The Role of Saltmarsh Plants for Flood Mitigation in Welsh Estuaries

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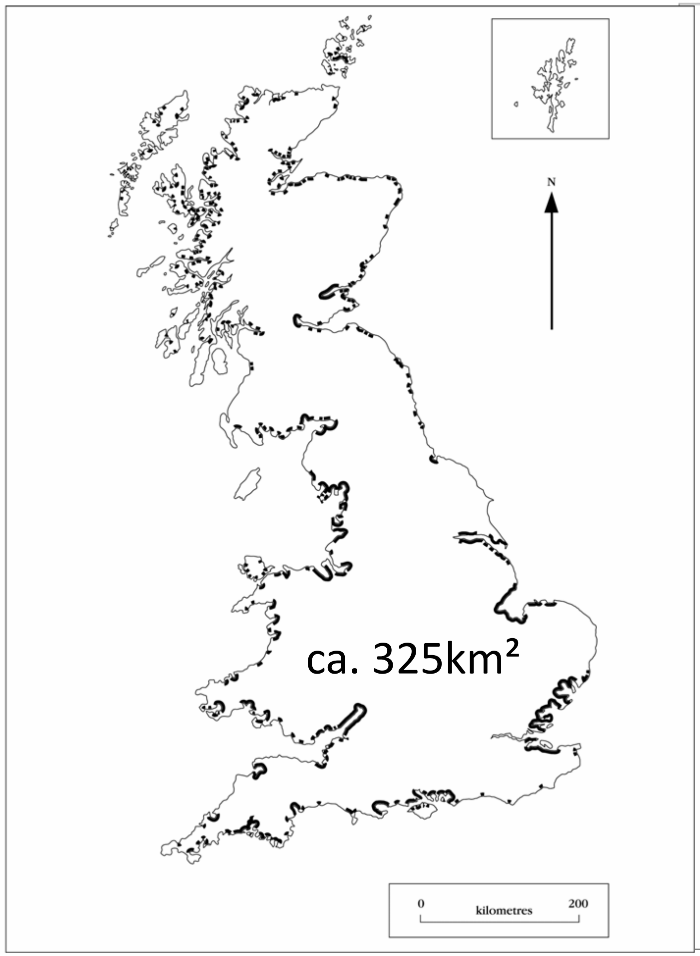
What Are Salt Marshes?



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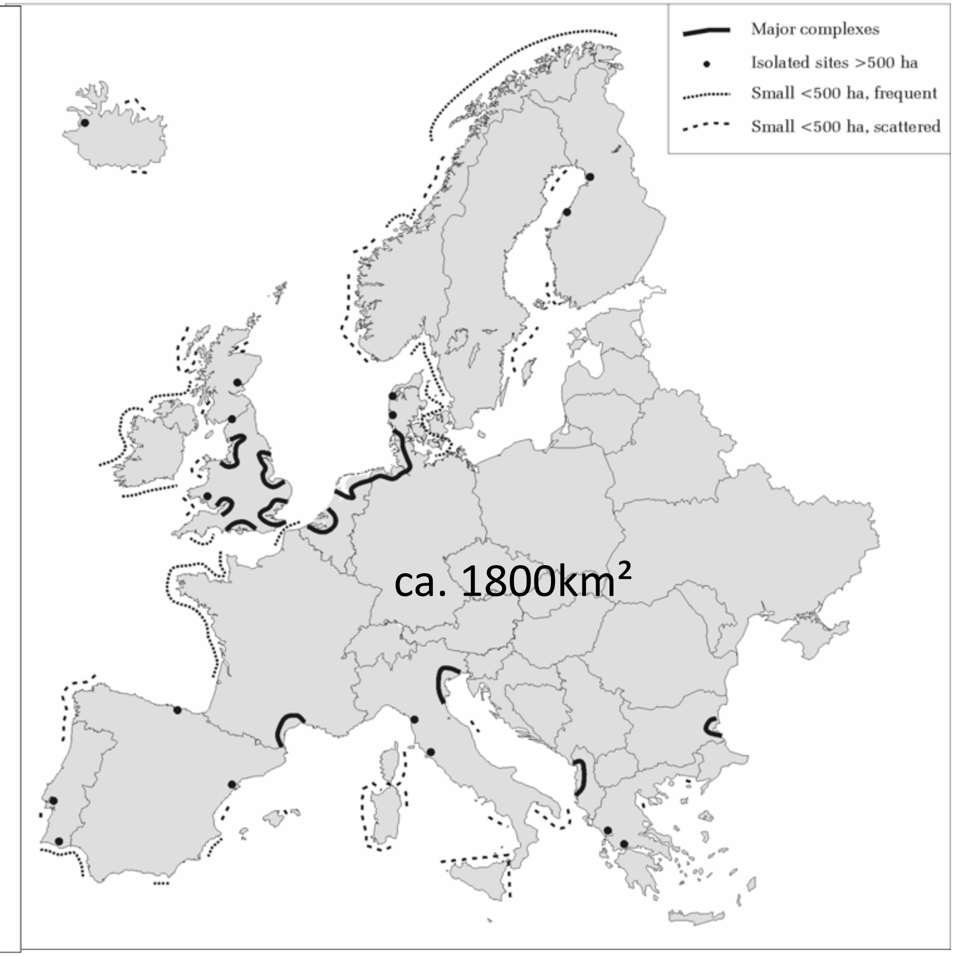

From: Dijkema *et al.,* 1984

- Coastal wetlands, inundated with marine to brackish waters with the tide
- Contain specialied plant and animal communities
- Distributed throughout the UK and Europe
- Important habitat for many birds
- Used extensively for grazing land

LETTER

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Coastal eutrophication as a driver of salt marsh loss

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Salt marshes are highly productive coastal wetlands that provide important ecosystem services such as storm protection for coastal cities, nutrient removal and carbon sequestration. Despite protective measures, however, worldwide losses of these ecosystems have accelerated in recent decades[1]. Here we present data from a nine-year whole-ecosystem nutrient-enrichment experiment. Our study demonstrates that nutrient enrichment, a global problem for coastal ecosystems[2–4], can be a driver of salt marsh loss. We show that nutrient levels commonly associated with coastal eutrophication increased above-ground leaf biomass, decreased the dense, below-ground biomass of bank-stabilizing roots, and increased microbial decomposition of organic matter. Alterations in these key ecosystem properties reduced geomorphic stability, resulting in creek-bank collapse with significant areas of creek-bank marsh converted to unvegetated mud. This pattern of marsh loss parallels observations for anthropogenically nutrient-enriched marshes worldwide, with creek-edge and bay-edge marsh evolving into mudflats and wider creeks[5–7]. Our work suggests that current nutrient loading rates to many coastal ecosystems have overwhelmed the capacity of marshes to remove nitrogen without deleterious effects. Projected increases in nitrogen flux to the coast, related to increased fertilizer use required to feed an expanding human population, may rapidly result in a coastal landscape with less marsh, which would reduce the capacity of coastal regions to provide important ecological and economic services.

An accelerated global nitrogen cycle[1–3] has greatly increased the flow of reactive nitrogen (primarily as NO_3^-) from land to coastal marine ecosystems, causing harmful algal blooms, hypoxia and fisheries losses[5,8]. Salt marshes occupy a critical interface between the land and the sea, where they provide important ecological and economic services, such as nutrient removal, storm protection for coastal cities and carbon sequestration, and habitats for numerous species of fish, birds and invertebrates. It is thought that salt marshes can protect coastal bays by removing land-derived nutrients[9,10], a conclusion based on measures of whole-system nutrient budgets[11,12] and plot-level experiments in which added nutrients were transformed into greater above-ground plant production (primarily cordgrass *Spartina* spp.) or denitrified[4]. Globally between a quarter and half of the area of the world's tidal marshes has been lost, and although multiple factors (sea-level rise, development, loss of sediment supply) are known to contribute to marsh loss[1], in some locations the drivers remain unexplained. Understanding the mechanisms underlying the continued loss of this ecologically and economically important ecosystem is a global priority.

Here we present an ecosystem-level experimental approach to understanding how the intertwined responses of plant biomass allocation, microbial decomposition, and geomorphic stability to coastal nutrient enrichment may drive salt marsh loss. For nine years (2004–2012) we have enriched multiple whole-ecosystem marsh landscapes to nutrient levels that correspond to moderately-to-highly eutrophic waters by adding dissolved nutrients to flooding tidal water[13]. Approximately 50%–60% of the added NO_3^- was processed (assimilated or denitrified) in the nutrient-enriched systems; the remainder was exported in ebbing tidal water[12]. The large scale of this experiment, which included creeks, mudflats, tall-form smooth cordgrass (*Spartina alterniflora*) at the creek-channel edge and saltmeadow cordgrass (*S. patens*) in the high marsh, has revealed interactions that would not be apparent from plot-level experiments in individual habitats.

Nutrient enrichment may invoke a series of positive feedbacks by altering ecosystem processes that affect below-ground dynamics and creek-bank stability, leaving marshes more susceptible to the erosive forces of storms and sea-level rise and gravitational slumping. In less than a decade, a cascade of changes induced by nutrient enrichment resulted in loss of low marsh along the creek-bank edge (Fig. 1a–f) and a corresponding loss of ecosystem function. Smooth cordgrass along the creek-bank edge responded to nutrient enrichment with increased above-ground biomass expressed as heavier, taller shoots (Fig. 2a), lower structural compounds (decrease of about half in foliar lignin), and increased N content (Table 1), with response ratios comparable to plot-level nutrient-enrichment experiments[4,14]. Increased plant height coupled with less structural tissue caused more extensive areas of smooth cordgrass to fall over (lodge)—a well-known response to over-fertilizing grasses[15]. Using permanent transects and high-precision global positioning system (GPS) mapping across the elevation gradient, we found no evidence (D.S.J., R.S.W. and L.A.D., manuscript in preparation) for the hypothesized shift in the up-elevation boundary between *S. alterniflora* and *S. patens* in response to nutrients[15]. In nutrient-enriched marshes, smooth cordgrass allocated less photosynthate to nutrient-gathering roots and storage rhizomes, resulting in a third less total below-ground biomass and a lower root:shoot ratio (Fig. 2b, c). Two smooth cordgrass growth attributes, a highly plastic above-ground/below-ground allocation[16] and foliar uptake of NO_3^- (ref. 17), contribute to the reductions in total below-ground biomass observed in nutrient-enriched marshes.

The continuous availability of high NO_3^- in the water and more decomposable marsh grass detritus (due to higher N content and lower lignin) increased decomposition rates (Table 1). Whole-ecosystem nitrate removal was 40 times higher in the nutrient-enriched marsh and was primarily attributable to microbial use of the added NO_3^- to decompose organic matter[12]. Potential denitrification—an indicator of anaerobic microbial decomposition using nitrate as an electron acceptor with the end product being N_2 gas—increased 1.7-fold in creek bank sediments, while litter respiration—a measure of aerobic microbial decomposition—almost doubled (1.9-fold). Denitrification is the highest energy-yielding decomposition process in anoxic marsh sediments and is favoured in the presence of high nitrate[5]. Accelerated decomposition increased the fraction of fine detrital organic matter, with 65% of the cores from nutrient-enriched creeks having a higher percentage of fine organic matter. As a result, the fine-grained, less-consolidated creek banks retained more water at low tide (Fig. 2d).

The combination of fewer roots and rhizomes, drag by tidal currents on lodged plants, more decomposed organic matter and higher water content undermines the structural integrity of the creek bank such that the effects of standard physical forces become enhanced. Loss of roots

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REVIEW

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Tidal wetland stability in the face of human impacts and sea-level rise

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Coastal populations and wetlands have been intertwined for centuries, whereby humans both influence and depend on the extensive ecosystem services that wetlands provide. Although coastal wetlands have long been considered vulnerable to sea-level rise, recent work has identified fascinating feedbacks between plant growth and geomorphology that allow wetlands to actively resist the deleterious effects of sea-level rise. Humans alter the strength of these feedbacks by changing the climate, nutrient inputs, sediment delivery and subsidence rates. Whether wetlands continue to survive sea-level rise depends largely on how human impacts interact with rapid sea-level rise, and socio-economic factors that influence transgression into adjacent uplands.

Coastal wetlands are simultaneously some of the most vulnerable and most economically important ecosystems on Earth. Marshes and mangroves protect coastal regions from storms, sequester carbon, transform nutrients and provide the organic matter and nursery grounds that support commercial fisheries[1]. Although these ecosystem services are valued at about US$10,000 per hectare[1], around 25–50% of the world's coastal tidal wetlands have been lost as a result of their direct conversion into land for agriculture and aquaculture uses[2–4]. Tidal wetland conversion to open water through sea-level rise is expected to accelerate, with regional assessments predicting a 20–45% loss of salt marsh during the current century[5]. However, forecasts of widespread wetland loss are difficult to defend on the basis of past accelerations of sea-level rise. There are relatively few examples of marsh loss in the historical record that are directly attributable to sea-level rise because feedbacks between flooding, plant growth and elevation change tend to stabilize submerging wetlands[6,7]. In fact, most coastal wetlands build vertically at rates similar to or that exceed the rate of historical sea-level rise[8,9]. Regions of the world with drastic wetland deterioration occur mainly in areas in which humans have accelerated subsidence rates and/or decreased sediment delivery rates to the coast (for example, coastal Louisiana, the Venice Lagoon and Chesapeake Bay). Nevertheless, past response to sea-level rise is an imperfect model for future response because the climate, water quality and sediment delivery rates continue to change with human activity. In this Review, we will discuss the processes that influence how tidal wetlands adapt to sea-level rise, and highlight how changing climate and socio-economic conditions may alter our emerging understanding of riveting feedbacks between ecology and geomorphology. We focus mainly on tidal marsh ecosystems for which the ecogeomorphic feedbacks are better understood, but also note instances in which data or general principles apply to mangroves. We argue that human impacts other than those that cause sea-level rise have dominated wetlands in the past, but that interactions between rapid sea-level rise and human impacts will drive wetland stability in the future. Whether these ecosystems continue to survive ever faster rates of sea-level rise depends principally on sediment availability, biotic responses to environmental change, the opportunity for wetlands to migrate inland, and environmental attitudes that influence land use, all of which are heavily determined by human socio-economic systems.

Biophysical feedbacks stabilize wetlands

Expansive tidal wetlands consisting of marshes and mangroves, and the channel networks that dissect them occupy about 20 million hectares worldwide[3], and have been a prominent component of coastal and estuarine landscapes for at least 4,000 years[10]. Over this period, the sea level has risen in most regions of the world by more than 2 metres[11,12]. However, observations of widespread wetland drowning are infrequent because of the fascinating interactions between plants and soil that allow wetlands to actively engineer their position within the intertidal zone in ways that enhance ecosystem persistence[7,13–15].

Vertical changes in wetland elevation

At the most basic level, a marsh or mangrove must build soil elevation at a rate faster than or equal to the rate of sea-level rise to survive in place[16]. Elevation gain occurs through biological and physical feedbacks that couple the rate of sea-level rise to the rate of vertical accretion (the increase in soil surface elevation) (Fig. 1). In their role as ecosystem engineers, plants set up distinct feedback loops above and below ground. Above ground, mineral sediment settles out of the water column and onto coastal wetland soils during periods of tidal flooding, so that deposition rates are highest in low elevation marshes that are inundated for long periods of time, and lowest in high elevation marshes that are more rarely flooded[17,18] (Fig. 2a). Plant shoots influence mineral sediment deposition by slowing water velocities[7], and add organic matter to the soil surface (Fig. 1). Below ground, the balance of plant root growth and decay directly adds organic matter to the soil profile, raising elevation by sub-surface expansion[19].

Coastal wetlands are among the most productive ecosystems on Earth, and recent work suggests that vegetation tends to stabilize their relative elevation and seaward extent through feedbacks that vary with the depth and duration of flooding. For example, growth of the grass *Spartina alterniflora* is positively correlated with interannual variations in sea level, such that productivity peaks at intermediate elevations within the intertidal zone, and declines at higher or lower elevations[20] (Fig. 2a). Although the response of mangrove productivity to interannual sea-level variation is unknown, other marsh species show similar — but species-specific — patterns[21,22]. Faster rates of above-ground plant growth promote greater standing biomass, which in turn slows water velocities on the marsh platform[23], lowers wave height[24], reduces erosion and enhances mineral sediment deposition[25]. Collectively, these feedbacks allow tidal

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FORUM

On the loss of saltmarshes in south-east England and methods for their restoration

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Summary

1. The saltmarshes of south-east England have been eroding rapidly for about the last 50 years, at a continuing rate of about 40 ha $year^{-1}$, with deleterious consequences for conservation and coastal flood defence. The possible reasons for this erosion and suitability of methods of saltmarsh restoration are discussed.
2. The prevailing hypothesis that the saltmarsh erosion is due to coastal squeeze, where sea walls prevent a landward migration of saltmarsh in response to sea level rise, is rejected because: (i) as the sea level rises saltmarshes accrete vertically as well, at least at the same rate, and may even extend seaward; (ii) in recent decades the rate of rise in sea level has been no higher than in the past when the saltmarshes developed; (iii) the pattern of vegetation loss, mostly of pioneer zone species, is opposite to that predicted by coastal squeeze, where the upper marsh plants should disappear first.
3. Alternative explanations and hypotheses are proposed that relate the recent saltmarsh erosion to changes to the intertidal biota, an increase in abundance of the infaunal polychaete *Nereis diversicolor*, and a decrease in abundance of intertidal seagrasses. Bioturbation and herbivory by *Nereis* cause the loss of pioneer zone plants, increase sediment instability and exacerbate the erosion of saltmarsh creeks. The erosion of the seaward edge of some marshes may also be due to increased wave action, and increased tidal current speeds in estuaries, following the loss of intertidal seagrasses since the 1930s through wasting disease.
4. *Synthesis and applications.* The current strategy for saltmarsh creation is based on managed realignment, where some sea walls are breached to provide new intertidal habitat. The conclusion that the causes of saltmarsh loss are not related to sea level rise calls into question this dependence on management realignment as the most appropriate means of saltmarsh creation, not least because many realignment areas are unlikely to develop vegetation. Other methods should be considered for creating new marshes and for reducing/reversing marsh erosion. These include, alone or in combinations, exclusion of the infauna, use of dredged material for strategic intertidal recharge, and transplantation of intertidal seagrasses.

Key-words: bioturbation, coastal squeeze, herbivory, *Nereis*, saltmarsh erosion

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Introduction

Coastal saltmarshes are areas of herbaceous vegetation that colonize intertidal sediments in wave-sheltered areas and are inundated by seawater by at least the highest spring tides of each lunar month. The plants show a vertical zonation where generally the lower limits of the different species are determined by their varied tolerances to several factors associated with immersion, including high sulphide concentrations, low pH and anoxia of the soil (Davy 2000). The upper limits of their distributions are generally determined by inter-specific competition with plants that live at higher elevations, because they are less well adapted to these conditions. Saltmarshes have a high primary productivity

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The Sea-Defence Value of Salt Marshes:

Swansea University Prifysgol Abertawe

CoastWEB

Coastal Flooding

- Economic Impact
- Individual Impact
- Societal Impact

Risks from storm events that coincide with (large) spring tides

Inundation and flooding risk due to waves

From https://www.cam.ac.uk/research/news/salt-marsh-plants-key-to-reducing-coastal-erosion-and-flooding

- Coastal wave defence provision, and the roles of salt marshes described by Möller *et al*., 1999, 2004, 2014; Yang *et al*., 2012
  - Reduce Wave set-up and height

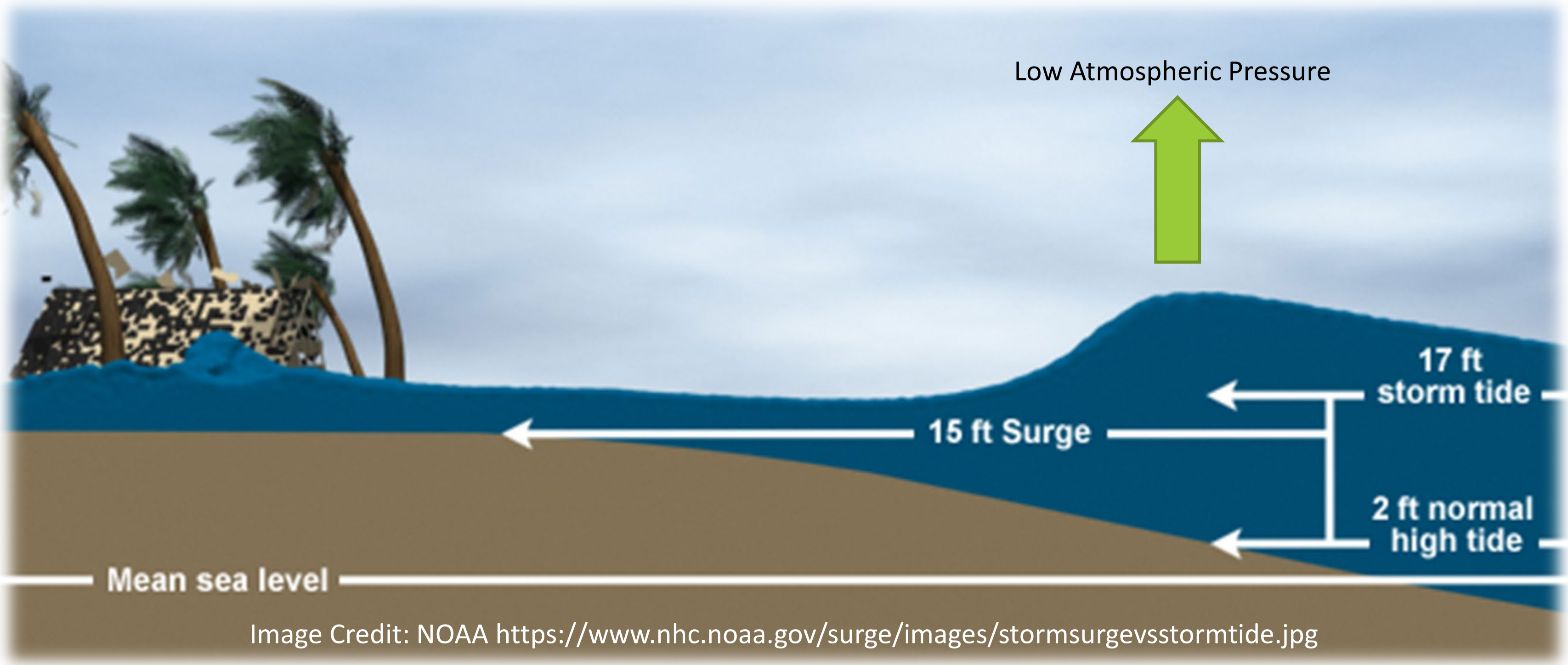


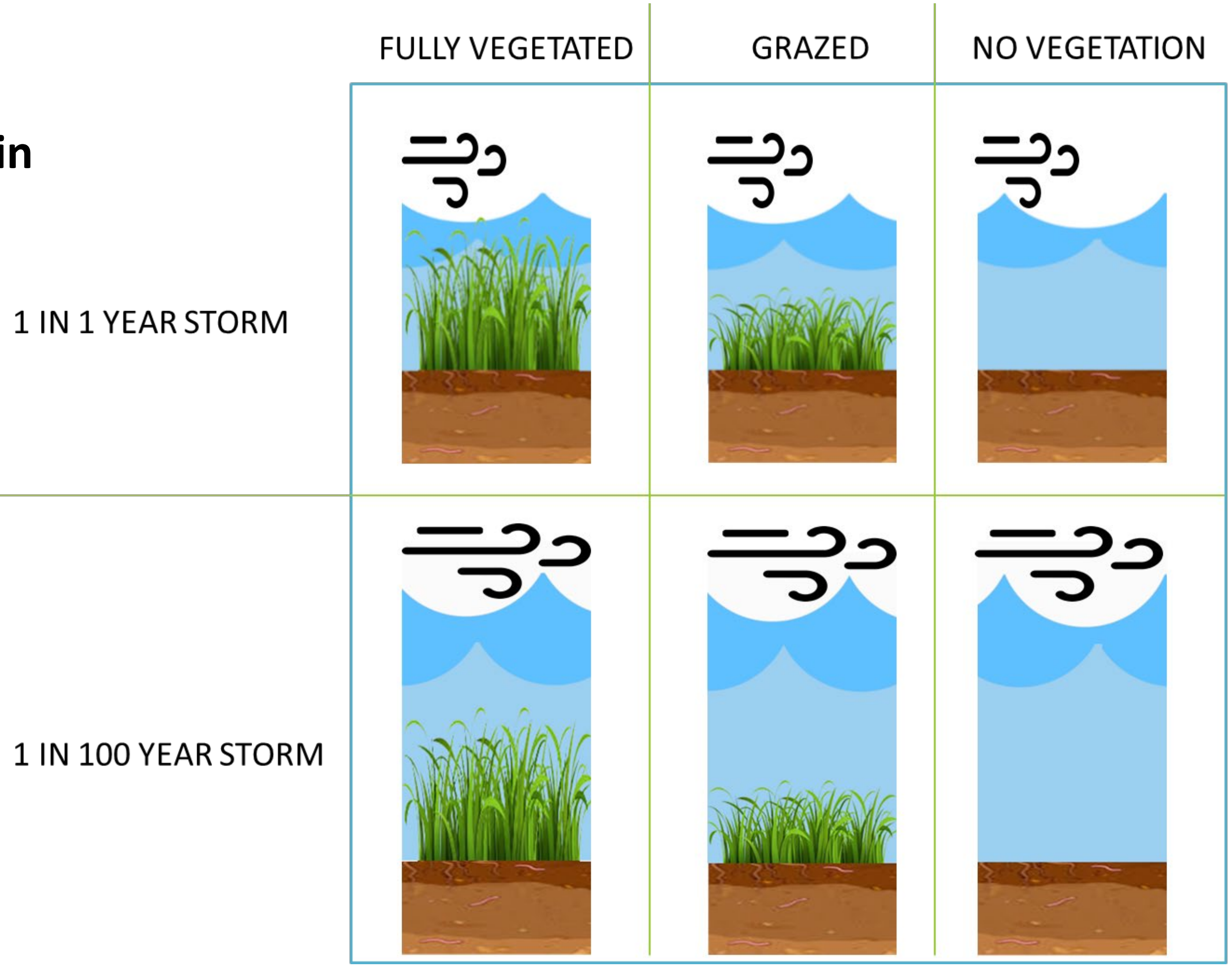
Image Credit: NOAA https://www.nhc.noaa.gov/surge/images/stormsurgevsstormtide.jpg

- Causes greater water depths than normal tidal levels, pushing much further upstream and landward
- Pose substantial risks to infrastructure and homes

What Role Does Salt Marsh Vegetation Play in Reducing Storm Flooding in Estuaries?

The generality and role of marsh vegetation in moderating:

- Local-scale effects (longitudinal wave reduction, longitudinal flood level reduction)
  - e.g. Möller *et al*., 1999;2002;2004;2014, Yang *et al*., 2012
- Regional scale (cumulative effects of marsh vegetation on hydrodynamics, flood depths and extents within estuary valleys)
- Whether vegetation state (i.e. grazed vs ungrazed) affects flood mitigation potential of marshes



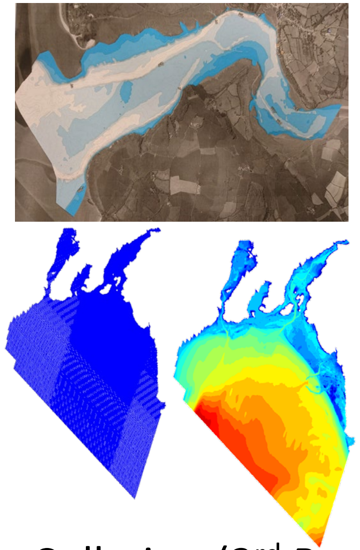
Generality or context dependence?

Create Wave-Flow-Tide coupled models using the Hydrodynamic simulation models SWAN and Delft3D-FLOW

Modeled 8 case study estuaries within Wales with different locations, tidal regimes, shapes and exposures:

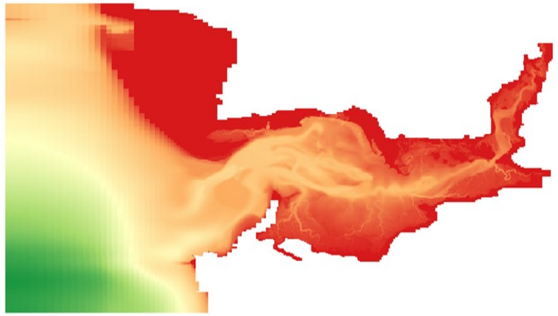
1. Dee Estuary
2. Loughor Estuary
3. Glaslyn Estuary
4. Taf Estuary, South Wales
5. Towy Estuary
6. Gwendraeth Estuary
7. Neath Estuary
8. Mawddach Estuary

Data Field Collection



Data Collation (3rd Party)

Data Pre-processing and Delft3D 2D Simulation



Outputs

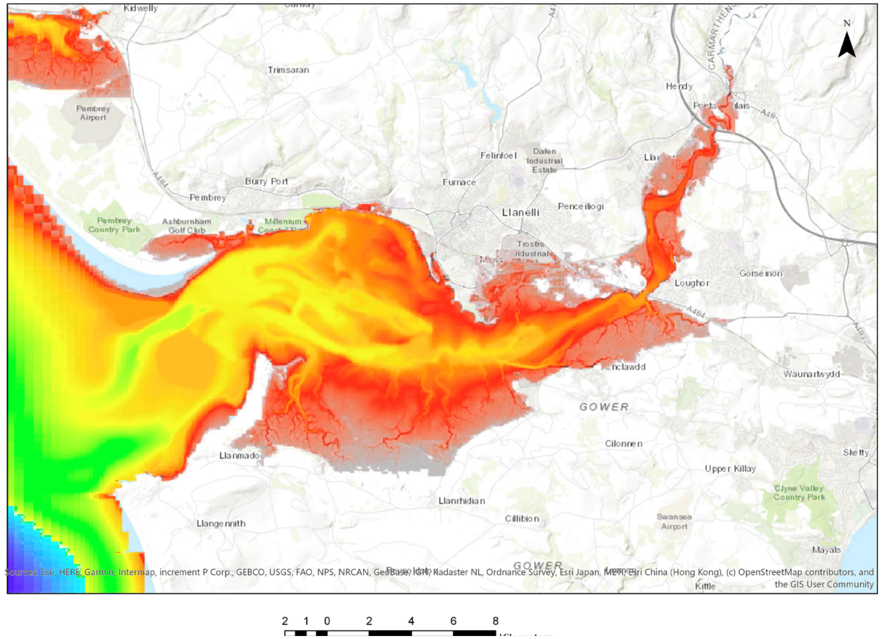
COUPLED WAVE-TIDE_RIVER MODELS WITH VEGETATION

Caveats

- Vegetation is limited to a single “type” specification
- The marsh platform, the sedimentary bank that builds up marsh beds, was still present in the Non-Vegetated scenarios*
- Models only provide a “snapshot” in time, and should not be used to infer management priorities for individual case-study estuaries that are presented.
- Simplification of physics from 3D to 2D

*This allowed us to examine the specific role of vegetation, rather than just the role of salt-marshes as a whole

Effects of Storms


Kidwelly
Trimsaran
Hendy
Pembrey Airport
Felinfoel
Dafen Industrial Estate
Furnace
Burry Port
Pembrey
Llanelli
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Pembrey Country Park
Ashburnham Golf Club
Loughor
Gorseinon
Waunarlwydd
GOWER
Cilonnen
Llanmadoc
Upper Killay
Llanrhidian
Cillibion
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Swansea Airport
Clyne Valley Country Park
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Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community
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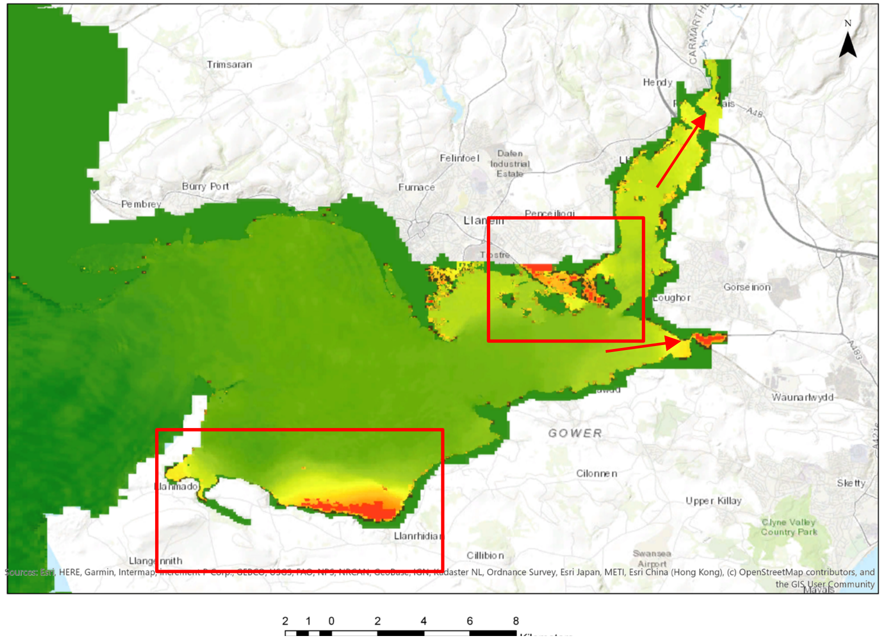
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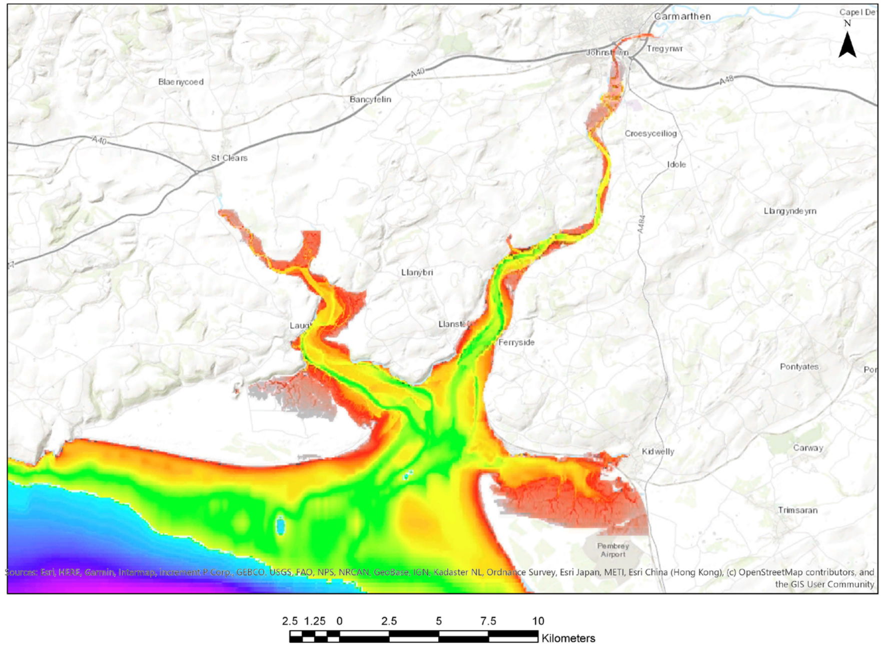
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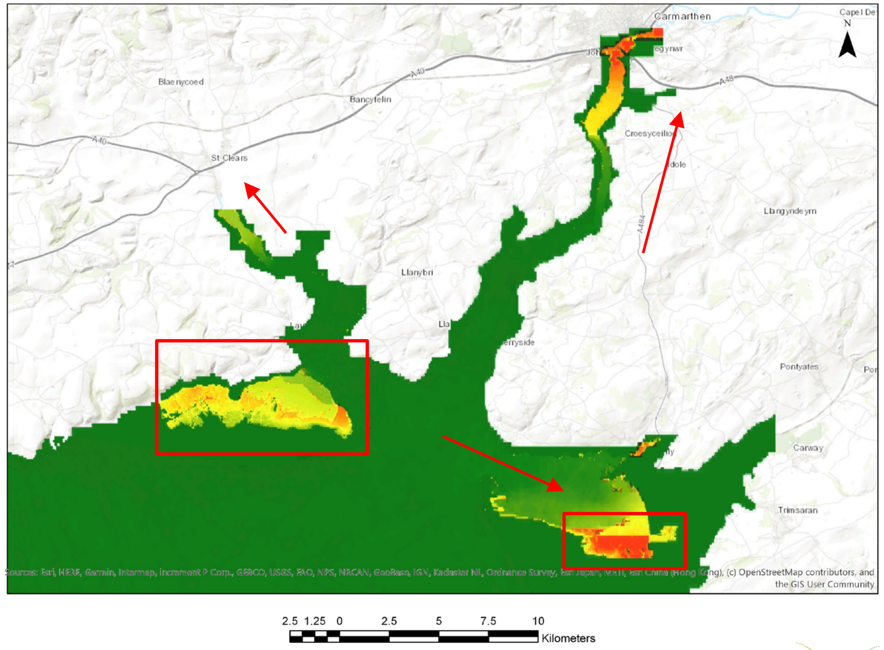
Kilometers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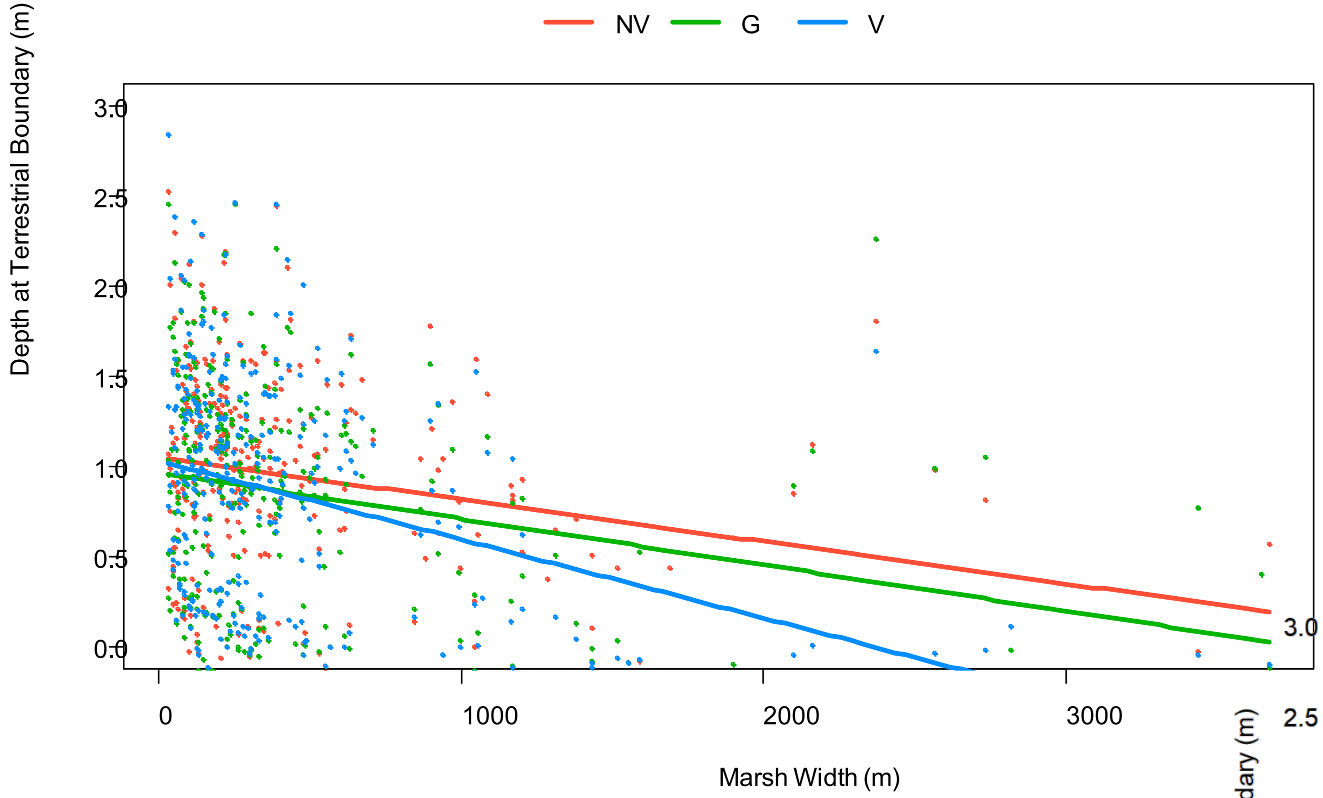
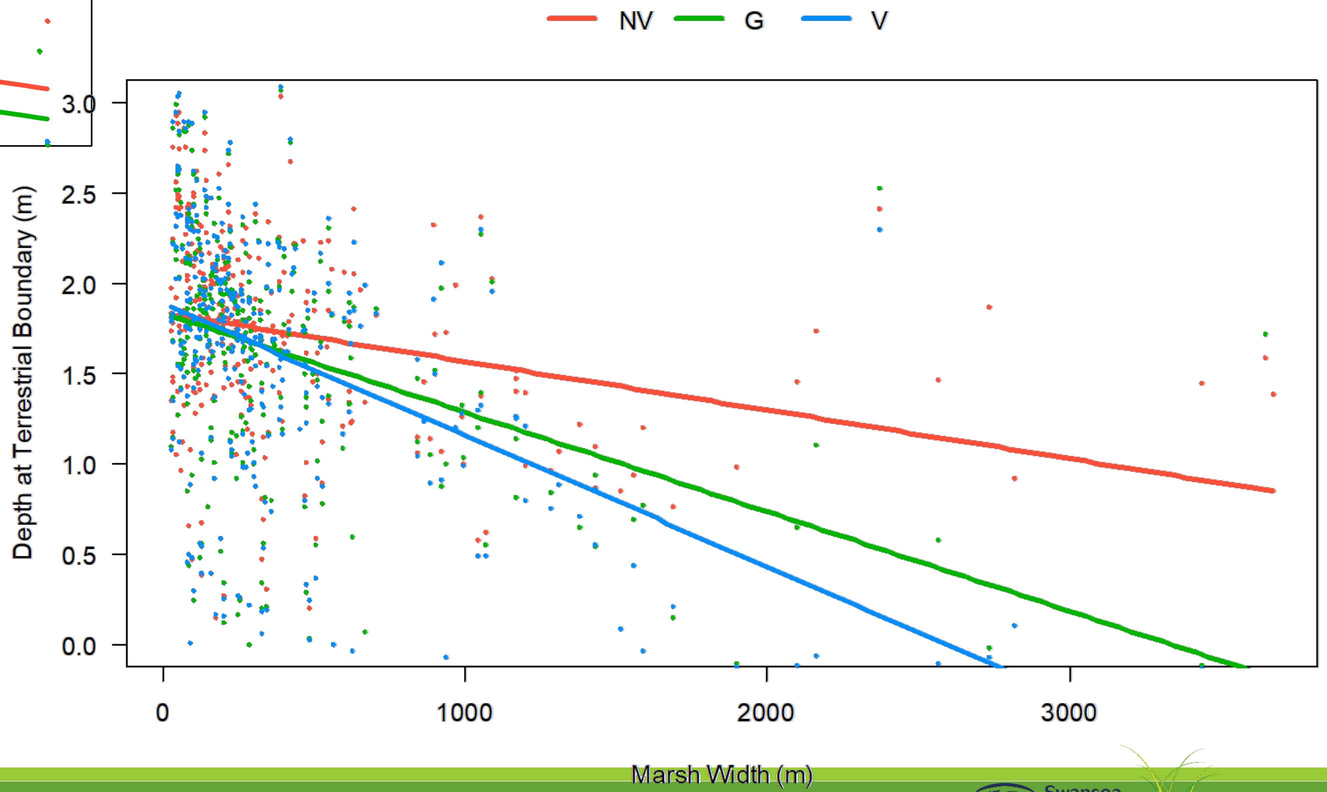
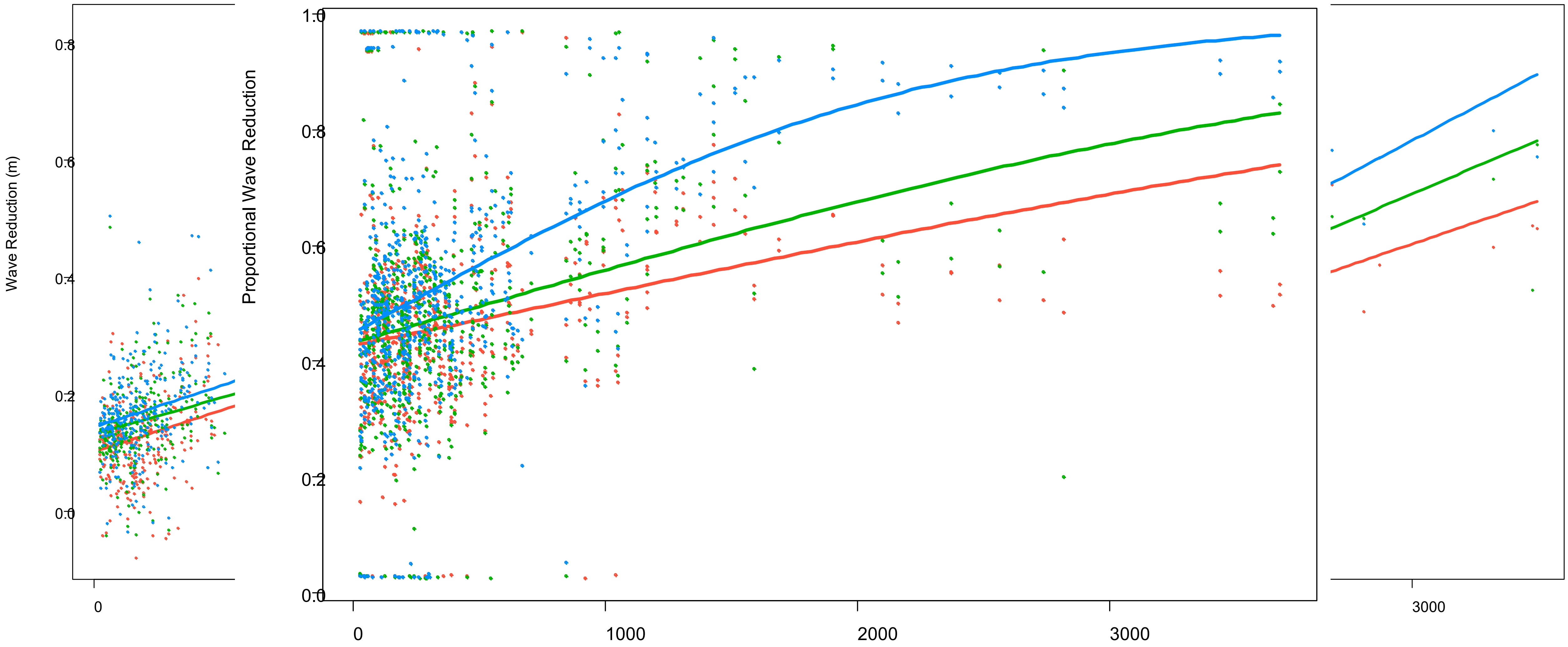
2.5 1.25 0 2.5 5 7.5 10
Kilometers

Local Effects

- Both Fully Vegetated and Grazed marshes are more effective at reducing localised flooding than the unvegetated marsh platforms







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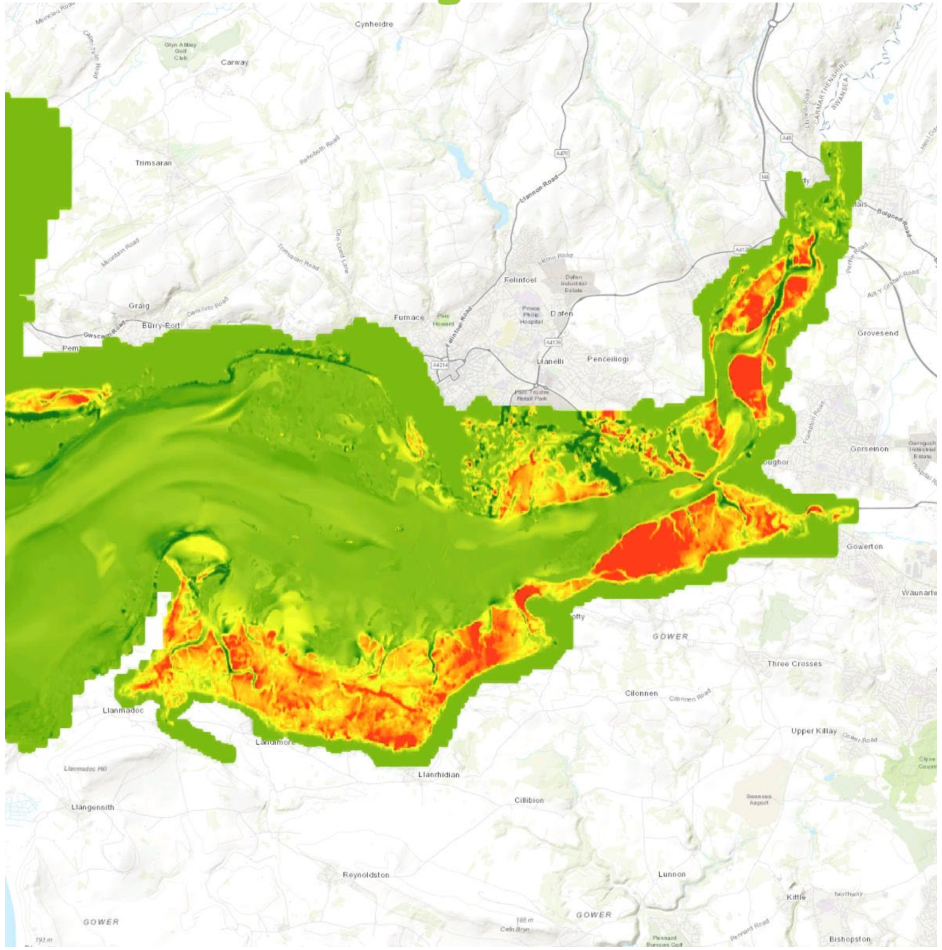
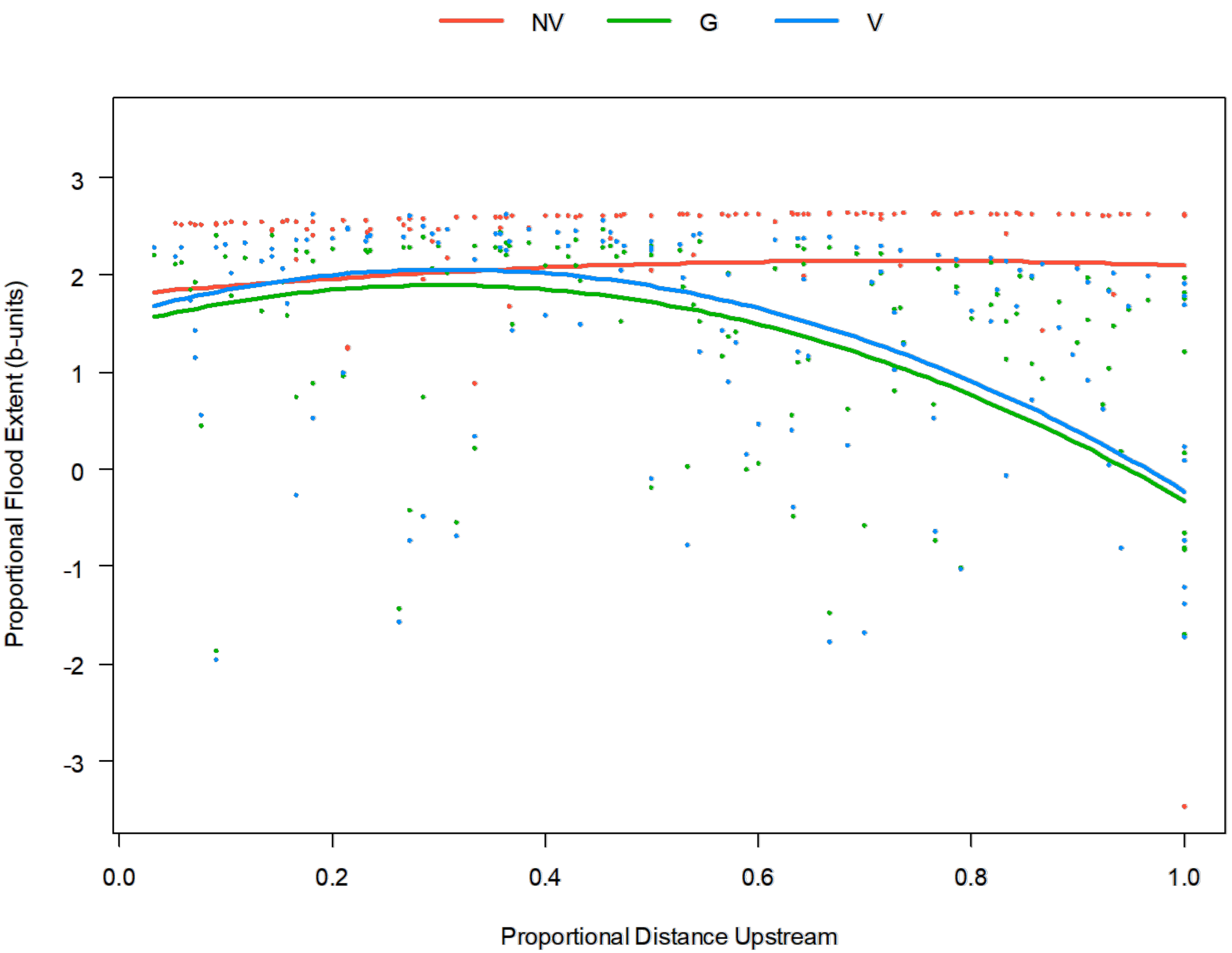
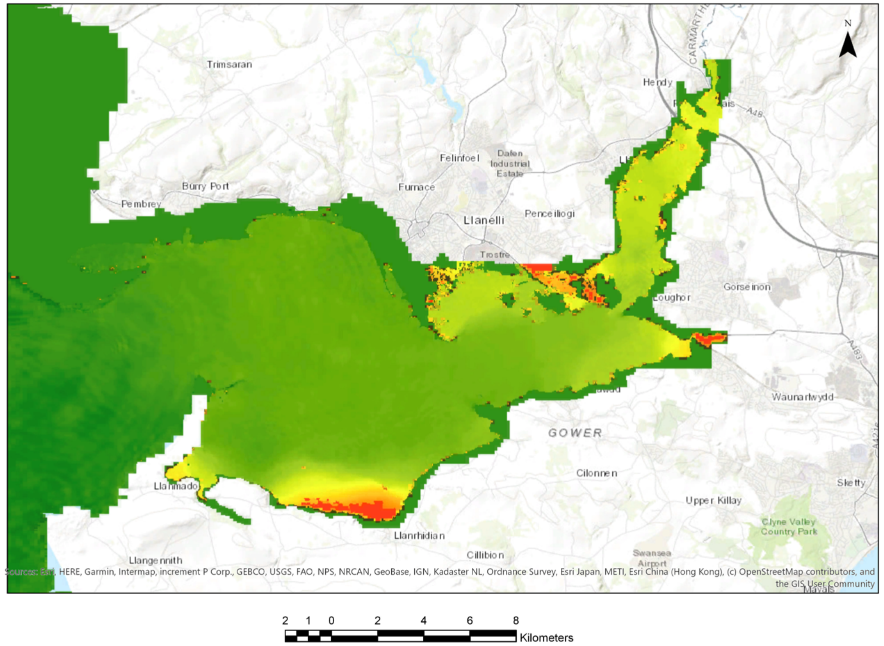
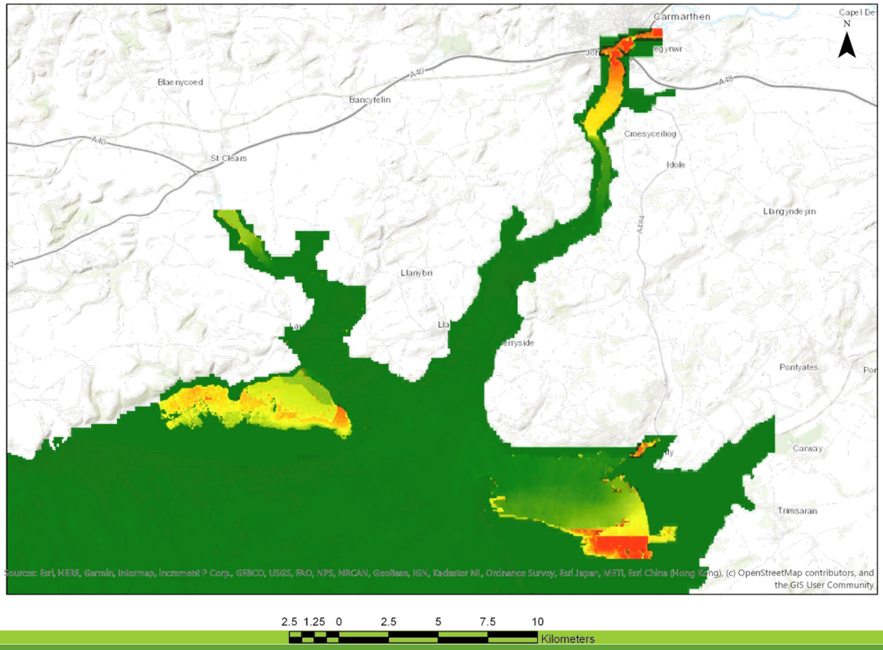
Estuary Effects









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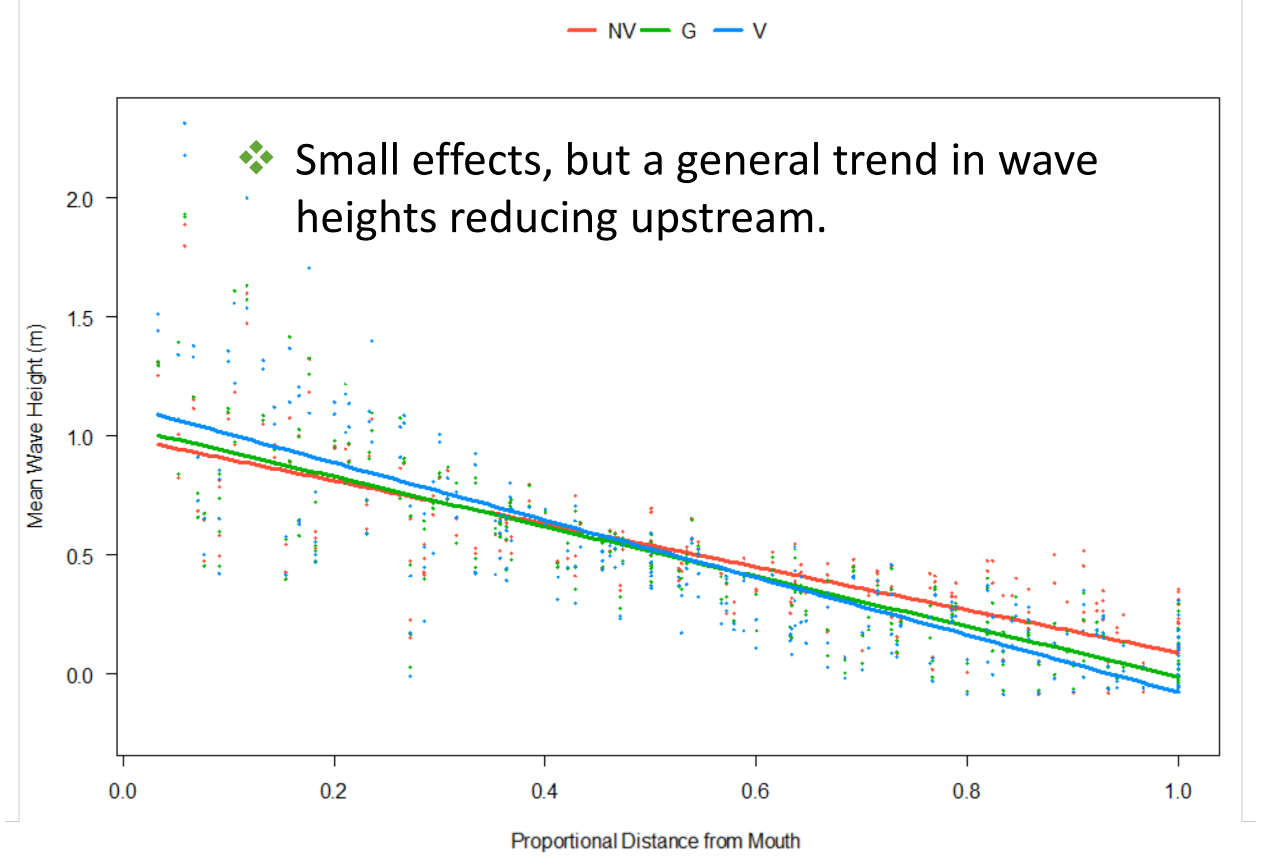
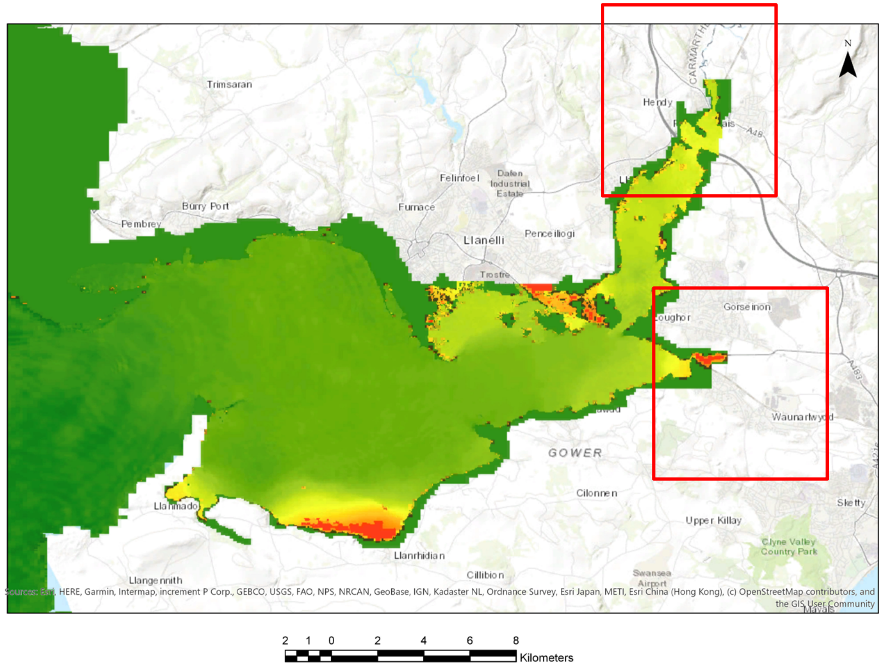
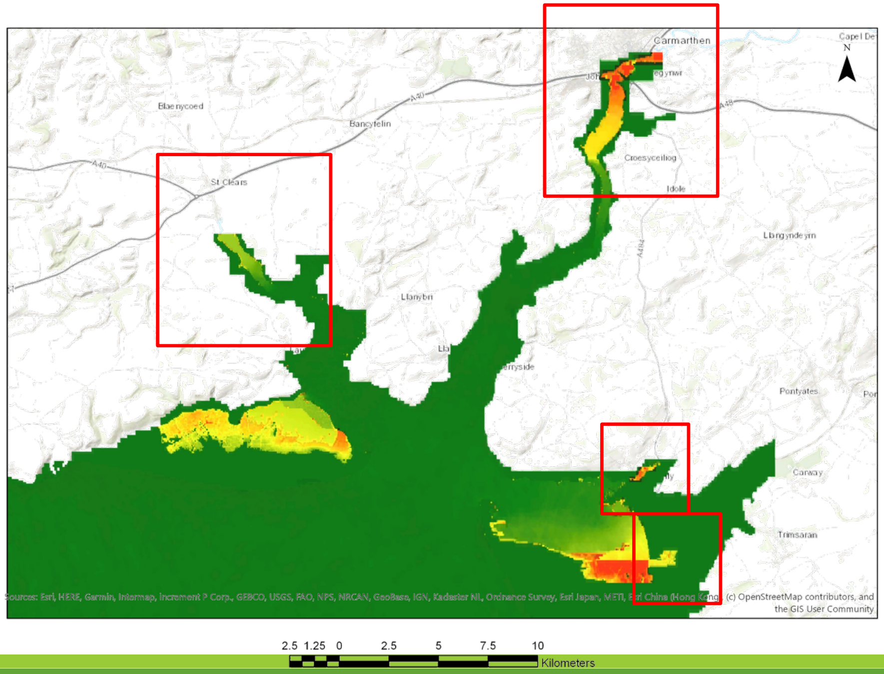
- Small effects, but a general trend in wave heights reducing upstream.



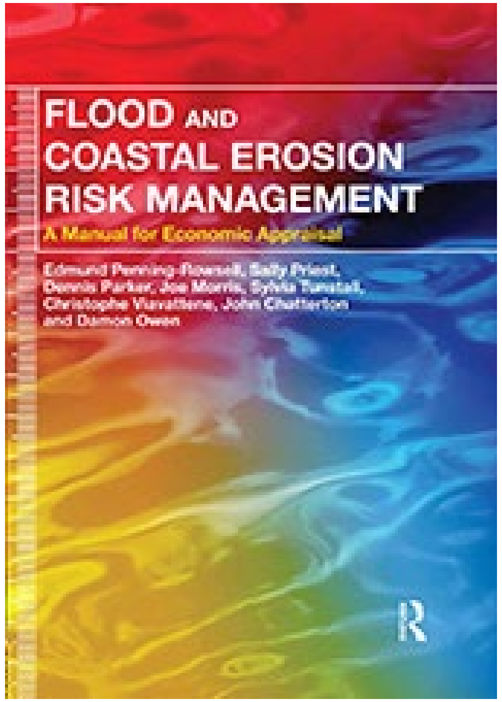
- Waves are initially enhanced by vegetation near the mouth as vegetation slows down upward movement of water, leading to deeper water and reducing wave-lowering friction
- Further up the estuary this is less important as depths are low, and vegetation exerts increased drag, attenuating waves more quickly



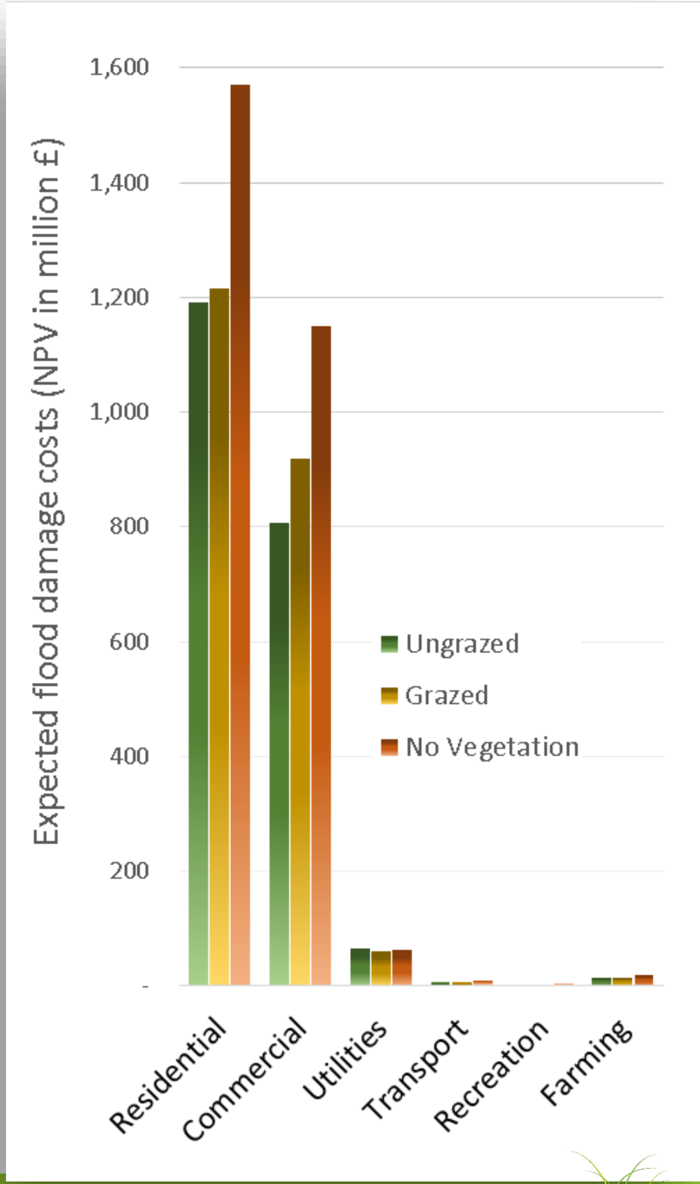


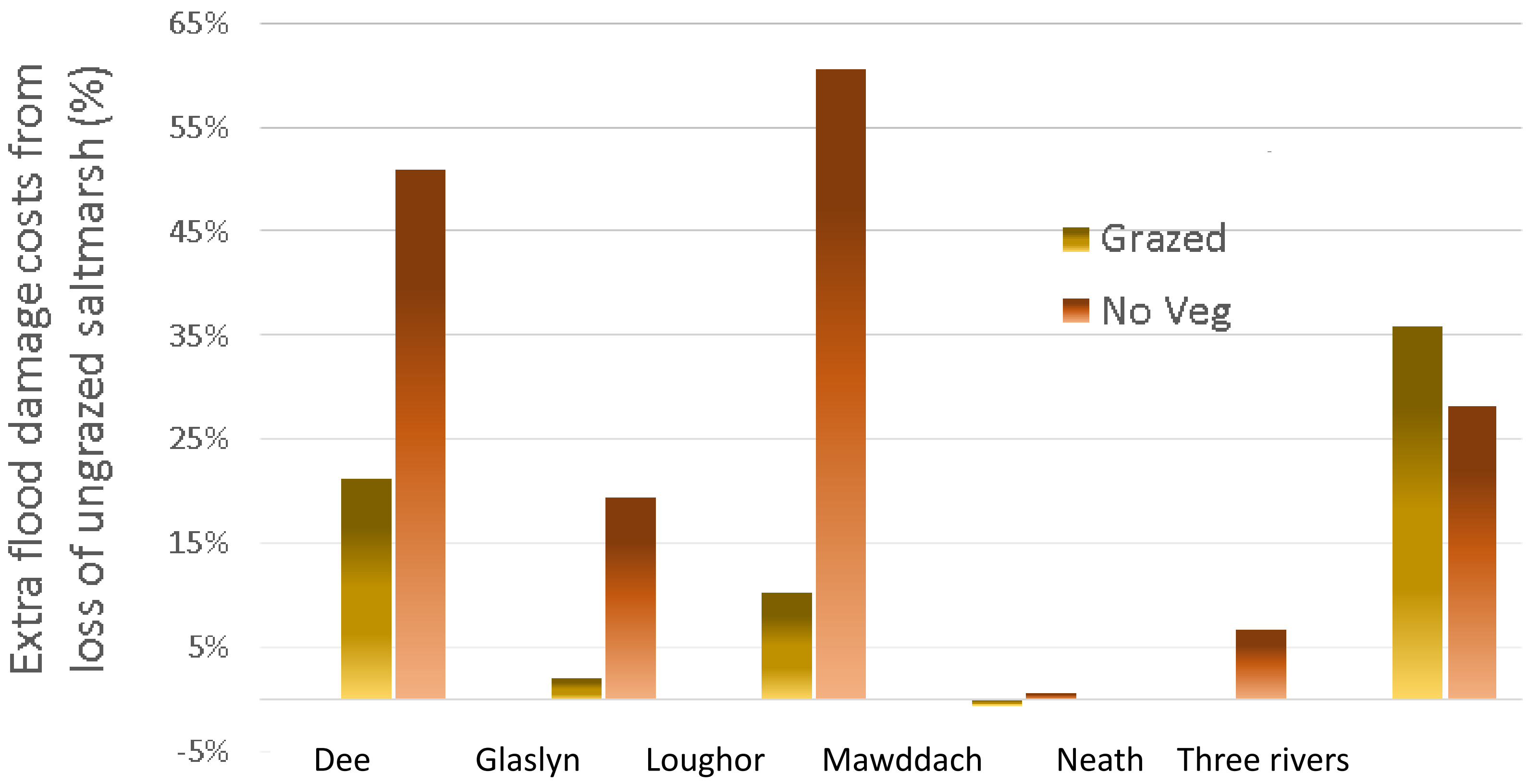
SURGE EFFECTS DOMINATE

Flood Damages



- Damages for:
  1 in 1, 1 in 10 & 1 in 100 year events
- Interpolate to a Net Present Value (NPV) using 3.5% discount rate





- Ungrazed saltmarsh reduces damages by between 55% & -1%
- Loughor:
  - Grazed: £ 102,907,730
  - No Veg: £ 603,576,232
- Savings on average:
  - Grazed: 9%
  - No Veg: 19%

Vegetation

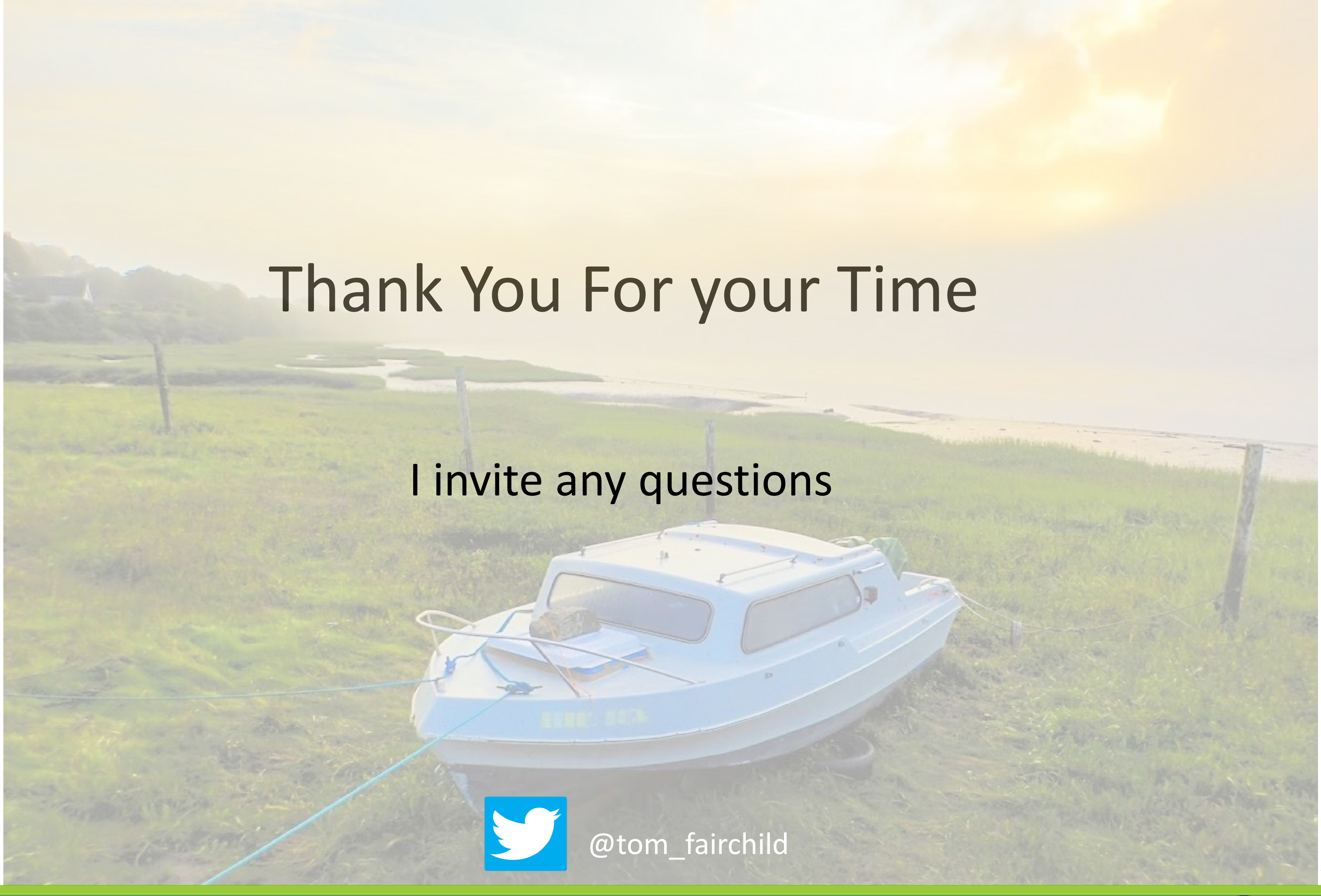
- Fully Vegetated marshes provide significant storm flood defense, reducing extent by up to 20%
- Local scale reductions in wave height and flooding potential, and estuary level reductions in flood extents and surge

Grazing

- Could reduce the effectiveness of marshes to prevent flooding, although some aspects of flooding benefit from having lower marsh vegetation heights

Take Home

- Vegetation doesn't only affect flooding by local-scale wave and surge reduction, but has a marked and large effect on upstream surge attenuation.



Thank You For your Time

I invite any questions

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