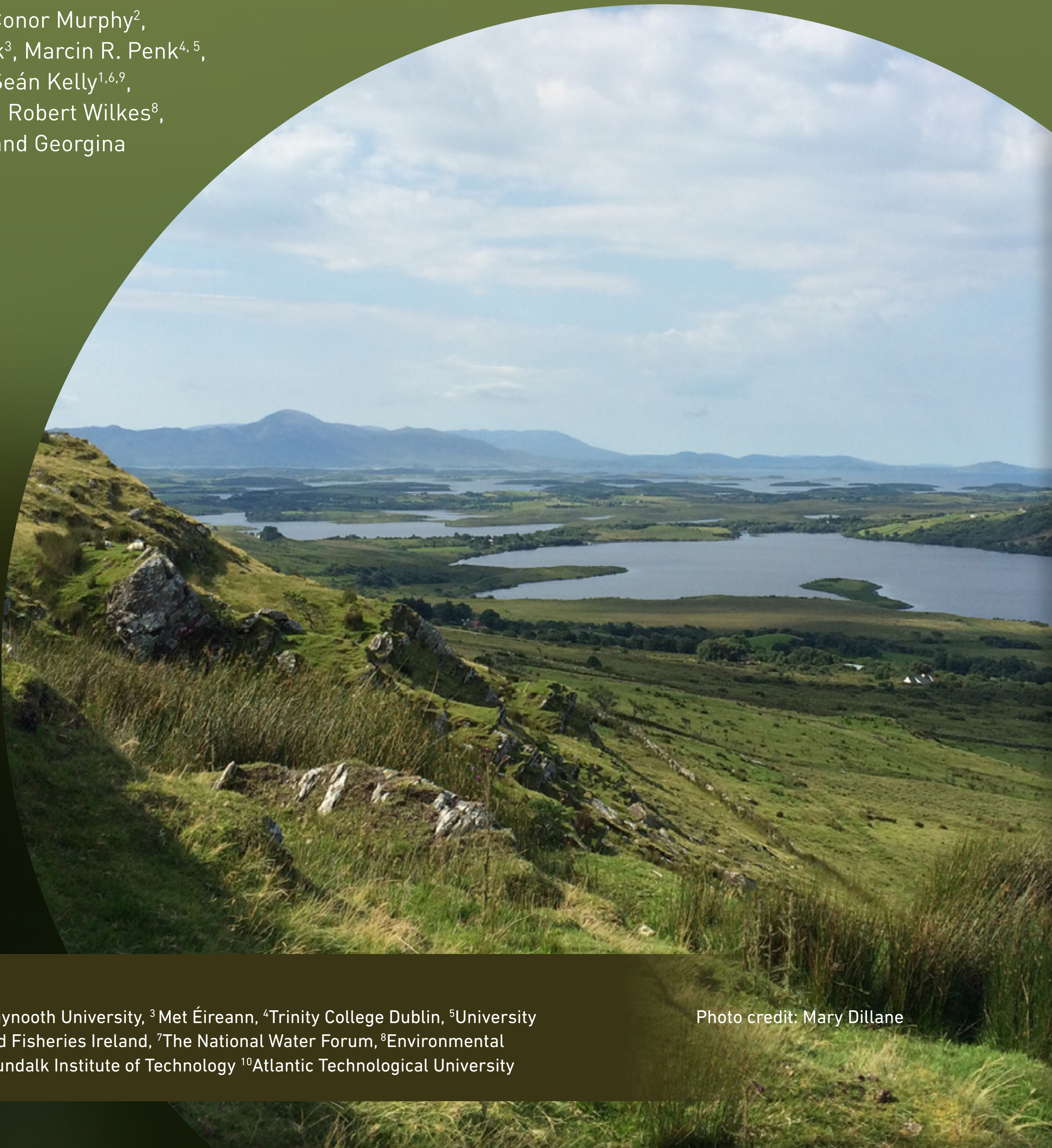
Foras na Mara
Marine Institute

CHAPTER 8

LAND OCEAN AQUATIC CONTINUUM

AUTHORS:
Elvira de Eyto[1], Conor Murphy[2], Ciaran Broderick[3], Marcin R. Penk[4, 5], Russell Poole[1], Seán Kelly[1,6,9], Triona McGrath[7], Robert Wilkes[8], Brian Doyle[1,9,10] and Georgina McDermott[8].



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[1]Marine Institute, [2] Maynooth University, [3] Met Éireann, [4]Trinity College Dublin, [5]University College Dublin, [6]Inland Fisheries Ireland, [7]The National Water Forum, [8]Environmental Protection Agency [9]Dundalk Institute of Technology [10]Atlantic Technological University

8.1 INTRODUCTION

Ireland is particularly influenced by the ocean as it is a small land mass bordering a large ocean (McCarthy *et al*., 2015). The terrestrial ecosystems of Ireland are strongly coupled to variability in the ocean, particularly in terms of hydrology. Previous chapters have outlined the changes occurring in the atmosphere and oceans surrounding the country, and in this chapter, we consider how these changes are likely to impact our terrestrial ecosystems and aquatic processes. Initially coined to refer to the changing biogeochemistry of nitrogen, phosphorus and silica from land to ocean by Billen *et al*. (1991), the Land Ocean Aquatic Continuum (LOAC) concept encapsulates the transition zone between terrestrial ecosystems and the open ocean and has been used to describe a series of biogeochemically and physically active systems that process carbon and other nutrients as these elements move from upland soils to the open ocean (see Xenopoulos *et al*., 2017 for overview). The LOAC concept recognises that changes in the transport and transformation of elements, as well as ecological functions, occur along this aquatic continuum, and that these changes are tightly coupled with the hydrological cycle.

Rainfall (particularly in winter) and the frequency of heavy rainfall events are increasing.

The hydrological cycle of Ireland is characterised by relatively short transport distances and rapid response times to precipitation. As the crow flies, there is no point in Ireland more than 100 km from the sea, and although the longest aquatic continuum (the Shannon) is 360 km from source to sea, the majority of Irish rivers are less than 30 km in length (Kelly-Quinn *et al*., 2020). Many drain the mountainous regions in the coastal counties, and respond to rainfall events in a matter of hours. The shape of the country, with its central depression, lends itself to an accumulation of water in ponds and lakes, and their surrounding wetlands. A recent inventory enumerated 12,205 lakes in Ireland, and highlighted the importance of lakes as hotspots for biochemical processing (Dalton, 2018).

Given the coupled nature of Ireland's land mass with the surrounding ocean, it is necessary to consider changes in the terrestrial environment in tandem with any review of ocean variables. The climatic conditions that are driven by Atlantic Ocean circulation, and the linked multidecadal oscillations in atmospheric teleconnections, influence a diverse range of ecosystem processes across the island. Here, we describe some of these processes along the aquatic continuum from upland headwater ecosystems to the ocean (hydrology, nutrient transport, carbon dynamics and ecology) that are impacted by climate change. Land use change in Ireland affects freshwater and coastal habitats and there may be substantial interactions between this and climate change. Agricultural eutrophication, land drainage, urbanisation, waste water treatment inadequacies and afforestation all have a role in shaping the current situation. Where monitoring occurs, 47.0% of rivers, 49.5% of lakes and 62.0% of transitional waters, are classified as either moderate or worse ecological status (O'Boyle *et al*., 2019). Adaptation to climate change will only be successful if a full awareness of interacting stressors is considered.

8.2 HYDROCLIMATE AND HYDROLOGY

The moderating influence of the Gulf stream and the North Atlantic current on Ireland's weather is well documented, with long-term records emphasising the dominant characteristics as "moist and equable" (Sweeney, 2014). Excessive air temperatures, such as those recorded on mainland Europe, are not yet a feature of our weather, and this pattern is carried through to freshwater aquatic habitats, where the water temperature of our lakes and rivers is also moderated. Comparisons of decadal lake surface temperatures across eight lakes in Europe indicate that Lough

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Feeagh, Co. Mayo has experienced less warming in summer than other lakes (Dokulil *et al*., 2021) with warming winter temperatures more apparent (Woolway *et al*., 2019). Future projections of winter water temperatures are a cause for concern for the species that rely on cool water temperatures for survival and reproduction, such as Arctic charr (Kelly *et al*., 2020b). Despite Ireland's moderate oceanic climate, heat waves are becoming more common (Cámaro García and Dwyer, 2021), and in the summer of 2021, surface waters of Lough Feeagh heated to 23.8°C, a value that had not previously been recorded in the 60 year dataset of water temperatures maintained by the Marine Institute (Figure 8.1).

The adjacent Atlantic Ocean delivers significant heat and moisture to Ireland and strongly influences changes in rainfall and hydrology. Analysis of gridded precipitation observations from Met Éireann for the period 1941 to present, indicate increasing trends in annual precipitation totals since the 1980s (Cámaro García and Dwyer, 2021). Given the large interdecadal variability of Irish precipitation, analysis of long-term records is critical to identify robust changes. Noone *et al*. (2016) developed a quality-assured precipitation series for the island dating back to 1850. Their results show winter rainfall is increasing, while summer rainfall is decreasing. Prior to this, Murphy *et al*. (2018) developed a 300-year precipitation series for the island, confirming the findings of Noone *et al*. (2016) and showing that recent decades are the wettest in the entire series.

Changes in extreme precipitation are driven by thermodynamic (warmer atmosphere) and dynamic (circulation) changes. In general, warming increases the water holding capacity of the atmosphere following the Clausius-Clapeyron (CC) relation, which results in increases in extreme precipitation at the global scale (around 6–7% per degree of warming near the Earth's surface). Harrigan (2016), in an analysis of daily precipitation records from the 1950s onwards, found increases in precipitation intensity consistent with expectations of a warming atmosphere, particularly in the east and southeast of the island in summer. Cámaro García *et al*. (2021) found increasing trends in the length of wet spells across the island over the period 1961 to present. Ryan *et al*. (2021, 2022) evaluated changes in precipitation extremes for daily observational records extending to early 20th century and found significant increasing trends in rainfall intensity, again predominant in the east and southeast,

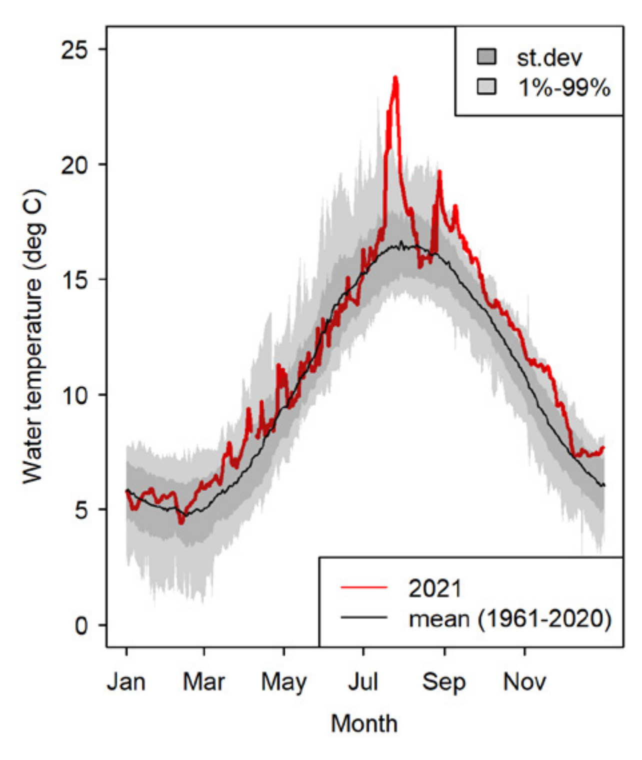

Figure 8.1 Lough Feeagh surface water temperature, 1961–2021. Red line indicates 2021, black line is the mean daily values recorded between 1961 and 2020.

while the contribution of heavy and extreme precipitation events to annual totals was also found to be increasing. Such heavy rainfall events can lead to prolonged disturbance of freshwater and coastal ecosystems, as described for Storm Desmond over Co. Mayo (Case Study - The impacts of storm Desmond on the Burrishoole catchment, Co. Mayo). Few studies have evaluated changes in meteorological drought in Ireland. One exception is Vicente-Serrano *et al.* (2021) who evaluated long-term variability and trends in meteorological droughts for western Europe over the period 1851–2018, including stations quality assured by Noone *et al.* (2016). Trends towards an increasing magnitude of summer drought conditions were found for Ireland and Britain over the period analysed. In an assessment of reconstructed river flows for Irish catchments, a tendency towards shorter, more intense meteorological and hydrological summer droughts over the past century was identified (O'Connor *et al.*, 2022b).

River discharge can be impacted by climate variability and change as well as land-use change, abstractions and discharges (Slater *et al.*, 2021). Moreover, river flow records tend to be shorter than those for precipitation. To address this, Murphy *et al.* (2013) developed an Irish Reference Network (IRN) of hydrometric stations across the island for climate change monitoring that attempts to minimize such confounding factors. An analysis of the updated network is provided in Cámaro García *et al.* (2021). Over the period 1972–2017, high flows (those exceeding 10% of the time) show significant increasing trends in magnitude, except for some stations in the southeast of the country, where non-significant decreases are evident. European scale studies that include records for Ireland also indicate changes in the timing (Blöschl *et al.*, 2017) and increased magnitude (Blöschl *et*

Photo credit: Coast Monkey

Occurrences of high discharges in rivers are increasing with some evidence for shorter more intense summer droughts.

al., 2019) of floods consistent with expectations of wetter winters from climate model simulations. In addition, Hodgkins *et al*. (2017) found significant increases in major flood occurrence for 50-year floods over the period 1961–2010 for medium size catchments (100–1000 km^2), particularly in temperate regions of Europe (such as Ireland).

Low flows (flow magnitude exceeded 90% of the time) in catchments contained in the Irish Reference Network over the period 1972–2017 show increasing trends, however, this is likely an artefact of record length, with the dry 1970s at the start of the record. Low flow discharge over the period 1992–2017 shows decreasing trends in parts of the southeast and few significant increasing trends. Significant drought events in 2018 and 2020 are likely to have strengthened this decreasing trend. Given short record lengths, however, along with large variability, trends in low flow magnitude are highly dependent on the period used for analysis. O'Connor *et al*. (2022a) evaluated trends in reconstructed annual, seasonal and monthly mean flows for Irish catchments for the period 1900–2016 to better understand the long-term pattern of behaviour. They found significant increasing trends in annual mean flows for western catchments. In winter, significant increasing trends dominate catchments on the western seaboard, with significant decreasing trends in the southeast. Few significant trends are found in spring and summer mean flows, while autumn shows significant increasing trends in northern catchments. Considerable global scientific effort is now being focused on the ecology of drying rivers (e.g. Keller *et al*., 2020), but as yet, it would appear that this is not particularly a cause for concern in Ireland.

CASE STUDY

THE IMPACTS OF STORM DESMOND ON THE BURRISHOOLE CATCHMENT, CO. MAYO.

The frequency and severity of storm category weather events during winter 2015/16 in Ireland and Britain was considered exceptional, peaking with the extratropical cyclone Storm Desmond during 4th–6th December 2015. Rainfall during Desmond broke the 24-hour and 48-hour British rainfall records and multiple rivers throughout Ireland and Britain recorded highest ever peak discharge. Desmond was caused by enhanced horizontal water vapour transport from the Atlantic Ocean, with the plume of moist air generating an 'atmospheric river,' and causing extreme precipitation along mountainous western Irish and British coastlines. These intense rainfall events can impact freshwater ecosystems by transporting large quantities of sediment and terrestrial matter into streams and lakes, altering physical and biogeochemical environments. The large volumes of river discharge can also impact downstream coastal zones. For example, during Storm Desmond the lagoonal estuary Lough Furnace in Co. Mayo received the largest volume of freshwater input on record (since 1976) resulting in fundamental changes to the salinity balance and estuarine circulation, with effects lingering for several months post-storm (Kelly *et al.*, 2020a). In addition, a 20-fold increase was estimated in the volume of seaward flowing low salinity water between Lough Furnace and the adjacent coastal waters of Clew Bay. Such a severe hydroclimatic event, which originated through ocean-atmosphere interactions and had impacts spanning the full catchment-to-coast continuum, exemplifies the intrinsic interactions between atmospheric, terrestrial, coastal and oceanic domains.


Photo credit: Mary Dillane

Figure CS8.1 Flooding at the north shore of Lough Feeagh, Co. Mayo, during Storm Desmond, December 2015.

8.3 NUTRIENTS AND PRIMARY PRODUCTIVITY

The hydrological cycle described above drives the processing and transport of nutrients (phosphorus, nitrogen and micronutrients such as iron, potassium and manganese) from terrestrial stores, leading to strong correlations between oceanic conditions and nutrient export. For example, the intensity of the North Atlantic Oscillation (NAO) (see Chapter 2 for detailed explanation of the NAO) has been linked to large shifts in baseline nutrient concentrations in agricultural catchments, which, in combination with episodic weather events and changing land use practices, has considerable implications for water quality (Mellander and Jordan, 2021). A positive relationship was observed between winter nitrate concentrations in two lakes in southwest Ireland and the latitudinal position of the Gulf Stream in the previous spring (Jennings and Allott, 2006). This variability has implications for the primary productivity in terrestrial and aquatic habitats. A positive winter NAO is related to early onset of the terrestrial growing season across Ireland and Great Britain (Craig and Allan, 2021), while variability in particular phytoplankton groups (such as diatoms) in White Lake, Co. Tyrone can be linked to the NAO index (Anderson *et al.*, 2012). In Co. Kerry, an inverse relationship was found between winter chlorophyll in Lough Leane and the NAO (Jennings *et al.*, 2000), with higher chlorophyll (indicative of phytoplankton biomass) being recorded in years when the winter NAO was negative.

As part of the Oslo Paris Convention for the Protection of the Marine Environment of the Northeast Atlantic (OSPAR), a Riverine Inputs and Direct Discharges (RID) programme has been in operation since 1990 to assess the annual inputs of nutrients and other substances to the marine environment from inland waters. Monthly samples are taken at 19 rivers around the country at the freshwater/saline interface. Loads of total phosphorus (TP) and total nitrogen (TN) show clear trends related to catchment activities since monitoring began (Figure 8.2). Inputs of both TN and TP were highest at the beginning of the time series but better wastewater treatment infrastructure and changes in farming practices produced substantial and significant decreases in the inputs of these nutrients. While significant decreases across the full time series are clear, upward trends are becoming apparent in recent years. The most substantial increases come from the rivers along the south and southeast coasts showing the largest increase in nutrients entering the marine environment (Trodd and O'Boyle, 2021). The reduction in TP has been much greater than any reduction in nitrogen compounds. This can influence the ratios of nutrients reaching the sea. Recent research indicates that the ratio of nitrogen to phosphorus loads being transported to transitional waters has increased significantly (O'Boyle *et al.*, 2017). This is a result of the greater overall reduction in phosphorus relative to nitrogen. It is likely that changes in agricultural practices and in particular the reduction in the use of inorganic phosphorus fertilizer may account for the largest reduction in riverine phosphorus loads (O'Boyle *et al.*, 2017). This imbalance can have implications for primary producers and the food webs that they support (Burson *et al.*, 2016). While climate factors are also likely to be a contributor, the inherent variability at the land-sea interface make this difficult to distinguish. Nevertheless, catchment management plans (aimed at reducing nutrient losses from terrestrial sources) must be future-proofed for the changing hydrological patterns described in the previous section.

> **Increased nutrients are draining off agricultural catchments to the sea causing an increased risk of phytoplankton and macroalgal booms.**

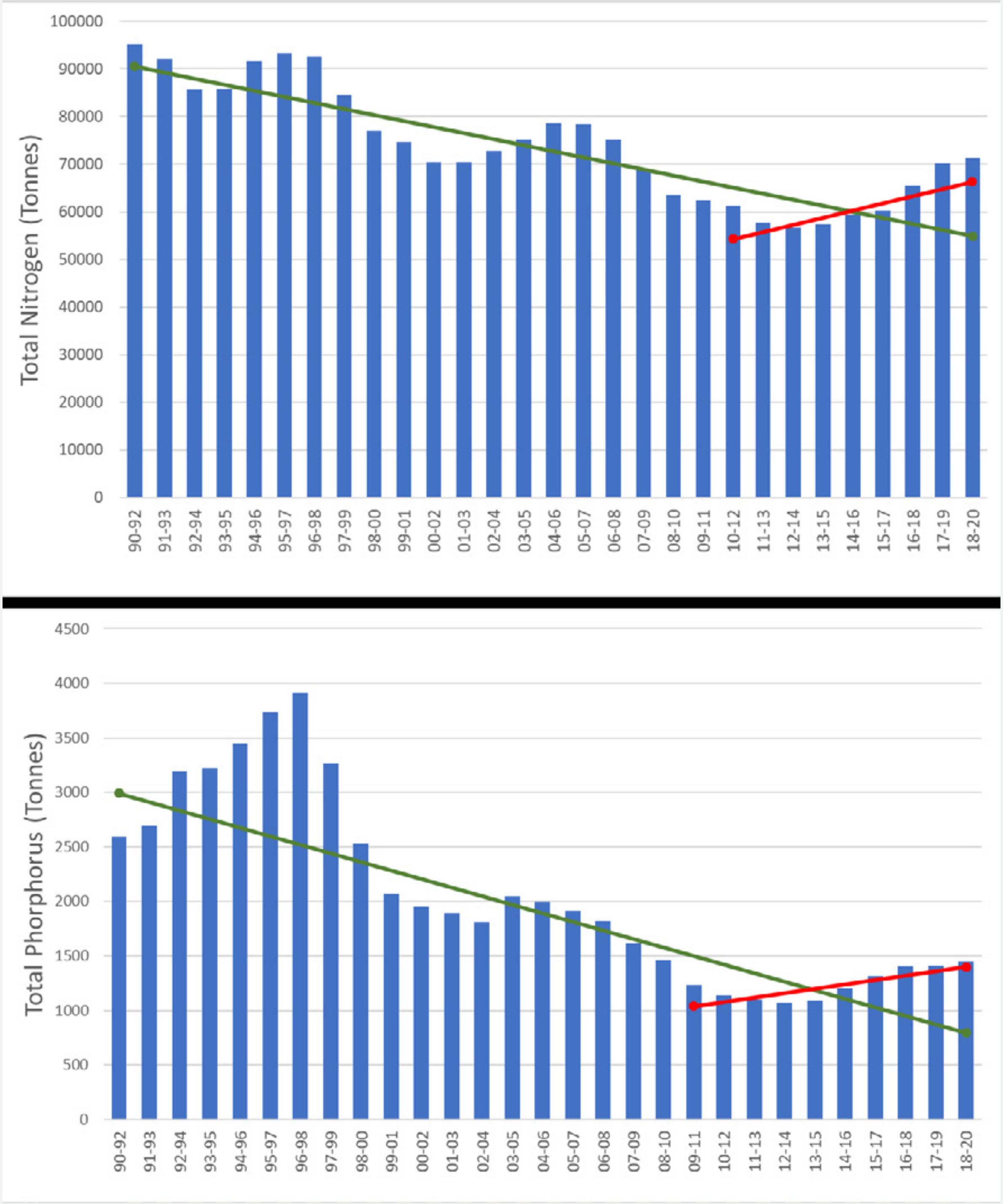

Figure 8.2 Flow normalized inputs of TN (top) and TP (bottom) to marine environment (three-year average period from 1990–1992 to 2018–2020). Green lines show significant downward trends and red lines show significant upward trend (Mann–kendall test).

Photo credit: Tomasz Szumski

8.4 CARBON

The LOAC (Land Ocean Aquatic Continuum) plays a key role in the global carbon cycle, transporting, processing and storing organic carbon (OC) from source to sea (Weyhenmeyer and Conley, 2017). A significant fraction of this lateral carbon flux is entirely "natural" and is thus a legacy of the pre-industrial component of carbon cycle. Changes in environmental conditions and land-use however, have caused an increase in the lateral transport of carbon along the LOAC – a perturbation that is relevant for the global carbon budget (Friedlingstein *et al.*, 2020). Movement of carbon from the extensive terrestrial stores in Ireland's bogs to inland waters is controlled by soil temperature and precipitation (Jennings *et al.*, 2010, 2020) and has a markedly seasonal pattern (Doyle *et al.*, 2019).

Understanding the potential sinks and sources for OC along the LOAC is crucial for adaptation measures designed to limit the amount of carbon loss from terrestrial sources. An OC budget for Lough Feeagh, an oligotrophic, peatland lake in west Co. Mayo, was estimated for 2017 (Doyle, 2021) using data collected as part of the long-term monitoring effort by the Marine Institute in the Burrishoole catchment. The principal OC fluxes and processing rates were calculated, and the study is considered to be the first OC budget presented for an Irish lake. The total OC load to the lake was estimated at 2,547 tonnes of carbon (t C), of which 51% and 41% were carried into the lake as dissolved and particulate fractions of peat-derived OC in surface water respectively. Small quantities entered the lake with ground water and rainwater. The total C exported from the lake to downstream Lough Furnace (a coastal lagoon) was estimated at 2,892 t C, of which 46% and 11% were exported as dissolved and particulate OC in the surface water outflow respectively. An estimated 485 t C of OC was mineralised and emitted as carbon dioxide (CO_2) to the atmosphere, while 754 t C of OC sank to the bottom of the lake as sediment, a portion of which will be preserved over the long-term. The completed budget revealed that OC in surface water inflows and outflows dominated the budget. The results highlight the substantial quantity of OC turned over in the lake during the study period. Overall, the study fills a considerable knowledge gap in the understanding of aquatic OC processing and emphasises how lakes in temperate, humic systems, common in the west of Ireland, are important to the amounts and quality of OC mobilised to the marine environment.

A follow on study is in progress, tracking the progress of carbon as it moves from the freshwater Lough Feeagh to downstream Lough Furnace (Marine Institute, unpublished data). Spot samples of surface water concentrations of carbon dioxide (pCO_2) are being taken from the surface of the two waterbodies at monthly intervals, and converted to flux using the Crusius and Wanninkhof (2003) approximation. Initial results from 2020 indicate that Lough Furnace emits far less CO_2 than Lough Feeagh (22 vs 318 tonnes CO_2-C, and even acts as a net sink of CO_2 in parts of the year) (Figure 8.3). This is somewhat surprising, as Borges *et al*. (2006) found that continental shelves are net sinks of atmospheric CO_2 while estuaries are significant CO_2 sources to the atmosphere. Some studies suggest that the concept of ocean acidification due to anthropogenic CO_2 emissions cannot be directly applied to coastal ecosystems, since decadal changes of up to 0.5 units in coastal pH have been caused by watershed changes in total alkalinity and CO_2 fluxes and up to 1 pH unit changes due to metabolic processes (Duarte *et al*., 2013 and references therein). In addition to inputs of organic and inorganic carbon from terrestrial sources as described above, changes in pH and carbonate chemistry in coastal waters are complicated by other drivers, including nutrient inputs, biological activity and upwelling (Doney *et al*., 2009; Duarte *et al*., 2013; Wallace *et al*., 2014).

McGrath *et al*. (2016, 2019) illustrated how the interplay of catchment geology, freshwater discharge and biological processes can result in large gradients in pH and CO_2 exchange between estuarine and coastal systems around Ireland,

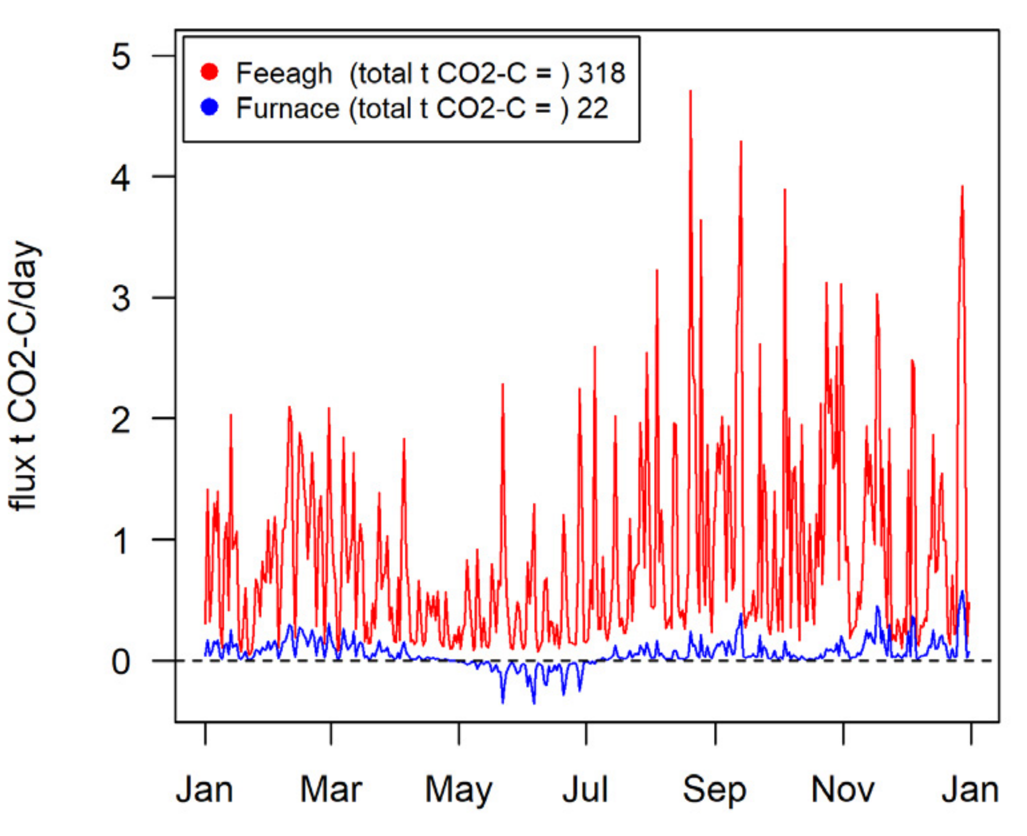

Figure 8.3 Daily CO_2 flux from the surface of Lough Feeagh (red) and Lough Furnace (blue) during 2020.

where the type of bedrock was the dominant control on regional carbonate chemistry. Weathering rates, which would influence the amount of alkalinity and dissolved inorganic carbon added to river water, are the highest for carbonate rocks, moderate for basalts and shales, followed by sandstones and acid volcanic rocks (Amiotte Suchet *et al.*, 2003). McGrath *et al.* (2019) found that rivers with a limestone (calcium carbonate) bedrock coincided with high dissolved inorganic carbon and total alkalinity, resulting in supersaturation of these estuarine waters with respect to atmospheric CO_2 throughout the year, despite seasonal primary production in surface waters. Calculated wintertime CO_2 fluxes for the Shannon and Suir estuaries were also positive (McGrath *et al.*, 2016), indicating a net flux of CO_2 from the sea to air from these limestone catchments. Primary production was the dominant driver in the non-limestone regions, where the granite and sandstone catchments had surface CO_2 close to atmospheric equilibrium in winter but were CO_2-undersaturated during productive months, where high rates of primary productivity in spring and summer remove CO_2 from surface waters (McGrath *et al.*, 2019).

It is expected that the gradual increase in baseline CO_2 will increase the incidence of extreme acidification events in coastal systems (Waldbusser and Salisbury, 2014); for example Hauri *et al.* (2013a, 2013b) and Harris *et al.* (Harris *et al.*, 2013) have already shown an increase in the frequency, magnitude, and duration of extreme events in the California Current System due to increasing CO_2, leading to conditions outside the normal range under preindustrial CO_2 levels and exceeding important thresholds for organisms. Coastal ecosystems including calcifying organisms are already adapted to naturally wide fluctuations in pCO_2 and pH. A significant proportion of benthic calcifying organisms potentially at risk from ocean acidification are however already experiencing significantly higher surface seawater pCO_2 and lower pH than expected from equilibrium with current atmospheric levels (e.g. Fagan and Mackenzie, 2007; Bates *et al.*, 2010; Andersson and Mackenzie, 2012). The variability in pH observed at four coastal sites around Ireland (ΔpH 0.2–1.0) was 10 to 50 times greater than decadal changes observed in Ireland's offshore waters of the Rockall Trough between 1991 and 2012 (McGrath, 2012) and all four sites had minimum pH values below the end of the 21st century predictions for open ocean waters of 7.8 (Caldeira and Wickett, 2003; Orr *et al.*, 2005).

While there may be an increase in baseline CO_2 (and subsequent decrease in pH) in coastal systems with increasing atmospheric CO_2, the cumulative impact of changing biogeochemical process is unclear. Eutrophication, for example, can result in an increase in pH due to enhanced uptake of CO_2 by primary producers (Borgesa and Gypensb, 2010), while it can amplify acidification through respiration of excess organic matter (Cai *et al.*, 2011). Duarte *et al.* (2013) concluded that anthropogenic CO_2 is a relatively minor component of pH fluctuations in many coastal ecosystems, where enhanced primary production or respiration is often the primary driver. Regional inputs of nutrients, inorganic and organic carbon, and acid and carbonate alkalinity from watersheds should be coupled with scenarios of global CO_2 emissions to assess local impacts on coastal ecosystems.

Changes in climate and land use are leading to unprecedented pressures along the land ocean aquatic continuum.

8.5 ECOLOGICAL PROCESSES

Causative links between oceanic conditions and terrestrial biological systems are complex, and often difficult to parse. Changes in the Atlantic Ocean, as described in previous chapters however, play a crucial role in driving ecological processes on the island of Ireland. For example, the NAO was related to breeding success in overwintering birds such as European Wigeon (Fox *et al.*, 2016), the growth in Hare populations between 1850 and 1910 (Reid *et al.*, 2021) and the survival of salmon in both their freshwater (de Eyto *et al.*, 2016) and marine phases (Peyronnet *et al.*, 2008).

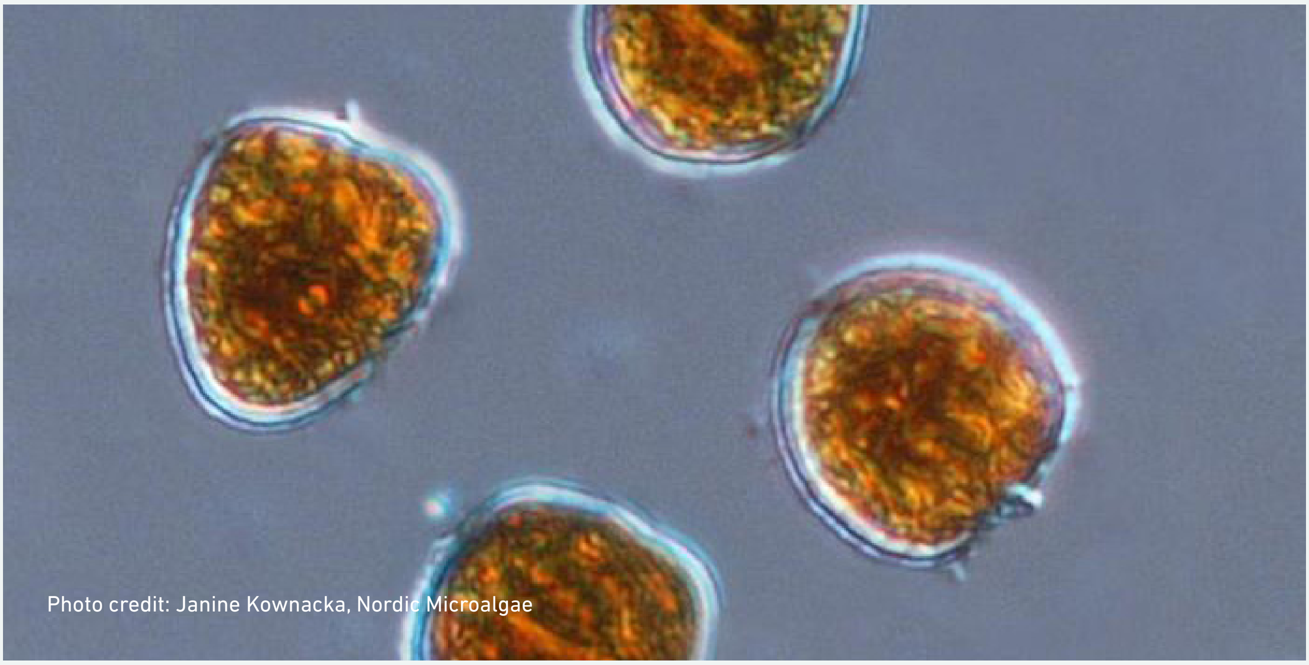
Photo credit: Janine Kownacka, Nordic Microalgae

Figure 8.4 *Prorocentrum minimum.*

Ecosystems along the LOAC are adapted to function within certain hydrological and biogeochemical boundaries, but as climate and land use change, these boundaries are being stretched, leading to episodic biological events and multiple pressures on sensitive habitats and species. Here we demonstrate these linked pressures using case studies along the LOAC.

8.5.1 ESTUARINE ALGAE BLOOMS

Prorocentrum cordatum (Ostenfeld) (previously named *P. minimum* (Pavillard)) (Figure 8.4) is a common, bloom-forming dinoflagellate and is the cause of many harmful blooms worldwide. While it is non-toxic to marine invertebrates in general, larger blooms have been reported to cause environmental damage due to high algal biomass and related effects such as localised oxygen depletion and pH change (Heil *et al.*, 2005). Previous studies have shown that it is an adaptable species that can grow quickly in a range of salinities and temperatures and uses both inorganic and organic forms of nutrients, giving it a range of physiological adaptations that makes it responsive to eutrophication (Heil *et al.*, 2005). In the summer of 2020, an exceptional bloom of this dinoflagellate occurred in the Lower Lee Estuary and Lough Mahon, Co Cork. In June, surface samples showed cell concentration of up to 19 million cells/L of *P. cordatum* in the Lower Lee Estuary while levels of dissolved oxygen supersaturation were elevated, peaking at 173.5%. This bloom persisted for the rest of the summer and reddish-brown water was again observed during the July survey with cell concentrations of 49 million cells/L and 31 million cells/L observed in Lough Mahon and Lower Lee Estuary respectively. By the end of August, cell numbers had reduced to just over 1 million cells/L in Lough Mahon. A similar pattern was seen in the Marine Institute weekly national phytoplankton monitoring programme where samples taken off Cobh showed cell concentrations of *P. cordatum* starting to rise in June, peaking mid-July and then starting to fall back in August (www.marine.ie/Home/site-area/data-services/interactive-maps). The Environmental Protection Agency (EPA) has been monitoring phytoplankton in estuaries and coastal waters since 2007 and this bloom in 2020 was the largest cell concentrations observed in the Lee Estuary since the start of this monitoring programme. These episodic biological events are likely caused by multiple stressors. In the EPA's most recent water quality assessment using 2018–2020 data, the highest median winter

Figure 8.5 Macroalgae bloom, Argideen Estuary, Co. Cork, 2018.

dissolved inorganic nitrogen concentrations were found in some of the estuaries in the south of the country (Trodd and O'Boyle, 2021). The estuaries feeding into Cork Harbour have some of the highest winter nutrient concentrations measured in Ireland, with the Glashboy, Owenacurra and Lee estuaries having concentrations more than 50% above the assessment criteria. In more recent years, an increase of nutrient inputs into the marine environment is being observed, especially in the south and southeast of the country. Although blooms of dinoflagellates are common around the coast of Ireland, it is likely that the combination of high nutrients over winter, and the warm growing season facilitated the excessive blooms described above.

8.5.2 MACROALGAE BLOOMS

Opportunistic macroalgal blooms are caused by large accumulations of sea lettuce, the common name for a group of seaweeds of the genus *Ulva*. While predominantly influenced by the inputs of elevated nutrients levels into the marine environment (Ní Longphuirt *et al*., 2016), the distribution of green algal blooms is related to their requirements regarding light, temperature and nutrients (Bermejo *et al*., 2019). Changes in the baseline of these factors such as increasing temperature, or increased freshwater runoff, will impact the scale or seasonality of these events. These seaweeds are a natural part of the Irish marine flora and, in undisturbed environments, are generally found throughout the middle to low intertidal zone (Wan *et al*., 2017). Although present naturally around our coasts, excessive growth of *Ulva* is driven by the presence of elevated nutrients in the environment (European Commission *et al*., 2018). Sea lettuce is considered an opportunistic species and when nutrient levels increase it can utilise these resources to grow very quickly. When conditions are suitable the algae multiply, creating very large accumulations. These excessive growths of sea lettuce can have many different effects on the associated ecosystem. Due to the structure of the seaweed mats, accumulations can affect the underlying sediments, causing changes in the structure and function of the benthic faunal communities. Mats can also affect the ability of other floral communities, such as seagrass, to survive by blanketing the substrate and smothering underlying organisms. This blanketing effect can create a hostile physico-chemical environment which can lead to anoxia and sulphide poisoning of the blanketed species or sediments.

8.5.3 SALT MARSHES

Salt marshes are intertidal salt-tolerant plant communities consisting of grasses, forbs and shrubs (Adam, 2002). In addition to containing habitats listed under Annex I of the Habitats Directive, saltmarshes fall under the angiosperm Biological Quality Element (BQE) of the Water Framework Directive (WFD) (2000/60/EC). They have attracted considerable attention for their capacity to store organic carbon in substrates, and thus contribute to climate change mitigation (Chmura *et al*., 2003; Mcleod *et al*., 2011). These organic carbon deposits come from the plants themselves, and also from marine sediment trapped by salt marsh vegetation. The combination of waterlogging and sulphate hinder microbiological decomposition (Weston *et al*., 2014) so carbon deposits 1 m deep or more can accumulate over centuries (Howard *et al*., 2014; Mueller *et al*., 2019). Ireland has approximately 70 km^2 of salt marshes (Penk, 2019). They are conservatively estimated to store at least 400,000 tonnes of organic carbon, small relative to the peat bogs of Ireland that store ~ 1.5 billion tonnes of organic carbon; however, this only accounts for the upper 10 cm of the soil, so the full carbon store is likely much larger. As much as four times the current salt marsh extent, and thus significant carbon sequestration potential, may have been lost to past land reclamation (Healy and Hickey, 2002; Penk, 2019).

Salt marshes are impacted by land conversion, eutrophication and invasive species, whereas climate change, and sea level rise in particular, is an increasing concern (Gedan *et al*., 2009; Horton *et al*., 2018). Salt marshes in Ireland take up as much as 1 km of the horizontal belt at the upper end of the intertidal zone, but they only occupy approximately 1 m of the elevation gradient (Penk and Perrin, 2022). Sediment deposition can help the ground elevation keep pace with the increasing sea level, but the survival of salt marsh habitats will also depend on compensatory migration up the shore. The potential for such a shift however, will be compounded in many places by walls and embankments, that typically protect the adjoining agricultural and built areas from tidal inundation. Indeed, there are not many salt marshes with natural transition to land. This leads to *coastal squeeze* (Torio and Chmura, 2013). A managed retreat (or realignment) strategy could potentially mitigate this by prioritising sacrificial land, such as low-productivity farmland, but there are only a few such examples in Ireland (Perrin *et al*., 2020). Salt marshes are renowned for a multitude of important ecosystem services, such as attenuation of wave energy and storm surge for coastal protection (Gedan *et al*., 2011; Fairchild *et al*., 2021) which should be considered together with carbon storage in coastal management to resolve conflicting short- and long-term interests.

8.6 DIADROMOUS FISHES

Diadromous fishes migrate between the sea and fresh water to complete their life cycle and these exemplar sentinel species therefore integrate signals of climate change and other stressors into their long-term population dynamics. Collection of data and associated information (e.g. archives of scales, otoliths and DNA) on diadromous fish and their environment over long time periods are extremely important in evaluating their potential for long-term survival and ability to adapt to current and future changes in the environment due to climate change. In Ireland, long-term monitoring of Atlantic Salmon (*Salmo salar*), Sea Trout (*Salmo trutta*) and European Eel (*Anguilla anguilla*) is primarily carried out by the Marine Institute and Inland Fisheries Ireland.

8.6.1 ATLANTIC SALMON

Atlantic salmon (*Salmo salar*) populations have declined across the North Atlantic in recent decades, with marine survival being of particular concern (ICES, 2021). It is listed in Annexes II and V of the EU Habitats Directive as a species of importance requiring conservation and their conservation status in Ireland is classified as vulnerable due to a decline in abundance, caused primarily by mortality at sea, habitat loss, barriers to migration, poor water quality, overfishing and sea lice. Currently, 44% of Irish salmon rivers and 50% of rivers in salmon Special Areas of Conservations (SACs) are failing to meet 50% of their conservation limit (Gargan *et al*., 2021).

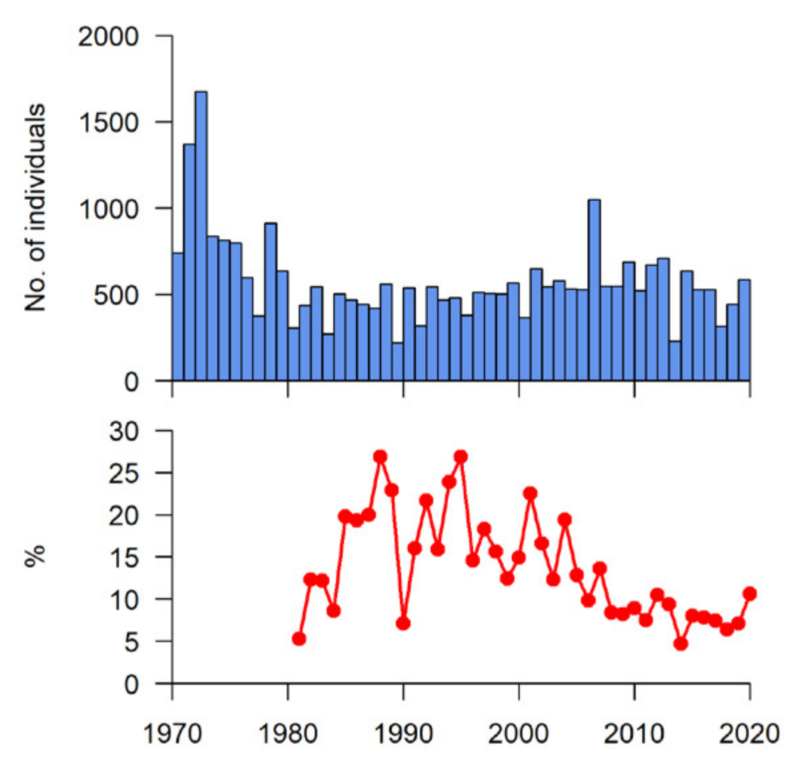

Figure 8.6 Annual wild grilse 1 sea winter salmon counts (top) and % marine returns (bottom) for the Burrishoole catchment, 1971–2020 (Marine Institute Data).

The drift net fishery for salmon off the Irish coast was a major determinant to the number of salmon returning to freshwater to spawn, intercepting between 60% and 80% between the 1980s and the early 2000s. While the cessation of the high seas mixed stock fishery in 2007 led to an increase in returns, drift-netting was not the only source of ocean mortality, and marine survival of salmon continues to decline (ICES, 2021). At the long-term monitoring station for diadromous fish run by the Marine Institute in the Burrishoole catchment, Co. Mayo, returns of grilse (salmon that have spent one winter at sea) to the catchment have ranged from almost 1,800 in 1973 to lows of 252 in 1990 and 279 in 2014 (Figure 8.6). Since 2007, the returns to the catchment have averaged just over 500 grilse per annum, below the conservation limit for the catchment. Marine survival has fallen from an average of ~17% in the 1980s and 1990s to 7.9% in the last five years (Figure 8.6). Coincident with reduced marine survival and decreasing body size, half of the upstream migrating salmon are returning between one and two months earlier from the marine environment compared to the 1970s, indicating considerable oceanic challenges for this species (de Eyto *et al.*, 2022). These trends in Burrishoole are reflective of the general status of salmon in Irish rivers. Poor survival in freshwater has been linked to climatic conditions such as warm, wet winters (McGinnity *et al.*, 2009; de Eyto *et al.*, 2016), while several studies indicate that the reduced number of Atlantic salmon returning from the sea is correlated to large-scale changes in the marine environment, such as increased water temperature or decreased abundance of plankton, leading to poor feeding opportunities (Utne *et al.*, 2021). The future for cold-water adapted species such as Atlantic salmon is uncertain under climate change projections for freshwater and marine habitats. Maintenance of genetic integrity and diversity of wild populations, eliminating poorly planned stocking, and minimising impacts that reduce population sizes to dangerously low levels will support the ability of Atlantic salmon to adapt to changing environments (Thorstad *et al.*, 2021).

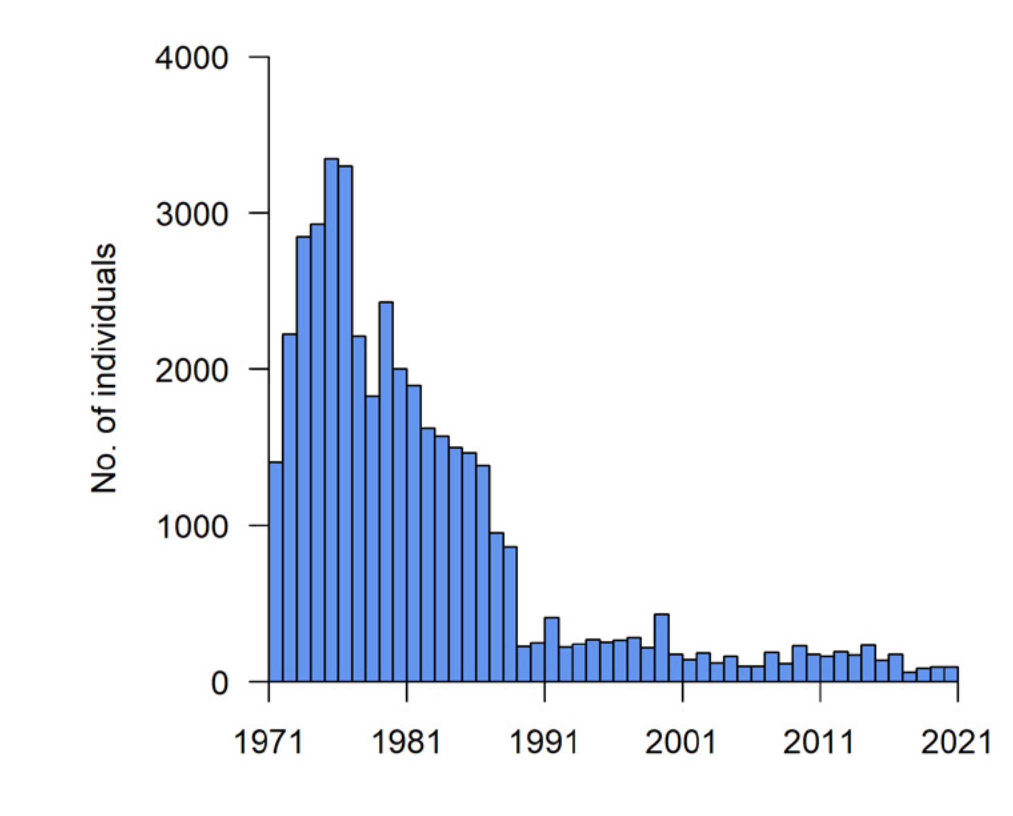

Figure 8.7 Annual count of trout, returning to the Burrishoole catchment, to spawn between 1971 and 2020 (Marine Institute Data).

8.6.2 SEA TROUT

Sea trout (*Salmo trutta*) are fully anadromous, feeding in the marine habitat before returning to freshwater to spawn, although they are genetically the same species as resident brown trout (see Nevoux *et al.*, 2019 for review). There is no co-ordinated framework for the conservation of Sea trout, and only two rivers in Ireland, Burrishoole and Erriff, have stock and recruitment data (Poole *et al.*, 2006; Gargan *et al.*, 2016). Trout in the Burrishoole system occur as both freshwater resident and anadromous forms. Before 1990, the average run of sea trout smolts (juvenile fish migrating to sea) out of Burrishoole was 4,100 fish, dropping to circa 250 in recent years. The stock collapsed in the late 1980s, with the spawning stock dropping from thousands to only 224 fish in 1989 (Figure 8.7). The stock has failed to recover and is currently at an all-time low of less than 50 fish. Many factors may impact the survival of sea trout (Nevoux *et al.*, 2019) and heavy infestations by the salmon louse, *Lepeophtheirus salmonis*, are known to decrease fish condition and increase mortality (Poole *et al.*, 1996; Gargan *et al.*, 2006). While the decline in spawning sea trout returns was already causing concern throughout the late 1980s, it is hypothesised that the warm winter of 1989/1990 may have resulted in higher numbers of generations of salmon lice to develop (Tully, 1992; Tully *et al.*, 1993), significantly increasing fish mortality in that season. This illustrates the potential for changes in climate to impact on the resilience of populations already under pressure from multiple stressors.

Multiple stressors, including climate change, are impacting on diadromous fish in all of their habitats.

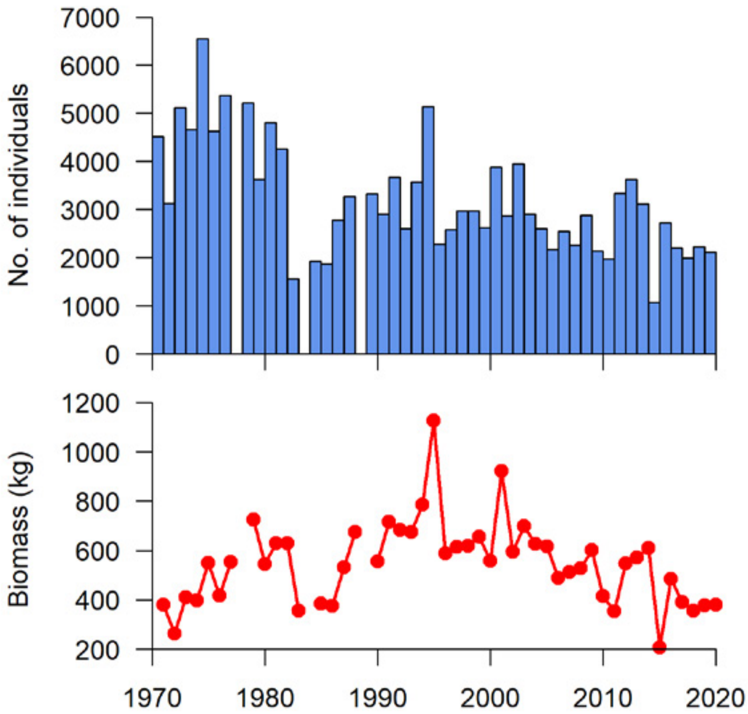

Figure 8.8 Annual count of silver eel (top), and total biomass of silver eel (bottom) leaving the Burrishoole catchment, 1971–2020 (Marine Institute Data).

8.6.3 EUROPEAN EEL

European eel (*Anguilla anguilla*) spawn in the Sargasso Sea and return to the European and North African continental habitats following a trans-Atlantic larval migration. On arrival, juvenile eel inhabit coastal and freshwater areas, where they live and grow for up to several decades before migrating seaward to spawn in the Sargasso Sea. This spawning migration occurs when adult eel transform into sexually mature silver eel. The global population has been in decline at least since the 1960s, with a severe reduction in juvenile eel recruitment occurring in the early 1980s (Moriarty, 1990). Eel recruitment is currently at about 5–6% of the historical mean in the Atlantic region and there is significant mortality at all life stages (ICES, 2020). Eel are listed on the International Union for Conservation of Nature (IUCN) red list as critically endangered and are currently the subject of specific legislation governing conservation and stock recovery measures within the European Union (EC, 2007).

Numbers of migrating silver eels has declined in Burrishoole, from an average of 4,500 eels per annum to approximately 2,200 eels average for the last five years (Figure 8.8). The biomass of eel migrating out of the catchment peaked in the 1990s, but is dropping again. This is likely a response to the lack of recruits, but may also be a consequence of changing water temperatures in recent years (Vaughan *et al.*, 2021). Day-to-day variation in the number of eels migrating is associated with conditions that minimise predation risk such as new moons, floods and the presence of other eel. The migration out of Burrishoole is commencing a month earlier now compared to the 1970s (Sandlund *et al.*, 2017; de Eyto *et al.*, 2022). Climate change has likely already impacted on the population structure and dynamics of this iconic species, along the full continuum of its habitats, from headwaters to the deep Atlantic (Friedland *et al.*, 2007; Arevalo *et al.*, 2021). As with the other diadromous fish species, minimising other anthropogenic stressors will be crucial to ensuring the resilience of this species.

8.7 RECOMMENDATIONS

1. It is critical that key long-term datasets, which capture disruption signals along the LOAC, are maintained and financially supported. Examples are:
    - Lough Feeagh (Mill Race) water temperature
    - Diadromous fish stocks as sentinel species
    - Greenhouse gas emissions along the aquatic continuum
    - Irish Reference Network (IRN) of hydrometric stations
    - Riverine Inputs and Direct Discharges (RID) programme
2. Modelling exercises using future climate projections are an essential decision support tool and should be used in future catchment management plans.
3. Assessment of future impacts of climate change for Ireland requires that monitoring and research of rivers, lakes and transitional waters are considered simultaneously.
4. Anthropogenic pressures, that reduce the resilience of sensitive habitats and species to climate change, must be reduced to ensure the conservation of Ireland's biodiversity.
5. Nature-based solutions should be included in climate change mitigation plans.

LIST OF FIGURES

LIST OF CASE STUDY FIGURES

BIBLIOGRAPHY

CHAPTER 8 – CLIMATE CHANGE IMPACTS ALONG THE AQUATIC CONTINUUM FROM TERRESTRIAL HABITATS TO THE OCEAN

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Foras na Mara
Marine Institute

HEADQUARTERS

MARINE INSTITUTE

Rinville
Oranmore
Co. Galway
H91 R673

Tel: +353 91 387 200
Fax: +353 91 387 201
Email: institute.mail@marine.ie

MARINE INSTITUTE REGIONAL OFFICES & LABORATORIES

MARINE INSTITUTE

Three Park Place
Hatch Street Upper
Dublin 2
D02 FX65

Tel: +353 91 387 200
Fax: +353 91 387 201

MARINE INSTITUTE

Furnace
Newport
Co. Mayo
F28 PF65

Tel: +353 98 42300