Sediment – soil - sediment transitions and the implications for the structure and function of restored wetlands

KL Spencer
SJ Carr, L Diggens, JA Tempest, GL Harvey and MA Morris.
k.spencer@qmul.ac.uk
Soils vs. Sediments

**Soils**
- Weathering of underlying bedrock.
- Chemistry/mineralogy dependent on geology.
- Horizontal structure – pedogenesis.
- Pore morphology – dessication, ploughing, roots, bioturbation.
- Terrestrial – biogeochemistry, oxygen, nutrient and contaminant availability.

**Sediment**
- Deposition of fluid-transported particulates.
- Chemistry/mineralogy dependent on sediment source and in situ biogeochemical conditions.
- Horizontal structure – sedimentary features.
- Pore morphology – roots, bioturbation.
- Terrestrial – biogeochemistry, oxygen, nutrient and contaminant availability.
History of land-use and disturbance in low-lying coastal wetlands

Sediments

- Salt marshes.
- Low lying coastal wetlands – formed during the marine transgression of the Holocene.
- C. 10 000 years.

Burnham salt marshes, Norfolk, UK.
History of land-use and disturbance in low-lying coastal wetlands

➡ Soils

• Reclaimed – embankment or poldering
• Drainage for agriculture.
• Romans, mid 12th Century, late 1800s, mid 20th Century.
• Sediments are de-watered, mineralised, farmed, compacted, disconnected from tidal hydrology.
• Pedogenesis?

Hadleigh Essex, UK
History of land-use and disturbance in low-lying coastal wetlands

➔ Sediments

• Restoration of salt marsh and mudflat sedimentary environments and habitats.
• Reconnecting previously drained areas with tidal hydrology through de-embankment, storm breach, managed realignment, managed retreat etc.

Orplands Farm Managed Realignment Scheme, Essex, UK.
Saltmarsh restoration drivers

• Re-creation of wetland habitat and increased biodiversity
• Sustainable coastal defence and flood storage.
• Sediment associated contaminant storage and denitrification.
• Climate Regulation: saltmarshes store up to 2.19 t C ha\(^{-1}\cdot yr\(^{-1}\)

• ‘Restore the physical structure of the system, then the rest will follow’ – HYDROPERIOD and ELEVATION
Is saltmarsh restoration entirely successful?

- Poor vegetation, invertebrate species and microhabitat diversity (e.g. Mazik et al. 2010; Mossman et al. 2012, Brooks et al. 2015).
- High emissions of greenhouse gases $\text{N}_2\text{O}$ and $\text{CH}_4$, varied denitrification rates (Kenny et al 2004; Adams et al. 2012).
- Less effective at net $\text{C}$ sequestration (Santin et al. 2009; Burden et al. 2013).
- Pollution ‘hotspots’ (Morris et al. 2014).

Species abundance in reference (open bar) and engineered sites (Brooks et al 2015)
Hydromorphic and biogeochemical linkages in restored inter-tidal wetlands (Spencer & Harvey 2012).

- How do soil-sediment transitions modify the ecosystem structural characteristics?
- ‘Disturbance’
Altered hydrology

Abbotts Hall Farm, R. Crouch – MR scheme

Lippenbroek, R. Schelde – CRT scheme

Restoring Europe’s rivers, 2016
Altered geomorphology, topography and drainage

- Engineering of surface elevation and creek systems.
- MR sites have less topographic heterogeneity, hence redox, salinity, vegetation.... (Veenklaas et al 2015; Morris et al 2015)

Topographic heterogeneity higher in natural sites (Brooks et al 2015)
Hydromorphic and biogeochemical linkages in restored inter-tidal wetlands (Spencer and Harvey 2012).

• Most studies focus on the surface environment – but what about the sub-surface?
Aim:
• To understand the impact of past land use on sub-surface structure and the potential consequences for functioning of restored coastal saltmarshes

Objectives:
• To examine physical subsurface structure in restored saltmarshes.
• To examine sub-surface hydrology and connectivity between the sub-surface environment and tidal floodwaters
• To examine the influence on sediment and porewater geochemistry.
Methodology

Restoration across the estuaries of SE England.

Orplands Farm, Essex, UK (de-embanked in 1995)

- Matched pairs from natural and restored sites at same elevation (hydroperiod).
- Sediment structure examined using 3D X-ray microtomography and porosity data extracted using greyscale thresholding.
- Sub-surface hydrology: installed pressure transducers for 5 months.
- Vertical profiles of sediment geochemistry.
3D sediment reconstruction

• Sediment components are segregated based on size, shape and greyscale using 2D transfer function in Drishti.
• Restored site – two distinct sediment units.

White – voids
Pink – low density matrix
Grey – high density matrix
Green – roots and organic matter
Red/Orange – Fe-rich root plaques and concretions.
3D sediment reconstruction: isolation of organic matter

Natural

Restored

Organic (roots) phase
3D sediment reconstruction: isolation of void space

Natural

Macro-pore phase

1 cm

Restored

Macro-pore phase
• The restored site has greater sediment porosity (volume).
• Euler number (indicates redundant connections in pore system) assesses connectivity and tortuosity of the pore system.
• Small Euler number (zero) = less tortuous and more hydraulically effective.
• Suggests that the restored site is less hydraulically effective and the pore system is poorly organised and poorly connected.
Sub-surface hydrology

In restored saltmarsh:
- Hydrological response to tidal flooding is subdued
- Water level is higher

Tempest et al. 2015
Connectivity with over-lying flood waters: Na concentrations in sediment with depth

- Na concentrations in restored sites are much lower.
- Suggests limited connectivity with over-lying flood waters.

(Spencer et al. 2008)
Iron geochemistry is indicative of the redox environment.

Surface enrichment of Fe indicates vertical tidal pumping of Fe-rich pore waters through the sediment.

Soluble Fe$^{2+}$ at depth precipitates as Fe$^{3+}$ in surface sediments.
Sediment redox environment: Iron concentrations in sediment with depth

- No evidence of vertical mobilisation of Fe
- (Abiotic) conditions for Fe reduction are unfavourable.
- Implications for other redox dependent biogeochemical reactions e.g. removal of nitrate through denitrification

Total Fe concentration with depth
Linking sediment structure and subsurface hydrology.

- Two distinct sediment units.
- Pre-restoration land-use (drainage) has resulted in high density compact soils.
- Hydrological connectivity and drainage is impeded.
- Pore geometry – less tortuosity – perhaps from ploughing?
- Flooding does not restore sediment fabric – due to Ca-poor clays and low organic matter.
Lateral flows favoured in the restored saltmarsh.

Therefore designing for elevation alone does not ‘re-create’ physical structure of the saltmarsh.

Roots can’t penetrate this sub-surface.

Implications for vegetation

See Tempest et al. 2014
Impacts on the sediment geochemical environment

- Implications for biogeochemical cycles that are driven by vertical chemical gradients.
- Geochemistry has not reverted to the same characteristics as the natural saltmarsh.
- Potential build up of toxic dissolved species e.g. sulphide with implications for germination and seedling development.
- Therefore designing for elevation alone does not ‘re-create’ chemical structure of the saltmarsh.
- See Morris et al. 2015
What about beneficial sediment re-use schemes?

- Beneficial sediment re-use scheme.
- Creation of 670 hectares of inter-tidal habitat on former reclaimed agricultural land.
- Heavily engineered system to re-create topographic features.

Wallasea Island wild coast project, River Crouch
Construction

- Sediment delivered by boat, transported on land using conveyor belts and re-distributed.
3 mill tonnes of Eocene (55M ya) sediment excavated from beneath London
Wallasea Island Material Handling Equipment
Conclusions

• Land-use history results in significant disturbance and relict soil structure persists for several decades.
• ‘Get the elevation right, and the rest will follow’ – the chemical and physical structure of these sites has NOT been restored.
• Significant impact on: plant colonization and species composition, hydrological functioning and biogeochemical cycling.
• Implications for beneficial sediment re-use schemes.
Is restoration ever a win-win situation?

- Doherty et al (2014) demonstrated the ecosystem services exist as ‘bundles’ and ‘trade-offs’
- Dependent on hydrological regime (drainage).
- 2 bundles – e.g. NPP, FA and ER where drainage was good.

Relative provision of ecosystem services in wetlands with different hydrological regimes (Doherty et al. 2014)
Do we need to refine the hydroperiod concept in terms of restoration design?
Value of saltmarshes

• Saltmarshes offer a range of ecosystem services: coastal defence, wild species diversity, water quality improvements.
• E.g. in the UK equivalent to c. 3.5 % of national income.
• 50% of saltmarshes worldwide have been degraded by human activity and this is likely to have significant impact on critical ecosystem services (Barbier et al., 2011).
• Restoration, remediation and rehabilitation strategies (Elliott et al., 2007) – managed realignment, de-embankment, CRT....