Loch Etive Case Study
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Loch Etive

MASTS Case Study Workshop Report

N Hicks, T Brand and the MASTS community

Executive Summary

In August 2016, a case study workshop on Loch Etive was funded by the Dynamics and Properties of Marine Systems (DPMS) theme within the Marine Alliance for Science and Technology for Scotland (MASTS). Loch Etive is one of the more economically and ecologically important sea lochs on the west coast of Scotland, supporting research and commercial fishing, and is the only known Scottish sea loch known to experience periodic hypoxia in the bottom waters. The workshop reviewed existing research knowledge and activity within the loch; current commercial activities and management plans; and identified gaps in knowledge and potential research activities. The workshop brought together researchers and stakeholders, and this report provides an overview of the information collected and discussed.

Introduction

Loch Etive is one of the most researched sea lochs on the west coast of Scotland, and is of significant economic and ecological importance. It is also the only Scottish sea loch to experience significant periodic hypoxia, making it an interesting and unique site for research. The loch itself is 30 km long, and is divided into an upper and lower basin by a shallow sill (~14 m, the Bonawe sill). This, together with large fresh water inputs, creates noticeable differences in the hydrography either side. The seaward lower basin is less stratified and largely ventilated to the bottom on almost all tides, whereas the upper basin is more stratified and bottom water can remain “isolated” for periods of several months to years. There is an additional sill at the entrance to the loch, where the Falls of Lora occur under Connel Bridge, connecting the loch to the Firth of Lorne (Figure 1). The deepest point of the loch occurs in the upper basin, just east of the Bonawe sill (~146 m). The river
catchment area for the loch is vast (1350 km$^2$), with three rivers (Awe, Etive and Kinglass) flowing directly into the upper basin. The loch supports trout aquaculture, has active leases

![Figure 1](image)

**Figure 1** (a) Loch Etive is located on the west coast of Scotland. (b) The bathymetry of Loch Etive splits the loch into two basins, separated by the Bonawe Sill. The deepest point occurs in the upper basin just after the sill. Figures courtesy of SAMS.
for shellfish aquaculture, and supports commercial and recreational fishing activities. The varied benthic habitats range from soft sediments in the deep basins, to rocky substrata and sandy sediments, and these support a high biodiversity of marine organisms, many of which are benthic organisms unique to West Scotland. This high species diversity is an important food source for local and migratory seabird populations and local seal colonies, which are often spotted around the Bonawe Sill. Loch Etive is also an important habitat for migrating salmon and trout, and supports an active population of elasmobranchs (particularly spurdogs and skates).

Due to the high freshwater runoff into the loch, the water in the upper basin is subject to strong stratification. Coupled with the bathymetry, this causes periods of restricted circulation and subsequent low oxygen levels in the bottom water, consequently this part of the loch frequently experiences periods of hypoxia. However, the benthic ecosystem in the upper basin seems tolerant of mild hypoxia, and recovers quickly after these hypoxic events. Overturning of the hypoxic bottom waters typically occurs on a flooding spring tide during a period of prolonged dry weather with reduced freshwater run off. With low fresh water input, the incoming marine water is able to retain sufficient density to flow over the Bonawe sill and displaces the older, stagnant bottom waters from the upper basin. These overturning events occur on average every 16 months (Edwards and Edelsten, 1977) and can happen at any time of year. Partial or incomplete flushing events also occur where new water renewal does not reach the sea floor but to some mid water depth or where the deep water is mixed with new dense water but is not completely replaced by it. Between these renewal events, the density of the bottom water is slowly reduced due to diffusive and advective mixing with the fresher waters above, therefore preparing the water for the next renewal event. When a total renewal event occurs it results in a 1psu salinity change in the bottom water and a warming or cooling by 1 or 2 degrees, dependent upon the time of year of the event. This situation echoes many other coastal and shelf systems (sea-lochs/fjords, bays, lagoons, marginal seas) with restricted exchange, and the observed increase in frequency and duration of these ‘hypoxic events’ since the 1960s (Diaz and Rosenberg, 2008) has been closely linked to rising seawater temperatures and other consequences of global warming. In the case of Loch Etive, increased precipitation will have the greatest effect of enhanced water column stratification and reduced exchange of the deep isolated water.
Thus, predicted climate changes may very well increase the duration and severity of hypoxia in Loch Etive, a fjord that already is classed as one of the most sensitive lochs in Scotland in terms of oxygen depletion (Gillibrand et al., 2007). Over the past decades, and as far back as the 1970s, much research has been carried out within Loch Etive, ranging from observational measurements and bathymetric surveys, to environmental impact assessments on fish farms and the thermal tolerance of specific fish species (elasmobranchs).

1. Research knowledge

Geology and catchment area

Like many Scottish sea lochs, Loch Etive is categorised as a glacially over-deepened trough (Audsley et al., 2016), formed during the retreat of glaciers from Scotland. The bathymetry of Loch Etive was most recently mapped in 2014 by the British Geological Society (BGS), although a legacy of previous data exists, made up of side-scan sonar, seismic and backscatter data. Researchers have collected 2-3 metre cores in locations throughout the loch, and these have been dated back to the last 8000-9000 years (Norgaard-Pedersen et al.,

![Figure 2](image-url.com)
2006). As part of one of the targeted research programmes in the late 1990s, regular GPS fixed study sites were established within the loch along a salinity gradient. These sites were set up under the Restricted Exchange Environmental Systems (REEES) programme, and the sites are known as the ‘RE’ (Restricted Exchange) sites, ranging in salinity from RE1 at the head of the loch, the most freshwater site, to RE8 which is the most open coastal site situated just outside the mouth of the loch (see Figure 2).

The total catchment area of the loch is around 1350 km$^2$ with an estimated annual discharge of $3 \times 10^9$ m$^3$ when based on the maximum rainfall of 2000 mm/year (Audsley et al., 2016). Of the three rivers that discharge directly into Loch Etive, River Awe is estimated to provide around 60 % of the total freshwater input, with Rivers Etive and Kinglass emptying smaller volumes into the upper basin. The catchment is dominated by four soil types (Figure 3): podzol (70.57 %), peat (20.86 %), brown earths (7.61 %) and gleys (0.96 %) each rich in organic carbon.

![Map of Loch Etive](image_url)

**Figure 3** The catchment area for Loch Etive contains relatively high organic carbon content. Figure from (Lilly et al., 2012)
The catchment has six main land cover types (Morton et al., 2011): bog (4.81 %), broadleaved woodland (1.76 %), coniferous woodland (24.79 %), rough grassland (4.83 %), improved grassland (52.97 %) and montane (10.84 %). The spatial distribution of these land cover types varies with the bog and montane environments largely found in the upper catchment, while the woodland and grassland habitats are located in the lower catchment area.

Much of the dissolved organic matter in coastal waters in West Scotland originates from freshwater river inputs that constitute a major carbon output from peatland systems in Scotland (Dinsmore et al., 2010). Additional input of terrestrial organic matter due to enhanced terrestrial decomposition of vegetation, an increased river runoff as well as higher surface water temperatures may increase the biological oxygen demand, decrease oxygen solubility and modify biogeochemical transformation of organic carbon. Low oxygen (hypoxic) or no oxygen (anoxic) conditions in the sediments enhance sequestration and preservation of organic carbon.

Figure 4: The seabed of Loch Etive is dominated by soft muddy sediment and sandy mud, with sand in the shallower depths. Figure courtesy of SAMS.
The sea bed of the loch is a mixture of solid geology of igneous and metamorphic rock, interspersed with soft muddy sediment in the deep basins and sandy mud or sand in the shallower depths (Figure 4). Recent bathymetry imagery has identified crescent-shaped sediment deposits along the eastern edge of the loch, potentially an erosive feature.

Loch Etive provides an ideal case study for examining the links between catchment areas (source) to marine ecosystems (sink). This is particularly key for carbon and iron cycles, as the iron minerals and organic matter stabilise each other (Kaiser and Guggenberger, 2000; Lalonde et al., 2012), which may result in enhanced transportation across the salinity gradient to the oceans or more stable carbon sequestration into the sediment. The humic-rich high latitude rivers that feed into Loch Etive have a higher iron carrying capacity than lower latitude rivers.

**Oceanography and Chemistry**

Due to the presence of the Bonawe sill, the deep water of the upper basin (predominantly around sampling site RE5) can become isolated from the surface waters, leading to stratification within the water column and depletion of oxygen in the deepest water layer. An initial series of studies in the 1970s (Edwards and Edelsten, 1977) established that this body of water is renewed on average every 16 months. Water column dissolved oxygen has been measured periodically since the 1970s and since 2010 more frequently to characterise the occurrence and duration of hypoxia in the upper basin. Oxygen measurements made in the latter part of 2015 showed that Loch Etive had experienced its most intense recorded
hypoxic state with concentrations below 10µM, the result of a prolonged period of restriction of almost 3 years since the previous full flushing event. This is the longest period of isolation that has been recorded at RES, and may be linked to changing meteorological patterns. Since 2015 flushing events have happened yearly, with the last full flushing event occurring within the first 2 weeks of June 2017. Based on oxygen measurements taken during the last year, the daily depletion rate for oxygen has been estimated at 0.30 mmol m$^{-3}$d$^{-1}$. However, there is still a lot of uncertainty as to the main driver of oxygen depletion in the upper basin, whether it is the pelagic or benthic oxygen demand, how this may change with season, and the relative contribution of molecular diffusion vs advective mixing in ventilating the deep water.

The change in concentration for nutrients such as silica, nitrate and phosphate is closely linked to the oxygen dynamics, with hypoxia leading to high concentrations of these nutrients. The chemistry of the water column changes during hypoxia, and following deep water renewal. The temperature of the water also helps to identify the age of the water (Figure 6).

![Figure 6](Temperature depth profile for the upper basin in October 2015 – the water masses are labelled 2015 AuW (Autumn Water) and 2013 SpW (Spring Water) as indicated by the temperature legend (in degrees Celsius). Figure courtesy of SAMS)

**Shelf modelling**

The Scottish Shelf Model (SSM) is a marine science community project which includes a case study for the wider Loch Linnhe area (Price et al., 2016; Wolf et al., 2016). That case study includes Loch Etive and a one-year climatological run representing an average year is available. A good representation of freshwater inflow into the model domain exists but
there is a problem with the distribution of the river flows into Loch Etive. The redistribution of the river flows into Loch Etive needs to be corrected, and the model rerun, before the SSM case study can be made widely available. Future plans also include Loch Etive as a case study for categorisation and classification of sea lochs based on physical dynamics as a basis for management support tools.

**Hydrodynamic modelling**

A hydrodynamic three-layer 1D box model (ACExR) was developed under the Scottish Aquaculture Research Forum (SARF, 2005-2007) to simulate the physical exchange of sea lochs. The model was developed as a management tool, and can be coupled to ecological models to predict the assimilative capacity of sea lochs. The model was fine-tuned to represent conditions in Loch Etive, using initial conditions of temperature and salinity from CTD (conductivity, temperature, depth) surveys (Gillibrand et al., 2013). Initial simulations were compared to observation data from the REES project, with monthly CTD surveys to support the dataset. Temperature and salinity were well represented in stations RE1-RE5 (upper basin), and the deep water renewal event in the hypoxia prone region was captured. The dissolved oxygen concentrations in each water layer of the model are controlled by four distinct processes:

- Pelagic biological oxygen demand (BOD) from biochemical processes in the water column
- Benthic BOD from biochemical processes in the sea loch benthos
- BOD deriving from organic matter deposited by finfish farms
- Supply of oxygen from internal mixing processes

The BOD rates from the benthos and bottom water oxygen fluxes were estimated, following the REES programme, at a benthic oxygen demand of 14.38 (± 1.77) mmol O₂ m⁻² d⁻¹ and a pelagic oxygen demand of 3.70 (± 2.18) mmol O₂ m⁻² d⁻¹ prior to a renewal event. After renewal the pelagic demand 13.35 (±0.46) exceeds the sediment oxygen demand (64.92 ±50.32). However, these measurements date back to 1999-2000, and as yet there is no comprehensive data on what drives the deep water biological oxygen demand.
The HYPOX project aimed to monitor physical processes to allow accurate prediction of the deep water renewal, and study the sensitivity of the system to changes in oceanographic and meteorological conditions. Started in 2009, it involved the installation of two hydrographic (temperature, salinity, oxygen) moorings (Figure 7a), one in the upper basin at RE5 and one in the lower basin at RE6. The mooring at RE5 was continuously powered through cables to the mainland. The project led to the development of a more advanced

Figure 7 (a) Moorings placed in Loch Etive as part of the HYPOX project. Figure courtesy of SAMS. (b) Time-series from the deepest sensor unit (124 m) are shown at lower panel: potential density (red line) and dissolved oxygen measured with an oxygen optode (type 3835, AADI, blue line) in the upper Loch Etive basin at the HYPOX mooring site. Blue squares and red diamonds represent validation data from CTD casts obtained with various Sea Bird Electronics CTD instruments (equipped with SBE oxygen sensors). The blue triangles represent oxygen concentrations of samples measured by Winkler titration. The three overturning events observed (~ 10 January, 17–23 February, 23–30 June 2010) are indicated by dashed vertical lines: Figure from (Friedrich et al., 2014).
model to characterise the factors preceding renewal, including wind conditions, which are particularly important for generating internal waves (40-60 m in depth) and currents. Most of the winds are usually south westerlies in this area. The wind creates a ‘tunnelling’ effect, which can affect the movement and upwelling of different water masses within the loch, particularly after a deep water renewal event. During a renewal event in June 2010, the vertical stratification was destroyed and surface waters were delivered to the bottom layer (Figure 7b). Stratification was quickly re-established with heavy rains in early July 2010, however, bio-fouling in the conductivity cell lead to the apparent extended presence of low-density waters at depth. The grey area in Figure 7b denotes hypoxic conditions with oxygen concentrations below 62.5 µmol L\(^{-1}\) (2mg L\(^{-1}\)) (Friedrich et al., 2014).

**Internal waves contribution into mixing process and 2-D models**

The hydrodynamics of Loch Etive are dominated by the prevailing winds aligned with the glen axis and strong tidal flows through the entrance over the sills under Connell Bridge and in Bon Awe. The tidal streams are often turbulent, strongly vertically sheared (Figure 8a, 8b) and could trigger the generation of internal waves on lee-side of the sills (Figure 8c, 8d) creating a highly dispersive environment. On spring tides the highest reported surface currents can exceed 4 m\(^{-1}\) s\(^{-1}\) in the narrow channels, with up to 7 km tidal excursions. Inall et al. (2004) found that the contribution due to bottom friction, barotropic form drag and freely radiating baroclinic waves drag are in a ratio 1:4:1 (1:4:3.3) at spring tides (neap tides).

The process of breaking internal waves on Loch Etive’s sloping boundary is less effective for mixing as revealed in a dye-release experiment (Inall, 2009). A more efficient process was observed near the Bonawe sill during the flood phase, when vertical mixing was intensified and an internal hydraulic jump occurs (Inall et al., 2004). The mixing is then enhanced by the internal waves reflected from the basin head and slopes. The presence of sub-surface fast-propagating trains (packets) of internal waves were detected and measured with fine velocity microstructure sensors mounted on a propeller-driven AUV in Ardmucknish Bay in December 2009 and May 2010 (Boyd et al., 2010) and February 2011 (Figure 8c, 8d). Non-linear wave generation, energy dissipation processes and particularly bottom friction effects and lee-wave drag in basins with sill geometry similar to the upper part of Loch Etive were the focus of a detailed study carried out using 2-D slicing of high resolution non-hydrostatic
models (Stashchuk et al., 2007; Xing and Davies, 2009). In the highly varying environments the frequency of deep basin overturning events directly dependent on the efficiency of a vertical mixing below sill depth and potentially can be determined with full 3D modelling approach with precisely defined initial and open boundary conditions.

![Figure 8](image)

**Figure 8 (a)** Time series of the vertical displacement of isotherms (black lines) are overlaid with horizontal currents speed (colors, cm·s$^{-1}$) measured at RES (Inall et al., 2004) **(b)** Vertical transect across the Bonawe sill shows isotherms displacement due to propagation of the internal tide (Loch Etive POLCOMs model, D. Aleynik). AUV transect in Ardmucknish Bay with salinity **(c)** and Turbulent Kinetic Energy values **(d)**, obtained from velocity microstructure sensor at a depth of 10 m in February 2011 (courtesy M. Toberman, published in (Tait et al., 2015).

**Unstructured 3D hydrodynamic model of Loch Etive**

The geometric flexibility of the unstructured finite volume coastal ocean model (FVCOM; Chen et al., 2011) was found to be suitable for complicate hydrodynamic environments and its regional application demonstrates high prediction skills in a series of intensive validation studies (Aleynik et al., 2016). Recently this coastal ocean model was coupled with the nested atmospheric model (WRF; Skamarock et al., 2008)) and since 2015 the West Scottish Coastal Operational Modeling System (WeStCOMS) has been run through the high performance computing cluster at SAMS. Weather forecasts are produced twice a week, and hindcasts once a week to provide meteorological forcing for the regional FVCOM coastal ocean model. The WeStCOMS is also capable of short term (4-5 days) forecasts of the sea state at high temporal (hourly) and spatial resolution and also provides lateral boundary forcing conditions for the nested Loch Etive model domain with substantially enhanced horizontal resolution (Figure 9).
To capture the wind tunnelling effects, a regional non-hydrostatic WRF model was nested within the 0.25° Global Forecasting System model and had three nested regions (18:6:2 km) with the highest horizontal resolution focused over the west coast of Scotland. This WRF model can also be used to estimate freshwater input via rainfall rate over the catchment areas of key rivers. The Loch Etive hydrodynamic model has 30 sigma-coordinate terrain-following vertical layers with increased resolution close to the surface and sea-bed.

Numerical solution of the momentum equations was performed as a calculation of the volume fluxes between non-overlapping triangular prism elements of variable size, allowing increased resolution in areas of essentially complex coastline or bathymetry. Mesh element size ranges between 400 m at the model open boundary to 30 m in constricted areas such as narrow channels and the heads of bays and river mouths. External lateral forcing was provided by sea-surface elevation time series constructed with 8 tidal constituents using OTIS inverse tidal solution (Egbert et al., 2010) with the nodal correction and time origin adjusted to match exactly observed tidal phase. The lateral open (water) WeStCOMS model boundaries was constructed with time series of temperature and salinity derived from North-East Atlantic operational ROMS model (Dabrowski et al., 2014) run by the Irish Marine Institute. Detailed information on the hydrodynamic model configuration (bathymetry data used, horizontal and vertical eddy viscosity and diffusivity and bottom

Figure 9 SAMS Loch Etive FVCOM unstructured model mesh (light blue) nested into WeStCOMS (green) and surrounding terrain topography (3D), courtesy of UK Ordnance Survey ter50m grid. Moorings and CTD station LY1 (stars) and temperature loggers (squares) provided by NERC Diving by Unit (M. Sayer) also included.
boundary layer parameterization etc.) and statistical analysis of the model performance skill against available hydro-physical observations are detailed in Aleynik et al. (2016).

Massive fresh water supply determines the range of salinity (below 28.5 psu) in the upper basin. Loch Etive has the largest ratio between its watershed and sea surface area (45:1) of all Scottish sea lochs, which leads to large annual fresh water input, accumulated from 12 rivers. The actual volume discharge data is crucially important for the accurate modelling of fresh water balance in a basin with topographically-restricted exchange to the neighboring water bodies. Exchange restriction often results in density stratifications, prolonged residence times of deep waters and the development of hypoxic conditions at depth.

The long term HYPOX monitoring program with density and oxygen time-series recorded at 124 m in Loch Etive revealed that stagnant periods with gradually decreasing oxygen concentrations represent the normal state for the deep water in the inner basin of Loch Etive, such as a period after July 2010 (Figure 7b). A slow decrease in deep-water salinity and density indicated a slow mixing process. However oxygen intrusions do not balance consumption, leading to almost hypoxic conditions at depth towards the end of the HYPOX recording period: in January 2012 oxygen concentrations < 62.5 µmol l⁻¹ (Figure 7b). In winter and early summer 2010 three bottom-water renewal events appear as sudden increases in oxygen and density (dashed vertical lines in Figure 7b) and two decreases and one increase in temperature (blue lines in Figure 10c). Tidal pressure sensors, CTDs, thermistors time series near Connell and in the Firth of Lorn, and in the lower and upper basins of the Loch Etive, accompanied with the weather stations records provided comprehensive boundary forcing data set for the Loch-Etive unstructured 3-D hydrodynamic model. This also helped to identify specific meteorological and oceanographic conditions required for deep-water renewal events to occur. All renewal events in 2010 happened at spring tide (Figure 10c) and coincided with a drop in air pressure of 30–50 hPa (not shown), that led to an additional sea level rise of 0.3–0.5m. The inverse barometer effect exaggerated the tidal sea-surface height oscillations and helped to force dense waters upwards and across the sill. Reduced freshwater input due to low precipitation and low discharge from the nearby Inverawe hydroelectric station (Figure 10b), coupled with frequent occurrence of temperatures below freezing point during 2010 winter, minimized the outflow of brackish surface water from the inner fjord. These exceptionally
dry and cold conditions facilitated the accumulation of dense saline and oxic waters at the entrance of Loch Etive in the Lynn of Lorne/Ardmucknish Bay.

Figure 10. (a) Vectors indicate winds strength and direction at Dunstaffnage weather station during three major renewal overturning events in upper basin of Loch Etive in 2010, denoted with dashed vertical lines and Latin numbers I, II, III. (b) Fresh water discharge rate (m$^3$s$^{-1}$) at River Awe hydroelectric station by types. (c) Sea surface elevation ($\zeta$, m) is shown with black line (on top) and sea water temperature time series recorded.

The inflow events were further supported by “down-fjord” winds (long periods in winter and short term event in summer: Figure 10a), that pushed stratified surface layers away from the lower Loch, thereby enhancing estuarine circulation and the delivery of dense water toward the entrance of the inner basin. After the deep-water renewal events the
weather reverted back to the long-term average conditions with higher temperatures and more precipitation. This resulted in a presence of a pool of low-salinity water at the entrance of Loch Etive and prevent further renewal events from summer 2010 until the end of the recorded data series in winter 2011/2012.

Due to favourable winds in the preceding weeks, the accumulation of denser (saltier) than usual seawater at the entrance to Loch Etive in Lynn of Lorn area is a crucially important precondition for deep-water renewal in the upper basin. Its presence in June 2010 and its absence in 2011 was captured with high accuracy by the West Coast FVCOM model both at the sea surface (Figure 11a,b) and in deeper layers, such as shown with observed and modelled time series at LY1 monitoring station (Figure 11c-f). The third overturning event occurred between 22 and 30 June 2010 in several (tidal) pulses. One of the later pulses can be seen as a series of vertical temperature and salinity transects across Bonawe sill in the upper basin of Loch Etive (Figure 12).

Numerical simulations helped to identify the hydrodynamic mechanisms that govern inflow events and demonstrate the complexity of the conditions required to convey deep-water renewal in a basin with restricted exchange with open sea. By applying the knowledge gained from combined online monitoring and modelling, it could be possible to manually provoke inflow events by reducing the freshwater supply from the Inverawe hydroelectric power station at times of favorable natural conditions and thereby mitigating deep-water hypoxia.

The coupling of coarse-resolution regional models with a fine-resolution nested model make it possible to develop realistic applications for search and rescue operations as well as detection of neutrally buoyant and various chemical continuous tracers, and Lagrangian particles spreading from a pollutant sources and aquaculture installations.
Figure 11 Low sea surface salinity plume at the entrance to Loch Etive at ebb (falling) tide phase day before the III$^{rd}$ overturning event in 2010 (a) and much wider plume spreading in summer 2011 (b), according to FVCOM model. Weekly vertical time-series of salinity profiles in Lynn of Lorne (LY1, station 56°28’91”N, 5°30’10”W, measured with CTD casts (left) and calculated with the FVCOM model (right) in summer of 2010 (c, d) and in 2011 (e, f). The onsets of the 3$^{rd}$ overturning event in the Loch Etive deep basin is indicated by dashed vertical line, (c-f from Friedrich et al 2014).
Figure 12 FVCOM model simulation of the third overturning event shows vertical transects of temperature (left) and salinity (right) across Bonawe sill in upper Loch Etive during a single flood-ebb cycle at 14, 16, 18, 20 and 22 hours, 30th June 2010.
**Biology and Ecology**

Loch Etive has been a regular research study site for various species since the 1970s, with publications from John Gage on the benthic macrofauna and descriptions of the sediment (Gage, 1972; Gage and Tett, 1973) and phytoplankton primary production in the lower basin (Wood et al., 1973).

The phytoplankton is made up predominantly by diatoms, with a small proportion of dinoflagellates. The dominant diatom is *Skeletonema*, which peaks in abundance in late spring and early summer, whilst medium-sized armoured or autotrophic dinoflagellates (MAD) bloom slightly later in the year. An initial study (Wood et al., 1973) used $^{14}$C uptake incubations to measure *in situ* production, which was estimated as 70g C/m$^2$ in the top 10m, accounting for respiration. There was also a strong correlation in carbon fixation per unit of chlorophyll with surface irradiance (Wood et al., 1973). Over forty years later, the population trend seen in *Skeletonema* has shifted and shortened, with the bloom starting a month later and finishing a month earlier (see Figure 13). In contrast, MAD have increased in abundance and season duration. Although the change in population dynamics has been

![Figure 13 Population trend of the diatom Skeletonema recorded in Loch Etive (cell abundance on y axis with day of the year along the x axis) from 1970/1971 (open circles) to 2012/2013 (red circles). Figure from P. Tett (SAMS).](image-url)
noted, there is no explanation yet for what has caused the changes, the potential effects on primary production, and what proportion of this production is sequestered in the sediments within the loch vs production that leaves the loch for sequestration in the wider marine environment.

Recent studies have illustrated there are 56 categories of phytoplankton within Loch Etive, made up of diatoms and dinoflagellates. The diatoms fuel the ecosystem within the loch, particularly in the upper basin, and provide a vital food resource to the zooplankton. Over 16 months of sampling in Loch Etive during 2012/2013 identified 96 categories of zooplankton (Mauchline, 1987). The copepod *Calanus finmarchicus* has a large population in Loch Etive, where it overwinters at ~100 m depth.

The population of *C. finmarchicus* in Loch Etive is pure, and the wax esters (omega 3 in lipids) that provide it with buoyancy are strongly linked to the diapause behaviour (Clark et al., 2012). Sampling with plankton nets has demonstrated the population of *C. finmarchicus* is unusually large in the upper basin. Recent research on the population dynamics during the 2012/2013 sampling period have demonstrated different dynamics by depth: the eggs are produced in late winter or early spring in the surface waters (0-50 m), and the final larval stage (stage 5.1) has highest abundance from mid-summer (July) for around six months at 50-140 m depth (Figure 14).
Zooplankton exhibit diel vertical migration (DVM) in open ocean temperate and tropical environments, with animals sinking to depth during the day and surfacing at night. Until recently, in polar regions and high latitudes it was assumed that this vertical migration ceased during the dark winters. However, it has been shown that this vertical migration shifts from a 24 hour solar day to a 24.8 hour lunar day, using the moon as a light cue last (Last et al., 2016). An acoustic mooring deployed at RE5 in Loch Etive, equipped with 2 x
Figure 15 Double plotted actogram of ADCP data from 18 m where each horizontal line represents one day. There is increased backscatter (red/orange) during the night and decreased backscatter (blue) during the day. Note the effect of storm “Barney” on the 17th November “disrupting” the classical DVM pattern for a number of days. Figure from K. Last (SAMS).

Acoustic Doppler Current Profilers (ADCP) and 2 x CTDs (one each at 25m and one each at 90m) and temperature sensors at 10m intervals, recorded backscatter and environmental data for a year. This data allowed tracking of the diel migration of the zooplankton population, as exemplified in Figure 15. The plot shows that DVM migrations (seen as sloping vertical lines) track the dawn/dusk change in annual photoperiod for this latitude and are near continuous throughout the year. The only deviation from this pattern occurs during the very darkest month and when winter storms arrest DVM.
Loch Etive has a high diversity of different fish species. Recent research has established that there is a significant population of elasmobranchs, particularly spurdogs (*Squalus acanthias*). This is a highly mobile species, and based on catch data within the loch, the population is relatively large. Data collected from data tags on individual fish allowed their movements to be tracked, by recording environmental data such as temperature and depth, indicating their use of the deepest levels of the upper basin (maximum recorded depth 140 m). It appears that the spurdogs have a ‘thermal niche’ within the upper basin, allowing them to overwinter in the loch instead of in open ocean environments (Thorburn et al., 2015). The genetic diversity of this population is representative of the rest of the UK, so the population appears to have high recruitment. However, there is a lot of uncertainty around what this species actually eats during loch residency; whether its diet or behaviour changes during the course of the year; and how many make up the Etive population. Marine Science Scotland, in partnership with Scottish Natural Heritage, has commenced an acoustic tagging programme, with ten receiver units situated in Loch Etive, fitted with temperature loggers.

That the spatially restricted but heterogeneous physical environment of Loch Etive appears utilised fully by seasonally resident tagged spurdogs indicates an ideal population with which to address fundamental ecological questions benefiting from environmental ‘omics approaches. Continuing integration of high resolution environmental data from Loch Etive with movement analyses, presents an unprecedented opportunity to investigate behaviour and gene-environment interactions in a tractable elasmobranch. This allows for the use of cutting edge genomic and transcriptomic approaches to determine habitat partitioning by geno- and phenotype. The implications of this work are of general significance to fish and fisheries management and conservation, and impact the wider ecological community.

*Carbon cycling and sequestration*

Sea lochs are an interface between terrestrial ecosystems and the marine environment, and the combined dynamics and interactions of these two very different habitats determines the biogeochemical processes that occur within the loch. The generally large catchment areas around sea lochs result in a large proportion of terrestrial organic carbon entering the loch. At the same time, there is an input of marine carbon from production within the loch, and organic matter brought in with each tide. The carbon is either processed within the loch;
deposited on the sediment and either remineralised or sequestered; or leaves the loch environment and enters the open marine environment.

Sea lochs and fjords are important sites of carbon sequestration, often portrayed as ‘hotspots’ for organic carbon burial as they sequester carbon at a faster rate compared to other coastal habitats (Smith et al., 2015). Despite this, Scotland’s 110 sea lochs have not been studied in terms of sedimentary carbon sequestration. Ongoing research in Scotland has combined seismic geophysics and geochemistry to quantify the amount of carbon held within loch sediments, making it easier to estimate the carbon stock within a loch’s sediment (Smeaton et al., 2016). Based on this technique, a preliminary estimate of 21 million tonnes (Mt) of total carbon are stored in Loch Etive’s sediment, of which organic carbon makes up over 12.6 Mt. Most of this is likely from postglacial deposition, with just over 3 Mt of total carbon deposition during the glacial period. The upper basin is a significant store of organic carbon compared to other lochs, although the storage of inorganic carbon is much lower, potentially due to acidic conditions caused by high organic carbon content. However there is still a lot of uncertainty around how the hypoxic conditions impact the benthic sequestration mechanism and certain benthic organisms (foraminifera), and how the proportion of terrestrial vs marine input of carbon may alter carbon sequestration. Thus the ‘blue carbon’ potential of sea lochs is still very uncertain, and although Loch Sunart is relatively well understood in terms of carbon accumulation or sequestration (Smeaton et al., 2016), Loch Etive remains an ideal study site for identifying the carbon burial mechanisms, particularly in hypoxic conditions.

Some work has been done on identifying the fate of organic carbon in Loch Etive, and the pathways of this organic carbon in benthic carbon cycling. A series of isotope experiments in the lower basin (RE6) have quantified the relative contributions of macrofauna living in the sediment, and microbial organisms, to biological benthic carbon cycling. A comparison study using sediment cores from RE6 (with fully oxygenated overlying water) and permeable sediment cores from an estuary (Ythan estuary, Aberdeenshire) demonstrated how the different oxygen dynamics determine the processing of carbon through the ecosystem. Macrofaunal uptake appears to be more important in the cohesive Loch Etive sediments, whilst bacterial uptake drives the process in permeable oxic sediments (Figure 16).
However, the mechanisms driving this process are still unclear, and may be due to the amount of organic carbon available, or the solute transport regimes. Oxygen availability has also been shown to determine the pattern of carbon uptake by benthic fauna in a similar set of experiments conducted across the Arabian Sea oxygen minimum zone (Woulds et al., 2007). This suggests that fluctuating oxygenation in Loch Etive will be a key driver of benthic carbon cycling, and manipulative experiments would help to shed more light on this.

Figure 16 Relative contribution of different trophic levels to carbon processing (top plot), and relative contribution of each trophic level at Loch Etive (bottom plot). Figures adapted from Woulds et al, 2016.
1. Commercial Activity

Aquaculture

Dawnfresh Seafoods are the main commercial users of Loch Etive, currently maintaining 8 farms, 61 employers with an £18m turnover, producing over 5000 annual tonnes of trout. Loch Etive supports the production of 2800 of the total 3500 tonnes of large loch trout. As part of their operation, they have a variety of moorings equipped with sensors for oxygen, temperature and salinity, and carry out regular benthic sampling for redox analysis to ensure they comply with farming standards. The Dawnfresh farms are located in the upper and lower basins of the loch (Figure 17).

![Trout fish farm locations for Dawnfresh in Loch Etive upper and lower basin.](image)

Figure 17 Trout fish farm locations for Dawnfresh in Loch Etive upper and lower basin.
2. **Uses and Management**

Loch Etive provides a variety of services to the local area, ranging from food and drink to bioresources and waste assimilation. The Loch Etive Management Plan, published in 2011 and produced by the Marine and Coastal Development Unit at Argyll and Bute Council, outlines the main activities that occur within Loch Etive. Several sectors of the blue economy – the industries that depend on the marine environment for their output – operate in Loch Etive: aquaculture and fishing, marine and coastal tourism, biotechnology, renewable energy and transport. The former four are part of Scotland’s growth sectors identified in Scotland’s Economic Strategy. Additionally, the services provided by Loch Etive as an ecosystem include waste assimilation, research and education, and carbon sequestration. Forestry and agriculture activity around the loch also impacts the ecosystem, as removal of trees and change in land use influences terrestrial input.

Most of these activities/services depend on the health of the marine and coastal ecosystems, and are regulated or monitored by different organisations, including Argyll and Bute Council, Marine Scotland Science, Scottish Environment Protection Agency, Scottish Natural Heritage and the Crown Estate (which is currently devolving this role).

The research carried out in the loch underpins many of these activities, such as the biodiversity within the loch impacting tourism and recreation, and the health of the loch (chemistry and oceanography) potentially affecting aquaculture production. The forested land around the loch (Loch Etive Woods) forms a Special Area of Conservation (SAC), consisting of eleven separate sites. There are seven Sites of Specific Scientific Interest (SSSI) along the borders of Loch Etive. There is also a Special Protection Area (SPA) in Glen Etive and Glen Fyne to protect habitats for a local golden eagle population.

The unique biodiversity within Loch Etive itself includes some species designated as Biodiversity Action Plan (BAP) priority species, such as the common seal *Phoca vitulina* and the fireworks anemone (*Pachcerianthus multiplicant*). Many of the habitats fall within the Priority Marine Features, which are considered for Marine Protected Area (MPA) designation, including burrowed mud, blue mussel beds, intertidal mudflats and blue mussel beds. Species that inhabit Loch Etive and are eligible for MPA designation include spiny dogfish (spurdog), northern featherstar, otter, and sand goby.
The integrated coastal zone management (ICZM) plan for Loch Etive was produced to support regional planning under the Marine Scotland Act (2011), and provides guidance for Local Authority planners as well as other regulators and stakeholders. This includes the monitoring of activities that take place in Loch Etive, and works closely with Scottish Natural Heritage (SNH) as a statutory advisor. Data collected through research in Loch Etive can directly feed into management plans for the future, particularly for large scale environmental issues such as climate change.
3. Research gaps and future work

Of all the Scottish sea lochs, Loch Etive is one of the most extensively researched, with a dataset dating back to the 1970s. Despite this, there are many gaps in knowledge that have been identified, and the use of modern techniques can start to address some of the larger scale questions. During the workshop, a few key ‘highlight’ areas were recognised, although the main focus of the workshop was to understand the oxygen dynamics that lead to hypoxia.

**Oxygen / hypoxia**

The oxygen dynamics within the waters of Loch Etive’s upper basin have been closely monitored over the last 10-15 years, with detailed data for two years for the duration of the cabled mooring at RE5. This has allowed definition of the physical conditions leading up to a renewal event, and development of an accurate hydrodynamic model. The dynamics in the water column are relatively well understood compared to the benthic dynamics, yet it is unclear whether the oxygen demand is driven by the pelagic or benthic demand. Values for the pelagic uptake rates are consistent with those previously measured, but the oxygen dynamics for the different types of sediment have not yet been measured. This data would feed directly into the hydrodynamic model, enhancing accurate prediction of hypoxia and deep water renewal events.

The current 2D hydrodynamic model could be improved to a 3D hydrodynamic model with this additional data. In addition, much of the freshwater input into Loch Etive comes from the river Awe. This is a manually controlled flow, due to the hydroelectric power station on Loch Awe, which affects the river flow and eventual discharge into Loch Etive. Capacity growth of the hydropower station may adversely affect the loch if the flow from Loch Awe becomes more irregular, as the renewal events occur when there is low freshwater runoff. However, this concept has not been fully explored, with the exception of Edwards and Edelsten (1976).

The organisms inhabiting the loch, including the zooplankton and the spurdogs, do not appear to be negatively affected by the occurrence of hypoxia. The zooplankton population
appear to benefit from the lack of predators, and are found in huge densities in the upper basin. The current acoustic tagging programme in Loch Etive will provide information on the distribution of the fish within the loch. The distribution of the zooplankton appears to match the depth of the pycnocline at ~100 m, which is where they overwinter.

The oxygen dynamics of the loch determine many other biogeochemical processes, such as the nutrient cycling (ammonia and nitrate concentrations). Phosphate, manganese and iron fluxes and cycling are affected by the occurrence and duration of hypoxia, although this has not been thoroughly investigated. Very high nitrite may lead to the release of nitrous oxide, a greenhouse gas. Photochemical emission of atmospheric gases from the loch is currently being undertaken in the loch as part of a project funded by the Carnegie Trust for the Universities of Scotland. The role of dimethyl sulfoxide (DMSO) and methane (CH₄) production, and the levels of DMSO and DMS at RE5 are currently being measured as part of an ongoing project, as the reduction of DMSO to DMS (a climatically active gas) may be more prevalent under low oxygen conditions.

**Carbon – carbon cycling and sequestration / future change**

Due to the unique hypoxic environment in Loch Etive, there is a huge amount of uncertainty around the carbon dynamics within the loch, from short term carbon cycling (seasonal and annual trends) to long term palaeoceanographical changes. The changes in sea level rise during the glacial and postglacial periods, combined with historical changes in climate, would affect both the amount and nature of terrestrial carbon inputs as well as the potential for carbon accumulation and sequestration. Understanding the past to interpret the modern and predict future carbon dynamics is imperative.

Linked to this, quantifying the input of marine carbon vs terrestrial carbon is instrumental in understanding the carbon dynamics in the loch, and provide a template for studying similar fjordic systems. The use of stable isotopes (δ¹³C and δ¹⁵N) and bulk elemental data (C/N) can be utilised to separate the terrestrial and marine components with surface sediments. Additionally, the use of biomarkers would be extremely useful in identifying more specific carbon sources (i.e. vegetation vs soil, phytoplankton vs microalgae) and tracking the changing carbon input to the loch through time. Proxies such as BIT index and hopanes
(derived from soil bacteria) can pinpoint the terrestrial input, and preliminary studies of $\delta^{13}$C on one of the hopane compounds, diploptene, can link to methanotrophic activity. The large catchment area around Loch Etive, populated by different habitats, makes it an ideal case study for tracking carbon from source to sink. The impact on increased jellyfish blooms which contribute a large source of carbon to the benthos when they die, and the faecal pellet flux from the large copepod populations, have not yet been measured.

The iron cycle is closely linked to the carbon cycle. Iron is a redox active agent, and iron minerals interact with each other as well as other molecules. This, and the often nanoparticulate size of reactive iron species, makes them notoriously hard to characterise. Proxy or traditional methods such as sequential extractions for measuring iron are not accurate for depicting a full picture of the iron cycle. Mössbauer spectroscopy can allow accurate characterisation of iron (Schröder et al., 2016), and simultaneously enhance understanding of the carbon cycle, particularly when linking terrestrial sources to marine sinks. Quantifying the dissolved organic carbon (DOC) inputs with the freshwater rivers would provide additional information on source of carbon.

The periodic hypoxia is likely to affect carbon cycling and sequestration, and targeted research would identify what effect the hypoxia has on these processes, providing information that would be globally applicable to many coastal environments that are susceptible to hypoxia, such as the Gulf of Mexico and the Baltic Sea.

**Ecology and foodweb of Loch Etive**

An ecosystem approach to integrate the knowledge on species living within Loch Etive and the niches they inhabit would provide a complete picture on Loch Etive’s ecology. Early research from the 1970’s established there are marine organisms (bivalves) at the head of the loch in the low salinity waters. Previous shellfish farms for *Mytilus edulis* were spread across Loch Etive, as this species is known to tolerate low pH conditions, and they may be reintroduced into the loch for aquaculture.

The transfer of carbon between the primary and secondary trophic levels has not been accurately quantified, and this would provide detail at the base of the foodweb. Benthic macrofauna have been examined, and sediment traps have indicated that less organic
matter reaches RE5 in the upper basin than RE6 in the lower basin, and that the most
diagenetically active benthic site appears to be RE6. However, this work has been limited to
a few points across the loch, and targeted studies could sample all the sediment types
across the loch to ‘scale up’ on an ecosystem level.

The microorganisms within Loch Etive are the least understood group, with little
information on their abundance, functional diversity and what role they may play in
contributing to biogeochemical cycles (carbon, oxygen, nitrogen, sulphur), although some
work has been done to identify the presence of sulphate reducing bacteria (Parkes et al.,
1989; Parkes et al., 1993). The occurrence and duration of hypoxia are likely to affect
microbial activity and their contribution to biogeochemical cycling, and this aspect also
needs to be identified. The use of metagenomics would be invaluable in understanding
these dynamics.

Summary of main research questions

- What drives the hypoxia in Loch Etive?
- How does the catchment area influence carbon accumulation?
- How does organic carbon preservation change under hypoxic conditions?
- What are the implications for global coastal ecosystems?
- What is the pH variability in the upper basin?
- How does the Holocene sea level change impact hypoxic events today?
- What are the sources of carbon (marine vs terrestrial) and how does this influence
  the biogeochemistry?
- How are different types of organic matter remineralised/buried/biologically
  processed?
- What is the influence of iron on carbon burial and/or transport?
- What is the fate of terrestrial organic matter in the Loch, and how much remains in
  the loch?
- What are the microbial assemblages doing? Can we quantify their uptake and
  metabolism with metagenomic approaches?
- How does increased oxygenation / deoxygenation impact benthic carbon cycling?
- To what extent are the carbon and nitrogen cycles coupled?
- What are the benthic fluxes of nitrogen and phosphate from the sediment, and how are these affected by changes in oxygen?
- What are the manganese and iron dynamics during a hypoxic event?
- Do the benthic fluxes of nitrogen and phosphate play a role in pelagic productivity?
- Why is biological carbon processing so high in Loch Etive – is it consistent in the upper and lower basins?
- How do the carbon accumulation rates vary with hypoxia, and in comparison to other lochs?
- What has caused the changes in the phytoplankton dynamics?
- What contribution do copepods make to water column respiration?
- What contribution do copepods make to carbon sequestration (the lipid pump) within the Loch?
- Are zooplankton DVM patterns influenced by water column oxygen profiles and how important is basin mixing to copepod survival?
- How do these phytoplankton population shifts affect productivity?
- What is the production of the in-loch sediments?
- Are there contaminants or heavy metals in the loch?
- Why are there crescent-shaped sediment deposits along the eastern edge of the loch? Is this an erosive feature?
- How does the long-term average of oxygen depletion look?
- Does genetic and behavioural diversity in spurdog reflect habitat partitioning?
- Does finfish aquaculture have an impact on the lochs carbon dynamics?
- Does shellfish aquaculture have a future in Loch Etive?
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