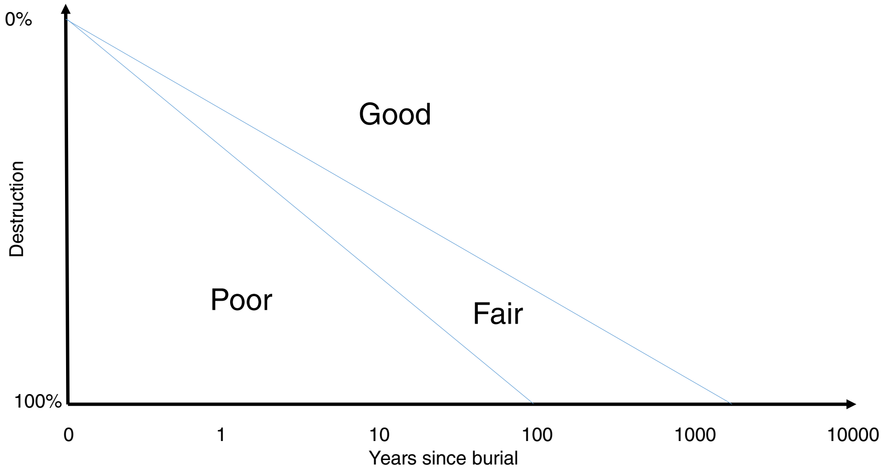

Fig. 1. Definition of categories of soils for preservation of material buried in soil.

SGDBE describe the soil types present within the SMU and the percentage of the SMU area occupied by each STU present within it. Thus multiple attribute values are linked to the polygons of the geometrical dataset. We assigned the appropriate preservation numeric score to each STU in each SMU and calculated the spatially weighted mean of these scores for each SMU. Areas of artificial surfaces, permanent ice or snow cover and water bodies were excluded from the analysis. We then mapped the mean scores for the SMUs across the European Union after assigning colours to a continuous scale of mean preservation score. The percentage areas of soil across the European Union that provide good (highest third of scale), fair and poor (lowest third of scale) preservation capacities for bones, teeth and shells; organic materials; and metals (Cu, bronze and Fe) were then calculated.

3. Results

3.1. Assignment of Soil Typological Units (STUs) to 'preservation categories'

A brief description follows of each soil type identified in the SGDBE, together with a summary of its properties and how these affect the preservation of buried materials and stratigraphy. This is followed by an assessment of the capacity of the soil type to preserve different buried materials and stratigraphy. For some soil types it is only necessary to assess them at the Reference Soil Group (RSG) level but for other types with a wider range of characteristics, the assessment needs to be taken to the second taxonomic level according to the assigned prefix qualifiers. The outputs from the description of soil properties are presented in Appendix A. The preservation service level for each STU is scored as Good, Fair or Poor, with the results presented in Appendix B. No assessment was made of capacity to preserve Au, Pb, ceramics, glass or stone as it was concluded that all types were similarly well-preserving of these materials. The potential influence of chloride was only noted for those soil types for which higher than background levels of chloride may be present.

Acrisols occur in warm temperate moist climatic zones that are rare in Europe. They are moist, strongly acidic soils with a low base saturation and low subsoil organic matter contents. Their physical stiffness is assessed as being above average relative to other soil types due to high levels of weathered clay in subsoil horizons. The moist and acidic soil environment in Acrisols will strongly degrade bones, teeth and shells, corrode metals, leach some glasses and degrade plaster. The warm and moist soil environment will encourage biological degradation of organic materials. The relative absence of roots in subsoil horizons may assist preservation of stratigraphy but these soils are vulnerable to erosion and are assessed as being poor for preservation of stratigraphy.

Albeluvisols occur in cool temperate moist and boreal moist climates. Their soil profiles indicate intermittent reducing conditions and some restricted drainage. They are wet and acidic with a low base saturation and a low subsoil organic matter content. Their physical stiffness is assessed as being average relative to other soil types. The wet and acidic soil environment in Albeluvisols will strongly degrade bones, teeth and shells, corrode metals, leach some glass and degrade plaster. The cool, wet and acidic soil environment may preserve some organic materials. The preservation of stratigraphy is assessed as fair in non-disturbed soil.

Andosols develop in volcanic parent material and are azonal, that is they are not confined to a particular climate zone, occurring in both cold temperate and warm temperate climates. They are generally acidic, have a low base saturation and have medium levels of organic matter in subsoil. Their physical stiffness is assessed as being less than average relative to other soil types due to the high levels of organic matter in surface horizons and continuing weathering of parent material to give a relatively open and loose soil structure. The acidic soil environment in Andosols will strongly degrade bones, teeth and shells, corrode metals, leach some glasses and degrade plaster. Their acidic and moist soil environment may partially preserve some organic materials. Preservation of stratigraphy is assessed as being poor due to the unconsolidated nature of many Andosol profiles.

Anthrosols are soils whose development has been profoundly influenced by human activity, such as the addition of waste or other materials, or irrigation. They are azonal and occur in climate zones that may be wet, moist or dry. In Europe, the largest extent is of Plaggic Anthrosols in the cool moist temperate climate zone: these soils have open, well-drained surface horizons and are moist, with neutral or slight acidity, enhanced base saturation, good levels of organic matter and high levels of phosphate (and potentially chloride) from addition of organic and other wastes. Their physical stiffness is assessed as being average relative to other soil types. The Plaggic Anthrosols are of particular cultural importance and contain fragments of ceramics and glass from added waste materials. Bones, teeth and shells, as well as metals and some organic materials may be preserved to a limited extent. Stratigraphy is likely to be compromised by continuing mechanical cultivation.

Arenosols develop in sandy parent material and are azonal. They are well-drained and droughty even in moist climates and tend to be acidic with a low base saturation and low organic matter contents. Chloride levels are likely to be enhanced in those Arenosols formed in coastal dunes. These soils are vulnerable to erosion and where not confined, for example on slopes, have a low stiffness. In moist climates, the freely drained and acidic soil environment in Arenosols will strongly degrade bones, teeth and shells, corrode metals and leach some glasses. However, some organic materials may be preserved where these soils are wet. In dry and more arid climates, bones, teeth and shells, metals, glass, plaster and organic materials will be preserved better. Preservation of stratigraphy may be good where the landscape is dynamic and eroded material accumulates over soil surfaces but will be poor where there is active erosion.

Calcisols occur in more arid parts of the warm dry temperate climate zone in Europe. These dry soils have a high base saturation and are alkaline. The dry alkaline soil conditions in Calcisols will preserve bones, teeth and shells and also metals and plaster. Some preservation of organic materials is possible in the driest of the Calcisols. Preservation of stratigraphy is assessed as good except where erosion has occurred.

Cambisols are widespread in Europe and are soils in which soil-forming processes remain active. The more acidic Dystric Cambisols with a low base saturation contrast with more alkaline or neutral Calcaric, Eutric and Mollic Cambisols that have a higher base saturation, but all are normally well-drained. The Calcaric Cambisols occur in drier regions. Gleyic and Vertic Cambisols have impeded drainage and are waterlogged at least seasonally. The more acidic Dystric Cambisols are likely to degrade bones, teeth, shells, some glasses, metals and plaster. The higher base saturation, alkaline pH and relative dryness of the Calcaric Cambisols will assist the preservation of bones, teeth and shells, but where there are moist soil conditions (as is more typical for the Eutric and Mollic Cambisols) degradation of metals and plaster is expected. Organic materials are unlikely to survive in well-aerated Cambisols but this is more likely in wetter ones (Gleyic and Vertic). The preservation of stratigraphy is expected to be average when compared to other soils.

Chernozems are soils of the Steppe and form in cool dry temperate climates in loess-rich parent materials. These well-drained soils are relatively dry during the summer months. They have deep profiles with good levels of organic matter and a high base saturation with a neutral to slightly alkaline pH. These freely drained soils are moist for part of the year and although they are not acidic some corrosion of metals is expected. Their high base saturation will assist preservation of bones, teeth and shells. The preservation of organic materials is uncertain but the well-aerated and warm moist soil conditions in early summer will encourage biological activity. These soils are subject to substantial perturbation by soil fauna to depth and this is likely to disturb and degrade stratigraphy.

Fluvisols are formed in alluvial, lacustrine or recent marine material and are azonal. The more acidic Dystric Fluvisols with a low base saturation contrast with the neutral or more alkaline pH of the Calcaric, Eutric and Mollic Fluvisols that have a higher base saturation, but all are well-drained. Gleyic Fluvisols have impeded drainage with at least seasonal waterlogging. Fluvisols formed in marine environments may have enhanced chloride levels and strongly acidic Thionic Fluvisols form in drained sulphur-rich marine sediments. The more acidic Dystric Fluvisols are likely to degrade bones, teeth, shells, some glass, metals and plaster. The highly acidic Thionic Fluvisols are perhaps the least preserving soil type. The higher base saturation and more alkaline pH of the Calcaric and to a lesser extent the Eutric and Mollic Fluvisols will assist the preservation of bones, teeth and shells, but where moist soil conditions prevail this will encourage corrosion of metals which will be accelerated in environments with higher chloride levels. Degradation of organic materials is anticipated in moist and well aerated Fluvisols but these materials may be preserved better in wetter subsoil horizons and in Gleyic Fluvisols. Stratigraphy preservation is expected to be good in Fluvisols, except where river-bank and other erosion processes are active, and be very good where there are regular additions of fresh sediment in flood events.

Gleysols are poorly drained with permanent or seasonal waterlogging by groundwater. Although azonal, they are most frequent in cool moist temperate and moist boreal climates. The more acidic Dystric Gleysols have a low base saturation in contrast with more alkaline or neutral Calcaric, Eutric and Mollic Gleysols that have a higher base saturation, but all Gleysols are poorly-drained and have some reducing conditions in their subsoil horizons. Organic matter decomposition in topsoil as well as subsoil is likely to be slower in those Gleysols with organic horizons (Histic, Humic, Mollic). Thionic Gleysols form in marine wetlands with sediments rich in sulphur and are highly acidic. The characteristic reducing conditions of Gleysols are partially preserving of metals and organic materials, although the former will be more quickly degraded where base saturation and the pH's of soil and groundwater are lower (Dystric and especially Thionic Gleysols). The survival of bones, teeth and shells will be best in Calcaric and least expected in Dystric Gleysols. Stratigraphy in general and especially that dependent on organic remnants will be well-preserved.

Gypsisols occur in very arid climates and are uncommon in Europe. They are characterised by an accumulation of gypsum (calcium sulphate) and have a high base saturation and an alkaline pH. The dry and alkaline conditions in Gypsisols are favourable for preserving all types of materials and where erosion is absent, stratigraphy.

Histosols form where there is permanent waterlogging and have reducing conditions that slow the decomposition of organic matter. They are widespread in cold moist temperate and moist boreal climates but also occur in wetlands in other climates. Dystric Histosols have a lower base saturation and are more acidic than are the Eutric Histosols which form where groundwater is more alkaline. The strongly reducing conditions within Histosols preserve organic materials and metals. This will be enhanced where groundwater is more alkaline (Eutric Histosols) as will the preservation of bones, teeth and shells, with the latter being degraded by the more acidic conditions found in Dystric Histosols. Stratigraphy will be well-preserved in undisturbed Histosols.

Kastanozems share many of the features and properties of Chernozems but occur in somewhat drier climates where less soil organic matter accumulates and the leaching of calcium is slower. Their capacity to preserve buried materials and stratigraphy will be similar but slightly better than that of Chernozems.

Leptosols are shallow soils with rocky parent material at shallow depth and are common throughout Europe, especially in upland and mountainous areas. Other than normally being well-drained, their properties are related to the nature of their parent material and prevailing climate. Calcaric and Eutric Leptosols form on calcareous and more basic rocks while Dystric Leptosols form on more acidic rock. Rendzic Leptosols are mainly located in moister climate zones on chalk and limestone and in their natural state have a characteristic highly organic surface horizon. Those Leptosols that are drier and calcareous and/or more alkaline will be most protective of bones, teeth, shells, metals and plaster. Where rainfall is higher and there is a greater flow of water through the soil profile, such as in moist and mountainous areas, this protection will be reduced and it will be less where the underlying rock is acidic, for example granite. As these are well-aerated soils, organic materials will not be preserved well in them except in the drier examples. Stratigraphy may be well-preserved but is likely to be less so on slopes, particularly where erosion processes are active.

Luvisols have a clay-depleted topsoil and a clay-enriched subsoil. They occur in all the major climate zones present in Europe, generally in flatter landscapes. They form in glacial till and other non-consolidated parent material in more northern and wetter landscapes, but are present in many regions of Europe. Most Luvisols (for example: Albic, Arenic, Chromic, Dystric and most Haplic) are relatively free-draining and well-aerated but others are less so (Gleyic and some Haplic). Depending on the parent material, the topsoil may be more or less acidic or alkaline, with the pH generally higher in the subsoil reflecting a higher base saturation. As most Luvisols are free-draining and well-aerated, the soil is aerobic in these and the pH neutral or slightly acidic so that bone, teeth, shells, some glass, organic materials and metals will degrade, although this will be slowed in Gleyic Luvisols. Those Luvisols that contain expansive clay minerals (including but not only Vertic Luvisols) will fracture objects and stratigraphy will be more disrupted in these compared to most Luvisols where it should be preserved.

Phaeozems share some similarities with Chernozems and Kastonozems but occur in somewhat moister climate conditions and consequently they have a lower base saturation. Their capacity to preserve buried materials and stratigraphy is similar but slightly less than that of Chernozems.

Planosols have an impermeable subsoil that impedes drainage resulting in seasonal waterlogging and reducing conditions in the upper soil profile. Dystric and Eutric Planosols have contrasting base saturations with the former being more acidic. The cycling of wet and reducing conditions and seasonal dryness in Planosols indicates that organic materials and metals will be degraded. In those Planosols that are neutral or more alkaline some preservation of bones, teeth and shells may occur. Stratigraphy preservation should be fair in non-disturbed profiles.

Podzols form under forest, moorland and heaths in sandy and other coarser parent material and on material formed from weathered acidic rock. They are most widespread in cool moist temperate and boreal moist climates, but also occur in somewhat drier conditions. They are acidic with a low base status and are characterised by a strongly leached subsoil horizon and accumulation of Fe and Al in lower horizons. The moist, aerated and acidic conditions in most Podzols will degrade bones, teeth, shells, some glass, metals and plaster, as well as organic materials. Those Podzols that have impeded drainage and are wetter (including Gleyic Podzols) and have more reducing conditions will be more conserving of organic materials and less degrading of metals but the acid conditions in all of these soils corrode metals and the conservation of stratigraphy may be compromised by strong leaching.

Regosols have a shallow soil development over poorly consolidated parent material such as gravels and rocky till. They occur widely in all climatic zones and most commonly in drier ones. The preservation of buried materials in Regosols will depend on their physical stability and soil depth. Regosols on slopes are prone to erosion processes which will degrade and disperse buried objects and stratigraphy. In drier climates, especially metal objects may survive well but in wetter ones the flow of well-aerated water will be degrading of metals as well as bones, teeth, shells and organic materials, especially where the parent material is acidic (such as for Dystric Regosols).

Solonchak soils form in drier climates where rising shallow saline groundwater accumulates salts in the upper soil horizons and on the soil surface. *Solonetz* soils form under similar but less extreme conditions where groundwater is less saline and they have more clay in subsoil than Solonchak soils. Both soil types are alkaline. The presence of high concentrations of salt and associated chloride in both Solonchak and Solonetz soils will accelerate corrosion of metals and loss of calcium from bones, teeth, shells and plaster. The preservation of organic materials is uncertain: strong alkaline solutions will solubilise some organic matter; reducing conditions that are protective of organic materials may occur depending on the extent of seasonal waterlogging.

Umbrisols form mainly in a cool moist temperate climate on acidic parent material under forest and have an organic surface horizon. In Europe they are found mainly in the southern parts of the western oceanic zone. The moist, acidic, well-drained conditions in Umbrisols will degrade bones, teeth, shells, some glass, metals and plaster. The presence of higher levels of soil organic matter in Umbrisols reflects continuing inputs from woody vegetation and is not indicative of a preserving environment for buried organic materials in the these well-drained and aerobic soils.

Vertisols form in warm moist climates with distinct dry and wet seasons and contain clay minerals that expand and contract over wetting and drying cycles. The result is continuing mixing of soil horizons. They have a medium base saturation and are neither strongly acidic nor basic. The dynamic physical conditions in Vertisols will be destructive and dispersive of buried objects and stratigraphy. Chemical degradation of bones, teeth, shells, glass, metals and plaster will be supported by the wetting and drying cycles that are typical for these soils.

3.2. Mapping the preservation service of soils for buried materials

Figs. 2, 3, 4 and 5 present maps of the preservation capacities for buried materials and stratigraphy provided by soils across the European

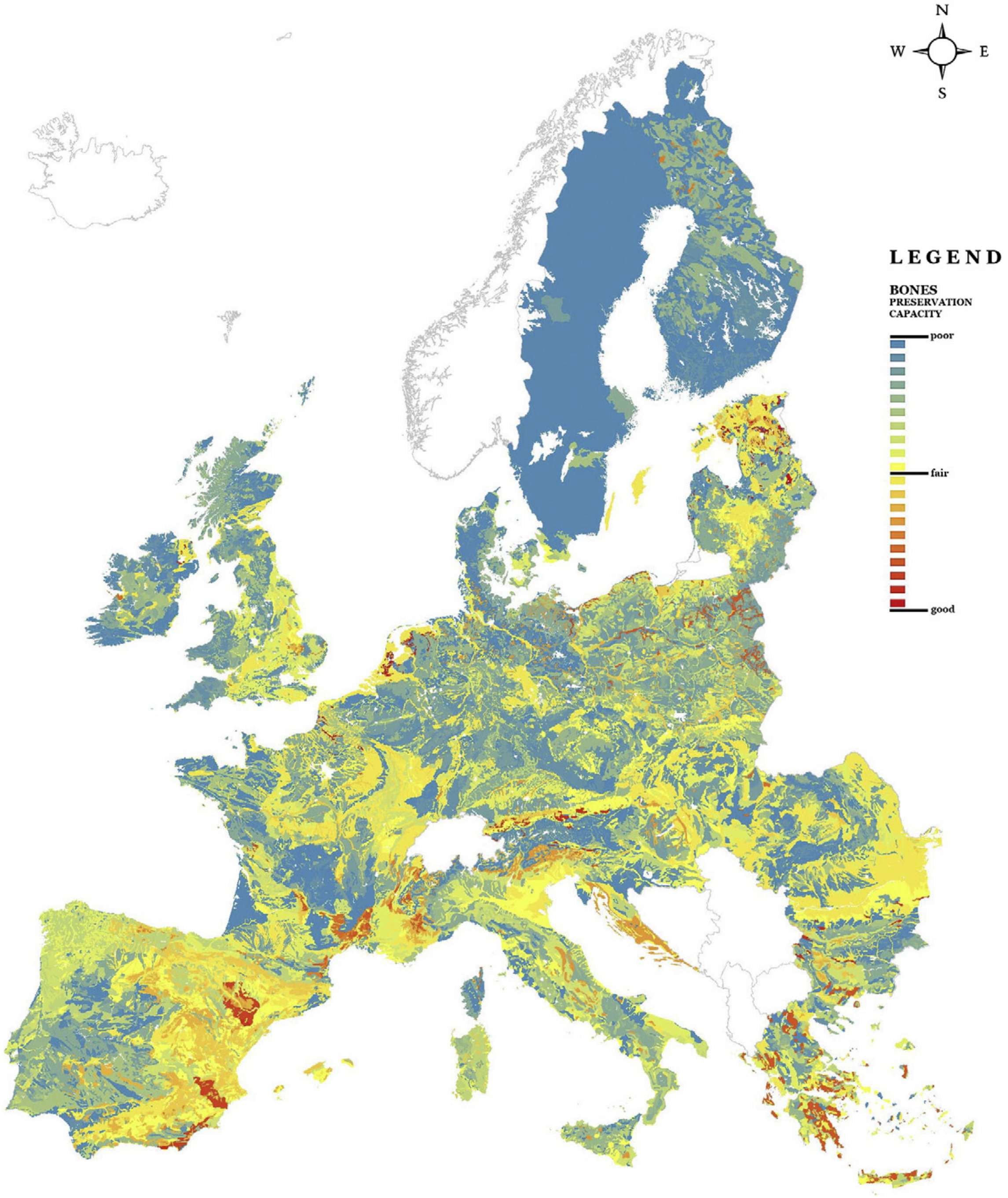

Fig. 2. Soil-based preservation capacity for buried bones, teeth and shells across the EU.

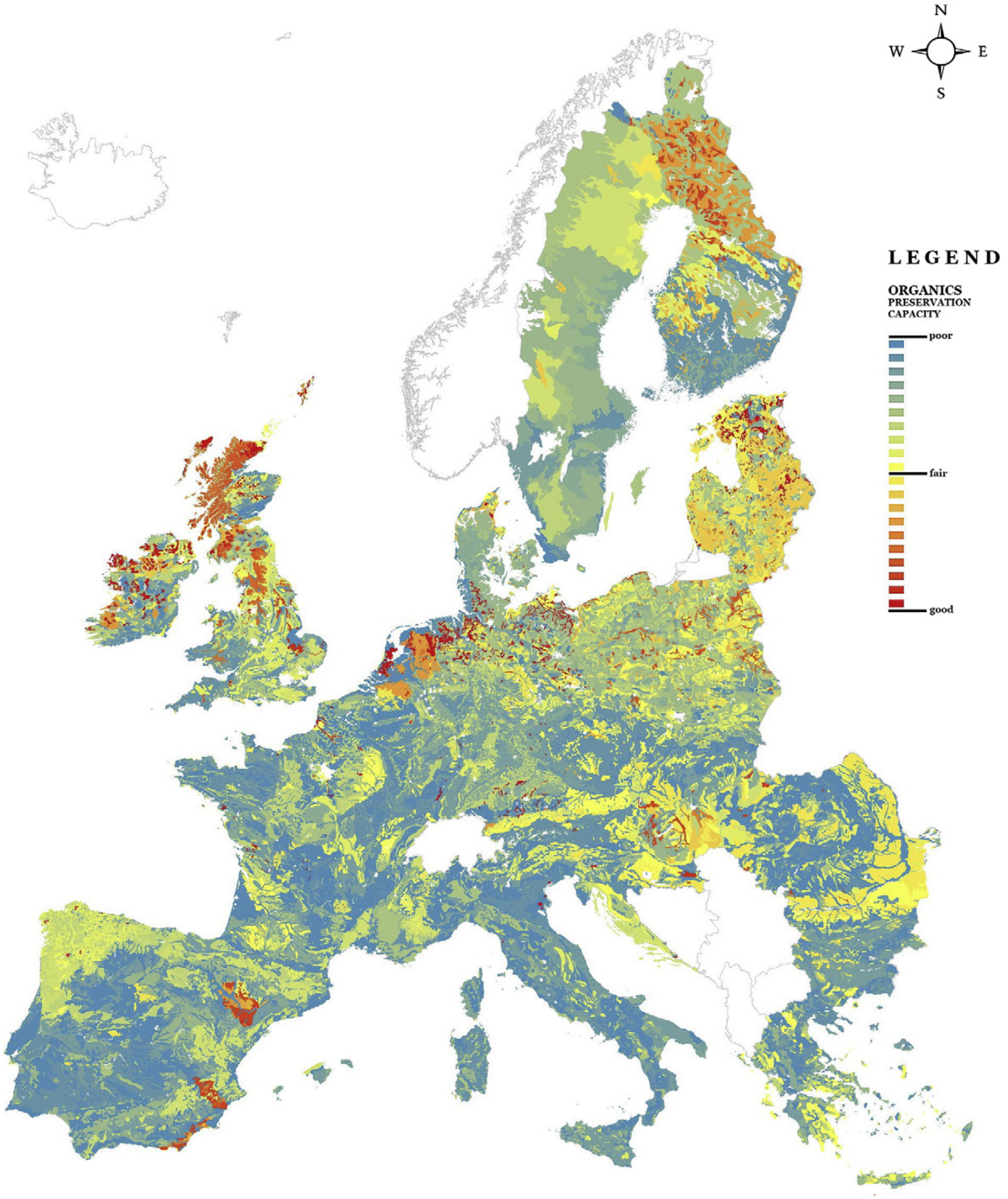

Fig. 3. Soil-based preservation capacity for organic materials across the EU.

Union, for bones and teeth, organic materials, metals (Cu, bronze and Fe) and stratigraphy respectively.

4. Discussion

4.1. Methodology

There are many combinations of soil types and materials and their interactions are complex. Consequently, predictions of the preservation of buried objects are uncertain, especially given that the properties of both individual soil types and materials extend over wide ranges. Another complication is that objects are often constructed from more than one material. Nonetheless, the approach used here of developing an interpretive narrative as a basis for categorising the preservation service for different materials provided by different soil types, allows an assessment of how this service varies between soil types and its consequent variation across the EU. Some soil types are much more common than others and assessing the preservation services that soil provides generally and across the EU depends especially on assessment of these common soil types. Cambisols, Luvisols, Podzols and Leptosols cover more than half the area of the EU (26.71%, 14.74%, 13.67% and 10.51% respectively). The assessment for these soils was extended to the second taxonomic level by reference to prefix qualifiers, including those indicative of wetness (Gleyic), pH (Dystric and Eutric) and higher organic matter content (Histic, Humic, Mollic). This helped to discriminate between soils with different hydrology and wetness but was limited by a predominance of Haplic forms i.e., those typical of the RSG and for which no special features are prominent or noted. Azonal soil

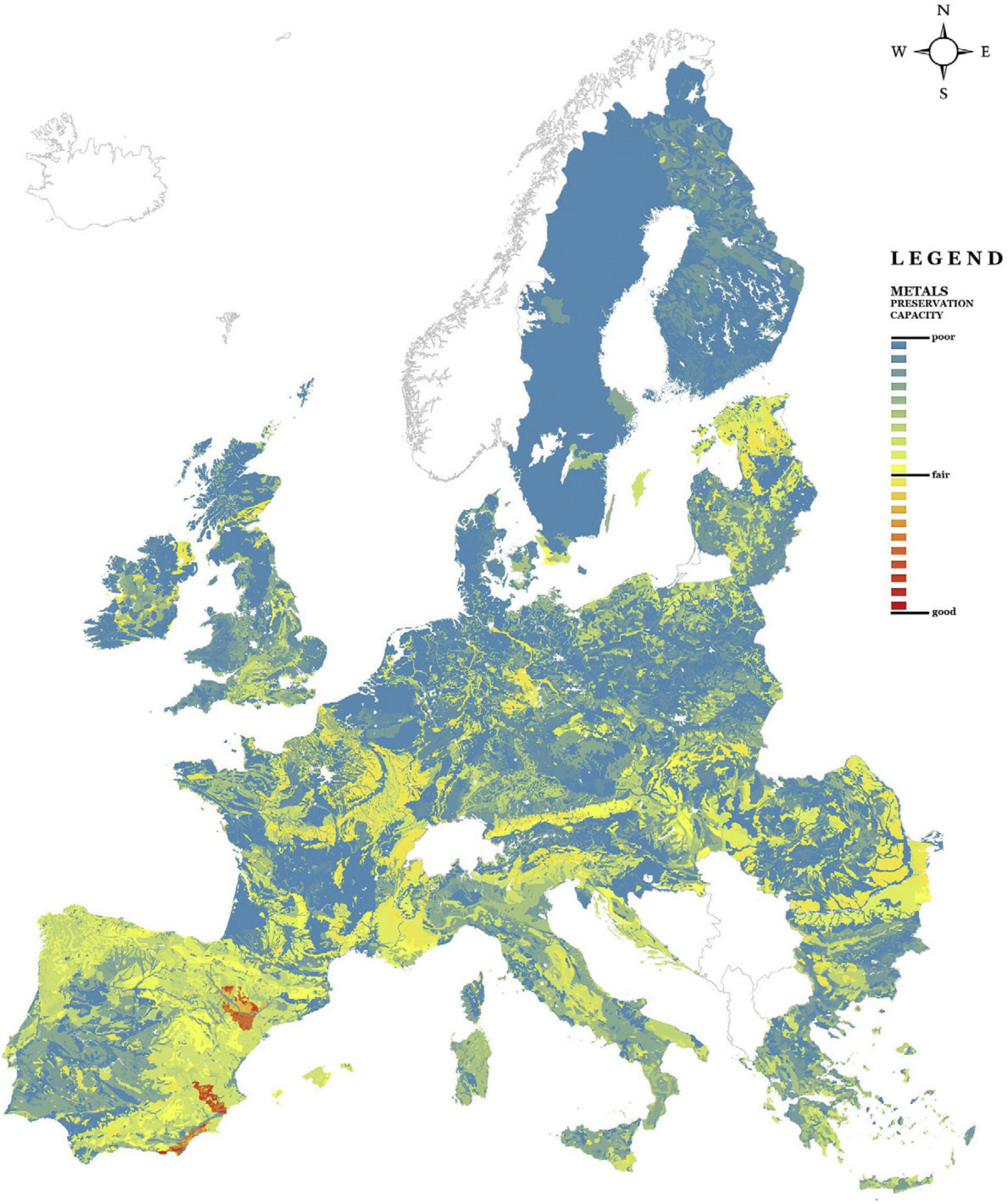

Fig. 4. Soil-based preservation capacity for metals (Cu, bronze and Fe) across the EU.

types that occur in all climate regions (e.g., Arenosols, Andosols) may be dry or moist and this creates uncertainty when predicting the level of preservation provided. It was assumed that all soils in these RSGs are moist which would tend to under estimate preservation in drier ones.

There is no meaningful timescale for destruction in soil of ceramics, glass, stone and plaster. Although glass becomes degraded aesthetically when basic ions (e.g., Na, K, Ca) are leached from it in moist soil, and the structural integrity of plaster objects may be degraded in wet and especially acidic soils, the morphology of objects made from these materials survives. Therefore it was decided that attempting to map the preservation service for these materials was not very informative.

An alternative more quantitative approach to the qualitative one adopted in this study was considered. This would set definitive ranges for soil properties that are preserving of different material types and compare these to spatial data on soil properties. However, this approach appears unworkable at present. Spatial data is available for some but not all of the relevant soil properties across the EU but mainly for topsoil only, whereas preservation depends on subsoil properties as much as or more than topsoil ones. Importantly, the seasonal dynamics of the whole soil profile and the processes within it and their impact on preservation need to be taken in to account and this may be more easily done by reviewing the profile characteristics that are specific to STU descriptions.

4.2. Preservation of buried materials

Many materials including ceramics, glass, stone and Au are preserved in most soils. Focusing, however, on those materials that are ultimately destroyed in soil (bones, teeth, shells, organic materials and

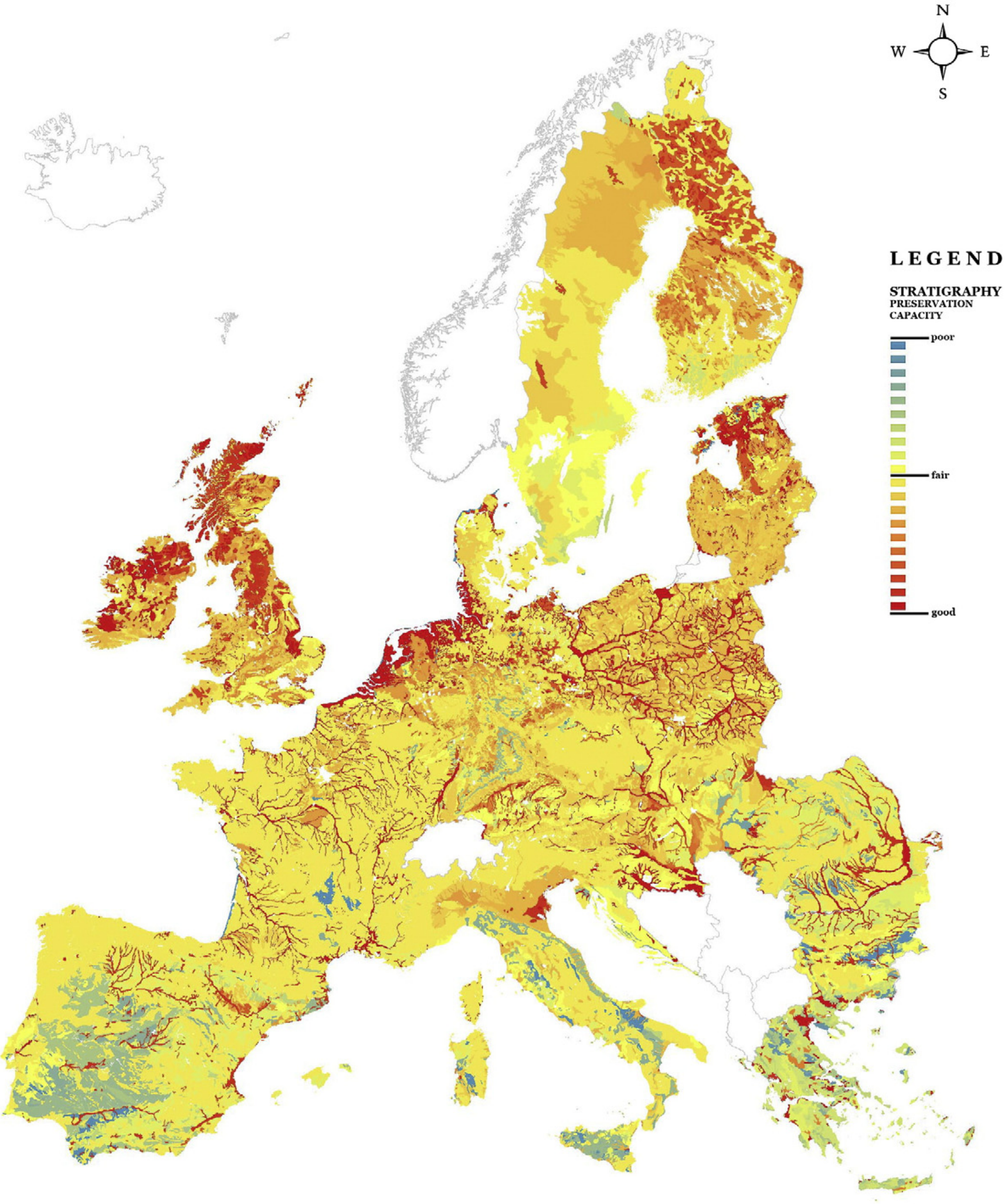

Fig. 5. Soil-based preservation capacity for stratigraphic evidence across the EU.

some metals), the most preserving soils for these materials are the driest, including Calcisols, Gypsisols and some drier Leptosols formed on limestone. These are, however, relatively uncommon in the EU and largely confined to small areas in Spain and Greece of relative aridity. Elsewhere in Europe, where precipitation is higher, soil hydrology is the dominant factor determining the preservation or degradation of these materials, moderated by the pH of the soil and associated groundwater and sometimes by the presence of chloride. The most favourable burial environment for bones, teeth, organic materials and Cu, bronze and Fe, other than a very dry one, is where the soil is permanently waterlogged and strongly anaerobic. The best preservation is anticipated where the groundwater is alkaline and stagnant as is typical of Eutric Histosols in some lowland peat lands in Northern and Western Europe; in these anoxic and alkaline soil environments bones, teeth, shells, metals and less tractable organic materials are expected to be well-preserved. The more acidic Dystric Histosols that cover relatively large areas of Northern and Western Europe in the cool moist temperate and moist boreal zones are expected to be less conserving of bones, teeth, shells and metals but will generally conserve organic materials well. Eutric and Calcic Leptosols formed from chalk and limestone parent materials are well-drained and aerobic which does not favour the preservation of organic materials but, as they are alkaline, they should be relatively preserving of bones, teeth, shells and to some extent metals including bronze, Cu and to a lesser degree Fe. These soils occur widely in Europe. Soils that have subsoil with gley features (including but not confined to Gleysols), indicative of anaerobic conditions due to waterlogging, should provide some preservation of bones, teeth, shells, organic materials and metals, depending on the permanence of waterlogging. Preservation will be less where waterlogging is seasonal as is common with soils that have gleyic features, such as Gleyic Cambisols, Gleyic Fluvisols and Gleyic Luvisols. Fluvisols emerge as an important soil type for preservation of cultural materials and evidence. Although not especially preserving of bones, teeth and shells, organic materials or metals, they appear important for preservation of stratigraphic evidence of the cultural and environmental context of materials that are preserved in them, including ceramics, glass and stone. Although the level of preservation service provided by Cambisols and Luvisols will be variable, overall, these relatively freely drained soils are assessed as not especially preserving of bones, teeth and shells, organic materials or metals. The Chernozem, Kastanozem and Phaeozem should support an intermediate level of preservation for bones, teeth, organic materials and metals. The characteristic perturbation that occurs in these soils due to burrowing mammals will compromise stratigraphic evidence. Of the group of soil types that are poorly preserving of bones, teeth and shells, organic materials and metals, the Podzols cover the largest area in the EU (others are Acrisols, Albeluvisols, Andosols, Arenosols, Leptosols, Planosols, Regosols, Solonchak, Solonetz and Vertisols).

The preservation capacity for bones, teeth and shells across the EU (Fig. 2) reflects the predominance of drier soils in the south, which are more preserving than the wetter soils in northern and western regions, excepting those with permanent waterlogging (e.g., in the Netherlands and Denmark) that have a neutral or slightly alkaline pH. The driest regions are those for which preservation is predicted to be greatest, notably parts of southern and eastern Spain and Greece.

The wettest soils of Northern Europe and some very dry soils in Spain provide most capacity for preserving organic materials (Fig. 3). The apparently low preservation capacity for organic materials in Northern Sweden is anomalous and considered inaccurate as it reflects the quality of underlying soil data, which has a poorer spatial resolution across Northern Sweden than, for example, the data for Finland where the common occurrence of Histosols is represented better.

There are only a few soils in the EU that offer very good preservation of metals including iron (Fig. 3) and these are the driest soils, including the Calcisols and Gypsisols that are confined to a small number of locations in Southern Europe. Lowland peat soils (Eutric Histosols) with shallow groundwater in Northern Europe are also relatively preserving. Metals' preservation is compromised where soils are freely-drained and there is a plentiful supply of oxygenated water, which is common across much of the EU. This norm is moderated, however, by soil pH and the more alkaline soils formed on chalk and limestone that are widespread provide a medium level of metals' preservation.

The driest soils (e.g., Calcisols, Gypsisols) are expected to be most preserving of the surfaces of glass objects and the most degrading soils for these are the most alkaline (Solonetz and Solonchak). The structural integrity of glass (and also ceramic) objects is perhaps more dependent on land use and land management than on soil type, although shattering and dispersion will be accelerated in Vertisols and other soils with Vertic tendencies that contain expansive clay minerals causing swelling and shrinking during wetting and drying cycles.

The good preservation capacity for stratigraphic evidence of Fluvisols is clearly identifiable in Fig. 5. These are widespread in the EU. Additionally, some areas of Histosols in the north and west stand out as preserving of stratigraphic evidence. The poor preservation capacity associated with Andosols (e.g., in Central France) and Regosols (e.g., in Southern Spain) is also clear.

4.3. Application of results

In this study, preservation capacities have been mapped using spatial data on the occurrence of soil types at a continental scale. This approach can, however, be applied at any scale for which spatial data on soil types are available. Data at national to regional scales (1:50,000) is available in many countries and finer scale data exists for many regions (FAO, 2015; Jones et al., 2005). Therefore the methodology we have used can be readily applied to provide information at scales that are relevant to spatial planning and land management in general. Specific applications could include: preliminary evaluations of where artefacts may exist that need to be identified and managed to inform environmental impact assessments; evaluating where existing or planned buried infrastructure (e.g., iron pipes) is likely to be better or worse preserved.

Many different waste materials are spread on land. This practice can support the beneficial recycling of nutrients but may also introduce materials that may persist in the soil environment. This study indicates that the persistence of different materials is controlled by soil type and conditions and the results suggest that soil type is a factor that should be included when assessing the suitability of wastes and land for spreading, especially where the waste may contain bone, ceramic, glass or metal objects or fragments. The survival of some materials in some soils but not others may also be relevant to investigations of options for the long-term disposal of hazardous wastes, as ancient metal, ceramic and glass artefacts found in the buried environment can act as proxies for long-term trials of similar materials that could be used to encapsulate wastes (Johnson and Francis, 1980; Neff et al., 2006). Our results confirm that a persistently dry and alkaline soil environment is the most preserving one for almost all materials.

Table 2
Percentages of the European Union area with soils assessed as having good, fair or poor preservation capacities for buried materials and stratigraphic evidence.

Preservation capacity	Poor	Fair	Good
Bones	55.6	39.7	4.7
Metals	68.2	31.5	0.3
Organics	59.3	32.4	8.2
Stratigraphic evidence	7.9	74.9	17.1

5. Conclusions

Burial in soil preserves almost all objects for at least a limited time and in many cases beyond 10^3 y. While the preservation capacities of different soils for different materials and for stratigraphy are variable, they are predictable. Some materials such as Au, ceramics, glasses, Pb and stone can survive almost indefinitely in most soil environments, albeit especially their surfaces may be altered. Bones, teeth and shells, organic materials and Al, Ag, bronze, Cu, Fe and Zn are not preserved in all soils, but their degradation and eventual destruction is slowed in those soils that provide a favourable burial environment. The methodology that has been developed can be readily applied at local to regional to national scales and the results interpreted to inform the management of buried objects, including contemporary infrastructure as well as cultural heritage. Table 2 shows the percentages of the EU area assessed as having good, fair and poor preservation capacities for some of these materials. Although $<10\%$ of the total area of soils in the EU are highly preserving of them, meaning that objects made of them are expected to survive in soil for at least 2000 y ($10^{3.3}$ y), soils in an additional 30% of the EU area are assessed as preserving of these materials for more than 10^2 y and potentially as much as $10^{3.3}$ y. The service that soil provides by preserving buried objects and stratigraphic evidence is considerable and this study illustrates its distribution at a continental scale.

Acknowledgement

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Appendix A. Soil properties descriptions for soil types

Soil type			Typical climate	Soil properties						
Reference group	Name in WRB 1998	Name in WRB 2006		Drainage	Wetness	pH status	Base satn	Chloride	Subsoil OM	Stiffness
Acrisol	Ferric Acrisol	Haplic Acrisol	Warm temperate moist	Fair	Moist	Acidic	Low	Low	Low	Medium
	Gleyic Acrisol	Gleyic Acrisol	Warm temperate moist	Fair	Moist	Acidic	Low	Low	Low	Medium
	Haplic Acrisol	Haplic Acrisol	Warm temperate moist	Fair	Moist	Acidic	Low	Low	Low	Medium
	Humic Acrisol	Humic Acrisol	Warm temperate moist	Fair	Moist	Acidic	Low	Low	Low	Medium
	Plinthic Acrisol	Plinthic Acrisol	Warm temperate moist	Fair	Moist	Acidic	Low	Low	Low	Medium
Alisol	Plinthic Alisol	Plinthic Alisol	Warm temperate moist	Fair	Moist	Acidic	Low	Low	Low	Medium
Albeluvisol	Endoeutric Albeluvisol	Haplic Albeluvisol	Cool temperate moist	Poor	High	Acidic	Low	Low	Low	Medium
	Gleyic Albeluvisol	Gleyic Albeluvisol	Cool temperate moist	Poor	High	Acidic	Low	Low	Low	Medium
	Haplic Albeluvisol	Haplic Albeluvisol	Cool temperate moist	Poor	High	Acidic	Low	Low	Low	Medium
	Histic Albeluvisol	Histic Albeluvisol	Cool temperate moist	Poor	High	Acidic	Low	Low	Medium	Medium
	Stagnic Albeluvisol	Stagnic Albeluvisol	Cool temperate moist	Poor	High	Acidic	Low	Low	Low	Medium
	Umbric Albeluvisol	Umbric Albeluvisol	Cool temperate moist	Poor	High	Acidic	Low	Low	Low	Medium
Andosol	Dystric Andosol	Aluandic Andosol	Varied climates	Good	Moist	Acidic	Low	Low	Low	Low
	Humic Andosol	Humic Andosol	Varied climates	Good	Moist	Acidic	Low	Low	Medium	Low
	Umbric Andosol	Umbric Andosol	Varied climates	Good	Moist	Acidic	Low	Low	Low	Low
	Mollic Andosol	Mollic Andosol	Varied climates	Good	Moist	Acidic	Medium	Low	Low	Low
	Vitric Andosol	Vitric Andosol	Varied climates	Good	Moist	Acidic	Low	Low	Low	Low
Anthrosol	Anthrosol	Anthrosol	Varied climates	Good	Moist	Acidic	Low	Low	Low	Low
	Plaggic Anthrosol	Plaggic Anthrosol	Cool temperate moist	Good	Moist	Acidic	Low	Low	Low	Low
Arenosol	Albic Arenosol	Albic Arenosol	Moist	Good	Moist	Acidic	Low	Low	Low	Low
	Haplic Arenosol	Haplic Arenosol	Moist	Good	Moist	Acidic	Low	Low	Low	Low
	Protic Arenosol	Protic Arenosol	Moist	Good	Moist	Acidic	Low	Low	Low	Low
	Haplic Arenosol	Haplic Arenosol	Dry	Good	Dry	Acidic	Low	Low	Low	Low
	Protic Arenosol	Protic Arenosol	Dry	Good	Dry	Acidic	Low	Low	Low	Low
Calcisol	Aridic Calcisol	Aridic Calcisol	Warm temperate dry	Impeded	Dry	Basic	High	Low	Low	Medium
Chernozem	Calcic Chernozem	Calcic Chernozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
	Chernozem	Haplic Chernozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
	Gleyic Chernozem	Gleyic Chernozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
	Haplic Chernozem	Haplic Chernozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
	Luvic Chernozem	Luvic Chernozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
Cambisol	Calcaric Cambisol	Haplic Cambisol	Temperate	Good	Moist	Neutral	Medium	Low	Low	Medium
	Chromic Cambisol	Haplic Cambisol	Temperate	Good	Moist	Neutral	Medium	Low	Low	Medium
	Dystric Cambisol	Haplic Cambisol	Temperate	Good	Moist	Acid	Low	Low	Low	Medium
	Eutric Cambisol	Haplic Cambisol	Temperate	Good	Moist	Neutral	Medium	Low	Low	Medium
	Gleyic Cambisol	Gleyic Cambisol	Temperate	Poor	Wet	Neutral	Medium	Low	Low	Medium
	Haplic Cambisol	Haplic Cambisol	Temperate	Good	Moist	Neutral	Medium	Low	Low	Medium
	Mollic Cambisol	Mollic Cambisol	Temperate	Good	Moist	Neutral	Medium	Low	Low	Medium
	Vertic Cambisol	Vertic Cambisol	Warm temperate dry	Fair	Moist	Neutral	Medium	Low	Low	Medium
Fluvisol	Calcaric Fluvisol	Haplic Fluvisol	Varied climates	Good	Moist	Alkaline	High	Low	Medium	Medium
	Dystric Fluvisol	Haplic Fluvisol	Varied climates	Good	Moist	Acid	Low	Low	Medium	Medium
	Eutric Fluvisol	Haplic Fluvisol	Varied climates	Good	Moist	Neutral	High	Low	Medium	Medium
	Gleyic Fluvisol	Gleyic Fluvisol	Varied climates	Fair	Moist	Neutral	Medium	Low	Medium	Medium
	Haplic Fluvisol	Haplic Fluvisol	Varied climates	Good	Moist	Neutral	Medium	Low	Medium	Medium
	Histic Fluvisol	Histic Fluvisol	Varied climates	Good	Moist	Neutral	High	Low	Medium	Medium
	Mollic Fluvisol	Mollic Fluvisol	Varied climates	Good	Moist	Neutral	High	Low	Medium	Medium
	Salic Fluvisol	Salic Fluvisol	Varied climates	Good	Moist	Neutral	High	High	Medium	Medium
	Thionic Fluvisol	Thionic Fluvisol	Varied climates	Fair	Moist	Acid	Low	Low	Medium	Medium
Gleysol	Calcaric Gleysol	Haplic Gleysol	Cool temperate moist	Poor	Moist	Alkaline	High	Low	Medium	Medium
	Dystric Gleysol	Haplic Gleysol	Cool temperate moist	Poor	Moist	Neutral	Low	Low	Medium	Medium
	Eutric Gleysol	Haplic Gleysol	Cool temperate moist	Poor	Moist	Neutral	High	Low	Medium	Medium
	Haplic Gleysol	Haplic Gleysol	Cool temperate moist	Poor	Moist	Neutral	Medium	Low	Medium	Medium
	Histic Gleysol	Histic Gleysol	Cool temperate moist	Poor	Moist	Neutral	Medium	Low	Medium	Medium
	Humic Gleysol	Haplic Gleysol	Cool temperate moist	Poor	Moist	Neutral	Medium	Low	Medium	Medium
	Mollic Gleysol	Mollic Gleysol	Cool temperate moist	Poor	Moist	Neutral	High	Low	Medium	Medium
	Thionic Gleysol	Thionic Gleysol	Cool temperate moist	Poor	Moist	Acid	Low	Low	Medium	Medium
Gypsisol	Aridic Gypsisol	Haplic Gypsisol	Warm temperate dry	Fair	Dry	Alkaline	High	Low	Low	High
Histosol	Dystric Histosol	Hemic Histosol	Cool temperate moist	Poor	Wet	Acid	Low	Low	High	Low
	Eutric Histosol	Hemic Histosol	Cool temperate moist	Poor	Wet	Neutral	High	Low	High	Low
	Fibric Histosol	Histosol	Cool temperate moist	Poor	Wet	Neutral	Medium	Low	High	Low
	Gelic Histosol	Histosol	Cool temperate moist	Poor	Wet	Neutral	Medium	Low	High	Low
	Sapric Histosol	Histosol	Cool temperate moist	Poor	Wet	Neutral	Medium	Low	High	Low
Kastanozem	Calcic Kastanozem	Calcic Kastanozem	Cool temperate dry	Good	Dry	Alkaline	High	Low	Medium	Medium
	Haplic Kastanozem	Haplic Kastanozem	Cool temperate dry	Good	Dry	Alkaline	High	Low	Medium	Medium
	Luvic Kastanozem	Luvic Kastanozem	Cool temperate dry	Good	Dry	Alkaline	High	Low	Medium	Medium
Leptosol	Calcaric Leptosol	Haplic Leptsol	Warm temperate dry	Good	Dry	Alkaline	High	Low	Medium	High
	Dystric Leptosol	Haplic Leptsol	Warm temperate dry	Good	Dry	Acid	Low	Low	Medium	High
	Eutric Leptosol	Haplic Leptsol	Warm temperate dry	Good	Dry	Neutral	High	Low	Medium	High
	Haplic Leptsol	Haplic Leptsol	Cool temperate moist	Good	Moist	Neutral	Medium	Low	Medium	High
	Humic Leptosol	Haplic Leptsol	Cool temperate moist	Good	Moist	Neutral	Medium	Low	Medium	High
	Rendzic Leptosol	Rendzic Leptosol	Cool temperate moist	Good	Moist	Alkaline	High	Low	High	High
	Lithic Leptosol	Lithic Leptosol	Warm temperate dry	Good	Dry	Neutral	Medium	Low	Low	High
Luvisol	Albic Luvisol	Albic Luvisol	Cool temperate moist	Fair	Wet	Neutral	Low	Low	Medium	Medium
	Arenic Luvisol	Haplic Luvisol	Cool temperate moist	Good	Moist	Neutral	Medium	Low	Medium	Medium

Appendix A (*continued*)

Soil type			Typical climate	Soil properties						
Reference group	Name in WRB 1998	Name in WRB 2006		Drainage	Wetness	pH status	Base satn	Chloride	Subsoil OM	Stiffness
	Calcic Luvisol	Calcic Luvisol	Cool temperate moist	Good	Moist	Alkaline	High	Low	Medium	Medium
	Chromic Luvisol	Haplic Luvisol	Cool temperate moist	Good	Moist	Neutral	Medium	Low	Medium	Medium
	Dystric Luvisol	Haplic Luvisol	Warm temperate dry	Good	Moist	Acid	Low	Low	Medium	Medium
	Ferric Luvisol	Haplic Luvisol	Warm temperate dry	Good	Moist	Acid	Low	Low	Medium	Medium
	Gleyic Luvisol	Gleyic Luvisol	Cool temperate moist	Good	Moist	Neutral	Medium	Low	Medium	Medium
	Haplic Luvisol	Haplic Luvisol	Cool temperate moist	Good	Most	Neutral	Medium	Low	Medium	Medium
	Vertic Luvisol	Vertic Luvisol	Warm temperate dry	Good	Moist	Neutral	Medium	Low	Medium	Medium
Phaeozem	Albic Phaeozem	Phaeozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
	Calcaric Phaeozem	Haplic Phaeozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
	Gleyic Phaeozem	Gleyic Phaeozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
	Haplic Phaeozem	Haplic Phaeozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
	Luvic Phaeozem	Luvic Phaeozem	Cool temperate dry	Good	Dry	Neutral	Medium	Low	Medium	Medium
	Sodic Phaeozem	Haplic Phaeozem	Cool temperate dry	Good	Dry	Neutral	Medium	High	Medium	Medium
Planosol	Dystric Planosol	Haplic Planosol	Cool temperate moist	Poor	Wet	Neutral	Medium	Low	Low	Medium
	Eutric Planosol	Haplic Planosol	Cool temperate moist	Poor	Wet	Neutral	Medium	Low	Low	Medium
	Haplic Planosol	Haplic Planosol	Cool temperate moist	Poor	Wet	Neutral	Medium	Low	Low	Medium
Podzol	Carbic Podzol	Haplic Podzol	Cool temperate moist	Good	Moist	Acid	Low	Low	Medium	Medium
	Entic Podzol	Haplic Podzol	Cool temperate moist	Good	Moist	Acid	Low	Low	Medium	Medium
	Gleyic Podzol	Gleyic Podzol	Cool temperate moist	Fair	Moist	Acid	Low	Low	Medium	Medium
	Haplic Podzol	Haplic Podzol	Cool temperate moist	Good	Moist	Acid	Low	Low	Medium	Medium
	Leptic Podzol	Leptic Podzol	Cool temperate moist	Good	Moist	Acid	Low	Low	Medium	Medium
	Placic Podzol	Placic Podzol	Cool temperate moist	Good	Moist	Acid	Low	Low	Medium	Medium
	Rustic Podzol	Haplic Podzol	Cool temperate moist	Good	Moist	Acid	Low	Low	Medium	Medium
	Umbric Podzol	Umbric Podzol	Cool temperate moist	Good	Moist	Acid	Low	Low	Medium	Medium
Regosol	Calcaric Regosol	Haplic Regosol	Various	Good	Moist	Alkaline	High	Low	Low	Low
	Dystric Regosol	Haplic Regosol	Cool temperate moist	Good	Moist	Acid	Low	Low	Low	Low
	Eutric Regosol	Haplic Regosol	Warm temperate dry	Good	Moist	Neutral	High	Low	Low	Low
	Haplic Regosol	Haplic Regosol	Various	Good	Moist	Neutral	Medium	Low	Low	Low
Solonchak	Gleyic Solonchak	Gleyic Solonchak	Warm temperate dry	Poor	Moist	Alkaline	High	High	Low	Medium
	Haplic Solonchak	Haplic Solonchak	Warm temperate dry	Poor	Moist	Alkaline	High	High	Low	Medium
	Takyric Solonchak	Haplic Solonchak	Warm temperate dry	Poor	Moist	Alkaline	High	High	Low	Medium
	Mollic Solonchak	Mollic Solonchak	Warm temperate dry	Poor	Moist	Alkaline	High	High	Medium	Medium
Solonetz	Gleyic Solonetz	Gleyic Solonetz	Warm temperate dry	Poor	Moist	Alkaline	High	High	Low	Medium
	Haplic Solonetz	Haplic Solonetz	Warm temperate dry	Poor	Moist	Alkaline	High	High	Low	Medium
	Mollic Solonetz	Mollic Solonetz	Warm temperate dry	Poor	Moist	Alkaline	High	High	Medium	Medium
Umbrisol	Arenic Umbrisol	Arenic Umbrisol	Cool temperate moist	Good	Moist	Acid	Low	High	Low	Medium
	Gleyic Umbrisol	Gleyic Umbrisol	Cool temperate moist	Poor	Moist	Acid	Low	High	Low	Medium
Vertisol	Chromic Vertisol	Haplic Vertisol	Warm temperate dry	Fair	Moist	Neutral	Medium	Low	Medium	Medium
	Haplic Vertisol	Haplic Vertisol	Warm temperate dry	Fair	Moist	Neutral	Medium	Low	Medium	Medium
	Pellic Vertisol	Haplic Vertisol	Warm temperate dry	Fair	Moist	Neutral	Medium	Low	Medium	Medium

Appendix B. Preservation capacities of different soil types for different buried materials and stratigraphy

Soil type					
Reference group	Name in WRB 1998	Bones etc.	Organics	Metals	Stratigraphy
Acrisol	Ferric Acrisol	Poor	Poor	Poor	Poor
	Gleyic Acrisol	Poor	Poor	Poor	Poor
	Haplic Acrisol	Poor	Poor	Poor	Poor
	Humic Acrisol	Poor	Poor	Poor	Poor
	Plinthic Acrisol	Poor	Poor	Poor	Poor
Alisol	Plinthic Alisol	Poor	Poor	Poor	Poor
Albeluvisol	Endoeutric Albeluvisol	Poor	Fair	Poor	Fair
	Gleyic Albeluvisol	Poor	Fair	Poor	Fair
	Haplic Albeluvisol	Poor	Fair	Poor	Fair
	Histic Albeluvisol	Poor	Fair	Poor	Fair
	Stagnic Albeluvisol	Poor	Fair	Poor	Fair
	Umbric Albeluvisol	Poor	Fair	Poor	Fair
Andosol	Dystric Andosol	Poor	Poor	Poor	Poor
	Humic Andosol	Poor	Poor	Poor	Poor
	Umbric Andosol	Poor	Poor	Poor	Poor
	Mollic Andosol	Poor	Poor	Poor	Poor
	Vitric Andosol	Poor	Poor	Poor	Poor
Anthrosol	Anthrosol	Poor	Poor	Poor	Fair
	Plaggic Anthrosol	Poor	Fair	Poor	Fair
Arenosol	Albic Arenosol	Poor	Fair	Poor	Fair
	Haplic Arenosol	Poor	Fair	Poor	Fair

(continued on next page)

Appendix B (*continued*)

Soil type					
Reference group	Name in WRB 1998	Bones etc.	Organics	Metals	Stratigraphy
	Protic Arenosol	Poor	Fair	Poor	Fair
Calcisol	Aridic Calcisol	Good	Good	Good	Fair
Chernozem	Calcic Chernozem	Fair	Fair	Fair	Fair
	Chernozem	Fair	Fair	Fair	Fair
	Gleyic Chernozem	Fair	Fair	Fair	Fair
	Haplic Chernozem	Fair	Fair	Fair	Fair
	Luvic Chernozem	Fair	Fair	Fair	Fair
Cambisol	Calcaric Cambisol	Fair	Poor	Fair	Fair
	Chromic Cambisol	Poor	Poor	Poor	Fair
	Dystric Cambisol	Poor	Poor	Poor	Fair
	Eutric Cambisol	Fair	Poor	Fair	Fair
	Gleyic Cambisol	Fair	Fair	Poor	Fair
	Haplic Cambisol	Poor	Poor	Poor	Fair
	Mollic Cambisol	Fair	Fair	Fair	Fair
	Vertic Cambisol	Poor	Poor	Poor	Poor
Fluvisol	Calcaric Fluvisol	Fair	Poor	Poor	Good
	Dystric Fluvisol	Poor	Poor	Poor	Good
	Eutric Fluvisol	Fair	Poor	Poor	Good
	Gleyic Fluvisol	Poor	Fair	Poor	Good
	Haplic Fluvisol	Poor	Poor	Poor	Good
	Histic Fluvisol	Poor	Fair	Poor	Good
	Mollic Fluvisol	Poor	Fair	Poor	Good
	Salic Fluvisol	Poor	Poor	Poor	Good
	Thionic Fluvisol	Poor	Poor	Poor	Good
Gleysol	Calcaric Gleysol	Fair	Fair	Fair	Good
	Dystric Gleysol	Poor	Fair	Poor	Good
	Eutric Gleysol	Fair	Fair	Fair	Good
	Haplic Gleysol	Fair	Fair	Poor	Good
	Histic Gleysol	Fair	Good	Poor	Good
	Humic Gleysol	Fair	Good	Poor	Good
	Mollic Gleysol	Fair	Good	Poor	Good
	Thionic Gleysol	Poor	Poor	Poor	Good
Gypsisol	Aridic Gypsisol	Good	Good	Good	Good
Histosol	Histosol	Fair	Good	Poor	Good
	Dystric Histosol	Poor	Good	Poor	Good
	Eutric Histosol	Good	Good	Fair	Good
	Fibric Histosol	Fair	Good	Poor	Good
	Gelic Histosol	Fair	Good	Poor	Good
	Sapric Histosol	Fair	Good	Poor	Good
Kastanozem	Calcic Kastanozem	Fair	Fair	Fair	Fair
	Haplic Kastanozem	Fair	Fair	Fair	Fair
	Luvic Kastanozem	Fair	Fair	Fair	Fair
Leptosol	Calcaric Leptosol	Good	Fair	Fair	Fair
	Dystric Leptosol	Poor	Poor	Poor	Fair
	Eutric Leptosol	Good	Fair	Fair	Fair
	Haplic Leptsol	Fair	Fair	Fair	Fair
	Humic Leptosol	Fair	Fair	Fair	Fair
	Rendzic Leptosol	Fair	Fair	Fair	Fair
	Lithic Leptosol	Fair	Poor	Fair	Fair
Luvisol	Albic Luvisol	Poor	Poor	Poor	Fair
	Arenic Luvisol	Poor	Poor	Poor	Fair
	Calcic Luvisol	Fair	Poor	Fair	Fair
	Chromic Luvisol	Poor	Poor	Poor	Fair
	Dystric Luvisol	Fair	Poor	Poor	Fair
	Ferric Luvisol	Fair	Poor	Poor	Fair
	Gleyic Luvisol	Fair	Fair	Poor	Fair
	Haplic Luvisol	Poor	Poor	Poor	Fair
	Vertic Luvisol	Poor	Poor	Poor	Poor
Phaeozem	Albic Phaeozem	Fair	Fair	Poor	Fair
	Calcaric Phaeozem	Fair	Fair	Fair	Fair
	Gleyic Phaeozem	Fair	Fair	Fair	Fair
	Haplic Phaeozem	Fair	Fair	Fair	Fair
	Luvic Phaeozem	Fair	Fair	Fair	Fair
	Sodic Phaeozem	Fair	Fair	Poor	Fair
Planosol	Dystric Planosol	Poor	Fair	Poor	Fair
	Eutric Planosol	Fair	Fair	Fair	Fair
	Haplic Planosol	Fair	Fair	Fair	Fair
Podzol	Carbic Podzol	Poor	Poor	Poor	Fair
	Entic Podzol	Poor	Poor	Poor	Fair
	Gleyic Podzol	Poor	Fair	Poor	Fair
	Haplic Podzol	Poor	Poor	Poor	Fair
	Leptic Podzol	Poor	Poor	Poor	Fair
	Placic Podzol	Poor	Poor	Poor	Fair
	Rustic Podzol	Poor	Poor	Poor	Fair
	Umbric Podzol	Poor	Poor	Poor	Fair

Appendix B (*continued*)

Soil type					
Reference group	Name in WRB 1998	Bones etc.	Organics	Metals	Stratigraphy
Regosol	Calcaric Regosol	Fair	Fair	Poor	Poor
	Dystric Regosol	Poor	Poor	Poor	Poor
	Eutric Regosol	Poor	Poor	Poor	Poor
	Haplic Regosol	Poor	Poor	Poor	Poor
Solonchak	Gleyic Solonchak	Poor	Poor	Poor	Fair
	Haplic Solonchak	Poor	Poor	Poor	Fair
	Takyric Solonchak	Poor	Poor	Poor	Fair
Solonetz	Gleyic Solonetz	Poor	Poor	Poor	Fair
	Haplic Solonetz	Poor	Poor	Poor	Fair
	Mollic Solonetz	Poor	Poor	Poor	Fair
Umbrisol	Arenic Umbrisol	Poor	Poor	Poor	Fair
	Gleyic Umbrisol	Poor	Fair	Poor	Fair
Vertisol	Chromic Vertisol	Poor	Poor	Poor	Poor
	Haplic Vertisol	Poor	Poor	Poor	Poor
	Pellic Vertisol	Poor	Poor	Poor	Poor

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