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Rhiannon E. Stevens[1,*], Hazel Reade[1], Daniel S. Read[2], Simon H. Bottrell[3], Delphine Frémondeau[1] and Sarah Wexler[1]

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*Correspondence: rhiannon.stevens@ucl.ac.uk
[1]UCL Institute of Archaeology, UK
[2]UK Centre for Ecology and Hydrology, UK
[3]School of Earth Sciences, University of Leeds, UK

Iso-Wetlands: unlocking wetland ecologies and agriculture in prehistory through sulfur isotopes

Rhiannon E. Stevens, Hazel Reade, Daniel S. Read, Simon H. Bottrell, Delphine Frémondeau and Sarah Wexler

Abstract

Iso-Wetlands is a new, NERC-funded collaborative research project involving researchers at UCL Institute of Archaeology, the University of Leeds and the UK Centre for Ecology and Hydrology. The project is developing sulfur isotope analysis of archaeological plants and animals as a new tool for exploring hydrological conditions under which agricultural production was taking place. This development has the potential to improve understanding of water management strategies in the past, particularly in relation to seasonal floodwater agriculture and wetland agriculture (for example, rice paddy systems). The project will open wider possibilities for the use of sulfur isotopes in archaeology and ecology to examine wetland habitat use by both people and animals.

Keywords: sulfur isotopes, bone, collagen, archaeobotany, waterlogged

Introduction

Since the advent of farming, water has been central to agricultural production, yet the use of natural and manipulated water resources in prehistoric agriculture is poorly understood. The selective distribution of Neolithic settlements in the Near East and Europe along rivers and floodplains was long argued as evidence for a dependence on floodplain cultivation (Sherratt 1980; Bogaard 2005). However, a more complex picture has since emerged, with evidence for both 'least-effort' floodplain cultivation, more labour-intensive garden cultivation and artificial manipulation of soil fertility and water taking place (Cappers and Raemaekers 2008; Bogaard 2004). The manipulation of water systems by early farmers to ensure crop productivity and to mitigate against the effect of environmental unpredictability led to agricultural surpluses that are argued to have underpinned the development of complex societies, particularly in Asia (Finlayson et al. 2011; Flohr et al. 2019). However, such developments came at a price, with anthropogenic manipulation of water systems leading to significant environmental consequences such as loss of biodiversity, disruption of sedimentation cycles and increased atmospheric methane emissions (Robinson and Lambrick 1984; Erickson 1992; Marston 2017; Fuller et al. 2011).

Despite human use of past natural and managed wetland environments being central to many important archaeological, environmental and climatological questions, methods for studying past water management regimes and agricultural strategies often solely rely on indirect evidence – such as irrigation infrastructure and weed ecology – or focus exclusively on water availability in arid environments (for example, cereal grain carbon isotopes) rather than wetland contexts (Styring et al. 2016; Wallace et al. 2013). These methods do not enable water conditions to be adequately inferred, limiting investigations and interpretations to a coarse resolution. There is thus a need for a new methodology that can provide more direct information on past soil hydrology; this in turn will lead to a step-change in the understanding of prehistoric agriculture and the use of natural and manipulated water resources. The Iso-Wetlands project is exploring the potential of sulfur isotopes of archaeological plant and animal remains as a new tool for establishing the hydrological conditions under which agricultural production was taking place.

Sulfur isotopes in archaeology

Since the start of the twenty-first century sulfur isotope ratios ($\delta^{34}S$) in archaeological plant, human and animal remains have been increasingly used to explore past diets and ancient human and animal mobility (Richards et al. 2003; Nehlich 2015). The majority of these investigations use sulfur isotopes to track movements or make geographical assignments (Nehlich 2015). This is possible as animal sulfur isotopes reflect those of the bioavailable sulfur (usually soil sulphate) at the base of their food chain. Bioavailable sulfur varies spatially, with isotope values being determined by underlying bedrock (Krouse 1980) and proximity to the ocean (due to sea spray) (Zazzo et al. 2011; Bataille et al. 2020; Guiry and Szpak 2020). Further studies use sulfur isotopes for a dietary or palaeodietary indicator, as marine and terrestrial resources have relatively distinct $\delta^{34}S$ values (Richards et al. 2003). Animal and human $\delta^{34}S$ values have thus been interpreted as reflecting one or more dietary sources, but these sources were assumed to not be influenced by environmental parameters.

However, this over-simplistic view is now beginning to be challenged. Research has started to indicate that environmental parameters can influence soil and plant $\delta^{34}S$ values to the extent that environmental conditions can sometimes be the primary driver of plant – and therefore animal – $\delta^{34}S$ values. Environmental parameters (for example, soil hydrology) that promote changes in soil microbial action and soil redox status seem to be of particular importance. In aerobic conditions (free draining soils) plants primarily reflect sulphate $\delta^{34}S$ derived from mineral weathering of parent material with little or no fractionation (Trust and Fry 1992). When anaerobic conditions prevail (for example, when there is extensive wetting and waterlogging of landscapes), however, soil redox is affected and microbially mediated dissimilatory sulphate reduction (DSR) occurs. This process can result in large (−46 to −40‰) isotopic fractionation between the different soil S pool available to plants (Thode 1991). Plants rooted in anaerobic soils have been shown to access depleted $\delta^{34}S$ sulphides either directly (if they are adapted to transport oxygen to their roots or are tolerant to sulphide toxicity) or indirectly after oxidisation to sulphate (Nitsch et al. 2019).

Evidence for such processes driving plant and animal $\delta^{34}S$ values is beginning to emerge in modern datasets. Low $\delta^{34}S$ values have been observed in birds from wetland habitats in North America, where they have been linked to high soil sulphide concentrations and DSR processes (Hebert and Wassenaar 2005). Likewise, within Britain lower plant $\delta^{34}S$ values occur in regions where the underlying geology promotes water retention in soils (for example, Jurassic clays), again suggesting that wetter soil conditions promote fractionation processes which produce pools of low $\delta^{34}S$ sulfur accessible to vegetation (Evans et al. 2018; Chenery 2018; Lamb et al. 2022). Low herbivore bone collagen $\delta^{34}S$ values are observed in wetland regions of Britain where low plant $\delta^{34}S$ sulfur has been reported (Somerset Levels, Cambridgeshire Fens) (Lamb et al. 2022). A correlation between plant $\delta^{34}S$ (barley, wheat, wild grasses) and local waterlogging has been observed on the Konya Plain, Turkey, with those from areas subject to flooding having lower $\delta^{34}S$ than those from non-flooded contexts (Nitsch et al. 2019). Similarly, low $\delta^{34}S$ values appear to be associated with paddy field agriculture. Particularly low $\delta^{34}S$ values have been observed in rice from regions where agricultural water management practices promote DSR (Chung et al. 2018), while plants grown in recently converted paddy fields, where repeated soil oxidation and reduction processes have occurred, were also found to have lower $\delta^{34}S$ values than the same plants grown in dry upland soils (Chung et al. 2017).

In the archaeological and palaeontological record, low (often negative) $\delta^{34}S$ values and temporal variability in $\delta^{34}S$ values are also evident. In Wales, Switzerland and the Czech Republic changes in herbivore $\delta^{34}S$ values during and at the end of the Last Glacial Maximum are argued to reflect locally variable hydrological dynamics linked to permafrost thaw (Reade et al. 2020, 2021; Stevens et al. 2021). Low faunal $\delta^{34}S$ values have also been identified in more recent Holocene archaeological assemblages. At a Roman site in the Thames Valley, low faunal $\delta^{34}S$ values appear to relate to riverine floodplain use (Nehlich et al. 2011), while a trend towards higher $\delta^{34}S$ values may relate to changes in the Thames palaeochannel from the early Holocene to recent times (Arthur 2022). Low faunal $\delta^{34}S$ values have been reported from Bronze Age, Roman and medieval sites in the wetland areas of the Somerset Levels and Cambridgeshire Fens (Lamb et al. 2022). Low human $\delta^{34}S$ values at the Mayan archaeological sites of Xunantunich and San Lorenzo in Belize have been postulated to be due to the consumption of maize cultivated on the floodplains of the Mopan River (Rand 2021).

In short, this evidence illuminates the challenges and potential pitfalls of using sulfur isotope data as a simple provenancing tool. Temporal and/or local-scale spatial variability in soil hydrology may over-print larger-scale spatial variation related to lithology or proximity to the coast/sources of isotopically distinct pollutants. While complicating the interpretation of sulfur isotope analysis for provenance studies and dietary reconstruction, this presents an emerging opportunity to develop sulfur isotopes as a proxy for hydrological conditions, which can then be used in both modern and archaeological investigations.

Iso-Wetlands project

The Iso-Wetlands project is investigating and quantifying the relationship between water availability, the soil environment (soil sulphate concentration, soil microbial community structure and redox status) and plant $\delta^{34}S$ using controlled growth experiments. This is necessary as we need to establish when and to what extent sulfur isotopes are impacted by hydrology before we can apply the proxy to archaeological case studies. We are growing a range of plant species in the UK Centre for Ecology and Hydrology's GroDome. The GroDome enables plants to be grown under strictly controlled experimental conditions, allowing the effect of different growth regimes on plant $\delta^{34}S$ to be tested and avoiding S input to the experiment from modern anthropogenic pollutants. We are in the first year of our experiments, so it will be some time before we can harvest our plants and sample the soils for isotope analysis. However, the results will inform interpretations in our archaeological case studies that explore floodplain agriculture and the development of wet-rice agricultural systems.

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Declarations and conflicts of interest

Research ethics statement

Not applicable to this article.

Consent for publication statement

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Conflicts of interest statement

The authors declare no conflict of interest with this work. All efforts to sufficiently anonymise the authors during peer review of this article have been made. The authors declare no further conflicts with this article.

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