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Acid sulfate soil evolution models and pedogenic pathways during drought and reflooding cycles in irrigated areas and adjacent natural wetlands

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ABSTRACT

The severe Millennium Drought (2007–2010) left an area of over 5000 ha in the Lower Murray River (South Australia) dried, cracked and acidified as river and groundwater levels fell nearly 2 m. In this study, we examined irrigated agricultural areas and an adjacent natural wetland for comparison, which were both affected by the drought. Approximately 3 m deep soil cores were collected along transects in three sections of the Lower Murray Reclaimed Irrigation Area (LMRIA) on multiple occasions between 2011 and 2015 and an adjacent natural wetland in 2007. Soil properties measured included pH, reduced inorganic sulfur (RIS, pyrite), titratable actual acidity (TAA), retained acidity, acid neutralising capacity (ANC), X-ray diffraction analyses and scanning electron microscopy. A series of explanatory soil-regolith hydro-toposequence models were developed during the pre-drought period, drying period, and subsequent wetting/reflooding post-drought period. These models indicate that prior to draining of the natural wetlands for irrigated agriculture the region cycled between wetting and flushing, and partial drying conditions in response to seasonal and climatic cycles causing the build-up of hypersulfidic material to be kept in check by oxidation of pyrite during dry periods/droughts and removal during scouring floods. As the region became managed for navigation and irrigation by installing barrages and locks, pyrite began to build-up. The extreme lowering of the water table during the Millennium Drought resulted in deep oxidation of sulfides in anaerobic hypersulfidic material to depths > 3.5 m in the previously saturated irrigated pastures and within 50 cm of the soil surface in the natural wetlands. Oxidation and acidification between 0.5 and 3.5 m of Hypersulfidic clayey soils was enhanced by the formation of large cracks up to 3.5 m deep. Rewetting and flooding after the drought caused mobilization of sulfuric acid, soluble sulfates, ferrous iron, nutrients and metals with transport into the River Murray. Our findings highlight that irrigated areas formed deeper sulfuric materials (> 3.5 m) than in adjacent natural wetlands (< 1 m) due to the difficulties in the management of water tables in irrigation areas because of the installation of high levee banks and deep drains. Maintaining water tables on agricultural soils via irrigation and subsequent drainage will promote the rapid formation of deep (> 3.5 m) acid sulfate soils with sulfuric material containing extensive retained acidity (jarosite), which can persist for decades or longer.

1. Introduction

Traditionally, acid sulfate soils (ASS) have been identified and studied in some detail in coastal regions (Pons, 1973; Dent, 1986; Dent and Pons, 1995; Fanning, 2002; Poch et al., 2009; Johnston et al., 2009) and acid mine drainage locations (e.g. Johnson and Hallberg, 2005; Milnes et al., 1992). More recently, investigations have been conducted in inland locations such as natural and disturbed wetlands, floodplains and lakes across Australia, especially in the Murray–Darling Basin (e.g. Fitzpatrick and Shand, 2008; Fitzpatrick et al., 2009). In general, modern irrigation systems are not thought susceptible to extreme acidification from the oxidation of pyrite in acid sulfate soils or sediments, primarily because it is considered easy to control and maintain high water table levels in irrigation systems to prevent the exposure of pyrite in hypersulfidic materials to air (oxygen). However, over the past decade the Lower Murray Reclaimed Irrigation Area (LMRIA), which comprises approximately 5200 ha of flood-irrigated agricultural land located on the historic floodplain of the River Murray between Mannum and Wellington (Fig. 1) has experienced widespread formation of deep (> 3 m) Sulfuric clay soils with sulfuric material (pH < 4) from the

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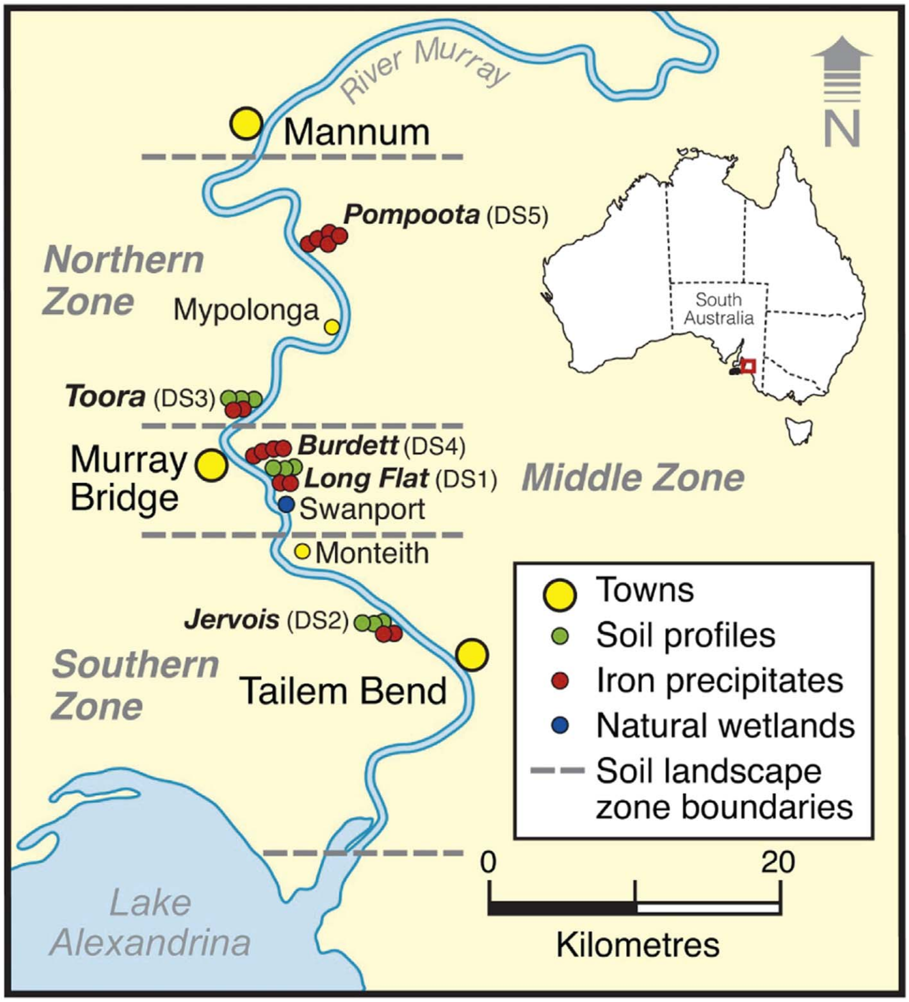

Fig. 1. Map of Murray Reclaimed Irrigation Area (LMRIA) showing: (i) the distribution of nine acid sulfate soil profiles from three irrigated transects at Toora, Long Flat and Jervois (green dots) and three acid sulfate soil profiles from a natural wetland transect at Swanport (blue dot) and (ii) three different soil landscape zones that correspond to a Northern zone, Middle zone and Southern zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

drying of hypersulfidic material (pH > 4) (Fitzpatrick et al., 2012b). This has led to major water quality, ecological and public health issues from metal/metalloid mobilization in drains and the River Murray (Fitzpatrick et al., 2009; Mosley et al., 2014a, 2014b; Simpson et al., 2010). Similar, irrigated environments with extensive hypersulfidic material exist in other regions around the world such as in the Mekong Delta in Vietnam (Andriesse and van Mensvoort, 2006) and Nation of Brunei (Grealish and Fitzpatrick, 2013, 2014). Thus the processes examined here will be applicable to other localities that have the potential to create extensive areas of ASS with sulfuric material.

Historically, the flood plains along the River Murray contained reed beds (*Phragmites Australis*) with regular flooding under natural river regime (Taylor and Poole, 1931). Drainage channels were constructed between 1881 and 1940 for the development of irrigated agriculture (dairy, beef and fodder) and have been successfully farmed for well over 100 years. However, the low water levels in the Lower Murray during the Millennium Drought from 2007 to 2010 and the irrigation restricted water allocations for irrigators meant that most of the LMRIA could not be irrigated for substantial periods of time, which led to a drop in the water table of up to 3 m from pre-drought levels (Mosley et al., 2009). As a consequence, the heavy clay soils dried, cracked and sulfuric materials formed at depths exceeding 3 m, resulting in major damage to irrigation bays and associated infrastructure causing major socio-economic impacts. From March 2010 to early 2011, increased rainfall within the Murray Darling Basin catchment resulted in water levels in the lower River Murray region to increase from approximately − 1.75 m AHD to 0.7 m AHD (Australian Height Datum or Mean Sea Level) causing the formation of iron-rich precipitates comprising dominantly schwertmannite with scavenged metals in acidic drain waters (Fitzpatrick et al., 2012b, 2017b-This Issue). This condition has persisted for over 7 years in most of the LMRIA drains with significant implications for short-term rehabilitation options.

The protection and management of the LMRIA is dependent on a detailed understanding of the long-term temporal and spatial variations in ASS subtypes during wetting/flooding and drying conditions. Understanding the link between various wetting-drying cycles and acid sulfate soil subtype-landscape features is critical to understanding and predicting pedogenic pathways. This suggests that combining acid sulfate soil and terrain attributes within soil-regolith hydro-toposequence models would inform prediction of soil temporal dynamics in both irrigated and adjacent natural wetland areas.

The aims of this study were to: (1) undertake a detailed pedological, geochemical and mineralogical study of a range of acid sulfate soils from three irrigated transects and an adjacent natural wetland transect for comparison during three cycles of wetting, drying and reflooding, (2) construct explanatory soil-regolith hydro-toposequence models to illustrate in detail the spatial distribution of the major horizons/layers (salt efflorescences), features (cracks), ASS materials and ASS subtypes during the three cycles of wetting, drying and reflooding and (3) construct well-constrained predictive soil-regolith evolutionary models to explain the ancient and contemporary biogeochemical transformations over time during various drying and wetting/reflooding cycles based on the 3-stage approach used by Fitzpatrick et al. (2012b).

Understanding the role of drought events and subsequent reflooding in pedogenesis is important for soil survey, ecological/biogeochemical modeling, agronomy/soil fertility and land-use management to protect