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

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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

Hadleigh Essex, UK

➔ **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?

History of land-use and disturbance in low-lying coastal wetlands

Orplands Farm Managed Realignment Scheme, Essex, UK.

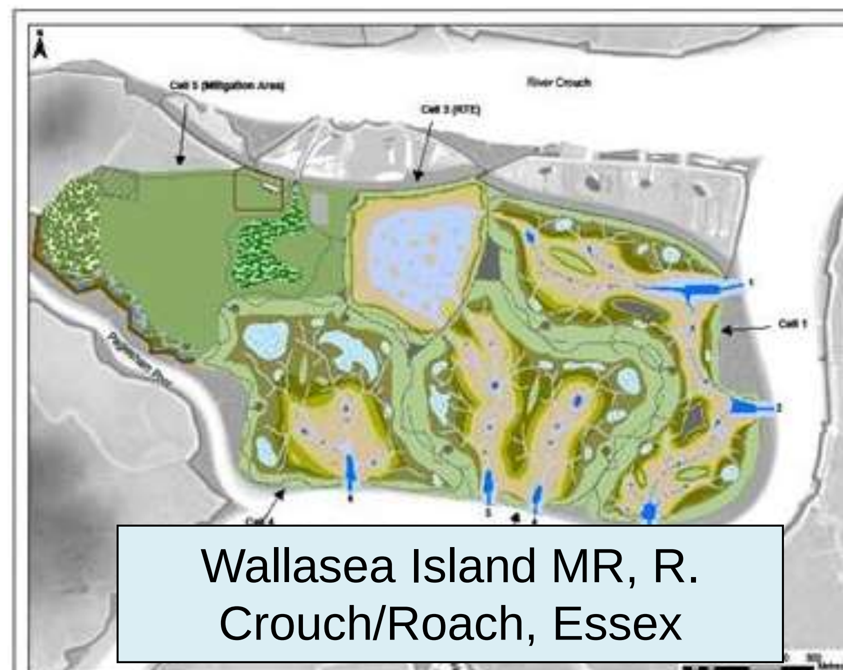
➔ **Sediments**

- 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.

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 $ha^{-1}yr^{-1}$
- ‘Restore the physical structure of the system, then the rest will follow’ – HYDROPERIOD and ELEVATION

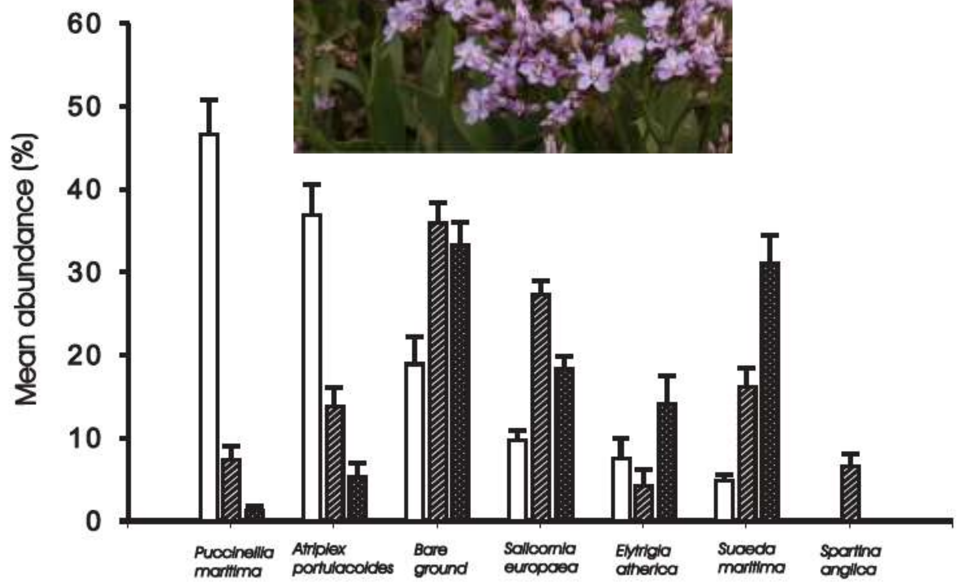
Orplands Farm MR, Blackwater Estuary Essex



Wallasea Island MR, R. Crouch/Roach, Essex

Is saltmarsh restoration entirely successful?

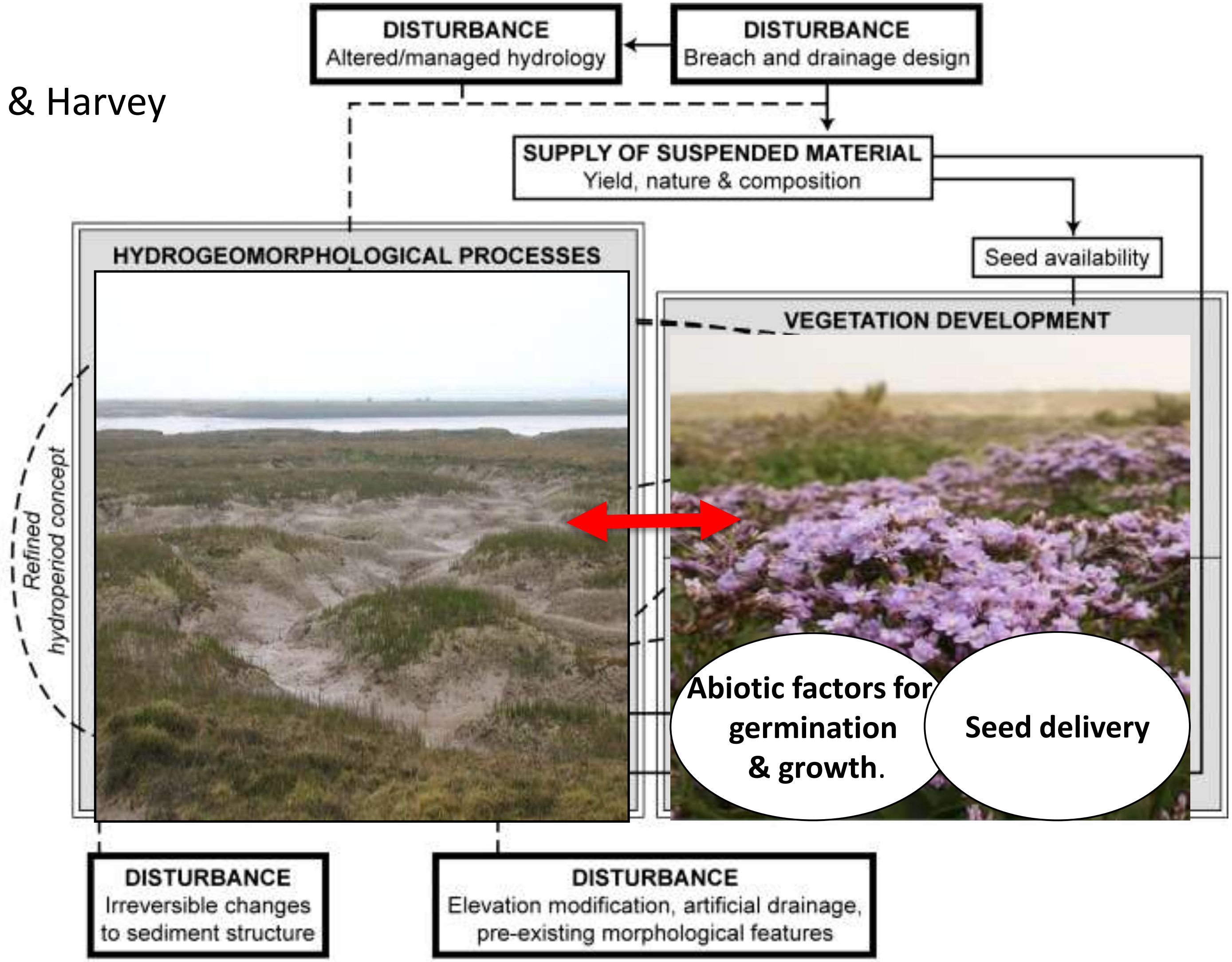
- Poor vegetation, invertebrate species and microhabitat diversity (e.g. Mazik et al. 2010; Mossman et al. 2012, Brooks et al. 2015).
- High emissions of greenhouse gases N_2O) and CH_4, varied denitrification rates (Kenny et al 2004; Adams et al. 2012).
- Less effective at net C sequestration (Santin et al. 2009; Burden et al. 2013).
- Pollution ‘hotspots’ (Morris et al. 2014).
- Why? Physically disturbed systems – modified hydrology, drainage, sub-surface structure.



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’

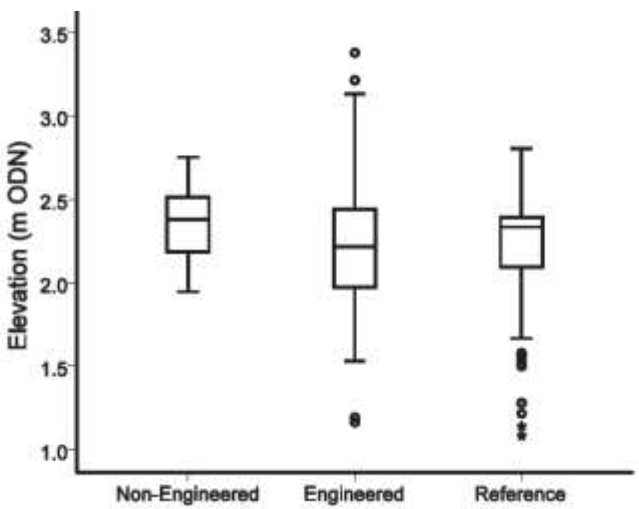
Altered hydrology

Abbotts Hall Farm, R. Crouch – MR scheme

Lippenbroek, R. Schelde – CRT scheme

Restoring Europe's rivers, 2016

Altered geomorphology, topography and drainage

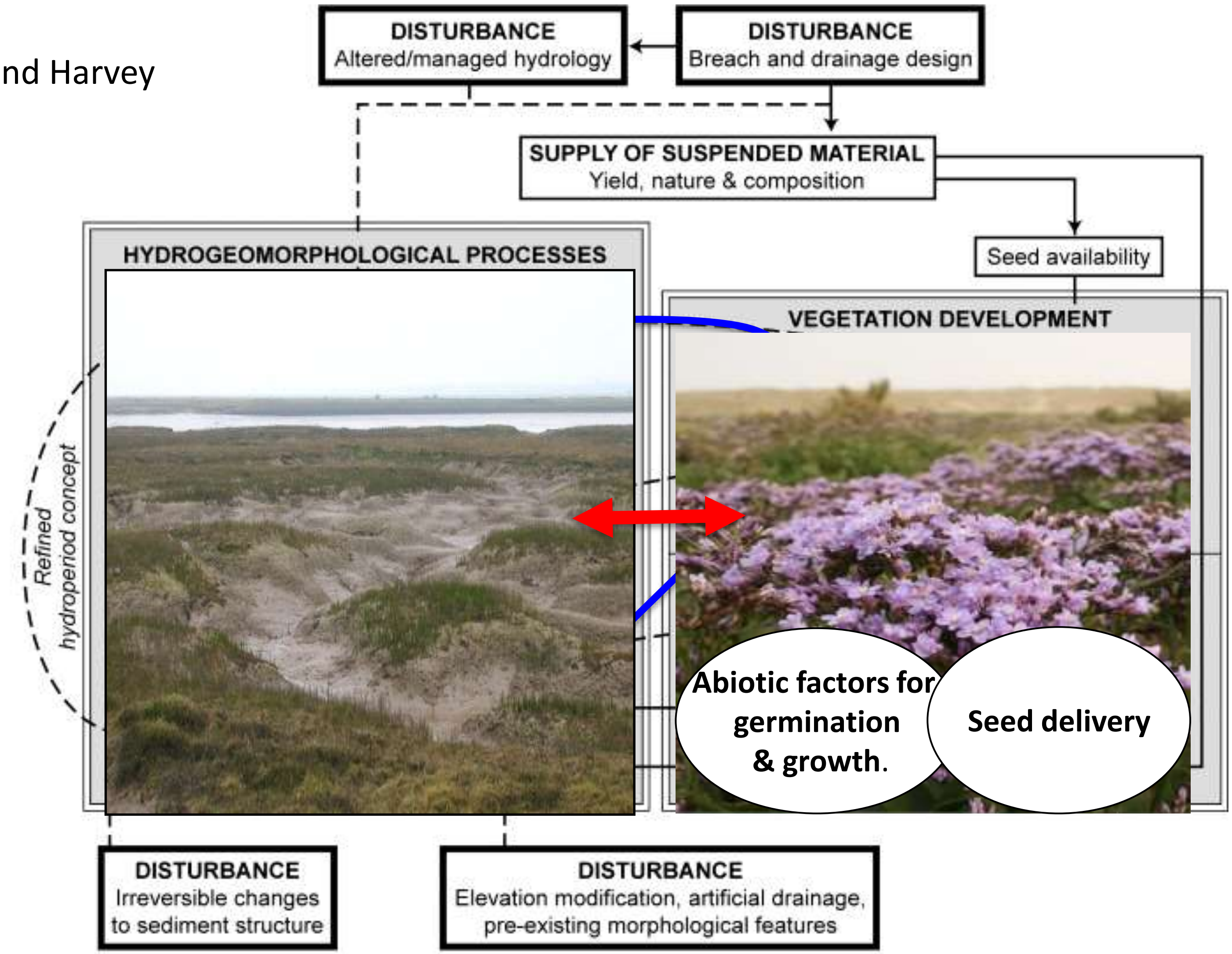


Topographic heterogeneity higher in natural sites (Brooks et al 2015)

- 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)

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

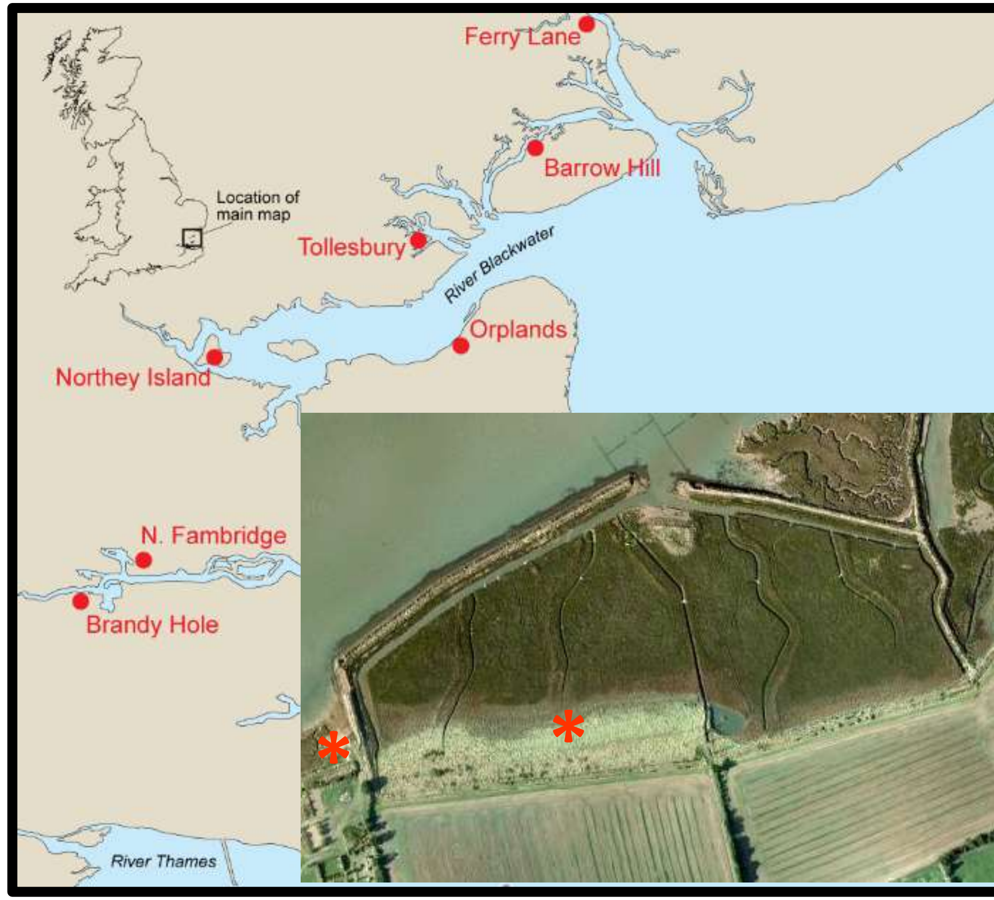
Objectives:

- 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

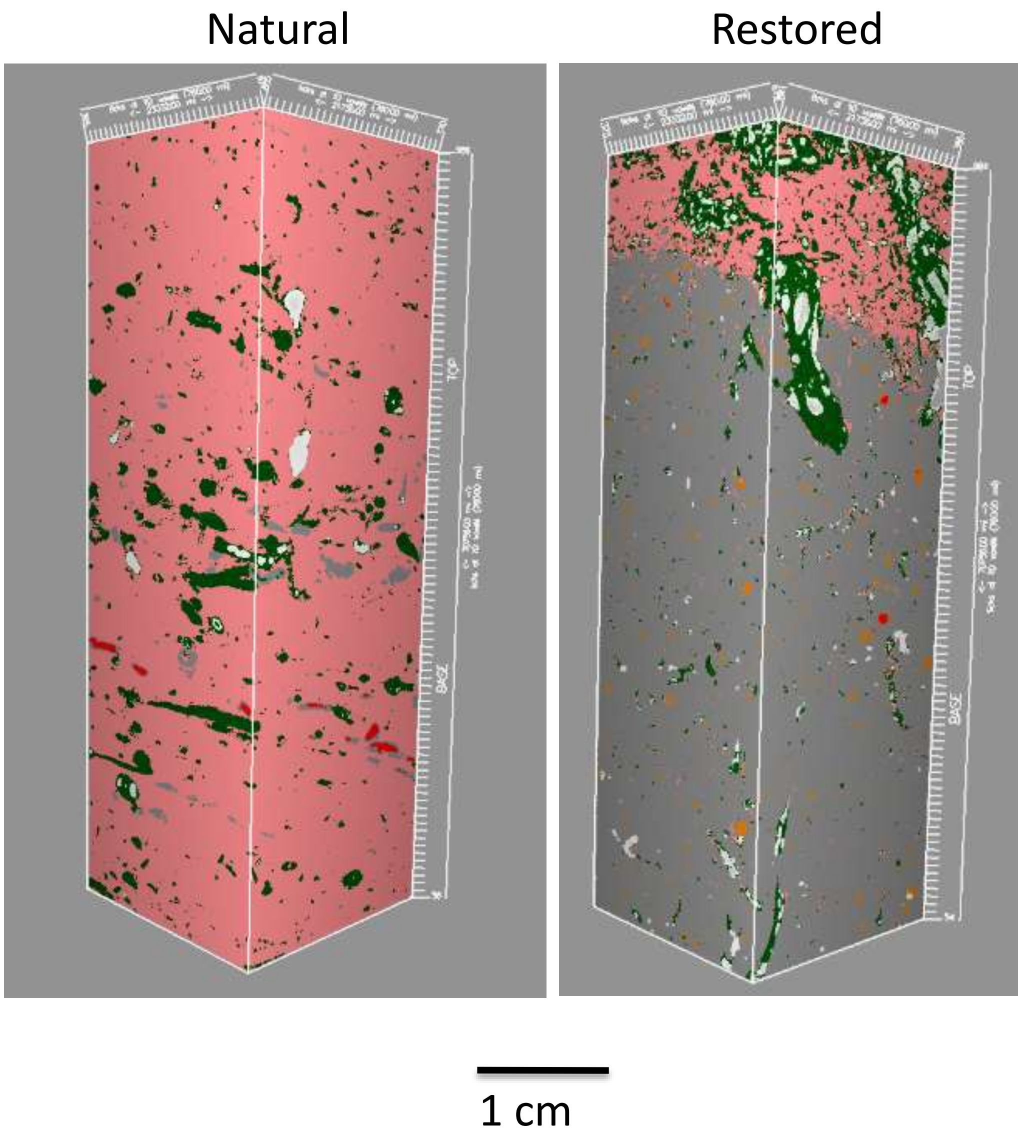
Restoration across the estuaries of SE England.

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.

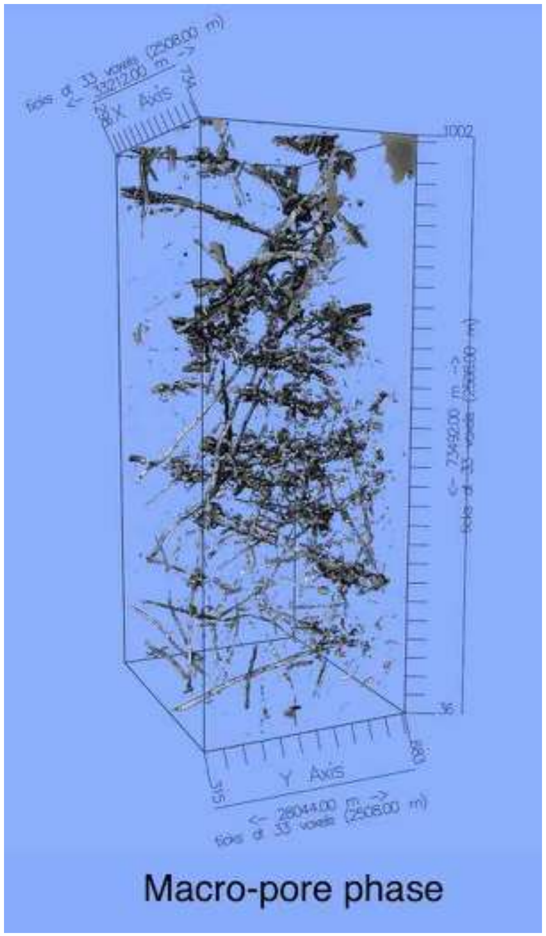
3D sediment reconstruction: isolation of organic matter

Natural

Restored

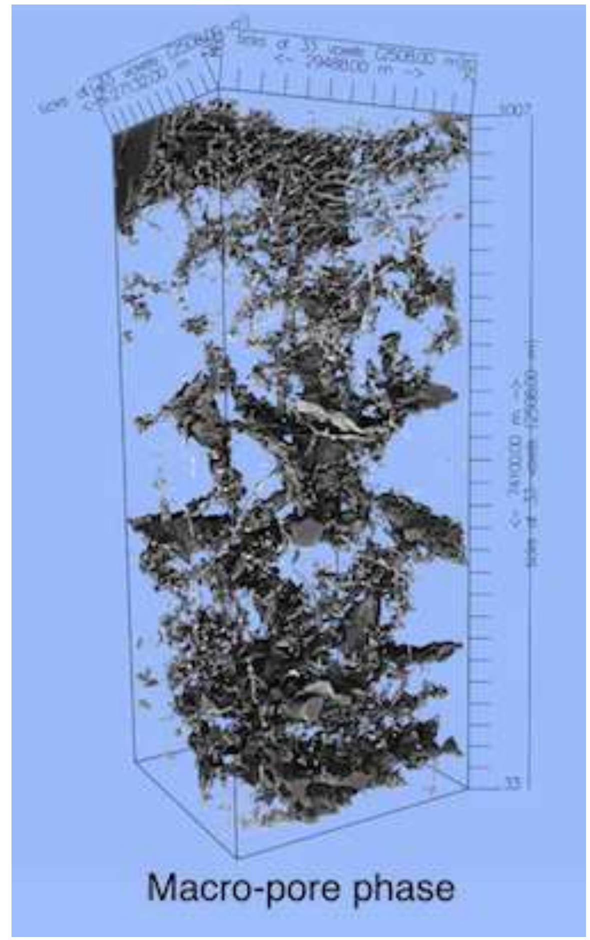
3D sediment reconstruction: isolation of void space

Natural

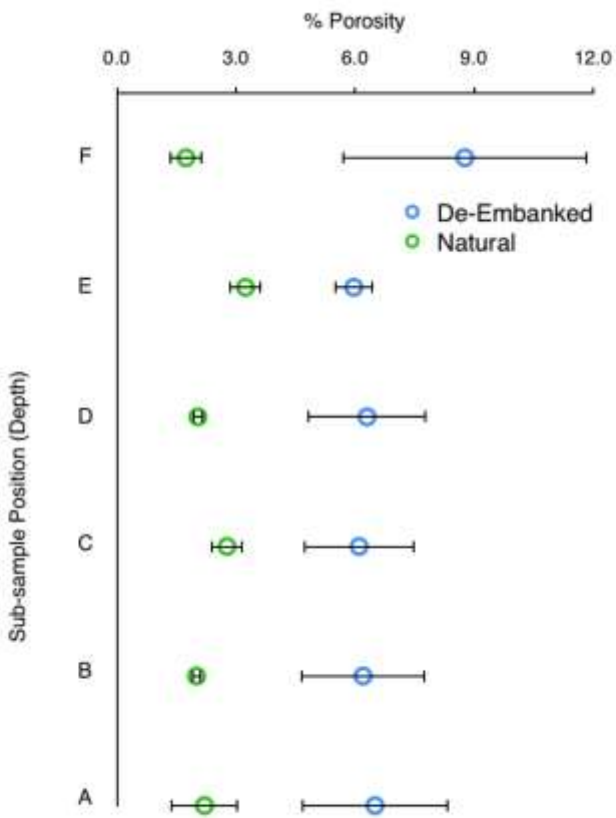


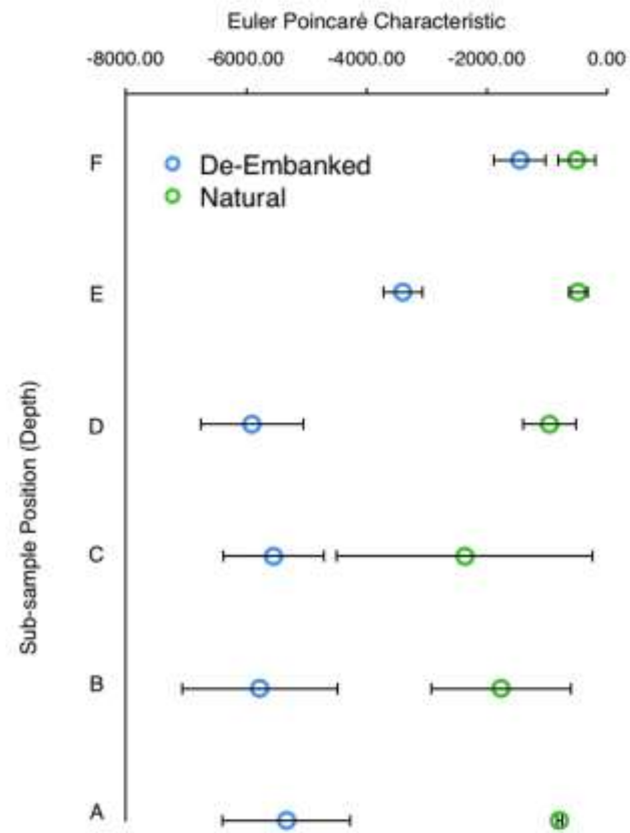
1 cm

Restored



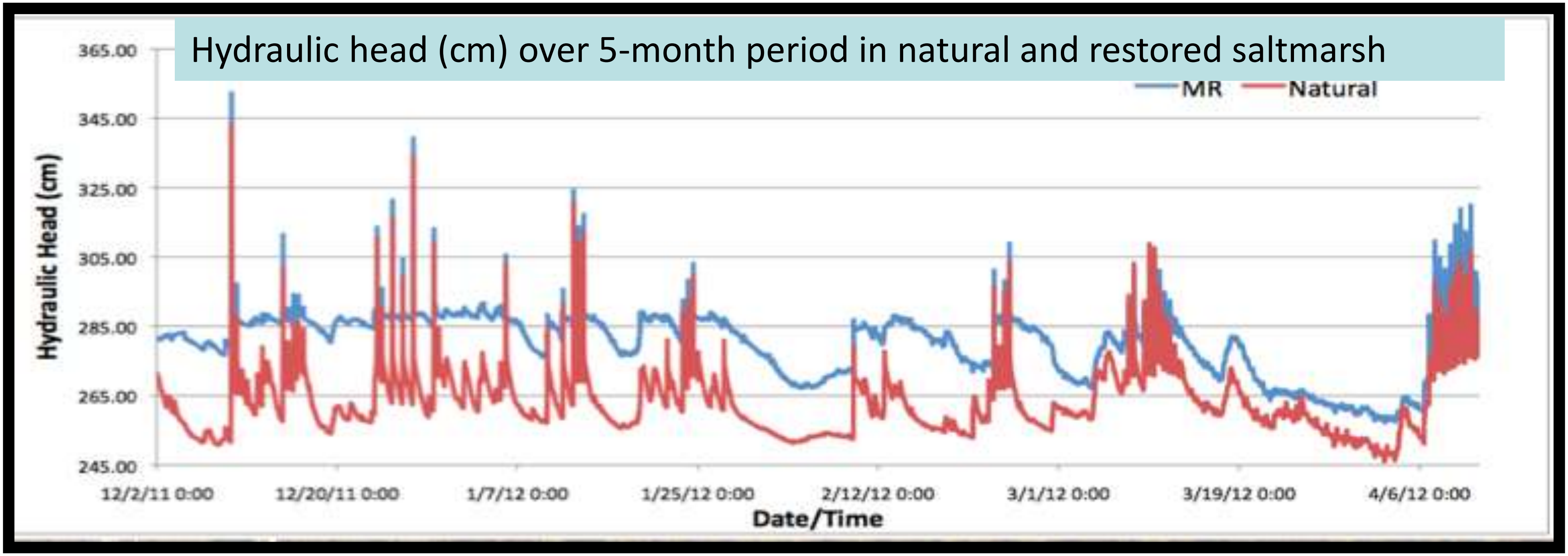
Porosity





- 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



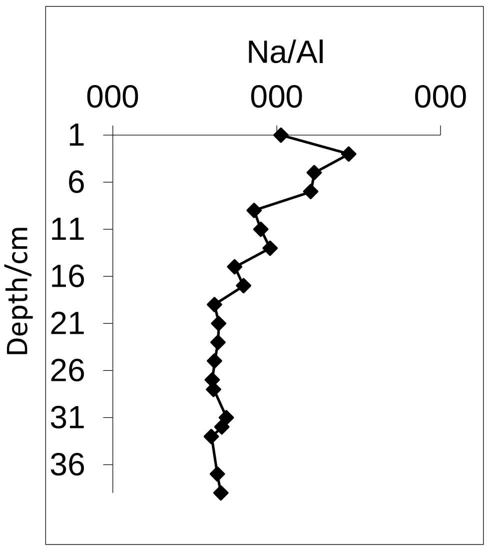
In restored saltmarsh:

- Hydrological response to tidal flooding is subdued
- Water level is higher

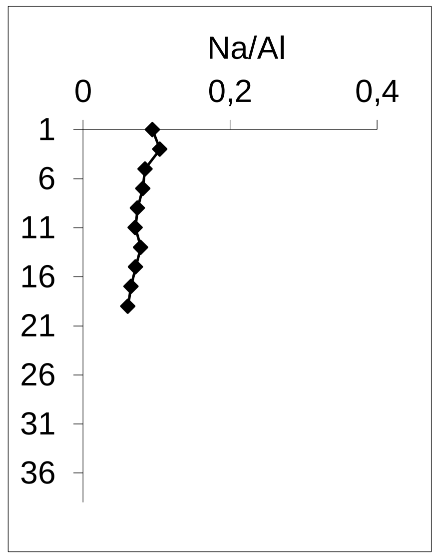
Tempest et al. 2015

Connectivity with over-lying flood waters: Na concentrations in sediment with depth

Natural



Restored/Disturbed

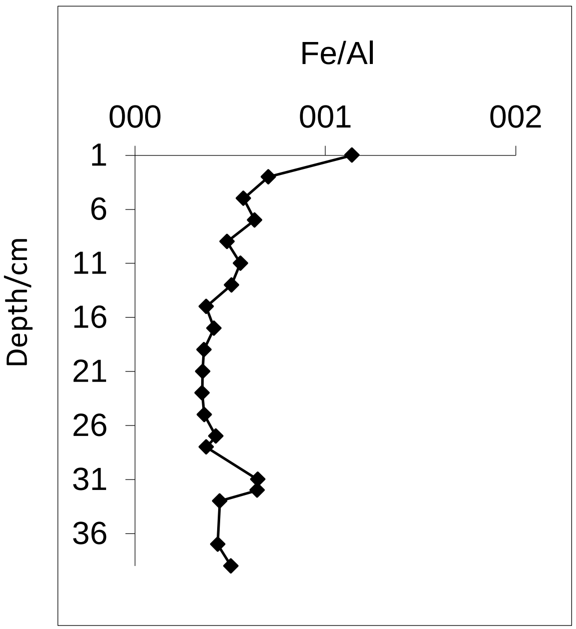


- Indicator of salinity and tidal flooding.
- Na concentrations are much lower in restored sites.
- Suggests limited connectivity with over-lying flood waters.

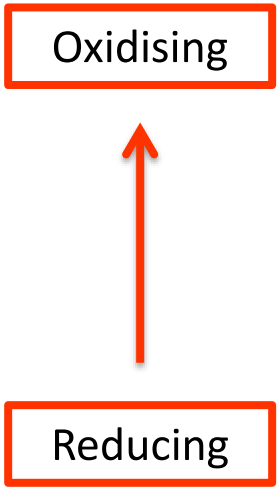
(Spencer et al. 2008)

Sediment redox environment: Iron concentrations in sediment with depth

Natural



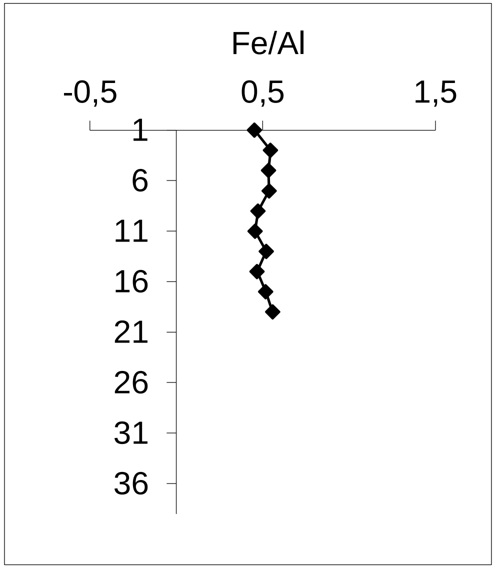
Total Fe concentration with depth



- 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

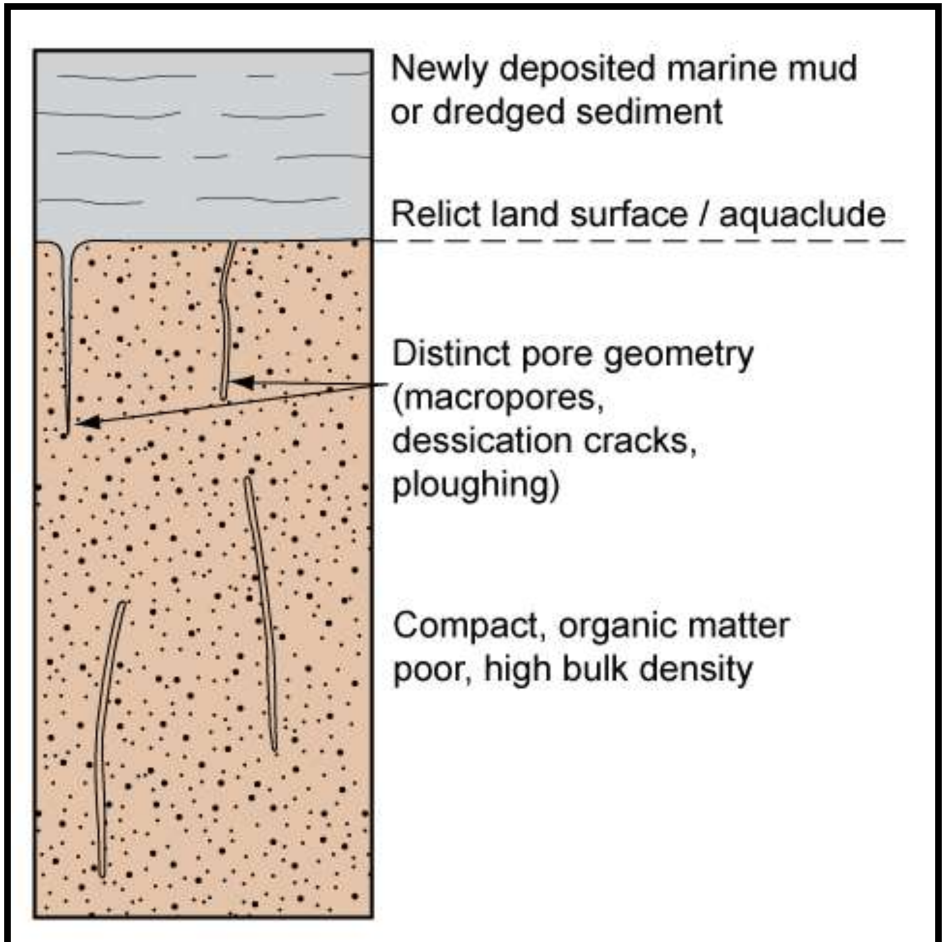
Restored/Disturbed



Total Fe concentration with depth

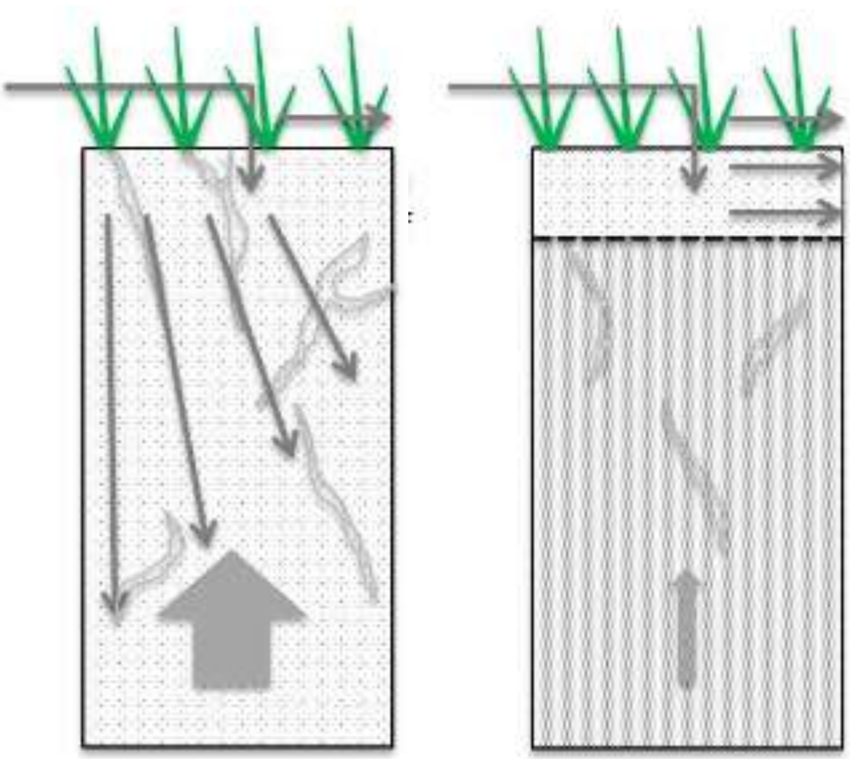
- No evidence of vertical mobilisation of Fe
- (Abiotic) conditions for Fe reduction are unfavourable.
- Implications for other redox dependent biogeochemical reactions e.g. removal of nitrate through denitrification

Linking sediment structure and sub-surface 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.

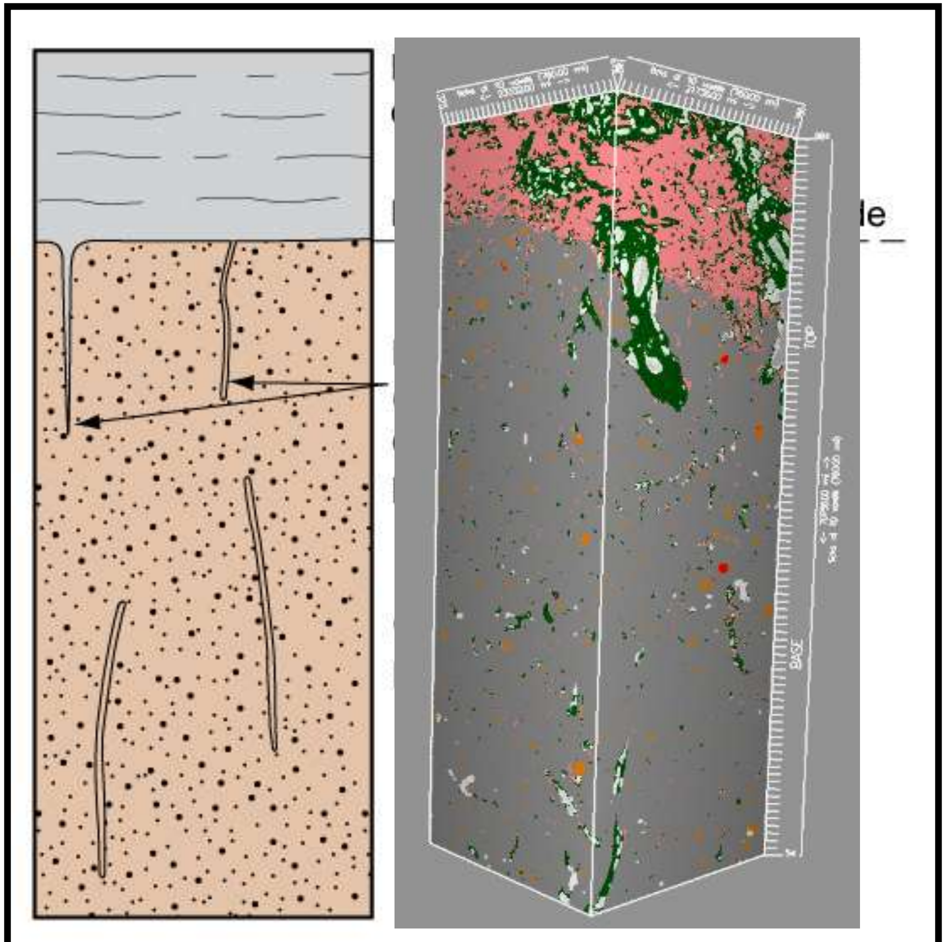
Potential flow pathways



Natural **Restored/Disturbed**

- 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?

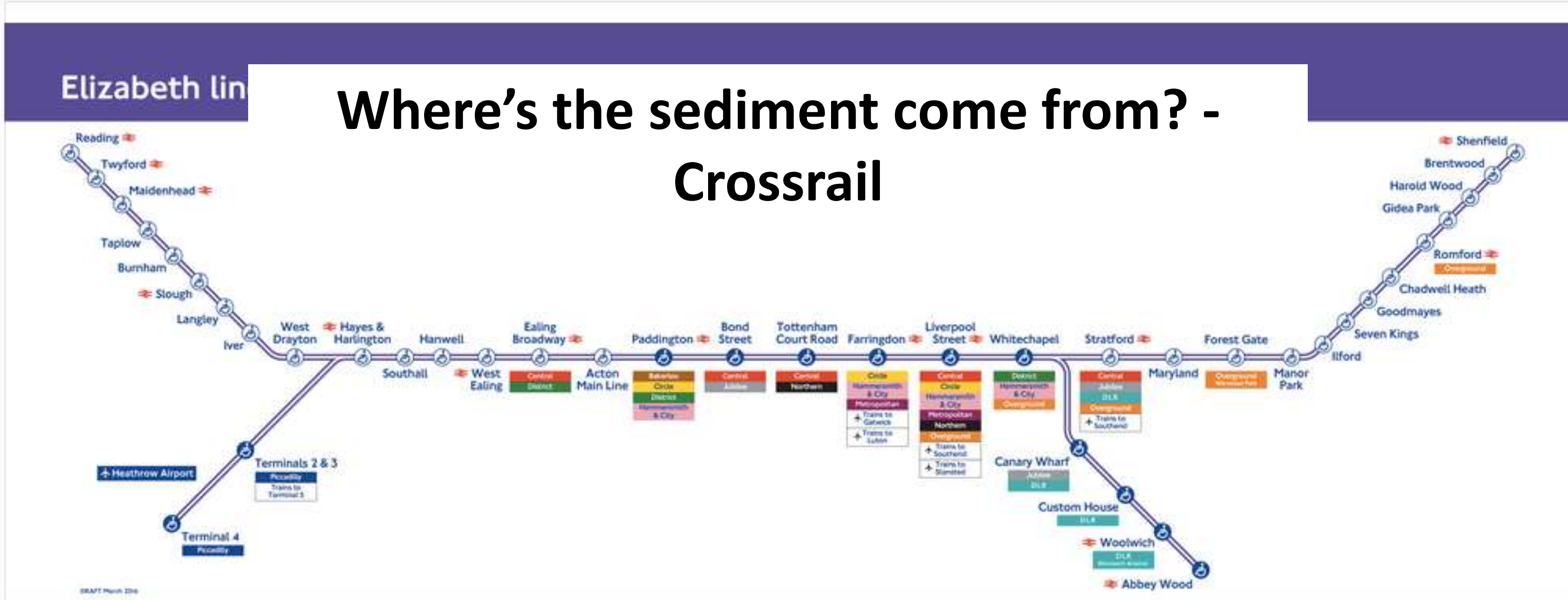
- Beneficial sediment re-use scheme.
- Creation of 670 hectares of inter-tidal habitat on former reclaimed agricultural land.
- Heavily engineered system to re-create topographic features.

Wallasea Island wild coast project, River Crouch

Construction

- Sediment delivered by boat, transported on land using conveyor belts and re-distributed.

Where's the sediment come from? - Crossrail



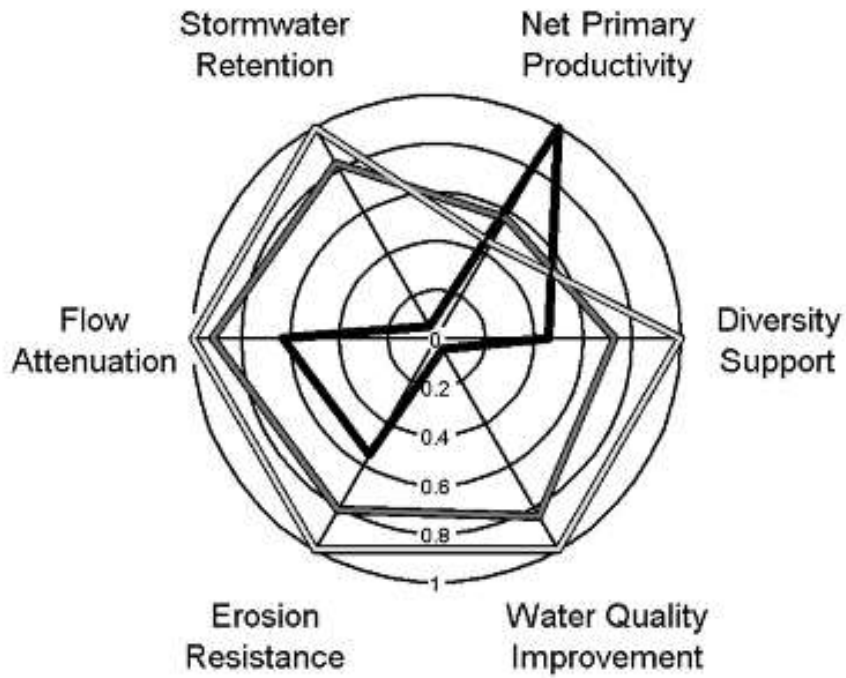
3 mill tonnes of Eocene (55M ya) sediment excavated from beneath London

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?

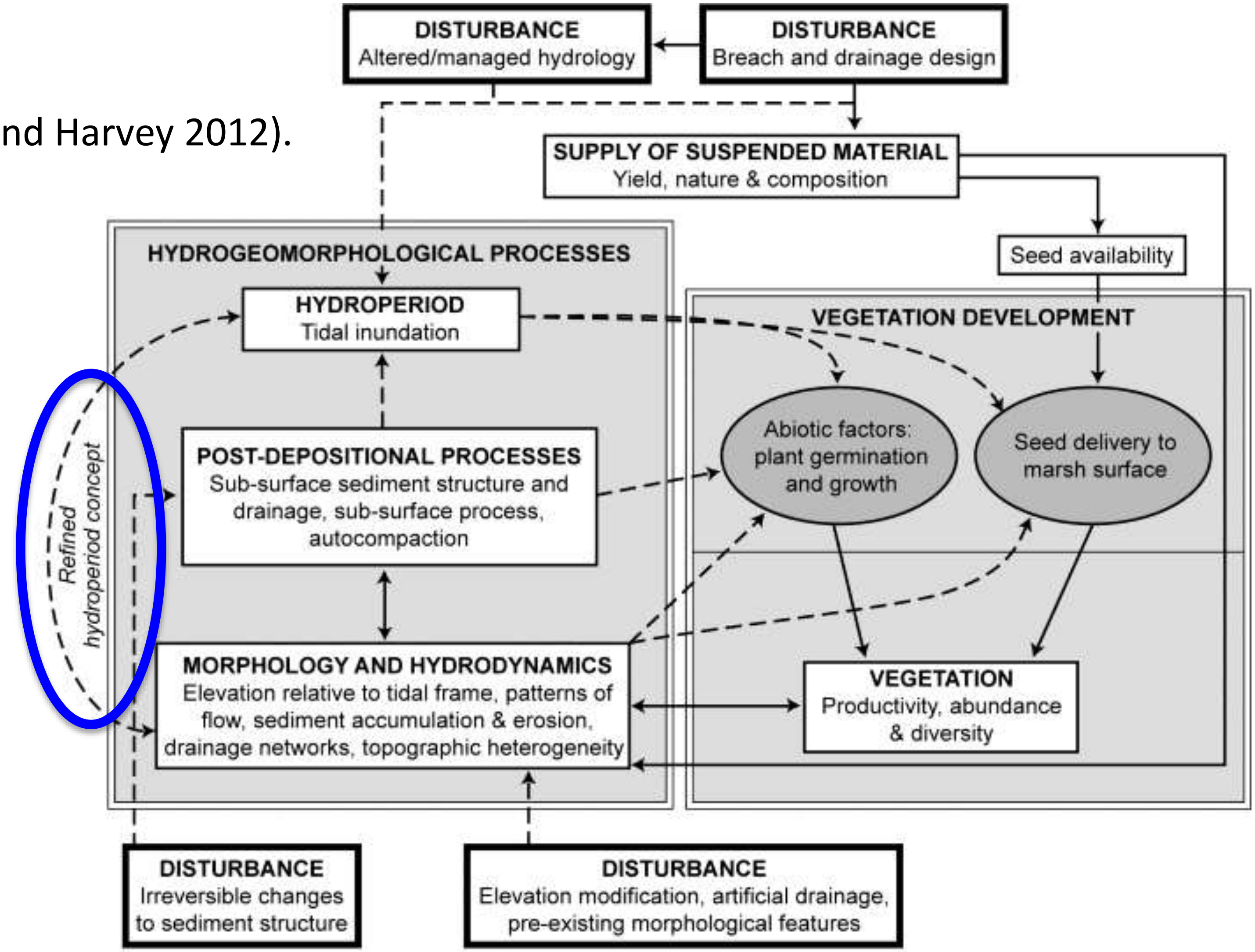


Relative provision of ecosystem services in wetlands with different hydrological regimes (Doherty et al. 2014)

- 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.

Hydrogeomorphic and biogeochemical linkages in restored inter-tidal wetlands

(Spencer and Harvey 2012).



- 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….