Riverine ecosystems and health: Soil-landscapes

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Above: The Murray River wending its way through eucalyptus forest. Auldist, iStock

EXECUTIVE SUMMARY

Fitzpatrick et al. overview the state of soil-landscape ecosystems across the Basin and their significant decline since European settlement. Soil-landscape ecosystems are closely linked to other natural features such as climate, vegetation, geology, hydrology, water availability, and overall ecosystem services and are therefore useful for assessing a 50-year future. Eight adaptive soil-landscape management recommendations are presented based on two scenarios — a drying and a wetting scenario — as soil-landscapes behave differently under each regime. The most significant impacts on soil-landscapes from these two scenarios include acid sulphate soil production, salt leaching and salt concentration, organic matter distribution, production of sodic and saline soils, soil erosion and bank slumping and soil compaction.

Soil landscapes are substantially impacted by overgrazing, drying and drought, wetting and floods, as well as infrastructure related disturbance. To achieve the best "sustainable soil-landscape management" for the MDB in 50 years, we need an integrated approach implementing a seasonal wetting and drying regime to the river and adjacent wetland regulation. This will substantially reduce the many risks related to the prolonged drying and subsequent rewetting, which can lead to the redistribution and accumulation of environmental hazards within a soil profile and the floodplain.

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Riverine ecosystems and health: soil-landscapes

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Abstract

Soil-landscape ecosystems in the Murray-Darling Basin (MDB) are closely linked to other natural features such as climate, vegetation, geology, hydrology, water availability, and overall ecosystem services. A soil-landscape is an area of land with unique landform features and characteristic soil types, which further encompasses various ecosystems and their processes. Consequently, soil-landscapes are one of the most appropriate, integrated conceptual, and practical concepts for developing long-term sustainability assessment and management policy to best adapt to climate change in the MDB.

This essay focuses on a 50-year vision for MDB soil-landscapes, focussing on wetlands and floodplains, by reviewing and synthesising recent literature on how soil-landscape degradation is modified under the influence of changing climate. An overview of recent advances is presented in our understanding of the key soil-landscape processes from extreme: 1) soil drying caused by prolonged drought conditions (and the impacts of increasing bushfires) and 2) wetting caused by extreme flooding. These processes have resulted in a wide range of soil-landscape degradation issues, namely: soil erosion, acidification, salinisation, clay dispersion/sodicity, waterlogging, soil compaction, production of noxious gases, monosulfide accumulation and disturbance.

Eight adaptive soil-landscape management recommendations to reduce risks of extreme droughts and flooding on soil-landscapes have been developed using two generalised soil-landscape transect diagrams, for the drying and wetting scenarios, and include:

Drying Scenario	Wetting Scenario
Slow the lowering of water levels where practical and promote the extension of colonising plants to increase plant productivity and thus soil organic matter content, which will improve soil structure, stabilise banks and reduce soil erosion.	Increased topsoil and subsoil supply of water, which will increase plant productivity and thus soil organic matter and nutients leading to improved soil structure, reduced risk of erosion and improved stream water quality,
Careful exposure (i.e. limiting extent and exposure time where practical) of hypersulfidic material (pH>4) with Reduced Inorganic Sulfur (RIS) to oxygen (air), which will allow oxidation to occur and reduce the quantity of accummulated RIS and minimise acidification risk (i.e. formation of sulfuric material: pH <4).	Leaching of salts deeper in the soil profile and washing away surface salts reduces soil salinity and sodicity, which reduces salt loads and improves downstream water quality.
Controlled drying, which will cause salts to leach out of saline soils leading to reduced salt loads in the longer-term 50-year hydroclimate changes leading to soil-landscape degradation.	Controlled exposure (via Weir Pool Lowering) and inundation (via Weir Pool Raising) of hypersulfidic material, which will reduce the accummulation of reduced inorganic sulfur (RIS) through improved redox cycling.
Use environmental and irrigation water where possible to prevent deep cracking and salinisation of clay soils and maintain plant cover.	Control inundation and flow rates were possible to prevent development of hypoxic blackwater events and scouring of sediment and monosulfidic black oozes (MBOs).

To show how the major soil-landscape processes impact on negative and positive outcomes from drying (drought) and rewetting (reflooding) scenarios, an interrelating flow diagram is used.

To achieve the goal of best “sustainable soil-landscape management” for the MDB in 50 years, we need an integrated approach to implement a **seasonal wetting and drying regime** to the river and adjacent wetland regulation, which will substantially reduce the many risks related to the **prolonged drying** and **subsequent rewetting**, which can potentially lead to the redistribution and accumulation of acidity and oxidation products (hazards) within a soil profile and the floodplain.

Our 50-year vision for MDB soil-landscapes is that they be adequately restored based on the eight adaptive soil-landscape management recommendations so they can be maintained as sustainable and robust environments, providing for the socio-ecological and economic needs of future generations in the face of the challenges of climate change.

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1. Introduction

This essay explores a 50-year vision of soil-landscapes in the Murray-Darling Basin through a lens of our changing climate and its influence on soil-landscape degradation. We use 'soil-landscapes' as the environmental unit of interest herein as it is an integrated conceptual and practical concept for developing long-term sustainability assessment and management policy to best adapt to climate change in the MDB. A 'soil-landscape' is an area of land with unique landform features and characteristic soil types, which further encompasses various ecosystems and their processes (Conacher 2009; WCED 1987). In the MDB, the following major soil-landscape degradation changes have emerged as a threat for sustainability of ecosystem functions: soil physical changes (soil erosion, structural and textural decline) and chemical changes (acidification, salinisation, and element oxidation or reduction). Already existing degradation processes are further being compounded by climate change and unsustainable land management practices.

This essay provides a summary update on the current state of the soil-landscape science in the MDB with a focus on projected changes in key wetting-drying variables for the dominant soil-landscapes in the next 50 years. We first provide a summary of the distribution of the main physiographic provinces, regions, and soil-landscapes in the MDB. This is followed by projected climate change impacts of several key temporal soil-landscape characteristics across the MDB from: (i) drying caused by prolonged drought conditions, and (ii) wetting caused by extreme flooding. Finally, we discuss the future challenges and opportunities for adaptive soil-landscape management to reduce risks of extreme droughts and flooding.

2. Physiographic provinces, main regions, and soil types of the MDB

The MDB is divided into the following six major physiographic provinces as shown in the physiographic map in Figure 1a. This indicates areas with similar landform histories that can be related to similar soil types in accordance with the Australian Soil Classification (Isbell & NCST 2021; Figure 2), geology and climatic impacts:

- Central Lowlands (37%): Kandosols, vertosols, and sodosols, overlying sandy, clayey, and stony plains with low sandy hills.
- Kosciuszkan Uplands (10%): Rudosols, chromosols, kandosols, tenosols, and sodosols overlying moderately high mountains and detached hills with intervening alluvial valley floors.
- New England–Moreton Uplands (7%): Chromosols, rudosols, ferrosols, and sodosols over mainly undulating granitic plateaus and metamorphic ridges and shale lowlands.
- Macquarie Uplands (6%): Kandosols, sodosols, chromosols, and rudosols overlying mainly granitic and basaltic tablelands with detached hills in the west.
- Murray Lowlands (37%): Calcarosols, vertosols, sodosols, rudosols, and hydrosols which contains over 30, 000 wetlands including 16 wetlands listed under the Ramsar Convention.
- Gulfs Ranges and Fitzroy Uplands (<3%): Rudosols, tenosols, kandosols, and sodosols.

About 85% of the MDB comprises four Australian Soil Classification soil orders (Figure 2; Isbell & NCST 2021), namely: sodosols, kandosols, vertosols, and calcarosols as described in more detail in Table 1. The soil types and associated physiographic provinces have distinct physical and geochemical characteristics that impact on erosion (Pain et al. 2011), cracking and exposure of acid sulfate soil materials (Fitzpatrick et al. 2017a), hydrological, and river/stream water quality processes (Murray-Darling Basin Commission 2008).

The role of agriculture in the MDB and the influence of salt on the MDB's soils and waters mean that its soil-landscapes are often considered through a framing of salt retention and movement. Soil-landscapes are considered key assets of the MDB under the Basin Plan as they are highly dependent on water resources and stores of 'salt loads' in the four main regions shown in Figure

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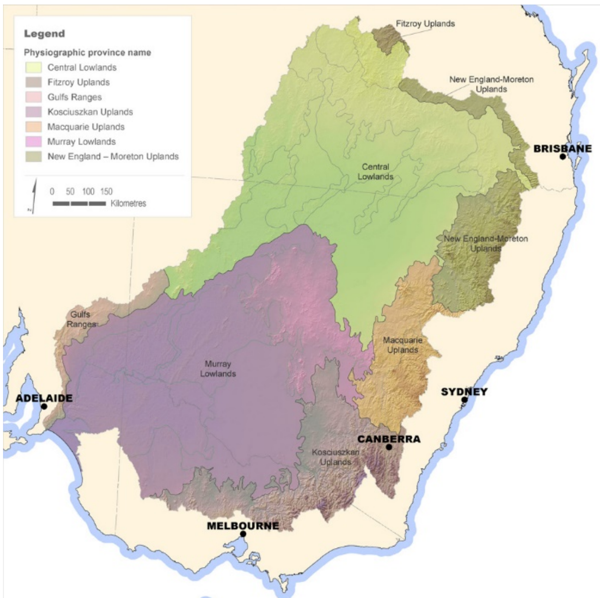
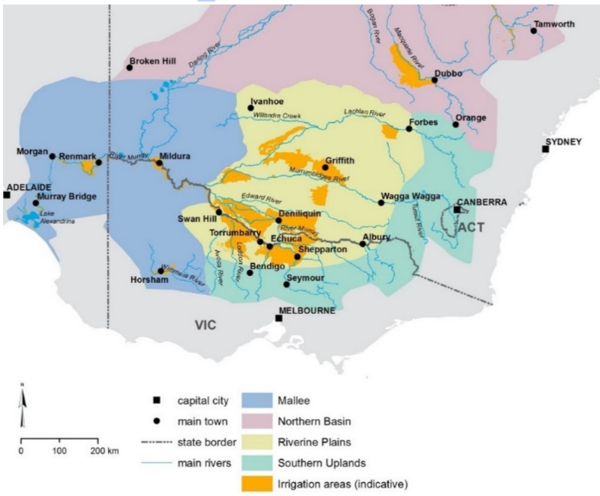
1b. According to Hart et al. (2020) 'salt loads' across the MDB can be divided into the following four main regions: Southern Uplands, Riverine Plains, Northern Basin, and the Mallee Region (Figure 1b). The relative water flow contributions and salt loads from these four regions is shown in Figure 3.





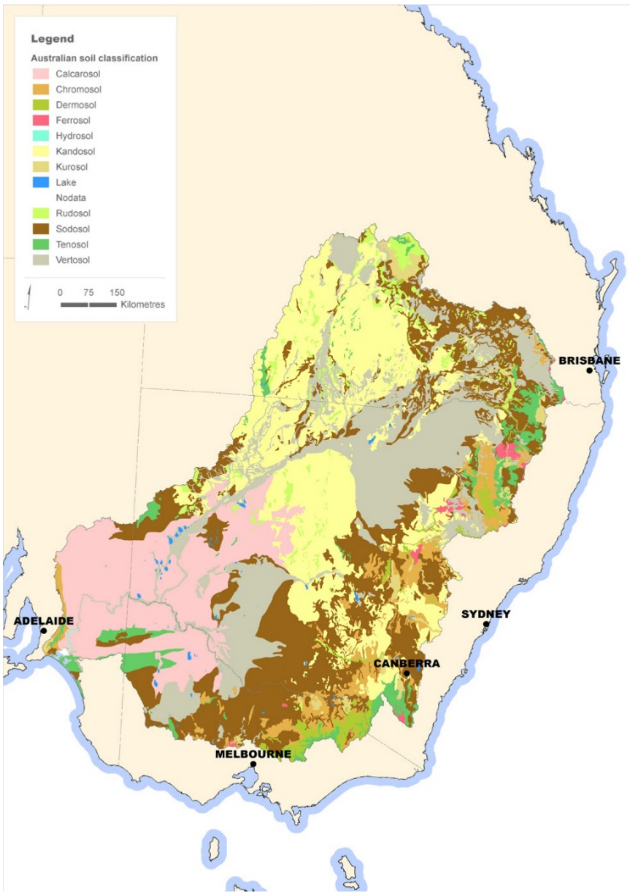


Figure 1a. Map above showing physiographic provinces of the MDB (from Australian Water Resources Assessment, 2012); Figure 1b Map below showing the four main regions in the MDB (Source MDBA 2008)

Figure 2. Soil type (Australian Soil Classification in accordance with Isbell & NCST, 2021) distribution in the Murray-Darling Basin from Australian Soil Resource Information System website www.asris.csiro.au

These average contributions of flow and salt loads to the River Murray salinity at Morgan show that the great bulk of the salt (approximately 70%) in the River Murray comes from the Riverine Plains and the Mallee, while the Southern Uplands contribute most of the flow. As such, an explanation for this can be linked to the distribution of the soil types with dominant Sodosols, Calcarosols and saline Hydrosols occurring in the Riverine Plains and the Mallee (Figure 2). In contrast, Kandosols with low salinity dominate across the Southern Uplands and Northern Basin.

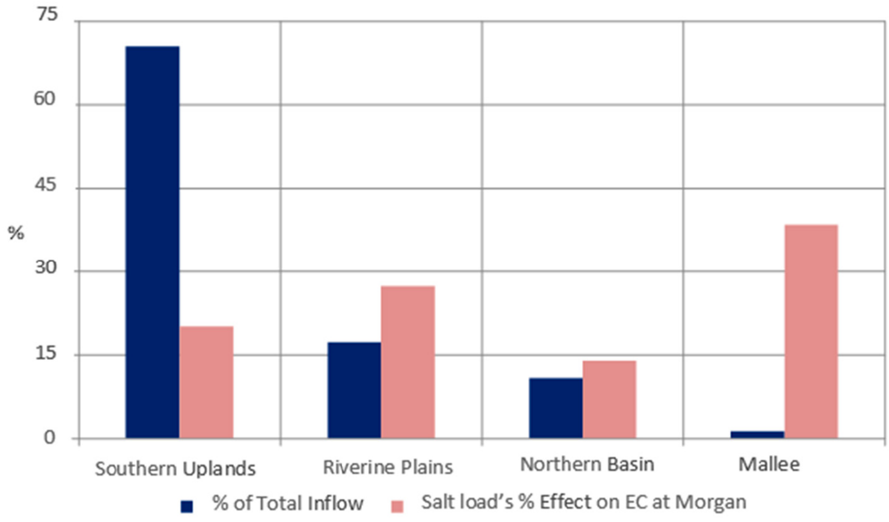


Figure 3. Average contributions of flow and salt loads to River Murray salinity at Morgan. See Figure 1b for locations of the main four regions (after Hart et al. 2020).

Table 1: Soil orders found in the MDB, their percentage coverage, dominant occurrence, land use, characteristics, and agricultural potential.

Soil type	%	Occurrence (Figs 1b & 2) and Land use	Characteristics	Agricultural Potential
Sodosols	24	South, southcentral as well as eastern parts (Mallee & Riverine plains). Used for dryland cropping and horticulture.	Soil with a strong texture contrast between the (upper) A and (lower) B horizons and possessing a high (>6%) exchangeable sodium percentage (ESP) in the B2 horizon. These soils have a relatively impermeable, sodic and clay-enriched subsoil.	Due to their potential for clay dispersion and structural instability, they are susceptible to tunnel and gully erosion as well as dryland salinity if vegetation is cleared. They also have poor water holding capacity and infiltration when dispersed.
Kandosols	23	Dominant in northwest and widely represented in the southeast of the region (Northern Basin and Southern Uplands). Mostly used for grazing.	Soils in which the B2 horizon structure is massive. May have a loamy to clayey texture. Often very deep (>3 metres). Do not have: (i) strong texture contrast (ii) colour change, or (iii) carbonate throughout their profile.	Low to moderate agricultural potential with moderate water holding capacity and chemical fertility. When grazed, these soils are susceptible to surface soil degradation, such as hardsetting and crusting even under low grazing intensities.
Vertosols	22	Stretched around the southcentral (Riverine Plains) to north-central part (Northern Basin). Mainly used for	Brown, grey or black soils with high clay contents (>35% throughout) and are highly structured with slickensides and open cracks at some time in most years.	Highly fertile and have a large water-holding capacity. However, they require a significant amount of water before water becomes available to

		dryland agriculture and horticulture.		plants and to prevent deep cracking which can damage farm infrastructure.
Calcarosols	15	Dominant in the lower parts of the MDB (Mallee). Mostly used for dryland crops and horticulture.	Have high calcium carbonate content, which occurs as soft or hard white fragments, or as solid layers. Often shallow with low water-holding capacity. Does not include deep sandy profiles.	Low to moderate agricultural potential and often have high salinity and pH levels. Alkalinity and boron toxicity may cause issues.
Hydrosols	10	Dominant soil types in the lowest lying and poorly drained positions in the floodplain (Mallee and Riverine Plains). Also found under evaporation ponds.	Soils where the major part of the profile is inundated for prolonged periods (2-3 months) in most years. Common soil subgroups are saline soils and acid sulfate soils, which may occur in saline lake deposits, lake beds, clay pans as well as in lagoons and swampy areas where organic matter has accumulated (may be buried).	Occur in over 30,000 natural wetlands across the MDB including the 16 wetlands listed under the Ramsar Convention (see part VII of this ATSE series on Ramsar Wetlands) - despite the fact that about 90% of the MDB is arid and semiarid. Shallow water tables are commonly saline and may need to be managed to prevent impacts on root zone.
Tenosols, **Rudosols,** **Dermosols,** **Kurosols,** **Ferrosols,** **Chromosols**	0.5 to 4	Minimal representation in the MDB. Rudosols occur mainly in higher parts of landscapes. Chromosols are largely associated with abandoned alluvial tracts in the east.	Rudosols: soils with no to limited pedological organisation. Tenosols: soils with only weak pedological organisation. Dermosols: non texture contrast soils in which the B horizon is structured Ferrosols: non texture contrast soils with high free iron. Kurosols: texture contrast soils in which the B2 horizon is strongly acidic. Chromosols: texture contrast soils in which the B2 horizon is not strongly acidic nor sodic.	Rudosols and Tenosols often have shallow, rocky and poorly developed soil profiles that are not optimal for agriculture. Kurosols generally have very low agricultural potential due to high acidity (pH < 5.5) in the subsoil and low chemical fertility.

3. Climate change impact on soil-landscapes of the MDB

Indigenous peoples in the MDB have recorded creation stories about the remarkable climate changes that occurred both when the sea level began rising 18,000 years ago and when the current sea level stabilised about 5,000 years ago. The creation stories and oral traditions of indigenous people have been passed down from generation to generation, especially about the detailed knowledge of nurseries such as wetlands or reed beds, which were much more extensive in the past. For example, the Ngarrindjeri people believe the land and water is a living body and that they are a part of its existence (Ngarrindjeri Tendi et al. 2007). In the Ngarrindjeri Nation *Yarluwar-Ruwe* plan (Ngarrindjeri Tendi et al. 2007) it is stated: “The land and waters must be healthy for the Ngarrindjeri people to be healthy. We say that if wetlands/nurseries die, our Ngartji (totem or special friend) die, then Ngarrindjeri will surely die."

The MDB has experienced a drying climate for the past 40 years and has also been in drought for much of the last 20 years (Bureau of Meteorology, 2020) with more recent climate modelling indicating that this trend will continue (Reisinger et al. 2024). Projections indicate a hotter and drier future, with more frequent drought periods and extreme weather events, including more extreme flooding events (e.g. CSIRO, 2012; CSIRO and Bureau of Meteorology, 2015; Pittock et al. 2015; Pittock, and Finlayson 2011; Chiew et al. 2023; Prosser et al. 2021; Zhang et al. 2023; Walker et al. 2021; Whetton et al. 2021).

Observations from the Millennium Drought provide insight into how fluctuations between inundation and subsequent extreme drying, events associated with periodically flooded soils, are major drivers of temporal differences in biogeochemical processes occurring in MDB floodplain soils (e.g. Fitzpatrick et al. 2009, 2017a, 2018; Mosley 2018; Stirling et al. 2020). For example, the alteration of subaqueous (submerged) and waterlogged soils due to drying causes physical, chemical, and biological changes that may have major interactive effects on soil properties (Figure 4). However, some soil-landscape changes in the MDB are cyclic and recover during the transition back to subaqueous phases, while others result in permanent or irreversible changes as drained phases.

Maintaining a sustainable use of soil-landscape properties for a 50-year future in the MDB is reliant on a wide variety of interdependent elements. Soil-landscape degradation is strongly dependent on soil-landscape drying (droughts) and wetting (reflooding) cycles as shown in Figure 4 and discussed in Sections 4 and 5. To mitigate soil-landscape degradation threats we make adaptive soil-landscape management recommendations to reduce the risks of extreme droughts and flooding in Section 6.

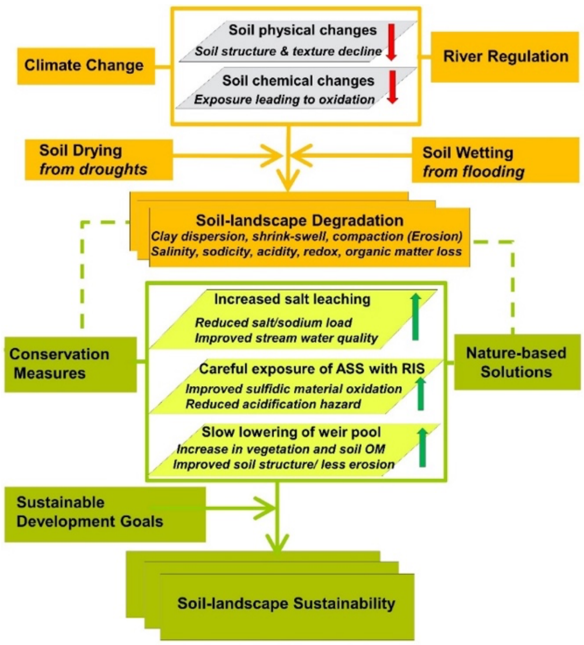


Figure 4. Framework for climate change and water regulation impacts on soil physical and chemical changes and soil-landscape degradation from soil drying (droughts) and wetting (flooding) and future sustainable management opportunities involving conservation measures and nature-based solutions. Where: Red down arrow implies negative outcomes; Green upward arrow implies positive outcomes; ASS = Acid Sulfate Soil; RIS = Reduced Inorganic Sulfur in sulfidic materials; OM = Organic Matter.

4. Climate change threats from prolonged drought on soil-landscape drying

The Millennium Drought (1998-2010) caused widespread lowering of water levels in lakes, wetlands, and the river channel leading to broadscale soil-landscape drying in the MDB (Fitzpatrick et al. 2009). Soil drying from exposure or drainage of formerly submerged soils and sediments due to prolonged drought conditions has also led to physical, chemical, and biological soil changes that have had further interactive effects on other soil properties. These are outlined below.

4.1 Soil physical changes: decline in soil structure and texture

River regulation and land use change across the MDB has led to the following landscape degradation processes with consequences that affect soil erosion, salinity, and soil formation within wetlands:

- Removal of native vegetation for dryland agriculture has increased groundwater recharge leading to rising saline water tables, secondary salinity, and salt storage within floodplains (Figure 5).
- Changed hydrology due to land use change have allowed salt efflorescences, sodic soil dispersion, and removal of surface soil layers by wind or sheet erosion which then form scalds and exposed hardpans (Figure 6).
- The loss of vegetation and organic surface soils within the floodplain has led to soil sealing in some areas and increased surface run-off (Figure 5).
- Tillage, logging, stock pugging, grazing pressure, and vehicle trafficking creating densipans (hard cemented layer of very fine silty sand) or introducing oxygen to saline discharge areas with hypersulfidic material (e.g. Fitzpatrick et al. 2009), which has resulted in affected areas with expanded erosion, salinity and sulfuric material (Figure 7 (c)).
- Prolonged drying of vertosols can form deep cracking, which increases oxygen penetration depth into hypersulfidic material to rapidy form sulfuric material (Figure 7 (c)).
- Sedimentation within the weir pool and behind weirs, blocking banks, levee banks, and drains resulting in burial of natural organic bottom sediments and raising of sill levels (Figure 8).
- Fine sediment deposition during flood events increases erosion potential (by water and wind) during prolonged droughts due to lowered water levels and sediment exposure.

4.1.1 Saline and sodic soil landscapes

Saline (or salt-affected) soils are those with large amounts of soluble salts, such as NaCl. Saline soil-landscapes in the MDB form under different environmental conditions as shown in Figure 5 and have the following hydrology defined saline land categories (Fitzpatrick 2008): (i) non-groundwater-associated salinity (NAS), or dry saline land or transient salinity, which is not hydrologically connected to a saline water table (see Figure 6 for more detail; Rengasamy 2002); (ii) deep NAS or 'salt bulges', which occur well below the root zone of former native vegetation (usually >2 m from soil surface); (iii) primary (natural) Groundwater Associated Salinity (GAS) or dryland salinity is caused by rising saline groundwater and salt accumulation in soils due to evaporative water loss in saline seeps and (iv) secondary (anthropogenic) Groundwater Associated Salinity (GAS) caused by rising saline groundwater and salt accumulation in soils due to evaporative water loss in saline seeps.

Saline soil-landscapes in the MBD have generally developed since European settlement due to extensive land clearing and the subsequent replacement of deeply rooted native vegetation by shallow rooted, water-inefficient annual crops and pastures. Evapoconcentration in previously vegetated and inundated soil-landscape surfaces has increased soil surface salinity, leading to salt scalds and the precipitation of salt efflorescences (Fitzpatrick 2008) with the following categories defined by hydrological and geochemical environments: (i) Alkaline (sodium carbonate dominant,

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pH >9), Halitic (sodium chloride dominant) and Gypsic (gypsum / calcium sulfate dominant). Highly soluble salts (such as NaCl and gypsum) precipitate out of solution as the water evaporates, creating surfaces that are inhospitable to most organisms (Fitzpatrick 2008; Stirling et al. 2020).

Across the MDB, salinisation of floodplain soils is considered a major factor in the declining health of floodplain trees (Hart et al. 2020; Walker et a. 2021, 2023). There has been extensive vegetation death in many areas with dieback being a function of the combined effects of rising saline groundwater and river regulation; salinisation dieback is exacerbated by the effects of drought.

Soil salinity induced by climate change refers to a significant increase in the concentration of soluble salts in the soil column caused by various climate change aspects including increasing air temperature and evaporation rates, changing rainfall patterns, rising sea level, and accelerating droughts.

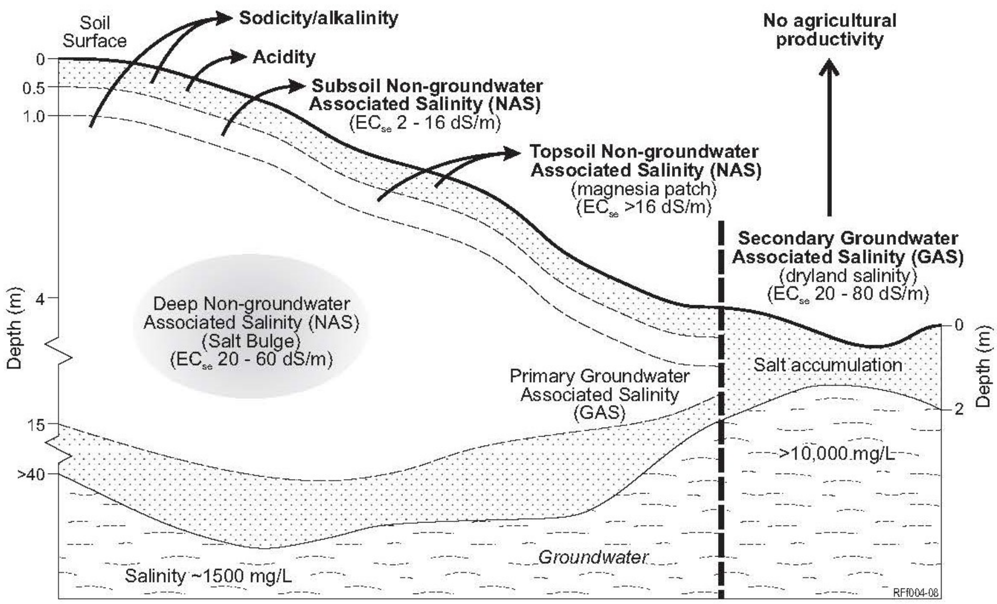

Figure 5. Schematic cross section showing various categories of saline land as defined by hydrology (after Fitzpatrick 2008)

When sodosols in the MDB (Figure. 6) are subjected to drying and wetting cycles, they are affected by the following key processes (Fitzpatrick et al. 1994; Fitzpatrick 2008; Rengasamy et al. 2010):

- **Soil physical changes** due to:
    - o Textural changes associated with clay dispersion, desiccation, shrinking and swelling, compaction and transport (e.g. erosion and deposition processes);
- **Soil chemical changes** due to:
    - Soil structure and physical changes that influence oxygen diffusion (e.g. sodicity causing waterlogging), organic matter decomposition, soil redox conditions and transport of nutrients, salinity, alkalinity, acidity and toxic elements.

Wetting and drying cycle driven processes are influenced strongly by soil texture and mineralogy, affecting how a specific soil profile (or wetland) may be impacted by flooding or drying through space and time. For example, sodosols have a dense structure and high strength when dry, are particularly susceptible to waterlogging with low oxygen availability, and have slow water infiltration through the subsoil (B horizons) resulting in perched water tables. These soils are

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usually strongly alkaline and often contain toxic concentrations of boron and salt, which, alongside the physical restraints, restricts root growth. Sodosols react completely differently on flooding or drying when compared to deep sandy loam soils with no physical, chemical or drainage issues.

Sodification of soils is a substantial risk in soils exposed to saline groundwater seeps during dry periods (Figure 6). On return to 'normal' conditions (i.e. exposure to rain or fresher channel water) the lower salinity water causes sodic clays to disperse. Clay dispersion degrades the water quality (via turbidity and salinity) of run-off and receiving waters, and can remove seed banks and seedlings by erosion of the lighter textured suface soils (A horizons) due to lateral water movement when water cannot infiltrate into the subsoils (B horizons) (Rengasamy et al. 2010). Drying of already sodic soils further increases soil EC and exchangeable sodium percentage (ESP) via increased saline groundwater inputs and evapoconcentration (Mosley et al. 2017).

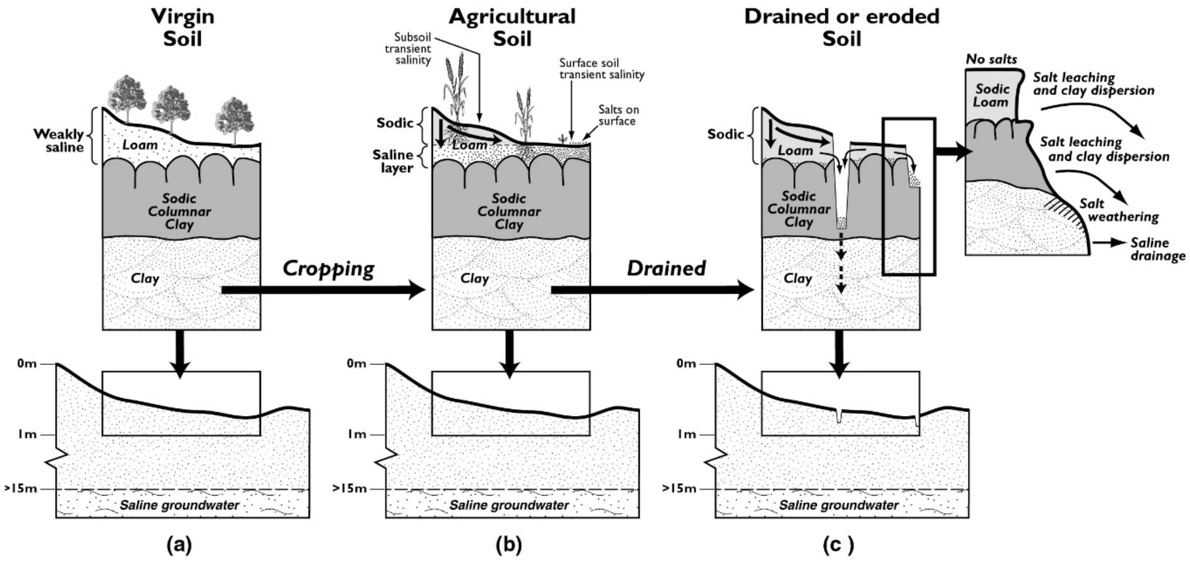

Figure 6. Soil-regolith model showing salt transport and erosion processes leading to formation of subsoil and surface soil transient salinity (not associated with the saline groundwater tables). NOTE: Sodic duplex soil (sodosol) is used here as an example but these processes also do occur in gradational soils or in soils with thin A horizons directly overlying saprolite (after Fitzpatrick 2008)

When shallow surface NAS soils are drained, soils are leached and salt efflorescences on the soil surface are dissolved (Figure 6 (b)). Salt crystals develop at depth in sodic soils where salt is leached through the subsoil clay layers on edges of gullies or drains (Figure 6 (c)). This causes stream banks to erode by salt weathering and if these processes are expresed on the surface of the soil, bare eroded saline scalds are evident (Fitzpatrick 2008; Rengasamy et al. 2010).

In alkaline soils, sodicity typically increases alongside clay content with depth. Sodicity in non-saline soils causes collapse of fine soil structures and the development of massive structures, which on drying causes the soil to have high strength (Rengasamy et al 2010), a process which reduces turbidity upon reflooding but also prevents root penetration. Dispersed sodic soil horizons are inhospitable to plant roots, can be poorly draining, and are highly susceptible to erosion when disturbed (Bethune and Batey 2002). On drying, the massive structure can restrict the uptake of water and nutrients due to waterlogging.

4.1.2 River bank slump and tunnel erosion

River banks along the Murray River and Darling River slump during soil drying and water level lowering through over steepening of the bank (bank toe erosion), or through the removal of water pressure from the pool (drawdown effect). Over steepening of the bank may occur where flow patterns cause scours to form at the channel margins and drawdown slumping is generally associated with poorly draining soils. Soil erosion caused by bank slumping has negative effects on water quality and can damage or destabilise nearby infrastructure (Hubble et al. 2014).

There is a risk of bank adjacent tunnel erosion and subsequent topsoil instability during changed subsurface soil drainage. Soil profiles at risk of tunnel erosion are those in which there is subsurface lateral water flow such as that caused by an impermeable subsoil horizon (e.g. in sodosols).

4.1.3 Soil compaction

Compaction of soil profiles under drying conditions occurs when pores that are usually filled with water empty and the weight of overlying soil 'crushes' the gas-filled voids. Compaction can significantly reduce profile drainage capacity, plant establishment, and soil structural stability, leading to increased risk of soil erosion (Stirling et al. 2020). Dewatering of organic matter rich horizons can lead to irreversible soil compaction as moisture and organic carbon is lost and voids are crushed by the weight of overlying materials. Compaction in this scenario may decrease organic matter decomposition rate due to limited oxygen exposure of the inner profile surfaces (Stirling et al. 2020). Compaction or the formation of hardpans or toxicity may also limit plant establishment in newly drained landscapes (Fitzpatrick et al. 1996; 2017a).

4.1.4 Vertosol (cracking clay) landscapes

Prolonged drying of vertosols forms large and connected pores and cracks that allow rapid infilration of fluids into the profile. Vertic soils within the Lower Murray Irrigation Area (LMRIA) are particularly susceptible to deep cracking, with cracks as large as 3.5 m deep observed at sites in the Lower Murray as a result of the Millennium Drought (Mosley et al. 2014; Fitzpatrick et al. 2017a). Cracking substantially increases oxygen penetration depth into the soil profile and increases the soil extent exposed to oxidising conditions. There is a substantial risk at sites where sulfide minerals (RIS materials) coexist with shrink/swell clay soils due to the potential for severe acidification if these materials are oxidised. Cracking can also cause severe damage to farm infrastructure.

Prolonged exposure of normally inundated or saturated vertosol soils may also exacerbated the development of saline sodic soils through the increased salt concentration from salt evapoconcentration. The inherent surface evaporation rate of exposed soils is constrained by water movement through the profile and therefore by soil texture and structure. Increased salinisation and sodificiation reduces soil water infiltration rates and therefore reduces recharge by rainfall, meaning the landscape has less capacity to flush floodplain salts.

4.2 Soil chemical changes: Exposure leading to oxidation

Soil exposure and the periodic draining of wetland soils in the MDB are major drivers of spatial and temporal differences in soil properties that affect the structural, textural and biogeochemical processes taking place (Fitzpatrick et al. 1996; Fanning et al. 2017). Periodic exposure of typically wet soils to air:

- Increases oxygen diffusion into the soil profile, increasing soil redox potential, leading to changes in pH, mineralogy and organic matter,

- Increases release and mobility of acidity and potentially toxic elements (PTEs) to porewaters and the environment, and
- Oxidises soil organic matter, thereby affecting carbon (CO_2 and CH_4 gas) emissions and nutrient cycling.

These processes are largely influenced by soil microbiology as microbial communities change from anaerobic dominated communities to aerobic dominated communities (Jayalath et al. 2016; Kölbl et al. 2017, Fanning et al. 2017; Stirling et al. 2020). Periodic exposure prevents the accumulation of materials that may pose a significant environmental threat under prolonged exposure events (as observed during the Millenium Drought).

4.2.1 Exposure of acid sulfate soil landscapes with hypersulfidic material

Acid sulfate soils (ASS) is the name given to soils in which sulfuric acid may be produced, is being produced or has been produced. Acid sulfate soils with hypersulfidic material (pH >4) contain sulfidic minerals (principally iron sulfides, such as iron pyrite FeS_2) and are formed under waterlogged (anaerobic) conditions and pose no problem if left undisturbed and saturated. If disturbed and aerated, ASS with hypersulfidic material can rapidly transform to sulfuric material (pH <4) and become 'the nastiest soil in the world' (Dent and Pons 1995). An estimated 16 million ha of acid sulfate soils in Australia is encountered in inland environments such as the MDB (Fitzpatrick et al. 2011).

Under more 'normal' conditions, such as prior to draining natural wetlands for agriculture on historic floodplains in the MDB, natural wetlands cycled between wetting and flushing, and partial drying conditions in response to seasonal and climatic cycles. These periods of wetting and drying would have prevented an excessive build-up of hypersulfidic material by both chemical and physical processes.

The subsequent post-European **construction of locks, barrages and levee banks** in the MDB has allowed accumulation of hypersulfidic material (pH >4) in subaqueous (saturated, waterlogged) soils (Figure 7 (a)) due to:

- Artificially stable water conditions in many wetlands for over 80 years that has resulted in considerable build-up of hypersulfidic, hyposulfidic and monosulfidic materials due to permanent waterlogging (i.e. lack of regular drying cycles to oxidise or "burn off" pyrite that has formed naturally).
- The evaporative concentration of sulfate (i.e. source of sulfur for pyrite formation) from groundwater-connected river salt loads during the period of stable pool level.
- The lack of natural scouring and seasonal flushing of wetlands.
- A plentiful supply of organic matter from aquatic vegetation (e.g. *Phragmites Australis* and *Typha* sp.).

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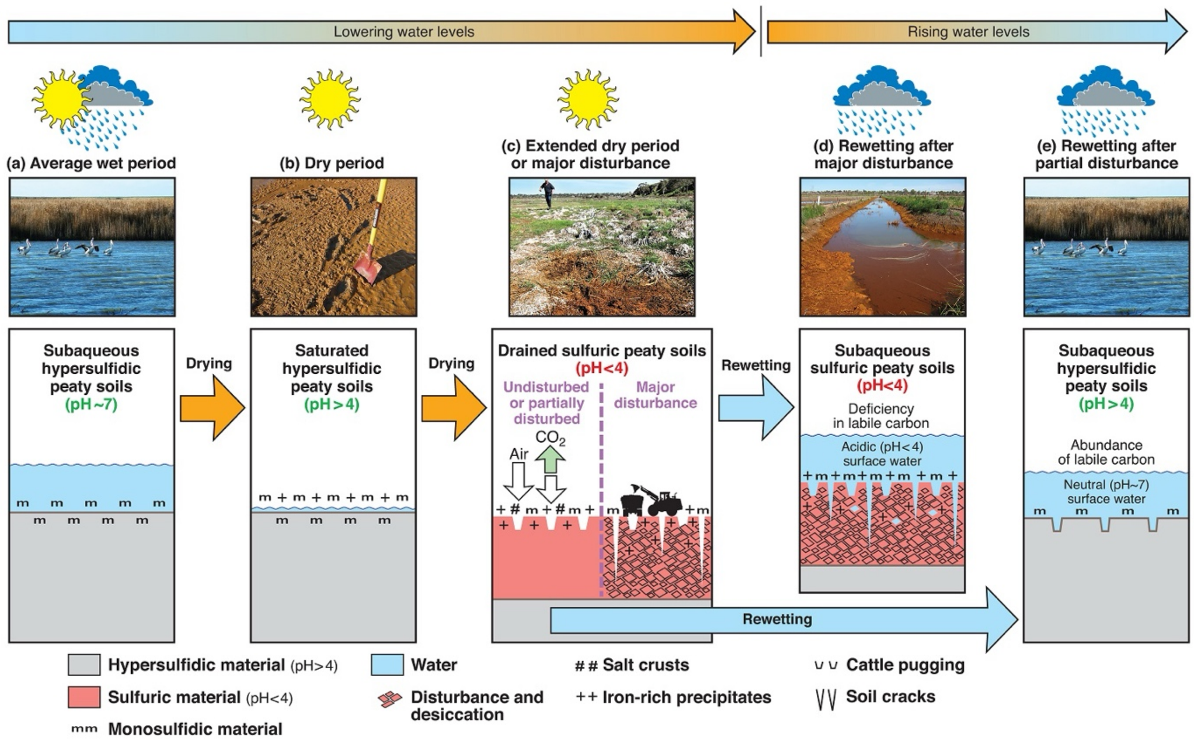

Figure 7. Conceptual model illustrating transformation processes of acid sulfate soil materials caused by drying (droughts) and rewetting (flooding) conditions (modified from Fitzpatrick et al. 2018).

Both natural (e.g. Millennium Drought, Figure 7 (b)) and anthropogenic processes caused by humans (e.g. excavation of wetlands) and cattle (e.g. pugging, Figure 7 (c)) cause these soils to dry. Drying and exposure results in the decline of the water table and exposure of the hypersulfidic material to air or oxygen, which induces oxidation of iron sulfides (FeS_2) and the formation of sulfuric acid or sulfuric material as shown in Figure 7 (c) (Fitzpatrick et al. 2009, 2017a; 2018; Fanning et al. 2017; Shand et al. 2009; 2010). Exposure allows microbially mediated oxidation of reduced inorganic sulfur (RIS) in hypersulfidic material and subsequent release of acidity (H+), which transforms hypersulfidic material (pH>4) to sulfuric material (pH<4). The initial form of acidity occurs as soluble or readily exchangeable acidity (i.e. sulfuric acid) in the soil profile pore waters. Secondary minerals, such as jarosite, sideronatrite and schwertmannite may also form within soil profiles, which act as 'stored' acidity (i.e., they are sparingly soluble and may produce acidity upon dissolution during re-wetting; Fig. 7 (d)) (Fitzpatrick et al. 2017b; Trueman et al. 2020). This 'stored' acidity in secondary minerals continues to be important as the Fe^{3+} in both jarosite and schwertmannite can undergo further hydrolysis and subsequently result in the release of acidity into the surrounding environment down the hydraulic gradient of the sulfuric acid sulfate soil source.

Evapo-concentration of saline acidic seepage containing dissolved Fe and Al will concentrate both soluble and retained acidity at the surface (and near surface to the capillary fringe of soil peds and columns) in the form of Fe or Al hydroxysulfate minerals and salt crusts or efflorescences (Fig. 7 (c)), such as jarosite and natrojarosite (Fitzpatrick et al. 2018, Creeper et al. 2015a,b; Mosley et al. 2017). Prolonged drying can potentially lead to the redistribution and accumulation of acidity and oxidation products (hazards) within a soil profile and the floodplain.

The following wide range of environmental hazards are generated by the oxidation of hypersulfidic material:

- Severe acidification of soil and drainage waters (<pH 4 and often <pH 3) (Figure 7 (d)),

- Mobilisation of metals (e.g. iron, aluminium, copper, cobalt, zinc), metalloids (e.g. arsenic), nutrients (e.g. phosphate), and rare earth elements (e.g. yttrium, lanthanum), deoxygenation of water bodies (Figure 7 (c) and (d)),
- Production of noxious gases (e.g. H_2S) and CO_2 (Figure 7 (c)) (Hicks and Fitzpatrick 2008).
- Scalding (i.e. de-vegetation) of landscapes (Figure 7 (d)).

The degree of acidification in MDB soils and water is partially determined by the substrate's acid neutralising capacity (ANC), which is determined by the content of organic matter, alkaline minerals, and clay particles in the soil environment (Fitzpatrick et al. 2009, Shand et al. 2010). ANC buffers against changes in pH by reacting with excess H^+ ions to form new compounds or by scavenging H^+ out of solution due to negative surface charges. Armouring of carbonate ANC material by coating with oxides, clays and organic residues may make it 'unavailable', reducing the effective acid neutralization capacity. The generation of sulfuric acid and formation of acidic minerals such as jarosite has been found to prevent (or delay) soils with sulfuric material in the MDB from returning to 'normal' during restoration (e.g. Mosley et al. 2014a,b; Fitzpatrick et al. 2017a).

4.2.2 Accumulation of monosulfidic soil material during drying

Formation of monosulfidic (FeS) material and finely divided organic matter is common in acid sulfate soil affected drainage channels, such as drains and waterways behind floodgates and barrages (Cheetham et al. 2012, Mosley et al. 2014a, Mosley et al. 2019, Thomas et al. 2019). Buildup of these materials is commonly called 'monosulfidic black ooze' (MBO). Hazards associated with monosulfide accumulation and disturbance include deoxygenation of water, severe acidification and the release of potentially toxic elements (for example metals and metalloids such as arsenic), and high levels of nutrients (Bush et al. 2004, Mosley et al. 2014a,b).

4.3 Airborne impacts

Odours and dust are the prominent airborne impacts of drying in normally inundated soil-landscapes. Drying anaerobic soils may release hydrogen sulfide and malodorous organic S compounds that naturally form by microbial metabolic processes when sulfur and organic matter are present (e.g. Hicks and Fitzpatrick 2008; Fitzpatrick et al. 2009). Complete desiccation of surface soils and loss of cover vegetation has led to raised dust in the Lower Lakes region, due to wind erosion of bare soils or salt efflorescences (Fitzpatrick et al. 2018). Soil particles susceptible to wind erosion are generally the most valuable particles in the soil, with high nutrient and organic matter concentrations. In addition to downwind human health concerns, downwind water bodies may experience decreased water quality (sedimentation/eutrophication) while the source site experiences an effectively irreversible loss of topsoil (Marx et al. 2009, Javadian et al. 2019).

4.4 Animal and human behaviours

Exposure of previously inundated wetland areas can lead to changed animal and human behaviour, potentially resulting in soil disturbance by livestock, people, vehicles, and local fauna. Pugging, wallowing, and vehicle use while moist will negatively affect surface soil structure and therefore leave soils more vulnerable to soil erosion once dry/desiccated (Fitzpatrick et al. 1996). Compaction from animal and vehicle use may also change profile drainage, reducing a profile's capacity to drain freely under gravity (Steward et al. 2012).

4.5 Bush fire impact on soil-landscapes

Exposure and drying of saline wetland soils during prolonged drought conditions followed by the so called "mega bushfires" in 2019-20 (Lane et al. 2022) resulted in the permanent or irreversible conversion of some minerals into new minerals under a range of temperature conditions (Fitzpatrick et al. 2014). Following this severe bushfire in the MDB, coarse soil fractions comprising hard, ceramic-like fragments were formed within clayey soils with high organic matter (e.g. burn peaty clays). These soil types have been identified in Australian soils and has led to the introduction of "burnt soil materials" in the Australia Soil Classification, now classified as "fusic material". Extremely high temperature fires (>800°C for more than 1 hour or 600°C for 80 hours) were shown to melt salt-rich saline acid sulfate soil types to form masses of glass-like groundmass. These solid masses reduce the chemical, physical, and consequently biological characteristics of soil condition. Fire in such areas leads to permanent soil loss by soil erosion.

4.6 Summary of soil-landscape threats from drying caused by prolonged drought

The following eight predicted threats/risks to future (50-year) MDB soil-landscapes as anticipated under the drying hydroclimate scenario caused by prolonged drought conditions is shown in the generalized soil-landscape transect conceptual model (Figure 8):

1. Unstable soils (decline in soil structure and texture as noted in Section 4.1) can lead to soil erosion, river bank collapse and slumping.
2. Drainage of sodic soils can lead to soil compaction and erosion forming gullies (as noted in Section 4.1.1; Figure 6).
3. Increased evapotranpiration can lead to increased soil salinity (as noted in Section 4.1.1; Figure. 5) and soil erosion (as noted in Section 4.1.1; Figure. 6).
4. Newly exposed organic matter will decompose during weir pool lowering and lead to soil instability and compaction (as noted in Section 4.1.3).
5. Excessive oxidation of flooded organic matter on return to Normal Pool Level (NPL) can lead to minor acidification and soil erosion via peat collapse (as noted in Section 4.2.1, Figure 7 (c)).
6. Exposure of hypersulfidic material leads to the formation of sulfuric material with potential stream acidification upon rewetting and mobilisation of metals (noted in Section 4.2.1, Figure 7 (d)).
7. Increased water velocities and rapid draw down can re-suspend monosulfidic material (MBO) leading to stream acidification (noted in Section 4.2.2, Figure 7 (d)).
8. Increased Ground Water (GW) discharge increases sulfur inputs, which can lead to RIS accumulation upon rewetting (as noted in Section 4.1.4, Figure 5).

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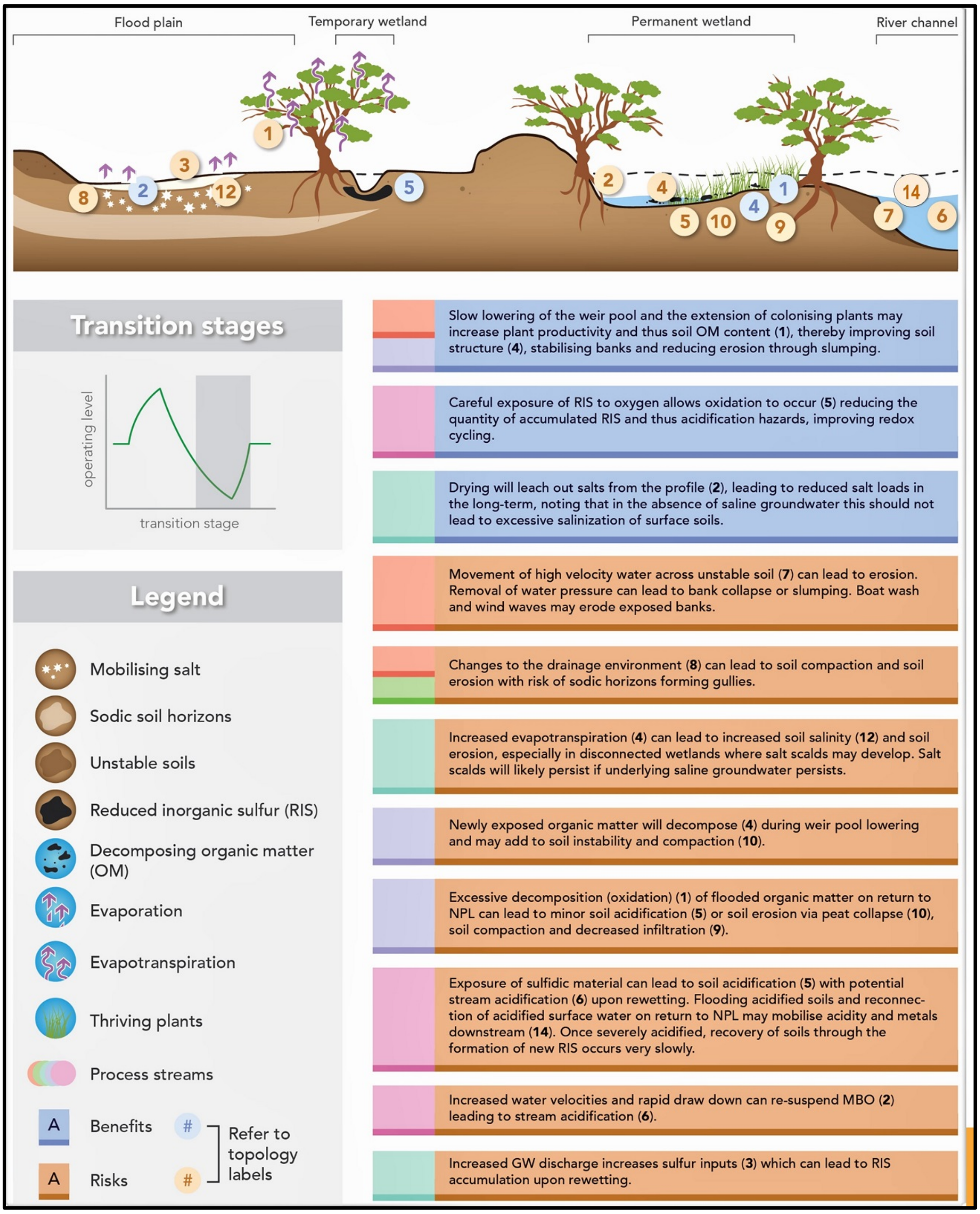

Figure 8. Generalized soil-landscape transects describing the distribution of the main soil types during the progressive stages of drying caused by prolonged drought conditions. Where: WPR = Weir Pool Raising, WRL = Weir Pool Lowering; NPL = Normal Pool Level. (modified from DEW 2021).

5. Climate change threats from prolonged flooding on soil-landscape wetting

Wetting of previously dry materials in several MDB wetlands caused physical, mineralogical and biochemical processes to proceed where they had previously been water limited (Fitzpatrick et al. 2017a,b; Stirling et al. 2020). Although these processes are not independent, typical soil biochemistry changes that occur as a soil profile is rewet or resubmerged include (Ponting et al. 2021):

- Depletion of oxygen that leads to anoxia, increased hydrogen sulfide and methane concentrations, nutrient availability and increased phytotoxins (e.g. sulfides) in the ‘reduced’ soils,

- As soil redox potential decreases the speciation and mobility of redox sensitive metals (e.g. Fe, Mn) and metalloids (e.g. As) are altered (e.g. Potentially Toxic Elements (PTEs) and manganese and iron hydroxides undergo reductive dissolution and may accumulate to levels that are toxic to plants,
- Sulfate is reduced, generating sulfidic materials (FeS, FeS_2) and alkalinity (increasing pH) while PTEs may be immobilised due to precipitation of metal sulfides, and
- As oxygen is depleted, dissolved organic matter (DOM) increases and nitrate is reduced to ammonia by some soil microorganisms to become the main form of plant available mineral nitrogen.

During flooding, these biochemical processes will primarily occur at the oxic-anoxic interface and in the anoxic soil layers. The kinetics of these processes are of great importance because the location of the oxic-anoxic interface is subject to change due to floodwater/re-filling residence times and fluctuating water table levels, meaning the effect of flooding is not easy to predict (Ponting et al. 2021). Chemical reduction processes will often occur in a known sequence in the soil profile, a so called 'redox ladder', and are also influenced by the availability of organic matter (Kolbl et al. 2017).

5.1 Soil structure and textural changes

Soil texture and structure interact with each other to determine soil pore size and connectivity; soil pores control water movement through the profile, with light textured soils (i.e. sands) or soils with large or well connected pores allowing greater saturated hydraulic conductivity rates (i.e. water movement through already wet soil) and heavy textured soils (i.e. clays) or soils with small or tortuous pores allowing greater unsaturated hydraulic conductivity (i.e. water movement into and through dry soil). As such, processes affected by water movement, such as mobilisation of acidity and accumulation of precipitates such as sulfur minerals or salts will vary throughout the reach and may require contrary management approaches during drying after flooding (e.g. Mosley et al. 2019).

5.2 Vertosols (cracking clay soils)

While most soils will swell to some degree when wetted from dry, soils containing substantial proportions of shrink/swell clays (Vertosols) have the greatest increase in volume. Vertosols in the LMRIA and elsewhere in the MDB develop *Gilgai* (Kamilaroi and Wiradhuri word meaning small water hole or depression that has been adopted into modern soil science (Aquatic Ecosystem Health Science Integration and Capacity Building Group 2013)) microrelief in response to an excess in water availability (Fitzpatrick et al 2017a, Arnold et al. 2020). This process effectively has the effect to 'bury' RIS and oxidation products, lowering the potential for re-oxidation and surface water impacts during subsequent drying (i.e. improved with each wetting and drying cycle). In summary, this process has positive implications ASS management as it assists to re-establish conditions conducive to RIS reduction at a lower position in the soil profile (Fitzpatrick et al 2017a).

Vertosols have a high moisture holding capacity that can support vegetation later into a dry summer compared sandy soils. Rewetting Vertosols will wash surface debris such fine self-mulching clay and organic matter into the cracks, increasing the speed with which the soil reincorporates itself.

5.3 Saline sodic soils

Re-inundation of saline-sodic soils presents a risk of dispersion, particularly as the flood water (or rainwater) typically has a lower ionic strength or salinity than the soil porewater (Rengasamy 2002, Rengasamy et al. 2010). Dispersion of sodic soil causes clay aggregates to dissolve as water fills the interlayer spaces and force clay particles apart, filling pore spaces with unstructured clay particles and significantly reducing hydraulic conductivity (Rengasamy 2002). Dispersed clay in the water column also decreases water quality through increased turbidity (Rengasamy 2002, Rengasamy et al. 2010). Clay dispersal at the soil surface poses an acute barrier to movement (vehicles/animals) and will form a hard-setting soil crust on drying (Fitzpatrick et al. 1994, 1996). Changes in water movement through the soil profile and decreased plant germination due to hardsetting surfaces further increase the risk of soil erosion (Mosley et al. 2017).

Inundation of saline sodic soils with freshwater with low calcium or magnesium content does not provide remediation of sodic soils, but rather leaches sodium cations leaving soil prone to structural collapse (Fitzpatrick et al. 1994). Inundation that inputs fresh water into the soil profile recharges shallow groundwater with fresh water, dissolves solid salt crystals, and provides a mechanism for salt export. However, irrigation and drainage with River Murray water has been shown to reduce soil salinity and sodicity in Vertosols in the LMRIA (Mosley et al. 2017).

5.4 River bank slumping

There is an increased risk of bank slumping and topsoil instability during re-flooding where soils have previously been eroded during water level lowering. Soil erosion caused by bank slumping has negative effects on water quality and can damage or de-stabilise nearby infrastructure (Hubble et al. 2014, Bovi et al. 2020). Furthermore, flooding, even at relatively low velocity may cause soil erosion in unvegetated sites where stream flow is concentrated and underlying soils are poorly structured and not massive. Shallow water velocities can lead to erosion of surfaces with a slope of at least 3.5% (e.g. Thomas et al, 2019, Wong et al 2016). Relatively minor erosional events may lead to gully formation in sodic or otherwise unstable soil profiles (Figure 6).

5.5 Changes in soil structure by wetting

Compaction that occurred under drying conditions may be irreversible where organic carbon was lost from organic horizons, where voids were crushed by the weight of overlying materials, or where the loss of soil mineral structure has occurred (Stirling et al. 2020, Fitzpatrick et al. 2017a). However, soil compaction may recover to some extent following inundation where increased moisture causes swelling of clays and the decomposition of organic matter generates soil vapours or allows aggregate formation. To this end, soil structure has been found to improve as organic matter is incorporated into the profile, which is further enhanced by the re-establishment of wetland vegetation increasing litter deposition and root growth.

Re-flooding and maintaining stable weir pool levels and groundwater levels reduces the storage capacity of soils within the catchment because saturated soils have severely limited air-filled porosity compared to non-saturated soils (Thomas et al. 2019). Rewetting of texture contrast soils with poorly structured B horizons may result in waterlogging as the dry subsoil horizons pose a substantial barrier to vertical water movement.

5.6 Reflooding leading to oxygen depletion and decreased soil redox potential

Inundation of acid sulfate soils that contained sulfuric materials (pH<4) in several wetlands in the MDB rapidly (i.e. within a few weeks) induced anoxia in the soils, particularly in soils with heavy texture and high organic matter contents with abundant labile carbon as shown in Figure 7(e) (Kölbl et al. 2017; Yuan et al. 2015, Jayalath et al. 2016, Fanning et al. 2017, Lee et al. 2021). Anoxic conditions generate carbon dioxide, nitrous oxide and methane, thereby adding to GHG emissions (Mosley et al. 2021). Nitrous oxide and methane production typically exists in a balance wherein the redox conditions for one are not suitable for the other; wet soils can cycle between producing these two gases in a diurnal rhythm (Stirling et al. 2020). As soil redox potential decreases in flooded wetlands, the speciation and mobility of redox sensitive metals and metalloids (e.g. PTEs) is altered and manganese and iron hydroxides undergo reductive dissolution, which can accumulate to levels that are toxic to plants.

The prime consumer of oxygen in wet soils is microbial organic matter decomposition and, while decomposition is necessary to release plant available nutrients, rapid decomposition of organic matter can lead to deoxygenation of both soils and water as has been observed in the Chowilla Floodplain region (Murray-Darling Basin Commission 2006).

The capacity for a wetland to capture organic matter is influenced by topography and water retention time with shallow wetlands and floodplains likely to provide more ecological benefits than deeply incised channels due to their greater horizontal area affected by changing water levels such as in the Nelwart Lagoon. Actively revegetating such wetlands with shoreline plants that extended into a lagoon floor can aid RIS formation by providing an additional source of labile organic matter and alkalinity (Shand et al. 2010) as shown in Figure 7 (e).

In soils with sulfur salts present (in the soil itself or dissolved in the water), anoxia typically leads to both abiotic and microbial sulfate reduction and the production of RIS materials (Fanning et al. 2017). Under optimal conditions, RIS starts forming within days of saturation; however, meaningful accumulation of RIS takes at least weeks-months (e.g. Jayalath et al. 2019). Re-establishment of reducing conditions and RIS production consumes acidity and generates alkalinity, thereby having a positive impact on improving pH of surface waters or by removing acidity by storage in reduced minerals such as pyrite (Figure 7(e)). Sulfate reduction is enhanced in the presence of low molecular weight organic matter or labile carbon, which is an energy source for microorganisms.

5.6.1 Acid sulfate soil materials during re-flooding

Reflooding a wetland following a period of managed drying (or prolonged drought) has potential to mobilise acidity (soluble and stored forms), salinity and or metals to the receiving environment (e.g. Simpson et al. 2010) as shown in Figure 7 (d). In highly acidified acid sulfate soil wetlands, reflooding has led to surface water acidification and a heightened risk of ecological damage through persisting periods (i.e. years) of low pH, increased metal mobilisation and off-site transportation of acidity and metal(loids) (Baker et al. 2013; Creeper et al., 2015a,b; Mosley et al., 2014b; Shand et al. 2009, 2010). Acidification can develop quite quickly (weeks) under suitable ASS conditions in many River Murray wetlands (Thomas et al. 2019a,b).

During reflooding, acidity and oxidation products may be mobilised by the in-flowing waters, either by surface run-off or by lateral through flow, potentially resulting in acidification of surface and near surface water (e.g. Wilson et al. 1999; Mosley et al. 2014a,b); however, the degree to which acidity will be mobilised (to surface waters) is specific to the soil and hydrological characteristics of each wetland. During reflooding of permeable sandy soils, acidity may be displaced downward, deeper into the profile by advective piston flow, where it may persist for many years (Creeper et al. 2015a,b; Mosley et al. 2017). In the absence of piston flow, a diffusive flux of acidity from the soil to surface water may result in surface water acidification. In less permeable clayey acid sulfate soil diffusion may not be sufficient to acidify surface waters during reflooding (Creeper et al. 2015a,b; Mosley et al. 2017).

Where subsurface transport of acidic water does occur, the acidic water will interact with a range of different soil materials that may neutralise the acidity and adsorb many of the substances that were mobilised during initial rewetting. During transport into surface waters, mixing with waters of differing pH, alkalinity and concentrations of suspended solids may also result in neutralisation of acidity and precipitation or adsorption of metals (Simpson et al. 2010). These observations indicate that inputs of dissolved metals from re-wetted acidic soil systems to the River Murray may be expected to be lower if acidic waters are transported through large masses of soil before reaching the river system (Simpson et al. 2010).

5.6.2 Resuspension of monosulfidic soil material during flooding

Rapid drawdown during weir pool lowering may re-suspend MBO if increased channel water velocity causes scouring (Mosley et al. 2014b, Thomas et al. 2019a,b). During managed inundations or weir pool lowering, relatively high water velocity within creek channels may generate sufficient turbulence (scour energy) to disperse soil crusts and mobilise monosulfides and organic matter (i.e. if the critical sediment shear stress is exceeded by moving water) (Thomas et al. 2019a,b). Values for critical bed shear stress (Newtons per square meter, $N\ m^{-2}$) indicate that shear stress values >0.04 Nm^{-2} are sufficient to re-suspend fine organic rich materials (Thomas et al. 2020). Resuspension can lead to latent acidification and complete consumption of dissolved oxygen in the water column (Bush et al. 2004, Cheetham et al. 2012, Mosley et al. 2014a,b; Sullivan et al. 2018).

During managed (or natural) floodplain inundations the highest in-stream velocities occur during the early phases of inundation, prior to tail waters becoming sufficiently elevated to reduce the hydraulic gradient and drive a decrease velocity and scour energy in these creeks. During weir pool manipulations, water velocities will increase marginally in the main river channel, but will not exceed flows under normal conditions. Weir pool lowering has the potential to marginally increase water velocities in anabranch creeks that flow around weirs, if the head difference across the weir is increased, but velocity increases are not expected to be sufficient to cause scouring. In contrast, in-stream regulators, culverts or drainage restrictions are likely to have higher velocities for short distances, and these structures may accumulate monosulfides behind them during periods of low water level (Mosely et al. 2019, Thomas et al. 2019a,b).

Shallowing of lagoons during river water level or weir pool lowering has potential to expose monosulfidic sediments, or to bring them to the near surface, where they will then be susceptible to scouring and re-suspension by windblown wave action (or seiche). These sites present a water quality risk to the lagoon and ultimately to any connected waterbodies down hydraulic gradient (such as the main river channel).

5.6.3 Excessive organic matter decomposition in the water column

While organic decomposition is a vital ecological process occurring in wetlands, rapid decomposition strips oxygen from the immediate environment and may kill adjacent aerobic organisms. Litter decomposition and mobilisation of DOC can lead to rapid (within days) hypoxia through bacterial respiration and stratification (Hladyz et al. 2011, Whitworth et al. 2012, Vithana et al. 2019). The risk of hypoxia after flooding is influenced by temperature, water volume, water exchange, and the quantity of organic matter entrapped by the waterbody. The highest risk environments are shallow waters with low exchange rates, high water temperatures (>20°C), and large quantities of dissolved organic carbon. As little as one month of plant litterfall can be sufficient to cause a hypoxic event if water conditions are appropriate (Mosley et al. 2021).

Forested sites tend to carry a higher risk of post-flood hypoxia; these sites can remain hypoxic for several months after inundation (Mosley et al. 2021). As water flows through a floodplain, oxygen concentrations will decrease proportionally to the distance travelled across the floodplain (during overland flow), while, turbidity, carbon dioxide and dissolved organic carbon concentrations will increase (Zuijdgeest et al. 2016).

Agricultural sites are less likely to contain enough organic matter to initiate an event, though they may still become hypoxic under the right conditions. Dry plant litter loading, and the proportion of 'readily degradable' components such as grasses and leaves are key variables in hypoxia risk (Mosley et al. 2021). Mineral nitrogen compounds are readily released from organic matter, however these compounds are relatively rapidly converted into oxidised nitrogen (nitrate and nitrite, NO_x) compounds and subsequently degassed to the atmosphere (i.e. via denitrification pathway) or leached downstream. Nutrient release from litters may also increase dissolved P loading (Zhang et al. 2021) that can promote formation of algal blooms.

5.7 Transport of surface/subsurface materials to new places

Inundation of land with river waters in the MDB will transport (mobilise) surface/subsurface materials and waters containing PTEs to new places (Mosley et al. 2014 b). The term "mobilisation" is a concept that has been frequently used to estimate the risk of contamination from the soil to the surrounding environment by PTEs (Mosley et al. 2014 b).

5.8 Subsequent plant growth will affect soil structure and nutrient conditions

Subsequent plant growth after weir pool raising will generate additional organic matter at the site (Thomas et al. 2019a). Similarly, below-ground biomass (roots) may also improve soil structure and subsequent infiltration capacity. Plant growth can also increase site roughness, increasing the amount of organic matter which may be trapped during future flood events. Additional nutrient capture in wetlands is likely to increase site productivity as microbial decomposition of organic matter increases the available nutrients for plants and other organisms (Stirling et al. 2020). Inundation of isolated wetlands and floodplains allows the transfer of allochthonous organic matter, nutrients and sediments between land and stream systems and improves ecosystem function.

5.9 Summary of soil-landscape threats from rewetting caused by prolonged high rainfall

The following six predicted threats/risks to future (50-year) MDB soil-landscapes as anticipated under the hydroclimate scenario caused by prolonged progressive stages of wetting (reflooding) from extreme rainfall events as shown in a generalized soil-landscape transect (Figure 9):

1. Movement of high velocity water across unstable soils can lead to erosion (decline in soil structure and texture as noted in Section 5.1).
2. Dispersion of clays can lead to decreased infiltration and increased soil erosion (as noted in Section 5.3; Figure 6).
3. Raised Ground Water (GW) levels and capillary rise can lead to salt salt scalds forming at the fringes of inundation (as noted in Section Section 5.6.1; Figure 7 (e)).
4. Excessive decomposition via oxidation of flooded organic matter during warm temperatures can lead to stream hypoxia and RIS accumulation (as noted in Section 5.6, Figure 7 (e)).
5. Mobilisation of monosulfidic materials (Monosulfidic Black Ooze: MBO) can lead to stream acidification or hypoxia and RIS accumulation (as noted in Section 5.6.2, Figure 7 (c; e)).
6. Extended inundation of acidified soils can lead to reduced inorganic sulfur accumulation patricularly in the presence of low molecular weight organic matter or labile carbon (as noted in Section 5.6.1; Figure 7 (e)).

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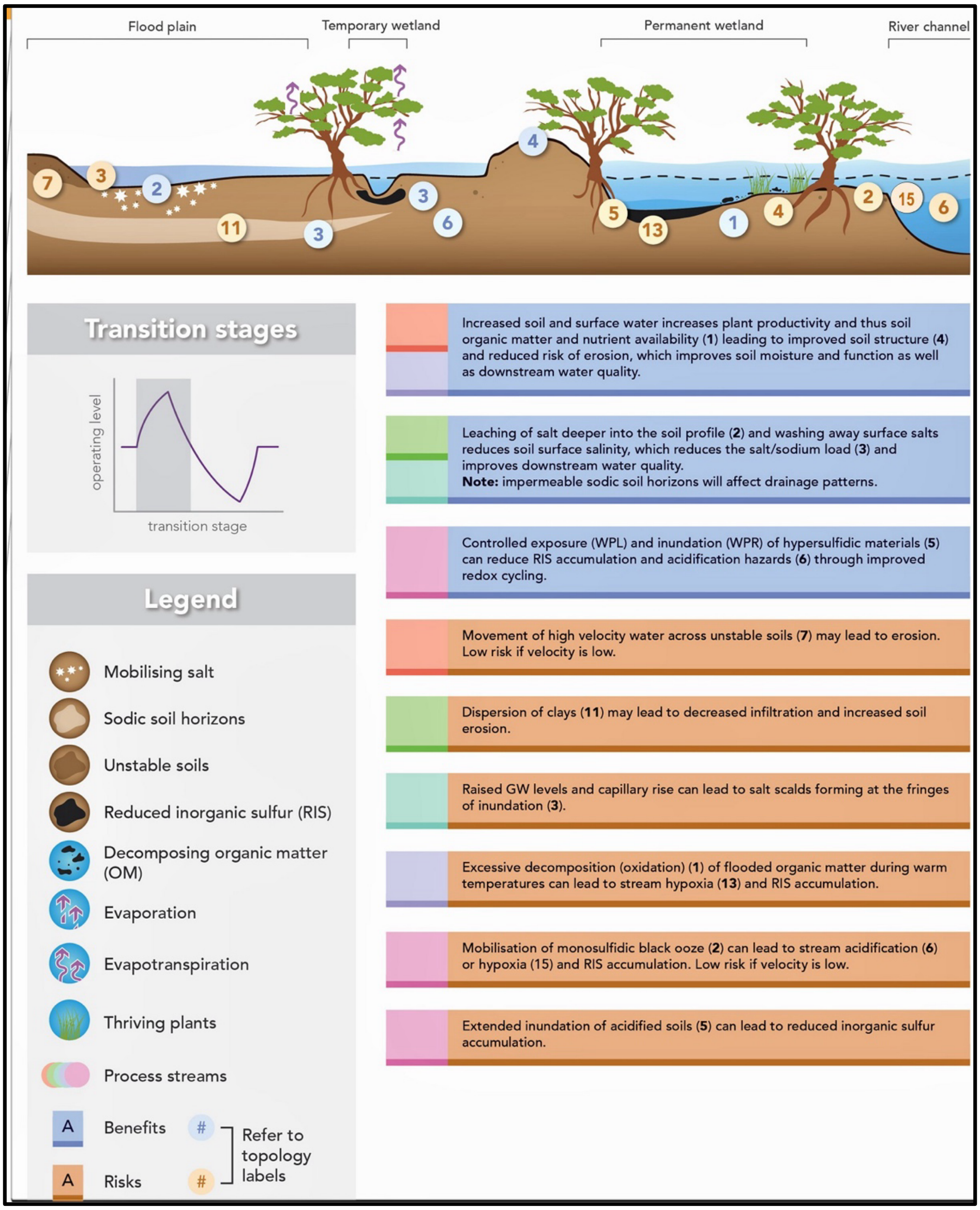

Figure 9. Generalized soil-landscape transects describing the distribution of the main soil types during the progressive stages of rewetting caused by reflooding from extreme above annual rainfall events (modified from DEW 2021). Where: WPR = Weir Pool Raising, WRL = Weir Pool Lowering; GW = Ground Water; RIS = Reduced Inorganic Sulfer (modified from DEW 2021).

6. Adaptive soil-landscape management under climate change

River regulation for more than 80 years in the MDB combined with frequent extreme soil drying and wetting caused largly by climate change (e.g. Millennium Drought across the MDB), has resulted in many soil-landscape degradation issues such as: soil erosion by water & wind, acidification, salinization, clay dispersion/sodicity, waterlogging, soil compaction, production of noxious gases, monosulfide accumulation & disturbance and bushfire impact.

Current scientific knowledge can support a range of possible conservation measures and nature-based solutions to rehabilitate MDB soil-landscape degradation in 50 years as outlined in Table 2.

Table 2. Adaptive soil-landscape management strategy recommendations

Drying Scenario	Wetting Scenario
Slow lowering of the weir pool and the extension of colonising plants to increase plant productivity and thus soil organic matter content, which will improve soil structure, stabilise banks and reduce soil erosion.	Increased topsoil and subsoil supply of water, which will increase plant productivity and thus soil organic matter and nutients leading to improved soil structure, reduced risk of erosion and improved stream water quality,
Careful exposures of hypersulfidic material with RIS to oxygen (air), which will allow oxidation to occur and reduce the quantity of accummulated RIS (i.e. hypersulfidic material) and thus acidification (i.e. formation of sulfuric material)[1].	Leaching of salts deeper in the soil profile and washing away suface salts reduces soil surface salinity, which reduces salt loads and improves downstream water quality.
Controlled drying, which will cause salts to leach out of soils leading to reduced salt loads in the longer-term 50-year hydroclimate changes leading to soil-landscape degradation.	Controlled exposure (via Weir Pool Raising: WPR) and inundation (via Weir Pool Lowering: WRL) of hypersulfidic material, which will reduce the accummulation of reduced inorganic sulfur (RIS) through improved redox cycling by managing reflooding to: (i) prevent further pyrite oxidation, (ii) neutralise acidity by introducing surface water alkalinity, (iii) establish reducing conditions to promote alkalinity generating geochemical reactions and the reformation of pyrite.
Use environmental and irrigation water where possible to prevent deep cracking and salinisation of clay soils and maintain plant cover.	Control inundation and flow rates were possible to prevent development of hypoxic blackwater events and scouring of sediment and monosulfidic black oozes (MBOs)

[1]Reduced sulfur species tend not to build up to harmful levels in wetlands that have frequent (annual) wetting and drying cycles (Fitzpatrick et al. 2009, Mosley et al. 2014a, 2019) due to: (i) regular 'burning off' of RIS materials in drying phases with limited time for build up in wetting phases, (ii) the periodic dilution and removal of sulfate, nutrient, salt loads to the river, (iii) seasonal flooding reworking and scouring fine (clay and MBO) surface sediments and organic matter, and (iv) flooding providing a supply of soluble ANC and decreasing stratification and anoxic conditions.

A summary of the positive and negative outcomes caused by drying and wetting scenarios are shown in an interactive flow diagram (Figure 10) together with the four key levers available for managing soil degradation processes and associated threats to surface and groundwater quality, whilst promoting other beneficial soil processes that contribute to a healthy functioning wetland.

However, some soil-landscape changes in the MDB are cyclic and recover from extreme acidification due to drying during the transition back to rewetting phases (i.e. because of the abundance of labile carbon as shown in Figure 7 (e)), while others result in permanent or irreversible changes to soil acidification (Mosley et al. 2017b) and hydrological properties (i.e. excavated and permanently drained landscape with deficient labile carbon as shown in Figure 7 (d)).

7. Conclusions

Soil-landscape degradation adaptation to climate change is challenging because of the cross-cutting issues connected to many disciplines as shown in the flow diagram (Figure 10). The flow diagram also shows the many interrelating positive and negative outcomes associated with soil drying and rewetting scenarios. To better understand the negative and positive soil-landscape degradation threats posed by climate change managers and policymakers should consult the flow diagram showing the soil processes related to drying and rewetting scenarios. Moreover, as shown in the interrelating flow diagram, it is no longer sufficient to manage only water quantity and quality issues in the MDB; soil-landscape management is also essential.

To achieve the goal of best “sustainable soil-landscape management” for the MDB in 50 years, we need an integrated approach to implement a **seasonal wetting and drying regime** to the river and adjacent wetland regulation, which will substantially reduce the many risks related to the **prolonged drying** and **subsequent rewetting**, which can potentially lead to the redistribution and accumulation of acidity and oxidation products (hazards) within a soil profile and the floodplain.

Climate change threats from prolonged drying and wetting increases the soil erosion rate in the dominant soil types, especially sodosols in the MDB. The higher soil erosion rate and the decline in soil structure lessens the soil organic carbon content in these soil types and acts as a carbon source to the atmosphere. In the MDB, these developments are acting as cyclic processes, which further enhances the global warming and eventually leads to enhanced climate change.

The risk of acidification in soils and water is partially determined by the substrate’s proximity to the surface and its inherent acid neutralising capacity (ANC), which is determined by the content of alkaline minerals, organic matter, and clay particles in the soil environment.

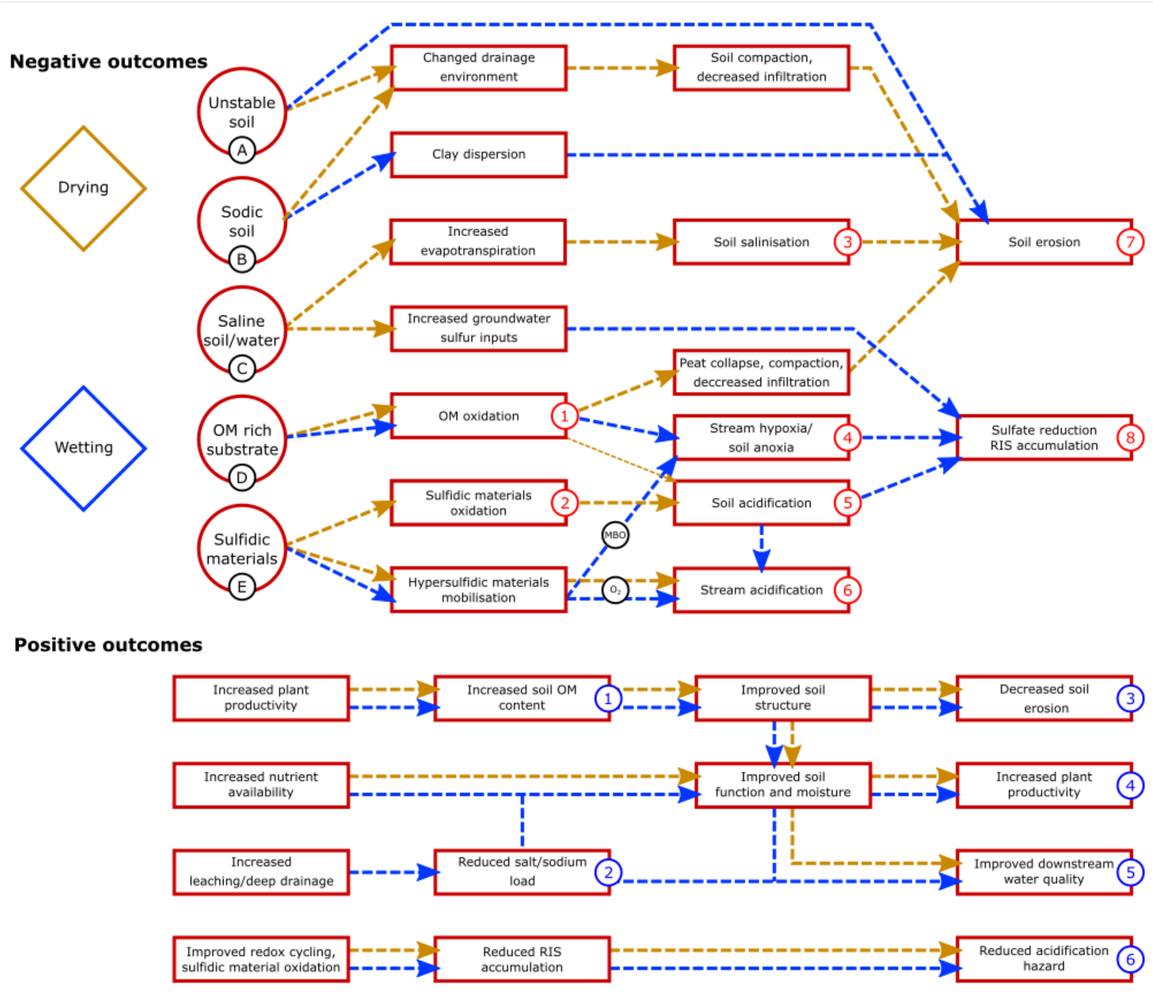

Figure 10. Flow diagram showing the soil processes relating to drying (brown arrows) and rewetting (blue arrows) scenarios, as demarcated and described in Figures 8 and 9 (modified from DEW 2021).

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