Impact of Roots and Rhizomes on Wetland Archaeology: A Review

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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.,
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 Spagnum 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-Jörgensen, 1959). For example, roots of lodgepole pine (*Pinus concorta*) 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 CO₂ 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 (Kuzyakov, 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; Ponnamperuma, 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](image-url) **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](https://example.com/figure2.png)

**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. Tjelldén.
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 Ádal, 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 (Tjelldén, et al., 2012). An in situ monitoring project from 2007–10 (Tjelldén, 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 m² 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](image-url)
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

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**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.
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.
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...
# WETLAND PLANT SPECIES THAT THREATEN OR POTENTIALLY THREATEN IN SITU ARCHAEOLOGY.

<table>
<thead>
<tr>
<th>Species</th>
<th>Root architecture(^a)</th>
<th>Preferred habitats(^b)</th>
<th>Documented damage(^c)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marsh horsetail (Equisetum palustre)</td>
<td>Horizontal rhizome / vertical penetration 1½–2 m</td>
<td>Moist or waterlogged / waterlogged</td>
<td>(^a)O(_2), (^b)penetration of organic artefacts</td>
<td>(^a)Pers. obs.; (^b)Gregory &amp; Matthiesen, 2012</td>
</tr>
<tr>
<td>Water horsetail (Equisetum fluviatile)</td>
<td>Horizontal rhizome / vertical penetration ½ m</td>
<td>Waterlogged, up to 2 m surface water</td>
<td>No documented damage found</td>
<td>Henriksen, 2006</td>
</tr>
<tr>
<td>Common reed (Phragmites australis)</td>
<td>Long, creeping horizontal rhizome and/or short vertical rhizomes / 1.8 m</td>
<td>Moist or waterlogged soils</td>
<td>(^a)O(_2) / (^b)org. acid</td>
<td>Armstrong, 1979; Čičková &amp; Lukavská, 1999; Zhai, et al., 2013</td>
</tr>
<tr>
<td>Great bulrush (Scirpus validus)</td>
<td>Creeping horizontal rhizome / 60 cm</td>
<td>Moist or waterlogged soils</td>
<td>(^a)O(_2)</td>
<td>(^a)Bezbaruah &amp; Zhang, 2004</td>
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<tr>
<td>Wood club-rush (Scirpus sylvaticus)</td>
<td>Creeping horizontal rhizome</td>
<td>Moist or waterlogged soils</td>
<td>No documented damage found</td>
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<tr>
<td>Common rush (Juncus effuses)</td>
<td>Long, creeping horizontal rhizome and/or short vertical rhizomes</td>
<td>Moist or waterlogged soils</td>
<td>(^a)O(_2) / (^b)org. acids</td>
<td>Visser, et al., 2000; Blossfeld, et al., 2011; Zhai, et al., 2013</td>
</tr>
<tr>
<td>Giant rush (Juncus ingens)</td>
<td>Long, creeping horizontal rhizome and/or short vertical rhizomes</td>
<td>Moist and waterlogged soils / (\rightarrow) 1 m</td>
<td>No documented damage found</td>
<td></td>
</tr>
<tr>
<td>Grey willow / willow sp. (Salix cinerea / sp.)</td>
<td>/ 4 m in aerated soil, 0.4 m in waterlogged</td>
<td>Moist soil</td>
<td>No documented damage found</td>
<td></td>
</tr>
<tr>
<td>Silver birch (Betula pendula)</td>
<td>Bell-shaped, / almost 5 m depth in waterlogged(^a)</td>
<td>Waterlogged soil / riparian zone(^a)</td>
<td>No documented damage found besides pers. comm.(^b)</td>
<td>Claessens, et al., 2010; (^b)C. Christensen, personal communication, February 11, 2015, Department of Environmental Archaeology and Materials Science, National Museum of Denmark</td>
</tr>
</tbody>
</table>

\(^a\)Root architecture gives the architectural type and maximum depth of roots/rhizomes.  
\(^b\)Preferred habitat is an estimate of how much surface water the species can survive in, and  
\(^c\)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 Spagnum cover and becoming dominated by vascular plants (Mauquoy & Yelloff, 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 2H and 18O 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 or
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 conven-
tional 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.

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IMPACT OF ROOTS AND RHIZOMES ON WETLAND ARCHAEOLOGY


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