

# Impact of Roots and Rhizomes on Wetland Archaeology: A Review

ANNA KATARINA EJGREEN TJELLDÉN

*Department of Geoscience, University of Aarhus, Denmark; Department of Archaeological Science and Conservation, Moesgaard Museum, Denmark*

SØREN MUNCH KRISTIANSEN

*Department of Geoscience, University of Aarhus, Denmark*

HENNING MATTHIESEN

*Department of Conservation and Natural Sciences, National Museum of Denmark, Denmark*

OLE PEDERSEN

*Freshwater Biological Laboratory, Department of Biology, University of Copenhagen, Denmark*

The general premise for successful archaeological *in situ* preservation in wetlands is that raising the water table will ‘seal the grave’ by preventing oxygen from reaching the deposit. The present review reveals that this may not be the entire picture, as a change in habitat may introduce new plant species that can damage site stratigraphy and artefacts. However, reviews on the types and degree of damage caused by vegetation to archaeological remains preserved *in situ* in wetlands have hitherto only been sporadically treated in the literature. Thus, this paper provides an overview of the adverse effects that various plants species have on the preservation status of wetland archaeology. Disturbance, due to growth of roots and rhizomes of the surrounding soil is denoted *contextual disturbance*, whereas deterioration of archaeological remains per se acts by several root-related factors that may be spatially and temporally concomitant. In waterlogged anoxic environments, deterioration is mainly related to (i) *preferential growth* of roots/rhizomes due to nutrient uptake and lesser soil resistance, (ii) *root etching* due to organic acid exudates, (iii) *microbial growth* due to root release of oxygen and labile organic compounds, and/or (iv)

*precipitation of hydroxides* due to root release of oxygen. For example, roots of some wetland plants, such as marsh horsetail (*Equisetum palustre*), have been documented to penetrate archaeological artefacts down to *c.* 2 m in waterlogged anoxic soils. Here, we demonstrate that cultural heritage site management may unintentionally introduce deep-rooted or exudate aggressive plants by invoking change in hydrological conditions. Moreover, the implementation of biomass energy utilization and agricultural root depth optimization on a worldwide basis stresses the need for more research within root and rhizome impact on archaeological remains in wetlands. In conclusion, the worst-case scenario may be *in situ deterioration* instead of *preservation*, and one essential threat to archaeological wetland sites is the impact of wetland vegetation.

KEYWORDS *in situ* preservation, preferential growth, root etching, root exudates, rhizomes

## Introduction

The concept of *in situ* preservation of archaeological remains has become a high-profile issue in many countries (Huisman, 2009). Ideally, *in situ* preservation of archaeological remains enables future methods of analysis to be conducted, as it creates ‘reserve zones for the preservation of material evidence to be excavated by later generations of archaeologists’ (Valetta Convention, 1992, article 2). However, such a vision of sustainable management securing the cultural heritage, as well as future research opportunities, is challenged by natural processes. Ecosystems as wetlands are inherently dynamic, and environmental ‘adjustments’ of landscapes are not as easily regulated as indoor storage rooms. A worst-case scenario may be *in situ deterioration* instead of *preservation*, and one essential threat to archaeological wetland sites is the impact of vegetation. Up until now, vegetation has only seldom been considered a threat to *in situ* preserved archaeological remains, and has accordingly not been included in mitigation strategies required to ensure sustainable management of archaeological sites. Hence, Lillie and Smith’s (2009) international literature review of *in situ* preservation research only mentions one reference in regards to roots (i.e. Baird, et al., 2004).

Waterlogged anoxic, environments preserve organic remains to an exceptional degree, but still the organic remains can be susceptible to penetration of roots. This is of high importance not only as wetlands are undergoing drastic changes following human activities such as agricultural, industrial, and residential land use (Holden, et al., 2006), but also due to the major peatland restoration and management programmes within the context of ecosystem services provision throughout Europe, for example the International Union for the Conservation of Nature Peatlands Programme in the UK (Bain, et al., 2011), which has proclaimed a goal of bringing one million hectares of peatlands into good condition or ‘restorative management’ by 2020 (Gearey, et al. 2014). Permanent waterlogging of find layers is traditionally considered sufficient to secure roots from affecting archaeological *in situ* preservation conditions independent of the vegetation or land use. A major threat to wetland archaeology is therefore considered to be drainage (Davis, 1994; Corfield, 1998; Fischer, et al., 2004; Chapman, 2005; Matthiesen & Jensen, 2005; Boreham, et al.,

2011), which is necessary to enable sufficient shallow rooting depth for most common agricultural grain crops (Jacobsen, 1946). While the majority of previous studies have focused on the access of oxygen and change of water quality, changes in hydrology may also result in a change in vegetation, resulting in root access to otherwise well-preserved anthropogenic layers in waterlogged anoxic subsoils. Prior to direct oxygen access, we may therefore consider both physical and chemical damage of archaeological remains due to introduced deep growing roots and rhizomes.

The focus of this paper is on damage caused by wetland plant species, and what may happen in regards to roots in a waterlogged environment when oxygen accesses the rhizosphere. The flora of undisturbed raised bogs and blanket bogs are not included as these habitats support species with shallow rooting only; the common perennial purple moor grass (*Molinia caerulea*) has a maximum rooting depth of <80 cm, while the heathland dominated by *Erica* and *Calluna* species (i.e. *C. vulgaris* and *E. tetralix*) has live roots reaching 30 cm or less (Rutter, 1955; Bannister, 1966). The relevance of *Sphagnum* sp. for the preservation of bog bodies have been evaluated elsewhere (e.g. McLean, 2008; Painter, 1991; Painter, 1995). Although 'pristine' raised bogs may present less of a problem as regards deep rooting vegetation, some famous wetland archaeological sites such as those of Somerset Levels, SW England, are preserved within prehistoric raised bog peat, which due to drainage have been colonised by other species with deeper roots (e.g. Brunning, 2013). Geochemical processes and influence of vegetation above the groundwater table on chemical weathering and physical disturbance have been the subject of several previous case studies and will not be covered here (see e.g. Caneva, et al., 2006; Crow & Moffat, 2005; Cox, et al., 2001; White & Hannus, 1983).

Macro- and mesofauna of the soil can have profound adverse impacts on archaeological remains preserved *in situ*, especially the activities of larger earthworm species. Wetland fauna such as the European water vole (*Arvicola amphibious*) can displace artefacts both up- and downwards but are, as with earthworms, generally restricted to the oxic zone. As the focus of this review is on the waterlogged anoxic zone, oxic biota will not be considered further.

During archaeological excavations of the Iron Age mass deposition of human remains at Alken Enge, Denmark in 2013–14 (Holst, et al., in prep.), archaeologists came across several types of damage by roots to human bones and wooden artefacts. It became clear, that there was a need for an overview of the types of root damages to *in situ* preserved artefacts in wetlands. This paper thus aims to provide an overview of existing literature on the adverse effects of different plants species on the preservation status of archaeological remains in wetland soils. The major contribution of references concerning this impact is related to wetlands of northern Europe, probably biased by the excessive excavations of peatlands and wetlands in the northern hemisphere. Focus is on root damage to archaeological deposits *in situ* due to root penetration and rhizosphere exudates. Furthermore, it outlines the necessity of an interdisciplinary approach in order to determine both potential and actual root threats to our hidden archaeological heritage in wetlands, and the consequences of different vegetation control strategies are summarised.

## Wetland roots and exudates

Trees and plants can exert a number of effects on the soil through, for example, changes in site hydrology, soil chemistry, pedoturbation from root growth and uprooted trees, root exudates or changes in soil structure and stability (Crow & Moffat, 2005). An overview of these biological effects follows.

### *Root architecture*

The commonly held idea of a tree's root system is that the volume of the canopy (branches) relates 1:1 to the volume of the roots (Dobson, 1995), giving the impression of a vast mass of subsurface roots. In reality, almost 90% of a tree's roots, including practically all the larger roots, can be found within the upper 0.6 m of the soil (Lutz, et al., 1937; Kochenderfer, 1973; Kodrik & Pavlik, 1992). Contrary to popular perception, the main orientation of a tree's root system is not vertical, but horizontal (Dobson & Moffat, 1995). Although rooting depth and architecture are highly dependent on water/nutrient access and soil conditions, Dobson and Moffat (1993) have listed some generalizations on the rooting architecture of major woody species, and Lopez-Zamora, et al. (2002) have discussed root isotropy and evaluated a method for measuring root distribution in soil trenches. Crow (2004) subsequently grouped these rooting characteristics into three main types, which may also be useful in describing non-woody wetland species:

- *taproot*, where a strong main root descends vertically from the underside of the trunk;
- *surface roots*, where large horizontal lateral roots extend below the surface, from which smaller roots descend vertically; and
- *heart root*, where large and small roots descend from the trunk diagonally into the soil.

Roots of common north European coniferous species, such as pines and spruces (*Picea* and *Pinus* sp.) are highly restricted by ponding groundwater (Holsteiner-Jørgensen, 1959). For example, roots of lodgepole pine (*Pinus contorta*) virtually do not grow below the highest groundwater table even if the water table was lowered after canopy closure in the spring (Boggie & Miller, 1976). Other deeper-rooted woody species such as European Ash (*Fraxinus excelsior*) have ecological preferences for wetter soils, and can apparently have roots below the water table as long as the groundwater is not stagnant. Other non-native European coniferous trees such as *Pinus elliottii* have massive taproots and vertical sinkers growing to depths as much as 0.9 m below seasonally low water table levels and into continually waterlogged soil (Schultz, 1972).

Although the risk of windthrow may be most prominent in woodlands, the risk is also present in wetlands that are covered with few trees, as shallow rooting depth promotes uprooting. Generally, the factors influencing uprooting frequency, depth and volume are topography, soil type, tree species, exposure to wind, and forest management (Quine & Gardiner, 1998; Langohr, 1993).

## Vegetation impact upon soil hydrology

In relation to fens, drained peatlands and raised bogs, the growth of woody plants may cause a great problem as they cause considerable water loss through higher evapotranspiration and are perennial, (e.g. Coles, 1995; Cox, et al., 2001). The evapotranspiration of grasses should, however, not be neglected as some grass species are very efficient at abstracting soil moisture to a depth of up to 1.5 m (Crow & Moffat, 2005).

Fast-growing woody species such as poplars (*Populus* sp.) and willows (*Salix* sp.) are currently introduced in so-called short rotation coppice (SRC) as a renewable energy source for biofuel and fiber production (Crow & Moffat, 2005). The hydrological effects of such coppice practices on archaeological remains in wetlands below such land uses may be adverse, as the aforementioned woody species are considered to have a higher water consumption than that of standard broad-leaved species (Hall, 1996), thereby potentially lowering the water table locally when planted on susceptible sites.

## Organic acid exudates

The composition and quantity of the organic compounds in root exudates vary extremely from plant to plant with two factors being important: (1) the plant's inherent biology, and (2) external environment for plant growth (Gregory & Atwell, 1991; Tu, et al., 2004). Root exudate production can be stimulated by nutrient limitation (Carvalhais, et al., 2011); high light intensity (Cakmak, et al., 1998; Zhai, et al., 2013); elevated atmospheric CO<sub>2</sub> concentrations (Haase, et al., 2007); the presence of toxic elements in the soil (Kochian, 1995); and temperature extremes (Vancura, 1967; Zhai, et al., 2013).

Plants take up most mineral nutrients through the root rhizosphere, where microorganisms interact with exudates consisting of a complex range of organic compounds such as sugars, amino acids, organic acids, vitamins, enzymes and purines/nucleosides (Dakora & Phillips, 2002). These carbon-containing compounds have a major direct or indirect effect on the acquisition of mineral nutrients required for plant growth (Curl & Truelove, 1986). Organic acids enhance nutrient availability (Walker, et al., 2003; Seguin, et al., 2004; De-la-Peña, et al., 2010) by solubilizing unavailable soil Ca, Fe and Al phosphates (Dakora & Phillips, 2002; Bais, et al., 2006; Rudrappa, et al., 2008). The acidic exudates can be utilized as substrates by various microorganisms (Armstrong & Armstrong, 1999) and stimulate microbial growth in the rhizosphere (Kuzakov, 2002; Shi, et al., 2011). The difference between roots and rhizomes has to do with the vegetative spreading of the plant and the uptake of water and nutrients. Rhizomes store nutrients and help spreading of the plant by lateral offsprings, while roots take up nutrients often in symbiosis with fungi known as mycorrhiza.

As an example of the above-mentioned research, Zhai, et al. (2013) investigated the composition and amounts of organic acids exuded from the roots of three wetland species, common reed, yellow iris and common rush (*Phragmites australis*, *Iris pseudacorus* and *Juncus effusus*) and found them dominated by formic and acetic acid. The pH of the root exudate solutions of iris and common rush decreased 1–2 pH units from the initial pH of 6.5 (Zhai, et al., 2013).

### *Oxygen deposition in the rhizosphere*

Radial oxygen loss (ROL) is a common feature of wetland plants (Colmer, 2003b). Wetland plants need to facilitate the transport of molecular oxygen to the root tips since most waterlogged soils are completely anoxic a few millimetres below the water-sediment surface (Armstrong, 1979; Ponnampereuma, 1984) or the redox boundary in the soil. Intra-plant oxygen transport in most cases takes place as passive molecular diffusion in gas spaces inside the root cortex (aerenchyma) (Armstrong, 1979), although the transport from the shoot to the root system can greatly be enhanced by convective flow in some plants such as species of *Typha* and *Phragmites* (e.g. Brix, et al., 1990; Sorrel & Hawes, 2010). Several wetland plants form a barrier to ROL in order to prevent the majority of oxygen being lost via ROL before it reaches the oxygen-demanding root meristems (the site of active cell division and growth) located in the tip of the roots (Colmer, 2003a; Colmer, 2003b). The same barrier also protects the root against invasion of gaseous sulphide and reduced metal ions which are toxic to the root (Armstrong & Armstrong, 2005). However, the roots are never completely gas tight so some oxygen is always lost to the surrounding rhizosphere via ROL. The flux of oxygen from roots to the rhizosphere is particularly pronounced immediately behind the root tip since the barrier to ROL has not yet been formed in the young tissue resulting in an oxic halo around most root tips of wetland plants (Colmer, 2003b).

Oxygen release from roots in otherwise anoxic environments may result in a temporary proliferation of aerobic microorganisms in the rhizosphere stimulated by the presence of phytotoxic substrates (Armstrong & Armstrong, 2001). In their study of great bulrush (*Scirpus validus*), Bezbaruah and Zhang (2004) stated that the extent of this oxygen layer is very limited (c. 1 mm). For comparison, the rhizosphere oxidation extended to

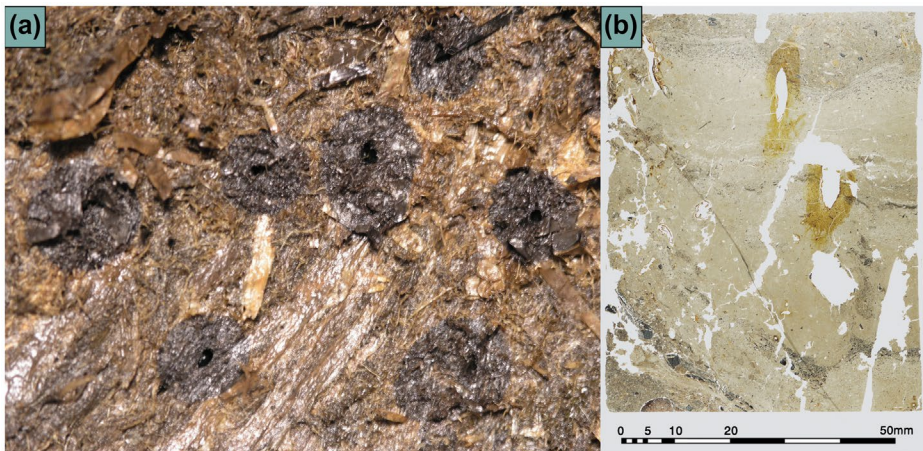


FIGURE 1 Two examples of oxidation areas around root holes. (a) The impact of ROL in peat caused by rhizomes of marsh horsetail (*Equisetum palustre*), Nydam Bog, Denmark. Each oxidized area has a diameter of c. 1 cm. (Photograph Henning Matthiesen). (b) Red halos of iron precipitation from ancient growth of reed roots at Swifterbant Middle, a Neolithic site in the Netherlands. (Photograph Hans Huisman).



c. 1 cm diameter around rhizomes from marsh horsetail (*Equisetum palustre*), visible by the oxidation of the peat around the rhizome holes (Figure 1a). Another example of the result of ROL on the biochemistry is seen in Figure 1b.

## Root damage to wetland archaeology

In order to classify the different types of root damage to archaeological deposits mentioned in the literature, three categories are considered: *contextual disturbance*, *physical penetration*, and *chemical etching*. Here, it should be noted that it remains difficult to define ‘deep roots’ in an absolute manner (Maeght, et al., 2013), although Stone and Kalisz (1991) used 1.5 m for woody plants. However, roots penetrating deeper than the permanent groundwater table are especially important in an *in situ* preservation context, and we use thus the term ‘deep rooted’ in this context.

### *Contextual disturbance*

The integrity of the soil context is crucial to all archaeological site interpretations. This is foremost the case when it is needed to tie a specific context to a specific time span, for example, when it is not possible to date through typological dating. Root growth has multiple effects on *in situ* preservation conditions: (1) it translocate soil material (Lutz & Griswold, 1939), (2) it may penetrate archaeological deposits (Huisman & Deeben, 2009), (3) it displaces archaeological artefacts (often to a lower level, Huisman and Deeben, 2009), and (4) it introduces modern-day carbon which may hinder reliable radiocarbon dating (Kristiansen, et al., 2003), which all makes contextual interpretations more difficult (Crow, 2004). Additionally, cavities left by decaying roots may also act as channels through which water and artefacts can be transported, mainly in a downward direction (Huisman & Deeben, 2009); and in a study of landscape development, Howard, et al. (2009) argue that the younger radiocarbon dates of the plant macrofossil remains appear to be the result of *Phragmites* roots pushing younger material through the sediment or opening up voids for material to fall through. Adverse soil physical features, including water tables, are probably the major causes of shallow root penetration of many woody plants. Studies focusing on rooting depth have clearly shown that woody plants are, on average, more deeply rooted than herbaceous ones (Maeght, et al., 2013). Some trees, however, are adapted to waterlogged anoxic soils and may penetrate to considerable depths. An example is black alder (*Alnus glutinosa* L.), which is known to transport oxygen to roots via enlarged lenticels on the stem, and to be very deep-rooted despite water tables, that is its roots are found to a depth of nearly 5 m (Claessens, et al., 2010). Most trees have, however, poorer growth when waterlogging occurs in the rooting zone, but some may tolerate prolonged waterlogging; for example, European ash (*Fraxinus excelsior* L.) can tolerate 30 days of waterlogging in the upper half of the root zone during growth, while oak (*Quercus* sp.) even less (Dobrowolska, et al., 2011). *Quercus robur* roots may nevertheless go, as a minimum, 1 m deeper than a winter season water table, apparently as long as the soil is only temporarily waterlogged (Holsteiner-Jørgensen, 1959).

Uprooting of woody plants can disturb significant amounts of subsoil material and to significant depths as reviewed by, for example, Schaetzl, et al. (1989), while Langohr (1993) reviewed tree windthrow in respect to artefact turbation and interpretations of

archaeological sites. Prehistoric uprooting may cause difficulties in contextual interpretation and dating. At the Iron Age human sacrifice site of Alken Enge, Denmark, the stratigraphy of the prehistoric lake basin consisted of overlapping layers of gyttja and peat, and the specific location of artefacts in this specific layer became crucial for interpreting the environmental context. However, at one incident, such correlation between find layer and strata was impossible as an isolated lance head apparently had been displaced by a prehistoric uprooted tree (M. Holst, personal communication, September 29, 2014, Department of Archaeology, Moesgaard Museum, Denmark).

In summary, tree uprooting may cause subsoil materials brought to the surface, additions of woody debris to the forest floor, exposure of bare mineral soil, and dislocation of artefacts from the surface to greater depths (Schaetzl, et al., 1989; Crombé, 1993; Langohr, 1993; Huisman & Deeben, 2009).

### **Physical penetration**

The process by which a root will grow towards a water supply is called *hydrotropism*, however no similar process is known whereby roots actively seek out nutritious deposits (Crow & Moffat, 2005), although fungal hyphae are well known to exploit the soils preferentially for nutrients. *Preferential growth* is when roots exploit water-retaining, nutrient-rich deposits or encounter soil features with less resistance, making it easier to proliferate. Differences in soil texture may also be the reason when roots favour anthropogenic soil features. The slightly higher organic matter content provides more moisture, more nutrients and less resistance (Huisman, et al., 2009). Preferential growth is often noticed in relation to archaeological degraded bone (Figure 2) due to the presence of nutrients, moisture and lesser resistance within the bone medullary cavity (Goldberg and Machphail, 1989; Huisman, et al., 2009; Pokines & Baker, 2014).

Roots may, however, create greater damage to structures than growing along their inner and outer surfaces, and as Behrensmeyer (1978) remarked, roots may penetrate bone, causing it to fracture. According to Pokines and Baker (2014), the fine lattice structure of trabecular bone greatly increases the surface area for potential release of nutrients. Furthermore, the porous structure of bone can trap water, further promoting the growth of plant roots through them. Root hairs can penetrate fissures as narrow as 100 µm, and

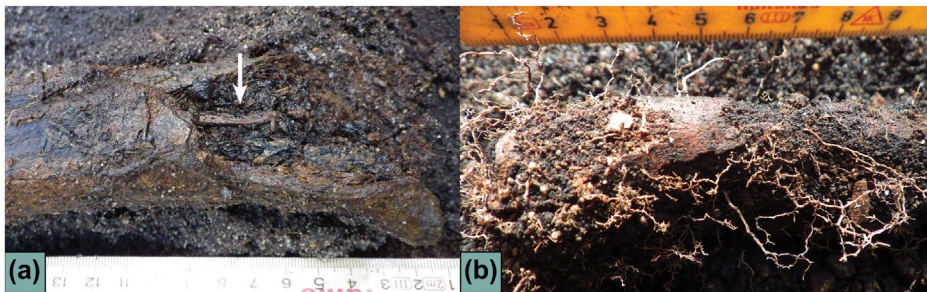


FIGURE 2 Examples of preferential growth of roots through the medullary cavity of a human long bone at (a) the Iron Age site of Alken Enge, Denmark (arrow points out root), and (b) the Stone Age site of Grisby, Bornholm, Denmark. Photographs A. Tjældén.



growth thickening of the root may destroy the bone from the inside (Pokines & Baker, 2014).

The penetration of roots through cultural material and the destruction of prehistoric remains have mostly been studied or mentioned in relation to the growth of trees (e.g. Crow, 2004; Crow & Moffat, 2005; Caneva, et al., 2006). The damage caused by herbaceous wetland species is much less studied, though examples of severe damage given below call for more attention and research on this preservation problem.

An example of physical root/rhizome penetration of archaeological remains is that of marsh horsetail (*Equisetum palustre*), at the site of the Iron Age weapon booty in Nydam, Denmark (Gregory & Matthiesen, 2012). Excavations during the 1990s showed severe damage to the organic artefacts caused by rhizomes down to a depth of 1–2 m (Gregory, et al., 2002) (Figure 3).

Similar damage was observed during the excavation of the valley peat wetlands next to the Danish Viking ring fortress Fyrkat (A. Dobat, personal communication, December 2, 2014, School of Culture and Society – Prehistoric Archaeology, Aarhus University, Denmark). When roots of such wetland plants penetrate archaeological artefacts at a depth of 2 m, very few *in situ* sites are safe from this type of threat.

Another extensive Iron Age war booty site is situated in Illerup Ådal, excavated 1950–56 and again in 1975–85 near Skanderborg in Denmark (Ilkjær, 1990). Here, 15,000 artefacts have been excavated but several thousand metal and organic objects (e.g. warriors' weapons, personal belongings, tools) are expected to be preserved *in situ* (Tjellén, et al., 2012). An *in situ* monitoring project from 2007–10 (Tjellén, 2010) documented the different species growing on the sacrificial bog such as wood club-rush (*Scirpus sylvaticus*), great bulrush (*Scirpus validus*) and common rush (*Juncus effusus*) but also a 2–400 m<sup>2</sup> area of grey willow (*Salix cinerea*). When the *in situ* project was continued in 2013, water horsetail was found on the sacrificial bog area, presenting a new threat to the organic archaeological remains. A few kilometres further down the Illerup Valley, excavations in 2013 at the Iron Age human deposition of Alken Enge, Denmark showed a large number of crafted prehistoric wood penetrated by roots, possibly by the common reed (*Phragmites australis*) (Figure 4a). Penetration by reeds in prehistoric times, when the water table was lower, has been documented at the excavation vicus Tasgetium in



FIGURE 3 Root and rhizome penetration of archaeological wooden artefacts. (a) An Iron Age shield from Nydam Bog penetrated 936 times by rhizomes of marsh horsetail (*Equisetum palustre*) with perforating holes of up to 0.5 cm (Aaby, et al., 1999). (b) A beautifully carved Iron Age sword scabbard also perforated by rhizomes, Nydam Bog, Denmark. Photographs Per Poulsen.



FIGURE 4 (a) Post-burial root penetration of Iron Age wood at the human war sacrifice, Alken Enge, Denmark. Presumably roots or rhizomes from the common reed, *Phragmites australis* B. Odgaard, personal communication, October 29, 2014, Department of Geoscience, Aarhus University. Photograph Anna Tjellén. (b) Prehistoric penetration of bottom of Roman barrel (dated to 95 AD) from the excavation vicus Tasgetium in Eschenz, Kanton Thurgau, Switzerland. Photograph Daniel Steiner.

Eschenz, Switzerland (Figure 4b). At the time of excavation, the wooden artefacts were situated in sediments deeper than the reach of reed roots, but there might be excavation contexts when separating prehistoric from more recent processes is less apparent, especially for relatively shallow archaeological sites.

Modern installation may also serve as pathways for penetrating roots, such as in the case at the excavations of Star Carr, Milner, et al. (2011). Here, extensive damage to the archaeological context and material was observed, caused by recent roots spreading from adjacent drains. The drains may lengthen the root structures and cause harm to objects in otherwise protected layers.

Penetration by roots therefore seems to be a potential threat in wetlands, which up until now has not been treated systematically throughout the *in situ* preservation literature.

### ***Chemical etching by root exudates***

There are several references to the term *root etching* in the taphonomic literature. The phenomenon is mainly mentioned in relation to bone material and described as ‘dendritic patterns of shallow grooves’ (Behrensmeyer, 1978) (Figure 5). These ‘dendritic’ (Morlan, 1980), ‘sinuous’ (Andrews & Cook, 1985), ‘spaghetti-like’ (Hesse & Wapnish, 1985), ‘reticulate’ (White, 2000) or ‘wavy’ (Lyman, 2004) networks of patterns differ from anthropogenic features such as butchery marks or prehistoric engravings by their smooth-bottomed, U-shaped cross section (Andrews & Cook, 1985). Although they are characteristic, they have been misinterpreted as human-generated (Binford, 1981; Morlan, 1984; D’Errico & Villa, 1997) or pathological changes (Wells, 1967). The ‘irregular multi channelled grooving of the outer bone cortex’ has also been noticed in forensic contexts (Rodriguez, 2006).

The cause of chemical etching has long been known as the result of dissolution by acids associated with the growth and decay of roots or fungi in direct contact with the bone surfaces (Behrensmeyer, 1978). White (1992) suggested that the presence of root marks on fracture surfaces or on the internal surface of limb-bone shafts could be essential clues to the relative timing of a bone fracture, meaning that if grooves are found on the fracture

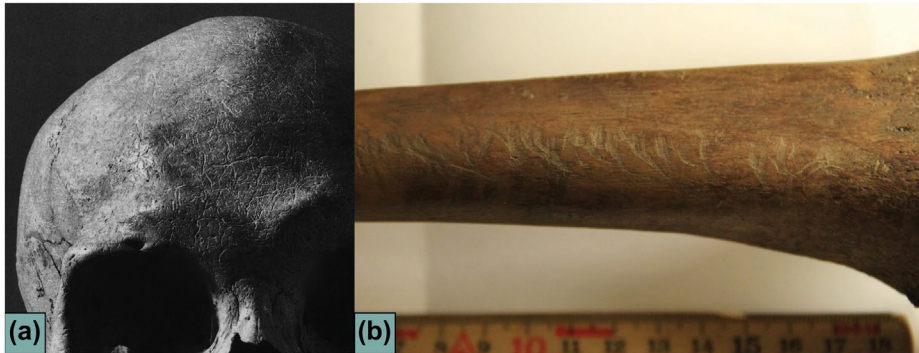


FIGURE 5 (a) Root etching grooves on human skull from a prehistoric Californian site (White, 2000). (b) Root etching grooves on an Iron Age human long bone from Alken Enge, Denmark. Photograph Anna Tjelldén.

surface, then the bone must have been broken prior to root etching and possibly prior to deposition. This, however, is highly uncertain as the time span and taphonomic history from deposition to root etching is unknown (Lyman, 2004). It is furthermore questionable as roots may themselves have caused the fracture by penetration (Behrensmeyer, 1978). It may, however, be used to differentiate between a primary and secondary deposition (Pokines & Baker, 2014), such as suggested by Geschwinde and Raetzel-Fabian (2009) where two skull fragments showed a remarkable amount of root etching compared to the other ‘complete and as if smoothly polished’ bones (author’s translation).

In conclusion, the rooting network can become so dense that the entire outer bone surface is etched away, resembling digestive or sedimentary corrosion (Andrews, 1990; White, 2000). It is, however, still questioned to what extent etching is due to the acidic exudates of roots or by fungi decomposing roots (Lyman, 2004).

### ***Precipitation of oxides and hydroxides***

Radial oxygen loss (ROL) may cause precipitation of Fe and Mn oxides and/or hydroxides on the surface of artefacts (Figure 6).

Such precipitations may deteriorate *in situ* preserved archaeological remains as (1) Fe and Mn oxides physically can cement artefacts and soil particles together, and (2) the oxidation of reduced Fe and Mn generates protons so the pH in the oxidation zone tends to decline (Kirk, 2004). Root cementations are frequently observed on wetland roots (Kirk, 2004) and are also found around tree roots when a groundwater table has been shifting. For example, taproots from the American slash pine (*Pinus elliottii*) have very prominent precipitations of hydroxides surrounding them in waterlogged soils (Fisher & Stone, 1991). Precipitation of hydroxides have only been sporadically reported in *in situ* preservation literature as a threat, however how common and how widespread this possible adverse effect is in wetland sites remains to be elucidated.



FIGURE 6 Streaks of Fe and Mn precipitations on Iron Age human bones. The Fe precipitations followed visible roots when excavated and are thus likely to be caused by the oxygen transported to this anoxic zone by the growing roots of an unidentified plant species. Example from Alken Enge, Denmark. Photograph Anna Tjelldén.

### ***Wetland plant species with documented adverse effects on in situ archaeology***

Table 1 lists a number of wetland trees and plants either (1) mentioned in the archaeological record due to inflicted damage *in situ*, or (2) studied in other contexts where results indicate that they are a potential threat to *in situ* archaeology. Thus, the table is by no means complete and stresses the need for more focused research and documentation of how wetland species impact upon *in situ* preservation.

The temperate climate species mentioned above are common in wet terrestrial environments such as bogs, fens, meadows, and marshlands. Their threat to wetland archaeological deposits *in situ* is clearly dependent on site-specific conditions, such as the depth of the find layer, type of archaeological material, etc. However, some plant species may be thought of as a general threat and highly destructive to archaeological remains — for example marsh horsetail (*Equisetum palustre*) due to their long, sharply pointed roots (Gregory & Matthiesen, 2012) — but more documentation is needed to verify if other *Equisetum* species are equally damaging.

Common reed (*Phragmites australis*) is very abundant and plays an important role in preventing wave and current erosion of river and lake banks. Common reed usually forms dense, nearly monospecific stands in the littoral zones of lakes, along rivers and irrigation/drainage canals, and in shallow, freshwater swamps (Brix, 1999). The effect of exudates from frequent wetland species such as common reed and great bulrush (*Scirpus validus*) on archaeological remains is yet to be documented, but circumstantial evidence (Table 1) suggests that they are potential threats to *in situ* archaeological preservation.

Woody plants, however, may be considered as a general threat to *in situ* archaeology in wetlands as tree roots physically disturb the soil and may penetrate organic artefacts in the oxic zone and at the interface to the anoxic zone. The issues regarding vigorous demand of water supply, subsequent lowering of water table and potential uprooting of woody plants add to the potential risks of damage to *in situ* archaeology. Especially the



Table 1  
WETLAND PLANT SPECIES THAT THREATEN OR POTENTIALLY THREATEN IN SITU ARCHAEOLOGY.

Species	Root architecture <sup>a</sup>	Preferred habitats <sup>b</sup>	Documented damage <sup>c</sup>	Reference
Marsh horsetail ( <i>Equisetum palustre</i> )	Horizontal rhizome / vertical penetration 1½–2 m	Moist or waterlogged / waterlogged	<sup>a</sup> O <sub>2</sub> / <sup>b</sup> penetration of organic artefacts	<sup>a</sup> Pers. obs.; <sup>b</sup> Gregory & Mathiesen, 2012
Water horsetail ( <i>Equisetum fluviatile</i> )	Horizontal rhizome / vertical penetration ½ m	Waterlogged, up to 2 m surface water	No documented damage found	Henriksen, 2006
Common reed ( <i>Phragmites australis</i> )	Long, creeping horizontal rhizome and/or short vertical rhizomes / 1.8 m	Moist or waterlogged soils	<sup>a</sup> O <sub>2</sub> / <sup>b</sup> org. acid	<sup>a</sup> Armstrong, 1979; <sup>b</sup> Čížková & Lukavská, 1999; Zhai, et al., 2013
Great bulrush ( <i>Scirpus validus</i> )	Creeping horizontal rhizome / 60 cm	Moist or waterlogged soils	<sup>a</sup> O <sub>2</sub>	<sup>a</sup> Bezbaruah & Zhang, 2004
Wood club-rush ( <i>Scirpus sylvaticus</i> )	Creeping horizontal rhizome	Moist or waterlogged soils	No documented damage found	
Common rush ( <i>Juncus effuses</i> )	Long, creeping horizontal rhizome and/or short vertical rhizomes	Moist or waterlogged soils	<sup>a</sup> O <sub>2</sub> / <sup>b</sup> org. acids	<sup>a</sup> Visser, et al., 2000; <sup>b</sup> Blossfeld, et al., 2011; Zhai, et al., 2013
Giant rush ( <i>Juncus ingens</i> )	Long, creeping horizontal rhizome and/or short vertical rhizomes	Moist and waterlogged soils / → 1 m	No documented damage found	
Grey willow / willow sp. ( <i>Salix cinerea</i> / sp.)		Moist soil	No documented damage found	
Silver birch ( <i>Betula pendula</i> )	/ 4 m in aerated soil, 0.4 m in waterlogged	Oxic soil	No documented damage found	
Black alder ( <i>Alnus glutinosa</i> L.)	Bell-shaped, / almost 5 m depth in waterlogged <sup>a</sup>	Waterlogged soil / riparian zone <sup>a</sup>	No documented damage found besides pers. comm. <sup>b</sup>	<sup>a</sup> Claessens, et al., 2010; <sup>b</sup> C. Christensen, personal communication, February 11, 2015, Department of Environmental Archaeology and Materials Science, National Museum of Denmark

<sup>a</sup>Root architecture gives the architectural type and maximum depth of roots/rhizomes.

<sup>b</sup>Preferred habitat is an estimate of how much surface water the species can survive in, and

<sup>c</sup>Documented damage lists published evidence of oxygen or organic acid release.



effects of the apparently deep-rooted black alder (Table 1) should be studied further, as this species is a very common riparian-zone tree.

## Vegetation control

### *Risk assessment and planning*

Prior to vegetation maintenance strategies with an archaeological preservation perspective, the cultural deposit must be located, that is subsurface depth of remains and extension of archaeological site. When the area is known, the next step is to map existing species in relation to potential/actual threats posed by their roots and rhizomes. This paper has outlined the few published cases on wetland species that could cause physical or chemical damage to artefacts or soil features, however, when estimating the threat of a specific wetland area, it is recommended that a local plant specialist be consulted. Finally, it is essential to plan what type of habitat preserves the hidden cultural heritage best, that is, how wet the environment has to be, and what type of vegetation does this promote? Further studies on this type of progressive habitat planning with focus on heritage preservation are needed, but in the following, a brief overview of different mitigation consequences are summarised.

### *Raising the water table*

Wetlands are dynamic ecosystems and, under certain conditions, some will naturally periodically dry out during prolonged periods of drought or as a consequence of climate changes (Coles, 1995). The impact of climate changes on wetland ecosystems is not further discussed here; however, certain predictions have discussed raised bogs losing their *Sphagnum* cover and becoming dominated by vascular plants (Mauquoy & Yeloff, 2008) with predictable implications for archaeological sites and remains. Not only climatic but also nitrogen deposition related changes of vegetational cover are observed in raised bogs and on wet heathland, though literature sources have so far only documented vegetation changes in regards to shallow rooted plants (Damgaard, et al., 2014). Fundamental to all types of wetland management is therefore control of water level (Rutter, 1955) and atmospheric deposition of anthropogenic compounds (Sheppard, et al., 2013), which will lead indirectly to a specific habitat for flora and fauna.

As mentioned previously, some tree species and shrubs are vigorous water consumers, and their removal can lead to a rise of the water table. Such cases are reported from, for example, Westhay Moor, UK (Hancock & Reid, 1993). Flooding and thus prolonged inundation may lead to the death of trees such as birch (*Betula* sp.), but it may not necessarily work quickly for all species (Coles, 1995). Willow (*Salix* spp.) are deep rooted when growing in wet, but temporarily unsaturated soils, and their roots are here found to significantly deteriorate archaeological remain *in situ* (Cox, et al., 2001), while their vertical root growth stops within a few weeks after flooding (Jackson & Attwood, 1997; Talbot, et al., 1987). However, at Brackagh Moss, UK, willows still survived after three years of permanent inundation (Coles, 1995) but their maximum root depth in waterlogged soils has not been found in the literature. Isotope studies of  $^2\text{H}$  and  $^{18}\text{O}$  nevertheless indicated that at least *Salix goddingii* consumed water directly from the groundwater

aquifers during the entire growing season and hence that it has deep roots (Busch, et al., 1992). Birch (*Betula pendula*) has the potential to root to a depth of at least 4 m in well-drained soils, but in waterlogged peat soils the root system is restricted to the upper oxic zone (here 0.4 m) according to Laitakari (1935).

Soil aeration below 10% air-filled pore space appears to be a commonly observed threshold for significantly inhibiting root growth (Dobson & Moffat, 1995). Richards and Cockcroft (1974) found that root growth stopped completely when air space dropped to 2 vol%. In compact soils, poor gas exchange between the soil and the atmosphere means that the oxygen is quickly utilized by plant roots and soil microorganisms, and is replaced by the waste products of respiration, carbon dioxide and in turn by methane produced by the microbial community (Dobson & Moffat, 1995).

Raising a water table at a site will evidently limit the oxygen supply and diminish the deterioration of the archaeological remains, it will slow down mineralization and further compaction of the peat surface and possibly stop the root growth of most trees and shrubs. When creating a wetland at the UNESCO World Heritage Site of Schokland in the Netherlands, the water table was only gradually raised to promote colonisation of grass species and furthermore to prevent the growth of reeds (Huisman & Mauro, 2013). By changing the water regime, a new habitat is created and new species may invade the wetter environment.

If, for some reason, flooding is not possible, manual maintenance such as different types of cutting has been used. If, however, the water is not raised or maintained at the site, roots and oxygen will eventually find its way to the archaeological objects, as drainage will lead to settling and mineralization of the upper soil layers (Gebhardt, et al., 2010). Maintaining the site with these issues in focus will make it possible to foresee and limit *in situ* deterioration due to root and rhizome growth.

### **Cutting and felling**

Usually, when site management involves felling of trees on sensitive archaeological sites, the stumps are left in the ground to rot to minimize physical soil disturbance. The remaining stump and root system can still produce growth long after the stem has been removed, especially if the tree species in question produce coppice shoots (Crow, 2004). It has therefore been recommended to spot treat the stumps with herbicide, though it may be considered environmentally undesirable, while the practicality of this management may be limited as herbicide is often only translocated a short distance (<0.5 m) into the stump (Biddle, 1998). Leaving the roots to rot may disturb the remains to a lesser degree than uprooting; however Karg and Henriksen (2012) noticed iron precipitation in the oxidized zone along decaying roots in a Bronze Age mound. They concluded that ambient oxygen can be conducted to the base of an anoxic zone via root canals. General cutting and management of trees should be done manually as heavy machinery and the uprooting activity can cause excess soil damage (Coles, 1995). Such site management is labour intensive and likely to be less cost-efficient, and in the long term it may prove insufficient to save archaeological remains.

### **Geosynthetic cover**

Geosynthetic covers such as geotextiles, geomembranes and biobarriers have been used to separate subsurface objects and features (Moffat, et al., 1998). Crow and Moffat (2005) questions the extensive use of geosynthetics as barriers to inhibit roots in woodlands due to the soil disturbance in their installation, their replacement every 30 years, and the costs involved. Nonetheless, they may prove very useful in specific wetland vegetation control. Attempts to eradicate *Equisetum palustre* and *E. fluviatile* in Nydam Bog, Denmark have proven very difficult. The problem relates to their extensive rhizomes, enabling new shoots although the top of the plant has been removed, and only years of shade will likely exterminate them permanently (Hansen, 2008). From 2000–2009, different strategies for eliminating or diminishing growth of *Equisetum* sp. were tested on site including both cutting/shredding and covering with different types of geotextile. Of these, a thermally bonded geotextile turned out to be the most effective as the *Equisetum* sp. rhizomes could not penetrate it. Relatively quickly the geotextile was overgrown by normal meadow vegetation and became a natural-looking part of the landscape (Gregory & Matthiesen, 2012).

### **Knowledge gaps and future research directions**

A general idea to archaeological *in situ* wetland preservation seems to be that raising the water table will ‘seal the grave’ by preventing oxygen from reaching the deposit. As exemplified in this review, this may not be the entire picture, as a change in habitat may introduce new plant species that may possibly damage the artefacts.

Our review revealed a limited number of studies reporting root damage to archaeological remains in wetlands. Focus until now in *in situ* preservation has been on monitoring parameters such as water table, water quality, pH, conductivity, oxygen and redox (Lillie & Smith, 2009; Williams, 2012) but mapping trees and non-woody species do not seem to be an integrated aspect to be considered. With the preliminary list of problematic species (Table 1) we hope to have taken a first step to include mapping of vegetation in monitoring schemes. However, more research is needed before the full effect of vegetation on wetland archaeology can be evaluated. Several questions on the interface between root/rhizome and archaeological artefact must be answered, by field and/or laboratory experiments; for example:

- What species have long, penetrating roots/rhizomes and what specific habitat do they live in?
- What species may create the etching of surfaces, and are there more aggressive species than others?
- How long does it take for roots in contact with, for instance, bone to etch the surface?
- What material types are in danger of root etching? Only nutrient-rich materials? To what extent does this include metal objects?
- What are the control strategies to be used on the different types of threat species?

The importance of this research field is not only stressed by the fact that we raise water tables without knowing the rooting consequences of a wetter environment. It is also highly relevant due to a rise in biomass energy utilization in our wetlands, for example, short rotation coppice of woody plants. The impact that this energy source has on

will have on known and potential archaeological remains *in situ* is directly linked to the damage caused by root growth, and a better understanding will give better arguments to protect our cultural heritage.

Moreover, recent agricultural research focuses on the optimization of root uptake of nutrients by organic and conventional agriculture (e.g. Thorup-Kristensen, et al., 2012; Dresbøll & Thomsen, 2013; Ponti, et al., 2012; Lynch, 2013). Additionally, sustainable organic farming practices aim at utilizing the soil volume much better than conventional agriculture, mainly due to deeper rooting systems (Dresbøll & Thomsen, 2013). Internationally, current agronomic efforts focus on optimizing the water and nitrogen take up by virtually all crops, following the motto ‘Steep, cheap and deep’ (Lynch, 2013). Since water and nitrogen enter deeper soil strata over time and are initially depleted in surface soil strata, roots systems with rapid exploitation of deep soil are introduced to optimize water and nitrogen capture in many high production agro-ecosystem (Lynch, 2013). Crops and catch crops with enhanced rooting abilities are anticipated to spread, even to areas with low phosphorus availability (Dresbøll & Thomsen, 2013) as peat soils. Knowing that many former wetland sites in industrial countries recently became highly productive farmland, the increase of multifunctional utilization schemes such as biomass energy and ‘steep, cheap and deep’ crops on these soils may considerably enhance the threat to *in situ* preserved archaeology on a global scale.

## Acknowledgements

We would like to thank Lene Mollerup for helpful assistance with the human bones from Alken Enge and Bent Vad Odgaard for discussion on fungi and rhizomes. We owe thanks to Hans Huisman for detailed comments and the illustration from Swifterbant Middle, and Vincent Jessen for Nydam illustrations. Finally, we would like to thank Niels Andersen, Mads Holst, Andres Dobat, Peter Steen Henriksen, Charlie Christensen and Peter Vang Petersen for providing reference material and for useful discussions. Finally, we would like to thank David Gregory and anonymous peer reviewers for highly relevant comments, remarks and proofreading, but they are not responsible for any shortcomings.

## References

- Aaby, B., Gregory, D., Jensen, P. & Sørensen, T.S. 1999. In situ-bevaring af oldsager i Nydam Mose [In Situ Preservation of Archaeological Remains in Nydam Bog]. In: S. Hvass ed. *Nationalmuseets Arbejdsmark, Nationalmuseet og Museumsklubben Nationalmuseets Venner*. Copenhagen: Nationalmuseet, pp. 35–44. (in Danish).
- Andrews, P. 1990. *Owls, Caves and Fossils*. Chicago, IL: University of Chicago Press.
- Andrews, P. & Cook, J. 1985. Natural Modifications to Bones in a Temperate Setting. *Man*, 20: 675–691.
- Armstrong, W. 1979. Aeration in Higher Plants. *Advances in Botanical Research*, 7: 225–332.
- Armstrong, J. & Armstrong, W. 1999. *Phragmites* Die-Back: Toxic Effects of Propionic, Butyric and Caproic Acids in Relation to PH. *New Phytologist*, 142: 201–217.
- Armstrong, J. & Armstrong, W. 2001. Rice and *Phragmites*: Effects of Organic Acid on Growth, Root Permeability, and Radial Oxygen Loss to the Rhizosphere. *American Journal of Botany*, 88: 1359–1370.
- Armstrong, J. & Armstrong, W. 2005. Rice: Sulfide-Induced Barriers to Root Radial Oxygen Loss, Fe<sup>2+</sup> and Water Uptake, and Lateral Root Emergence. *Annals of Botany*, 96(4): 625–638.
- Bain, C., Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Gearey, B., Howat, M., Joosten, H., Keenleyside, C., Labadz, J., Lindsay, R., Littlewood, N., Lunt, P., Miller, C.J., Moxey, A., Orr, H., Reed, M., Smith, P., Swales, V., Thompson, P.S., Van de Noort, R., Wilson, J.D. & Worrall, F. 2011. *Commission of Inquiry on Peatlands*. Edinburgh: IUCN UK Peatland Programme.

- Baird, A.J., SurrIDGE, B.W.J. & Money, R.P. 2004. An Assessment of the Piezometer Method for Measuring the Hydraulic Conductivity of a *Cladium Mariscus-Phragmites Australis* Root Mat in a Norfolk (UK) Fen. *Hydrological Processes*, 18: 1–17.
- Bais, H.P., Weir, T.L., Perry, G., Gilroy, S. & Vivanco, J.M. 2006. The Role of Root Exudates in Rhizosphere Interactions with Plants and Other Organisms. *Annual Review of Plant Biology*, 57: 233–266.
- Bannister, P. 1966. Erica Tetralix L. *Journal of Ecology*, 54: 795–813.
- Behrensmeier, A.K. 1978. Taphonomic and Ecologic Information from Bone Weathering. *Paleobiology*, 4: 150–162.
- Bezbaruah, A.N. & Zhang, T.C. 2004. PH, Redox, and Oxygen Microprofiles in Rhizosphere of Bulrush (*Scirpus Validus*) in a Constructed Wetland Treating Municipal Wastewater. *Biotechnology and Bioengineering*, 88: 60–70.
- Biddle, P.G. 1998. *Tree Root Damage to Buildings: Causes, Diagnosis and Remedy*. Wantage: Willowmead Publishing.
- Binford, L.R. 1981. *Bones: Ancient Men and Modern Myths*. New York, NY: Academic Press.
- Blossfeld, S., Gansert, D., Thiele, B., Kuhn, A.J. & Lösch, R. 2011. The Dynamics of Oxygen Concentration, PH Value, and Organic Acids in the Rhizosphere of *Juncus* Spp. *Soil Biology and Biochemistry*, 43(6): 1186–1197.
- Boggie, R. & Miller, H.G. 1976. Growth of *Pinus Contorta* at Different Water-Table Levels in Deep Blanket Peat. *Forestry*, 49: 123–131.
- Boreham, S., Conneller, C., Milner, N., Taylor, B., Needham, A., Boreham, J. & Rolfe, S.J. 2011. Geochemical Indicators of Preservation Status and Site Deterioration at Star Carr. *Journal of Archaeological Science*, 38(10): 2833–2857.
- Brix, H. 1999. Genetic Diversity, Ecophysiology and Growth Dynamics of Reed (*Phragmites Australis*). *Aquatic Botany*, 64: 179–184.
- Brix, H., Sorrel, B.K. & Hirons, G.J.M. 1990. Internal Pressurization and Convective Gas Flow in Some Emergent. *Limnology and Oceanography*, 37(7): 1420–1433.
- Brunning, R. 2013. *Somerset's Peatland Archaeology*. Oxford: Oxbow.
- Busch, D.E., Ingraham, N.L. & Smith, S.D. 1992. Water Uptake in Woody Riparian Phreatophytes of the Southwestern United States: A Stable Isotope Study. *Ecological Applications*, 2: 450–459.
- Cakmak, I., Erenoglu, B., Gulut, K.Y., Derici, R. & Romheld, V. 1998. Light-Mediated Release of Phytosiderophores in Wheat and Barley under Iron or Zinc Deficiency. *Plant and Soil*, 202: 309–315.
- Caneva, G., Geschin, S. & Marco, G.D. 2006. Mapping the Risk of Damage from Tree Roots for the Conservation of Archaeological Sites: The Case of the Domus Aurea. *Rome, Conservation and Management of Archaeological Sites*, 7: 163–170.
- Carvalho, L.C., Dennis, P.G., Fedoseyenko, D., Hajirezaei, M.R., Borriss, R. & von Wiren, N. 2011. Root Exudation of Sugars, Amino Acids, and Organic Acids by Maize as Affected by Nitrogen, Phosphorus, Potassium, and Iron Deficiency. *Journal of Plant Nutrition and Soil Science*, 174: 3–11.
- Chapman, P.J. 2005. Soil and the Environment. In: J. Holden, eds. *An Introduction to Physical Geography and the Environment*. London: Pearson Education Limited, pp. 143–174.
- Čížková, H. & Lukavská, J. 1999. Rhizome Age Structure of Three Populations of *Phragmites Australis* (Cav.) Trin. Ex Steud.: Biomass and Mineral Nutrient Concentrations. *Folia Geobotanica*, 34: 209–220.
- Claessens, H., Oosterbaan, A., Savill, P. & Rondeux, J. 2010. A Review of the Characteristics of Black Alder (*Alnus Glutinosa* (L.) Gaertn.) and Their Implications for Silvicultural Practices. *Forestry*, 83: 163–175.
- Coles, B. 1995. *Wetland Management, a Survey for English Heritage*. Exeter: Short Run Press Ltd.
- Colmer, T.D. 2003a. Aerenchyma and an Inducible Barrier to Radial Oxygen Loss Facilitate Root Aeration in Upland, Paddy and Deep-Water Rice (*Oryza Sativa* L.). *Annals of Botany*, 91(2): 301–309.
- Colmer, T.D. 2003b. Long-Distance Transport of Gases in Plants: A Perspective on Internal Aeration and Radial Oxygen Loss from Roots. *Plant, Cell & Environment*, 26(1): 17–36.
- Corfield, M. 1998. The Role of Monitoring in the Assessment and Management of Archaeological Sites. In: K. Bernick, eds. *Hidden Dimensions: The Cultural Significance of Wetland Archaeology*. British Columbia, Canada: University of British Columbia Press, pp. 302–316.
- Cox, M., Earwood, C., Jones, E.B.G., Jones, J., Straker, V., Robinson, M., Tibbett, M. & West, S. 2001. An Assessment of the Impact of Trees upon Archaeology within a Relict Wetland. *Journal of Archaeological Science*, 28: 1069–1084.
- Curl, E.A. & Truelove, B. 1986. *The Rhizosphere*. Berlin: Springer-Verlag.
- Crombé, P. 1993. Tree-Fall Features on Final Palaeolithic and Mesolithic Sites Situated on Sandy Soils: How to Deal with It. *Helinium*, 23: 50–66.
- Crow, P. 2004. Trees and Forestry on Archaeological Sites in the UK: A Review Document. Forest Research, An agency of the Forestry Commission, Web version. Available at: <[http://www.forestry.gov.uk/pdf/FR\\_archaeological\\_review.pdf/\\$FILE/FR\\_archaeological\\_review.pdf](http://www.forestry.gov.uk/pdf/FR_archaeological_review.pdf/$FILE/FR_archaeological_review.pdf)>
- Crow, P. & Moffat, A.J. 2005. The Management of the Archaeological Resource in UK Wooded Landscapes. *An Environmental Perspective, Conservation and Management of Archaeological Sites*, 7: 103–116.



- D'Errico, F. & Villa, P. 1997. Holes and Grooves: The Contribution of Microscopy and Taphonomy to the Problem of Art Origins. *Journal of Human Evolution*, 33: 1–31.
- Dakora, F.D. & Phillips, D.A. 2002. Root Exudates as Mediators of Mineral Acquisition in Low-Nutrient Environments. *Plant and Soil*, 245: 35–47.
- Damgaard, C., Strandberg, M., Kristiansen, S.M., Nielsen, K.E. & Bak, J.L. 2014. Is *Erica Tetralix* Abundance on Wet Heathlands Controlled by Nitrogen Deposition or Soil Acidification? *Environmental Pollution*, 184: 1–8.
- Davis, M.J. 1994. Changing Hydrological Conditions and the Preservation of Organic Remains in Fenland. *Southeast England Soils Discussion Group*, 10: 85–92.
- De-la-Peña, C., Badri, C.D.V., Lei, Z., Watson, B.S., Branda, M.M., Silva-Filho, M.C., Sumner, L.W. & Vivanco, J.M. 2010. Root Secretion of Defense-Related Proteins is Development-Dependent and Correlated with Flowering Time. *The Journal of Biological Chemistry*, 285: 30654–30665.
- Dobrowska, D., Hein, S., Oosterbaan, A., Wagner, S., Clark, J. & Skovsgaard, J.P. 2011. A Review of European Ash (*Fraxinus Excelsior* L.): Implications for Silviculture. *Forestry*, 84(2): 133–148.
- Dobson, M.C. 1995. *Tree Root Systems, Arboriculture Research and Information Note 130/95/ARB*. Farnham: Arboricultural Advisory and Information Service.
- Dobson, M.C. & Moffat, A.J. 1993. *The Potential for Woodland Establishment on Landfill Sites*. London: Department of the Environment, HMSO.
- Dobson, M.C. & Moffat, A.J. 1995. A Re-Evaluation of Objections to Tree Planting on Containment Landfills. *Waste Management & Research*, 13: 579–600.
- Dresbøll, D.B. & Thomsen, R.P. 2013. Plantens Liv under Jorden [The Life of the Plant below Ground]. *Aktuel Naturvidenskab*, 4: 38–43. (in Danish).
- Fischer, A., Schlichtherle, H. & Pétrquin, P. 2004. Steps towards the Heritage Management of Wetlands in Europe: Response and Reflection. *Journal of Wetland Archaeology*, 4: 199–206.
- Fisher, H.M. & Stone, E.L. 1991. Iron Oxidation at the Surfaces of Slash Pine Roots from Saturated Soils. *Soil Science Society of America Journal*, 55: 1123–1129.
- Gearey, B.R., Fletcher, W. & Fyfe, R. 2014. Managing, Valuing and Protecting Heritage Resources in the 21st Century: Peatland Archaeology, the Ecosystem Services Framework and the Kyoto Protocol. *Conservation and Management of Archaeological Sites*, 16(3): 236–244.
- Gebhardt, S., Fleige, H. & Horn, R. 2010. Shrinkage Processes of a Drained Riparian Peatland with Subsidence Morphology. *Journal of Soil Sediments*, 10: 484–493.
- Geschwinde, M. & Raetzl-Fabian, D. 2009. Naturwissenschaftliche Beiträge, in “EWBSL – Eine Fallstudie Zu Den Jungneolithischen Erdwerken Am Nordrand Der Mittelgebirge”. *Verlag Marie Leidorf GmbH* 265–316.
- Goldberg, P. & Machphail, R.I. 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.
- Gregory, D. & Matthiesen, H. 2012. Nydam Mose. In *Situ Preservation at Work, Conservation and Management of Archaeological Sites*, 14: 479–486.
- Gregory, D., Matthiesen, H. & Bjørdal, C. 2002. In Situ Preservation of Artefacts in Nydam Mose: Studies into Environmental Monitoring and the Deterioration of Wooden Artefacts. In: P. Hoffmann, J.A. Spriggs, T. Grant, C. Cook & A. Recht, eds. 8th WOAM Conference, Stockholm 11–15th June, pp. 213–223.
- Gregory, P.J. & Atwell, B.J. 1991. The Fate of Carbon in Pulse-Labeled Crops of Barley and Wheat. *Plant Soil*, 136: 205–213.
- Haase, S., Neumann, G., Kania, A., Kuzyakov, Y., Romheld, V. & Kandeler, E. 2007. Elevation of Atmospheric CO<sub>2</sub> and N-Nutritional Status Modify Nodulation, Nodule-Carbon Supply, and Root Exudation of *Phaseolus Vulgaris* L. *Soil Biology & Biochemistry*, 39: 2208–2221.
- Hall, R. 1996. *Hydrological Effects of Short Rotation Coppice*. ETSU Report B/W5/00275/REP. Harwell: Energy Technology Support Unit.
- Hancock, C. & Reid, D. 1993. Attempts to Rescue Mires on the Somerset Levels. Paper presented at Institute of British Geographers Annual Conference, Hydrology and Hydrochemistry of British Wetlands Section.
- Hansen, U.R. 2008. Planter uden blade [Plants with no Leaves]. Fortidsplanter på Holmstrup mark, *Skrappebladet*, 3: 2–5. (in Danish).
- Henriksen, P.S. 2006. Prøvegravning i Nydam Mose 22-24/8 2006 med henblik på at vurdere Dynd-Padderokkens skadevirkning på de arkæologiske værdier i mosen [Test Excavation at Nydam Bog 22-24<sup>th</sup> August 2006 with the Intention of Evaluating the Adverse Effect of Horsetail on the Archaeological Remains in the Bog]. Unpublished report, 5/12/2006, Department of Conservation and Natural Sciences, National Museum of Denmark (in Danish).
- Hesse, B. & Wapnish, P. 1985. *Animal Bone Archaeology: From Objectives to Analysis, in Manuals on Archaeology No. 5*. Washington: Taraxacum.
- Holden, J., West L.J., Howard A.J., Maxfield E., Panter I. & Oxley J. 2006. Hydrological Controls of *in Situ* Preservation of Waterlogged Archaeological Deposits. *Earth-Science Reviews*, 78(1–2): 59–83.

- Holst, M.K., Heinemeier, J., Hertz, E., Jensen, P., Kristiansen, S.M., Møllerup, L. & Sørensen, N.E. (In prep.). Direct Evidence of a Large North European Roman Time Martial Event and Post Battle Corpse Manipulation.
- Holsteiner-Jørgensen, H. 1959. Investigations of Root Systems of Oak, Beech and Norway Spruce on Groundwater Affected Moraine Soils. *Det Forstlige Forsøgsvæsen*, XXV(II, 3): 227–289.
- Howard, A.J., Gearey, B.R., Fletcher, W., Hill, T.C.B. & Marshall, P. 2009. Fluvial Sediments, Correlations and Palaeoenvironmental Reconstruction: The Development of Robust Radiocarbon Chronologies. *Journal of Archaeological Science* 36: 2680–2688.
- Huisman, D.J. 2009. Degradation of Archaeological Remains. In: D.J. Huisman, ed. *Degradation of Archaeological Remains*, Sdu Uitgevers: Den Haag, pp. 13–14.
- Huisman, D.J. & Deeben, J. 2009. Soil Features. In: D.J. Huisman, ed. *Degradation of Archaeological Remains*, Sdu Uitgevers: Den Haag, pp. 147–176.
- Huisman, D.J., Luwrier, R.C.G.M., Jans, M.M.E., Cuijpers, A.G.F.M. & Laarman, F.J. 2009. Bone. In: D.J. Huisman, ed. *Degradation of Archaeological Remains*, Sdu Uitgevers: Den Haag, pp. 33–54.
- Huisman, D.J. & Mauro, G. 2013. *Archaeological Heritage Management Reports 209 Schokland UNESCO World Heritage Site, 3rd Monitoring round*. Amersfoort: Cultural Heritage Agency of the Netherlands.
- Ilkjær, J. 1990. *Illerup Ådal 1. Die Lanzen und Speere*. Højbjerg, Denmark: Jysk Arkæologisk Selskab.
- Jackson, M.B. & Attwood, P.A. 1997. Roots of Willow (*Salix viminalis* L.) Show Marked Tolerance to Oxygen Shortage in Flooded Soils and in Solution Culture. *Plant and Soil*, 187: 37–45.
- Jacobsen. 1946. *Vejledning i dræning* [Guidance in Drainage]. Det Kgl. Danske Landhusholdningsselskab (in Danish).
- Karg, S. & Henriksen, P.S. 2012. The Modern Vegetation on Skelhøj. In: M.K. Holst & M. Rasmussen (eds.) *Skelhøj and the Bronze Age Barrows of Southern Scandinavia*. Aarhus: Jysk Arkæologisk Selskab 1: 163–168.
- Kirk, G. 2004. *The Biogeochemistry of Submerged Soils*. London: Wiley.
- Kochenderfer, J.N. 1973. Root Distribution under Some Forest Types Native to West Virginia. *Ecology*, 54: 445–448.
- Kochian, L.V. 1995. Cellular Mechanisms of Aluminum Toxicity and Resistance in Plants. *Annual Review of Plant Physiology and Plant Molecular Biology* 46: 237–260.
- Kodrik, J. & Pavlik, M. 1992. The Root System and the Static Stability of Oak Trees. *Lesnictvi* 38: 987–996.
- Kristiansen, S.M., Dalsgaard, K., Holst, M.K., Aaby, B. & Heinemeier, J. 2003. Dating of Prehistoric Burial Mounds by C-14 Analysis of Soil Organic Matter Fractions. *Radiocarbon* 45: 101–112.
- Kuz'yakov, Y. 2002. Review: Factors Affecting Rhizosphere Priming Effects. *Journal of Plant Nutrition and Soil Science*, 165: 382–396.
- Laitakari, E. 1935. The Root System of Birch (*Betula Verrucosa* and *Odorata*), *Acta Forestalia Fennica*, 41: 1–168 (Finnish with English summary).
- Lillie, M. & Smith, R.S. 2009. *International Literary Review: In Situ Preservation of Organic Archaeological Remains*. Hull: Wetland, Archaeology & Environments Research Centre, Department of Geography, University of Hull.
- Langohr, R. 1993. Types of Windthrow, Their Impact on the Environment and Their Importance for Understanding of Archaeological Excavation Data. *Helinium*, XXXIII(1): 36–49.
- Lopez-Zamora, I., Falcao N., Comerford N.B. & Barros N.F. 2002. Root Isotropy and an Evaluation of a Method for Measuring Root Distribution in Soil Trenches. *Forest Ecology and Management* 166(1–3): 303–310.
- Lutz, H.J., Ely, J.B. & Little, S. 1937. The Influence of Soil Profile Horizons on Root Distribution of White Pine (*Pinus Strobus*). *Yale University School of Forestry Bulletin*, 44: 155–156.
- Lutz, H.J. & F.S. Griswold. 1939. The Influence of Tree Roots on Soil Morphology. *American Journal of Science*, 237(6): 389–400.
- Lyman, R.L. 2004. Other Biostratigraphic Factors – Root Etching. In: R.L. Lyman, ed. *Vertebrate Taphonomy*. Cambridge: Cambridge University Press, pp. 375–377.
- Lynch, J.P. 2013. Steep, Cheap and Deep: An Ideotype to Optimize Water and N Acquisition by Maize Root Systems. *Annals of Botany* 112: 347–357.
- Mauquoy, D. & Yeloff, D. 2008. Raised Bog Peat Development and Possible Responses to Environmental Changes during the mid Holocene: Can the Palaeoecological Record Be Used to Predict the Nature and Response of Raised Bog Peats to Future Climate Change? *Biodiversity and Conservation* 17 (9): 2139–2151.
- Maeght, J.L., Rewald, B. & Pierret, A. 2013. How to Study Deep Roots—And Why It Matters. *Frontiers in Plant Science*, 4: 115–128. <http://dx.doi.org/10.3389/fpls.2013.00299>.
- Matthiesen, H. & Jensen, P. 2005. Bevaring i Åmosen – hvor vådt er vådt nok [Preservation in Åmosen – how Wet is Wet enough?] In: Steering Committee for Amosen-Tissø, ed. *Kulturarv i Naturpark Åmosen-Tissø*, Special-Trykkeriet Viborg Amosen: Styregruppen for Naturpark Amosen-Tissø, pp. 43–52 (in Danish).
- McLean, S. 2008. Bodies from the Bog: Metamorphosis, Non-Human Agency and the Making of “Collective” Memory. *Trametes* 12: 299–308.

- Milner, N., Conneller, C., Elliott, B., Koon, H., Panter, I., Penkman, K., Taylor, B. & Taylor, M. 2011. From Riches to Rags: Organic Deterioration at Star Car. *Journal of Archaeological Science*, 38(10): 2818–2832.
- Moffat, A.J., N.A.D. Bending & M.C. Dobson. 1998. *Barriers against Tree Roots – An Experimental Investigation*, *Arboriculture Research and Information Note 141/98/ERB*. Farnham: Arboricultural Advisory and Information Service.
- Morlan, R.E. 1980. *Taphonomy and Archaeology in the Upper Pleistocene of the Northern Yukon Territory: A Glimpse of the Peopling of the New World*. Archaeological Survey of Canada, Paper no. 94, Mercury Series, Ottawa: National Museum of Man.
- Morlan, R.E. 1984. Toward the Definition of Criteria for the Recognition of Artificial Bone Alterations. *Quaternary Research*, 22: 160–171.
- Painter, T.J. 1991. Lindow Man. *Tollund Man and Other Peat-Bog Bodies: The Preservative and Antimicrobial Action of Sphagnum, a Reactive Glycuronoglycan with Tanning and Sequestering Properties*, *Carbohydrate Polymers*, 15: 123–142.
- Painter, T.J. 1995. Chemical and Microbiological Aspects of the Preservation Process in *Sphagnum* Peat. In: R.C. Turner & R.G. Scaife, eds. *Bog Bodies. New Discoveries and New Perspectives*. London: British Museum Press, pp. 88–99.
- Pokines, J.T. & Baker J.E. 2014. Effects of Burial Environment on Osseous Remains. In: J.T. Pokines & S.A. Symes, eds. *Manual of Forensic Taphonomy*. Boca Raton, FL: Taylor & Francis Group, CRC Press, pp. 73–114.
- Ponnampertuma, F. 1984. Effects of Flooding on Soils. In: T. Kozłowski (ed.) *Flooding and Plant Growth*. New York, NY: Academic Press, pp. 9–45.
- Ponti, T.d., Rijk, B. & Ittersum, M.K.V. 2012. The Crop Yield Gap between Organic and Conventional Agriculture. *Agricultural Systems*, 108: 1–9.
- Quine, C.P. & Gardiner, B.A. 1998. Forest GALES – Replacing the Windthrow Hazard Classification. In: *Forests Research Annual Report and Accounts 1997–98*, 26–31. Edinburgh: Stationery Office.
- Richards, D. & Cockcroft, B. 1974. Soil Physical Properties and Root Concentrations in an Irrigated Apple Orchard. *Australian Journal of Experimental Agriculture and Animal Husbandry*, 14: 103–107.
- Rodriguez, W.C. 2006. Decomposition of Buried and Submerged Bodies. In: W.D. Haglund & M.H. Sorg, eds. *Advances in Forensic Taphonomy. Method, Theory, and Archaeological Perspectives*. New Jersey, NJ: CRC Press, pp. 459–467.
- Rudrappa, T., Czymbek, K.J., Paré, P.W. & Bais, H.P. 2008. Root-Secreted Malic Acid Recruits Beneficial Soil Bacteria. *Plant Physiology*, 148: 1547–1556.
- Rutter, A.J. 1955. The Composition of Wet-Heath Vegetation in Relation to the Water-Table. *Journal of Ecology*, 43: 507–543.
- Schaetzl, R.J., Burns, S.F., Johnson, D.L. & Small, T.W. 1989. Tree Uprooting: Review of Impacts on Forest Ecology. *Vegetatio*, 79: 165–176.
- Schultz, R.P. 1972. Root Development of Intensively Cultivated Slash Pine. *Soil Science Society of America Proceedings*, 36: 158–162.
- Sequin, V., Gagnon, C. & Courchesne, F. 2004. Changes in Water Extractable Metals, PH and Organic Carbon Concentrations at the Soil-Root Interface of Forested Soils. *Plant and Soil*, 260: 1–17.
- Sheppard, L.J., Leith, I.D., Leeson, S.R., van Dijk, N., Field, C. & Levy, P. 2013. Fate of N in a Peatland, Whim Bog: Immobilisation in the Vegetation and Peat, Leakage into Pore Water and Losses as N<sub>2</sub>O Depend on the Form of N. *Biogeosciences*, 10: 149–160.
- Shi, S.J., Richardson, A.E., O'Callaghan, M., DeAngelis, K.M., Stewart, E.E., Firestone, M.K. & Condron, L.M. 2011. Effects of Selected Root Exudate Components on Soil Bacterial Communities. *Fems Microbiological Ecology*, 77: 600–610.
- Sorrel, B.K. & Hawes, I. 2010. Convective Gas Flow Development and the Maximum Depths Achieved by Helophyte Vegetation in Lakes. *Annals of Botany*, 105 (1): 165–174.
- Stone, E.L. & Kalisz, P.J. 1991. On the Maximum Extent of Tree Roots. *Forest Ecology and Management* 46: 59–102.
- Talbot, J.R., Etherington, J.R. & Bryant, J.A. 1987. Comparative Studies of Plant Growth and Distribution in Relation to Waterlogging. XII. Growth, Photosynthetic Capacity and Ion Uptake in *Salix Caprea* and *C. cinerea* Sp. *Oliefolia, New Phytologist*, 105: 563–574.
- Thorup-Kristensen, K., Dresbøll, D.B. & Kristensen, H.L. 2012. Crop Yield, Root Growth, and Nutrient Dynamics in a Conventional and Three Organic Cropping Systems with Different Levels of External Inputs and N Re-Cycling through Fertility Building Crops. *European Journal of Agronomy*, 37: 66–82.
- Tjeldén, A.K.E. 2010. In situ bevaring af våbenofferfundet i Illerup Ådal – en vurdering af bevaringsforholdene i den nordlige del af offermosen anno 2009 [In situ Preservation of the Weapon Booty in Illerup Ådal – an Evaluation of the Preservation Conditions in the Northern Part of the Sacrificial Bog Anno 2009], Master thesis, School of Conservation, Copenhagen, 96 pp. (in Danish).
- Tjeldén, A.K.E., Kristiansen, S.M. & Botfeldt, K.B. 2012. Preservation Status and Priorities for *in Situ* Monitoring of the Weapon Sacrifice in Illerup Ådal. *Denmark, Conservation and Management of Archaeological Sites*, 14: 150–158.

- Tu, S.X., Ma, L. & Luongo, T. 2004. Root Exudates and Arsenic Accumulation in Arsenic Hyperaccumulating *Pteris Vittata* and Non-Hyperaccumulating *Nephrolepis Exaltata*. *Plant and Soil*, 258: 9–19.
- Valetta Convention. 1992. European Convention on the Protection of the Archaeological Heritage, article 2. Available at: <<http://conventions.coe.int/Treaty/en/Treaties/html/143.htm>>
- Vancura, V. 1967. Root Exudates of Plants. 3. Effect of Temperature and Cold Shock on Exudation of Various Compounds from Seeds and Seedlings of Maize and Cucumber. *Plant and Soil*, 27: 319–328.
- Visser, E.J.W., Colmer, T.D., Blom, C.W.P.M. & Voesenek, L.A.C.J. 2000. Changes in Growth, Porosity, and Radial Oxygen Loss from Adventitious Roots of Selected Mono- and Dicotyledonous Wetland Species with Contrasting Types of Aerenchyma. *Plant, Cell & Environment*, 23(11): 1237–1245.
- Walker, T.S., Bais, H.P., Grotewold, E. & Vivanco, J.M. 2003. Root Exudation and Rhizosphere Biology. *Plant Physiology*, 132: 44–51.
- Wells, C. 1967. Pseudopathology. In: D.R. Brothwell & A.T. Sandison, eds. *Diseases in Antiquity*. Illinois: Charles C. Thomas, pp. 5–19.
- White, T.D. 1992. *Prehistoric Cannibalism at Mancos 5MTUMR-2346*. Princeton: Princeton University Press.
- White, T.D. 2000. Bone Modification by Nonhuman Biological Agents. In: T.D. White, ed. *Human Osteology*. 2nd Ed. San Diego: Academic Press, pp. 413–415.
- White, E.M. & Hannus, L.A. 1983. Chemical-Weathering of Bone in Archaeological Soils. *American Antiquity*, 48: 316–322.
- Williams, J. 2012. Thirty Years of Monitoring in England — What Have We Learnt? *Conservation and Management of Archaeological Sites*, 14: 442–457.
- Zhai, X., Piwpuan, N. & Brix, H. 2013. Composition of Organic Acids in Root Exudates of Three Wetland Species as Affected by Temperature and Light-Regime, part of Ph.D. thesis, 41–66.

## Notes on contributors

Anna Katarina Ejgreen Tjellén is in the Department of Geoscience, University of Aarhus, Denmark.

Correspondence to: Anna Katarina Ejgreen Tjellén. Email: [akt@moesgaardmuseum.dk](mailto:akt@moesgaardmuseum.dk)

Søren Munch Kristiansen is in the Department of Geoscience, University of Aarhus, Denmark.

Henning Matthiesen is in the Department of Conservation and Natural Sciences, National Museum of Denmark.

Ole Pedersen is at the Freshwater Biological Laboratory, Department of Biology, University of Copenhagen, Denmark.

Copyright of Conservation & Management of Archaeological Sites is the property of Taylor & Francis Ltd and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.