BLUE MARINE FOUNDATION

UK KELP RECOVERY

Barriers and Optimum Conditions

Newcastle University

Sussex IFCA
Inshore Fisheries and Conservation Authority

ZSL
Zoological Society of London

Sussex Kelp Recovery Project

CONTENTS

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UK Kelp Recovery: Barriers and Optimum Conditions.
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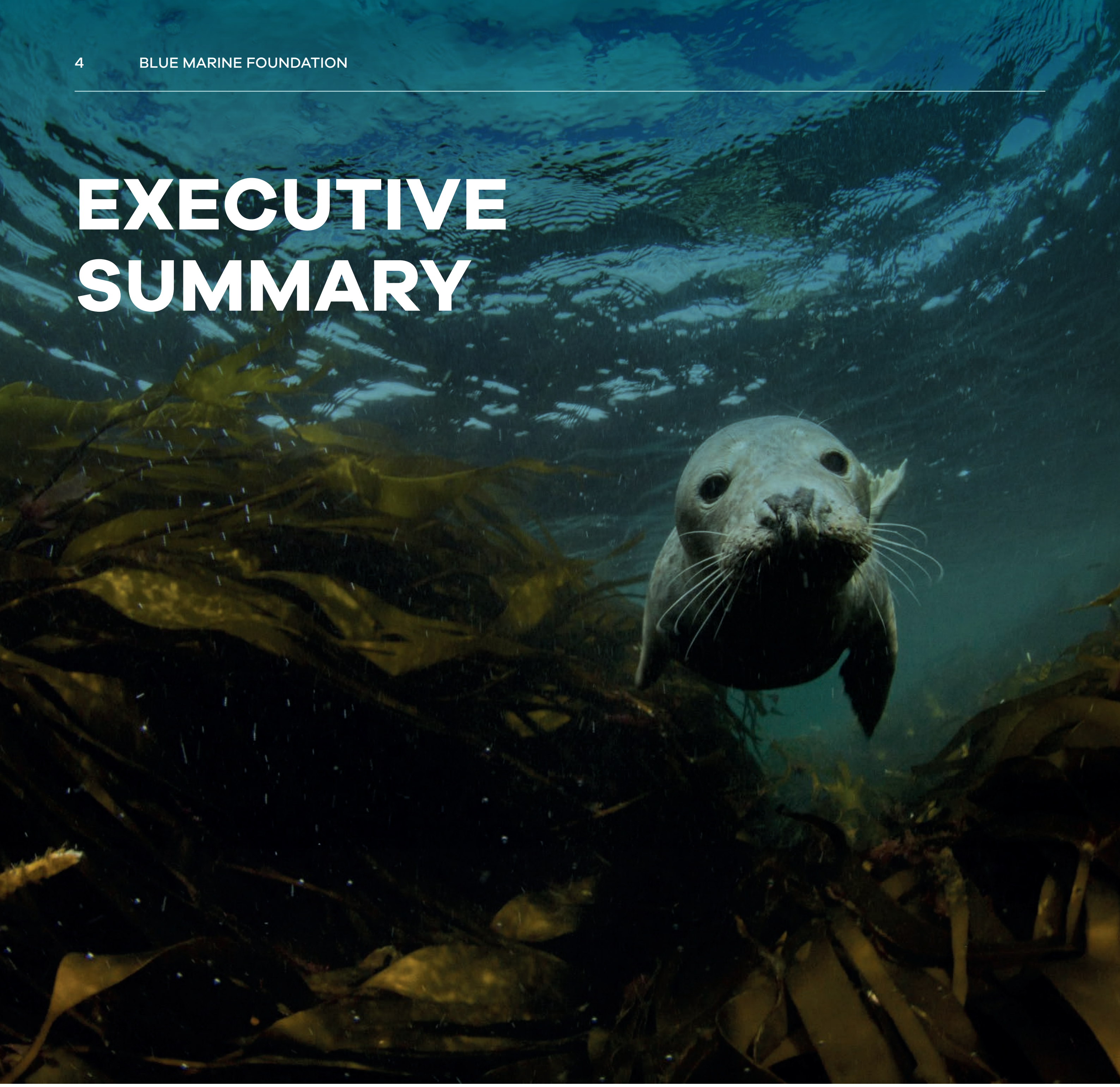
EXECUTIVE SUMMARY



Kelp forests (dense stands of large brown seaweed primarily of the Order Laminariales), dominate rocky reefs along temperate and subpolar coastlines around the world. These forests are considered among the most diverse and productive ecosystems on Earth that modify local environmental conditions and provide a three-dimensional habitat for an array of marine life.

These forests are similar in structure to terrestrial forests, with a canopy layer that facilitates the formation of rich understorey algal assemblages, that in turn provides food and shelter for macroinvertebrates, which are food for species from higher trophic levels such as fishes.

Collectively, kelp forests and their associated assemblages provide an array of ecologically, socially, and economically valuable ecosystem services such as a habitat and nursery ground for commercially important species, taking up and storing carbon dioxide, protecting coastlines from erosion, and supporting recreational activities. Yet despite their importance, kelp forests are threatened by interacting global-, regional-, and local-scale stressors including climate change in the form of rising sea temperatures and increases in the frequency, intensity, and duration of extreme weather events, as well as anthropogenic activities such as trawling and dredging, eutrophication, pollution, sedimentation, and the introduction of invasive species. As a result, kelp forests are believed to have been degraded and/or lost in many regions around the world.

Kelp forests and beds of large brown seaweeds are estimated to occur along ~60% of the coastline of the United Kingdom (UK) where there is appropriate rocky substrate they can attach to and suitable water quality. These forests are home to several kelp species, with *Laminaria hyperborea* generally dominant, while the abundance of other species is more variable due to their environmental tolerances.

It is thought that kelp forests around the UK are relatively stable, with little evidence of widespread losses or local extinctions. Along the coastline of West Sussex however, once extensive kelp forests have significantly declined, with less than 5% of the historic area estimated to remain.

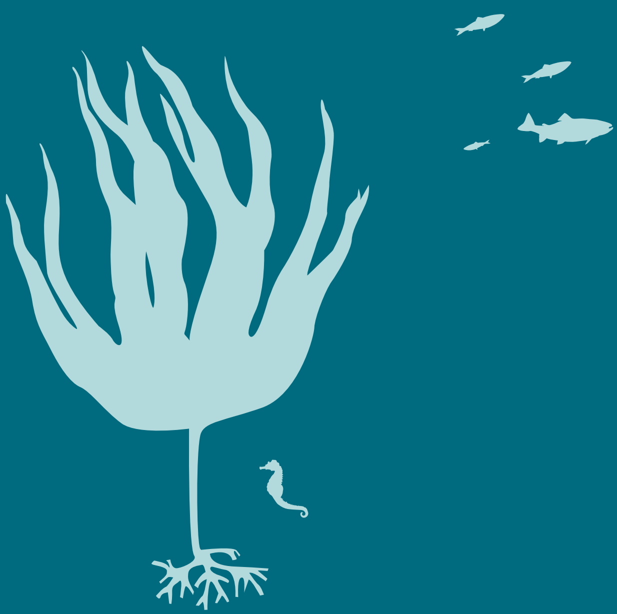
The decline was likely triggered by the Great Storm of 1987 which caused significant kelp dislodgement and opened up areas previously inaccessible to fishers, the subsequent development in fishing technology and reductions in coastal water quality further degraded these kelp beds and prevented kelp recovery.

The Sussex Inshore Fisheries and Conservation Authority (IFCA) established the Nearshore Trawling Byelaw in 2021 which prohibited the use of bottom trawling along large sections of the Sussex coast, with the aim of facilitating the recovery of essential fish habitat, including kelp beds and their associated assemblages and ecosystem services. It is however possible that the trawling byelaw alone may not lead to a regeneration of kelp beds along the Sussex coastline and that curtailing other pressures or restoration activities may be required to aid recovery in some areas.

To inform future work, Blue Marine Foundation commissioned this report to investigate: the environmental conditions necessary for kelp recovery and the factors that could limit kelp recovery; what a trajectory of natural kelp recovery may look like along the Sussex coastline; the active restoration techniques that may be beneficial in the area should they be required; and recommendations for future research, monitoring, and management.

Natural kelp recovery around Sussex is dependent upon there being a supply of kelp spores reaching areas where habitats have been degraded/lost. Given that water motion along the Sussex coast generally occurs in an eastward direction, driven in part by prevailing south-westerly winds and residual currents in the English Channel, it is plausible that kelp spores will be carried in an eastward direction and that recovery (should it occur) may occur from west to east.

Natural kelp recovery is also reliant on the mitigation of stressors that caused the initial kelp degradation/loss, resulting in environmental conditions that are favourable for kelp settlement, growth to maturity, and reproduction. In Sussex, sedimentation (from cliff erosion, terrestrial run-off, and nearshore dredging), and the resuspension of fine particles within the system by water motion, pose a threat to kelp recovery. These factors can limit the availability of suitable substrate for kelp settlement, bury kelp spores, and reduce water clarity (and therefore light penetration) which can negatively impact kelp productivity and survival.



Sea temperature may also impede kelp recovery, as although temperatures are currently within the tolerance limit of kelp species known to the area, extreme temperatures have been experienced on the south coast of the UK in recent years. Collectively these factors, along with other factors that are not currently being monitored in the Sussex area (e.g., nutrient and pollution concentrations) may impede kelp recovery along the Sussex coast or influence the structure and abundance of kelp assemblages in the area, with species that were historically present potentially replaced by those more tolerant to the present environmental conditions.

Where environmental conditions are favourable for kelp to persist (i.e., stressors that caused the initial degradation/loss have been mitigated), but natural recovery of kelp beds remains limited, kelp restoration techniques may be appropriate to aid the reestablishment of kelp beds along the Sussex coast. Identifying the most appropriate target species for such restoration is challenging but given that kelp beds along the Sussex coast were historically comprised of *Saccharina latissima*, *Laminaria digitata* and *L. hyperborea*, these would be the most appropriate candidates for initial restoration activities. Similarly, identifying the most appropriate sites for restoration is challenging, and environmental conditions at potential sites should be monitored before commencing restoration activities to ensure they are suitable for the target kelp species.

Along the West Sussex coastline, once extensive kelp beds have significantly declined

Transplantation is the most common kelp restoration technique and has been relatively successful for kelp species that are similar in structure to those historically found in Sussex. In the Sussex area, transplantation using 'green gravel' is likely to be the most promising kelp restoration technique. Seeding may also be a useful restoration technique; however, it would be best employed in areas adjacent to extant kelp as this is believed to enhance success.

Given that there is a lack of precedent for kelp restoration projects in the UK, it is important that any efforts in Sussex adhere to international principles and standards, and that a thorough review of scientific literature concerning the target kelp species, restoration technique, and restoration of areas with comparable environmental conditions is undertaken. Prior to commencing any large-scale restoration efforts, pilot studies would need to be conducted to determine the most appropriate kelp species, restoration site, and technique.

Original artwork © Lucy Chapman

Monitoring is fundamental to determine whether natural kelp recovery is occurring, as well as the effectiveness of any future restoration efforts. Factors that could be beneficial to monitor include substrate type, sedimentation, water quality (i.e., turbidity, light, nutrient and pollution concentrations), and the abundance and composition of kelp and other benthic assemblages.

Monitoring of these factors should be undertaken at least once every month or season where possible and conducted using scientifically sound protocols that are replicated and compared to reference or 'control' areas - where possible/appropriate using before-after control-impact (BACI) designs and best practice guidelines. It would also be beneficial to consider ecosystem-based management approaches regarding both the extant kelp beds around Sussex that may provide a source of spores for kelp recovery, alongside areas where restoration may be conducted. Such approaches need to be underpinned by robust monitoring and collaborations.

WHAT IS KELP?

Kelp is the common name given to approximately 128 species of large brown algae or seaweed (Order Laminariales) that primarily occur along rocky shorelines in cool, temperate and subpolar regions around the world (Graham *et al.* 2007; Guiry and Guiry 2023; Steneck *et al.* 2002; Wernberg *et al.* 2019). Kelp often grow together in large numbers, forming a forest-like habitat at times referred to as a kelp 'bed' or 'forest' (Wernberg and Filbee-Dexter 2019). However, these underwater forests are quite different from those on land. First of all, kelp does not have roots that extend into the seabed, instead it has a root-like structure called a **holdfast** that anchors the kelp to rocks or other hard substrate on the seafloor. The stem of a kelp, which is relatively flexible, is known as the **stipe** and its role is to support the **blades** (Figure 1).

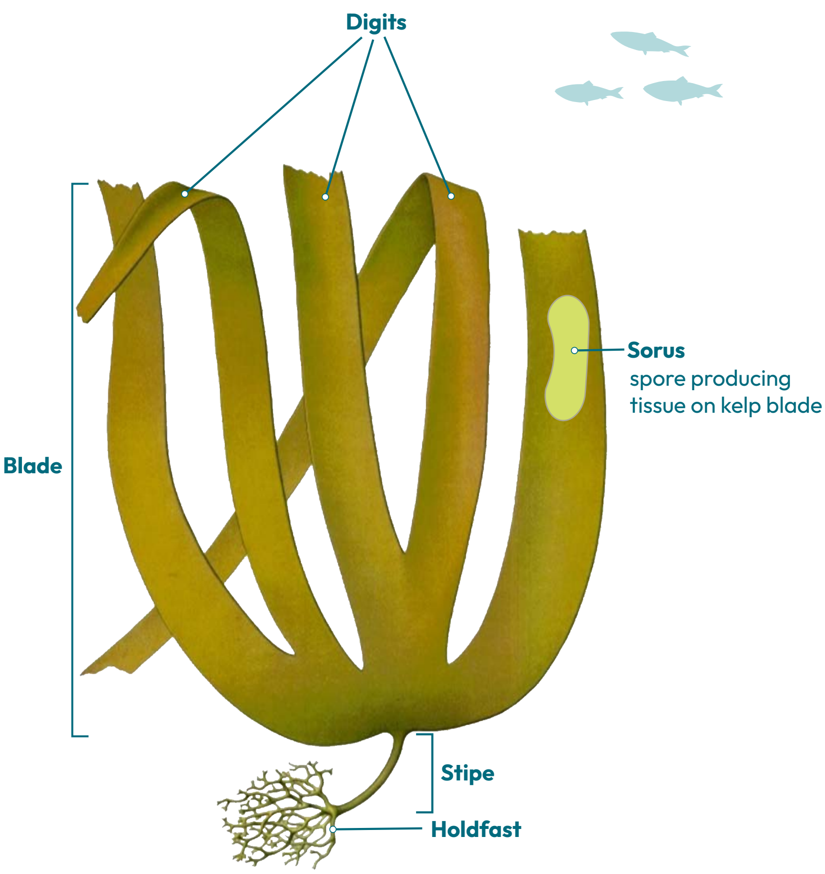


Figure 1: Structure of a kelp plant

The blades, which form the uppermost layer of the forest known as the canopy, are similar to the leaves of a land plant and are where energy from sunlight is used to make carbohydrates and sugars to fuel growth and reproduction through **photosynthesis**, absorbing carbon dioxide and releasing oxygen in the process. This basic structure varies across kelp species, with some species having only one stipe and blade, while others have several stipes and blades, or a blade that may be separated into multiple **digits**, and some have bladders filled with air called **pneumatocysts** that provide buoyancy and help them stand up in the water and grow towards the sea surface. In addition to true kelps, there are several other large brown seaweeds (sometimes called pseudo-kelp, from the Orders Fucales and Tilopteridales) that are similar in structure and can form large beds.

The kelp we know today are believed to have evolved over 20 million years ago (Domning 2008; Estes and Steinberg 1988), and the forests they form are considered among the most important marine ecosystems. Over 500 plant and animal species have been recorded associated with UK kelp beds (Smale, unpublished) and a single kelp can support 80,000 individual organisms (Christie *et al*. 2003). Kelp forests provide a vital multi-structural habitat for thousands of small organisms including worms, starfish and tiny snails (Bué *et al*. 2020; Christie *et al*. 2003; King *et al*. 2021; Teagle *et al*. 2018), while others, including fish and squid use kelp forests to breed and as nurseries to raise their young (Rosenfeld *et al*. 2014; Smale *et al*. 2022). Larger animals such as seals, sea otters and some whales use kelp forests to hide from predators and shelter from storms, while others such as sharks visit kelp forests to hunt for food (Jewell *et al*. 2019). Kelp habitats are also very important for humans.

Firstly, many of the animals found in and around kelp, for example fish, lobsters, and abalone, are commercially exploited (Smale *et al*. 2022), and in some regions, the kelp itself is harvested or cultivated for food, or is used in products such as cosmetics and fertiliser (Vásquez 2016). Kelp habitats also provide valuable protection for coastal communities by reducing the impact of oceanic storms and protecting the coastline from wave erosion (Morris *et al*. 2020a). More recently, kelp has been found to help reduce the impact of climate change by taking up and storing carbon from the atmosphere, although the carbon benefits of kelp habitats vary by species and location and are the subject of ongoing debate and investigation (Duarte *et al*. 2022; Filbee-Dexter *et al*. 2022; Pessarrodona *et al*. 2018). These attributes and benefits are collectively described as **ecosystem services**.

Despite their importance, in recent years, kelp habitats have been degraded and/or have declined in many areas as a result of interacting global-, regional- and local-scale stressors (Krumhansl *et al*. 2016). These stressors include climate change in the form of rising seawater temperatures or marine heatwaves (Wernberg *et al*. 2013), ocean acidification and increases in the number and intensity of storms (Filbee-Dexter and Scheibling 2012; Smale and Vance 2016), alongside pressures associated with human activities, such as coastal development, recreational activities, trawling (Christie *et al*. 1998), herbivory linked to overfishing of predators or range-shifting grazers (Ling *et al*. 2009; Vergés *et al*. 2016), kelp harvesting (Gouraguine *et al*. 2021), reductions in water quality from eutrophication, pollution and sedimentation (Coleman *et al*. 2008; Diez *et al*. 2013; Jones 1971; Sales *et al*. 2011) , and invasive species and diseases (Arnold *et al*. 2016; Easton *et al*. 1997; O'Brien and Scheibling 2018; Saier and Chapman 2004).

These stressors can influence the growth and survival of kelp leading to a transition from once extensive, dense, and complex kelp forest ecosystems to barren areas home to only sea urchins and/or small turf algae. Consequently, there is a growing interest in restoring kelp in areas where they have declined or been lost.

Furbellows

Saccorhiza polyschides

GLOBAL STATUS OF KELP HABITATS AND RECENT HISTORIC TRENDS

Kelp habitats are found along one-quarter to one-third of the world's coastlines, extending from the Arctic to cool waters in both the northern and southern hemisphere, and has been called the world's largest marine biome, covering an area up to five times greater than coral reefs (Jayathilakea and Costello 2021; Starko *et al.* 2021; UNEP 2023; Wernberg *et al.* 2019). Large canopy-forming kelp dominates the coastlines of the western Americas, South Africa, New Zealand, and Tasmania, while smaller kelp, known as **stipitate kelp** and **prostrate kelp**, are more common along the east coast of North America, Europe, and Japan.

In 2016, a team of scientists investigated the health of kelp forests across 34 regions of the world and found that kelp had declined in almost 40% of regions but increased in over 25% of regions (Krumhansl *et al.* 2016). They believe these differences were partly due to different kelp stressors in different regions. For example, in Australia, kelp forests along the west coast were negatively impacted by an extreme marine heatwave in 2011 (Wernberg *et al.* 2013, 2016), whereas in Tasmania they are likely due to the arrival of a species of kelp-eating sea urchin and a decrease in the number of lobsters (due to fishing) that eat the sea urchin (Ling *et al.* 2009). Furthermore, declines in habitat forming macroalgae along the south and south-eastern coast of Australia are believed to be the result of declines in water quality due to sewage outflows and increased turbidity and sedimentation from coastal urbanisation (Coleman *et al.* 2008; Connell *et al.* 2008). Another significant problem the scientists uncovered is that in many areas, there is no historic or current information about kelp habitats, so we do not know if and/or how they may be changing (Duarte *et al.* 2022).

Smale (2020) synthesised over 30 recent (2005-2019) field-based studies that examined responses of kelp communities to increased sea temperatures (Figure 2). The review found compelling evidence of recent impacts of ocean warming on kelp forests particularly along the Iberian Peninsula spanning the coasts of Spain and Portugal where there are increasing reports of kelp decline or loss occurring coincident with warming trends.

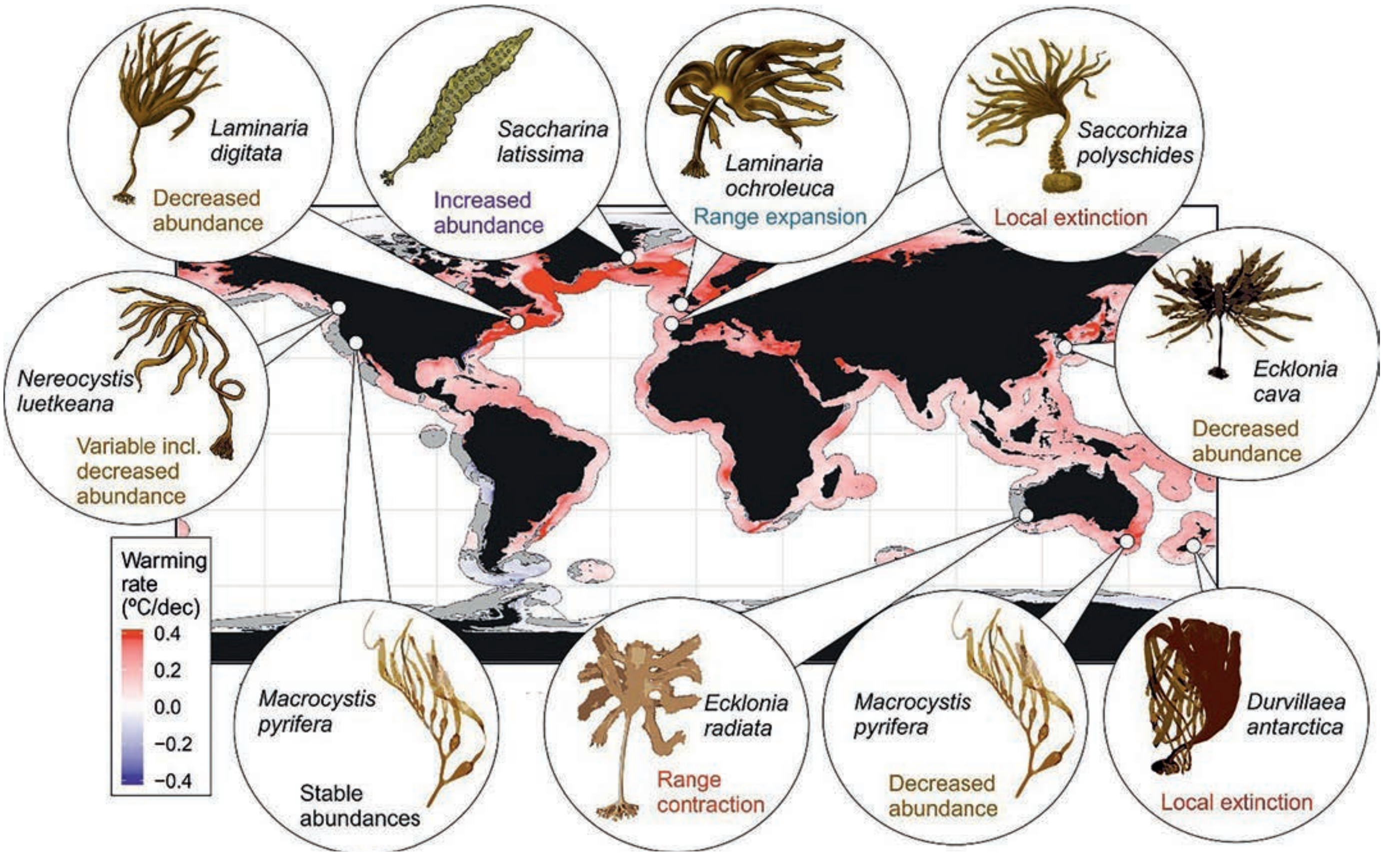


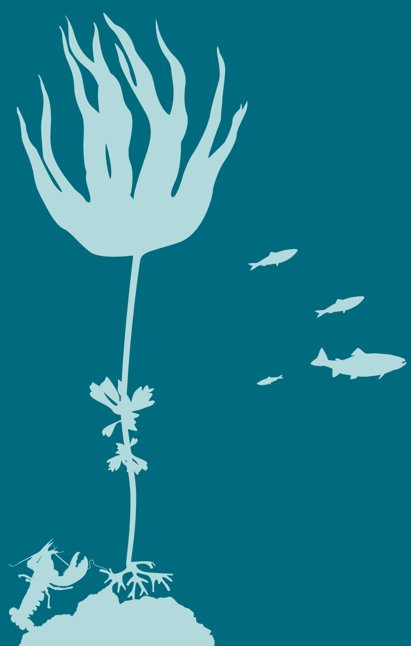
Figure 2: Global distribution of key kelp species and areas of significant change. Source: Smale, D.A. (2020), Impacts of ocean warming on kelp forest ecosystems. New Phytol, 225: 1447-1454. https://doi.org/10.1111/nph.16107

STATUS OF UK KELP HABITATS AND RECENT HISTORIC TRENDS

Kelp forests and beds of large brown seaweeds are estimated to occur along >19,000 km, or approximately 60% of the UK's coastline where there is rocky seafloor or hard artificial structures that they can attach to, alongside suitable water quality (Smale *et al.* 2013; Yesson *et al.* 2015).

In such places, kelp can be found from the low intertidal zone to depths of over 40 m. Along the south-eastern coast of the UK, from the Wash to the Thames estuary, kelp is less common compared to other regions due to the prevalence of sandy and muddy seabed that provide no substrate for kelp attachment (Birkett *et al.* 1998).

There is limited historical data regarding UK kelp habitats, meaning there are gaps in our understanding of how UK kelp have changed over time or in response to various stressors (Smale *et al.* 2013). Burrows *et al.* (2014) further highlighted critical deficiencies in our knowledge and understanding of the dynamics of UK kelp populations and habitats and proposed recommendations for monitoring in order to build a Good Environmental Status indicator for UK kelp. For the most part however, it is thought that UK kelp habitats have remained stable for at least a decade, with little evidence of widespread losses or local extinctions (Wilding *et al.* 2023; Smale *et al.* in review) (but see Box 1 for a case study on localised loss). The Red List for British seaweeds assessed 617 species of seaweed against the IUCN criteria and reported that 7% of the seaweed species fell into the threatened categories Critically Endangered (CR), Endangered (EN) and Vulnerable (VU). In terms of kelp, *Alaria esculenta* was classified as Endangered, *L. digitata* as Vulnerable, and *L. hyperborea, L. ochroleuca* and *S. latissima* as Near Threatened (Brodie *et al.* 2023).



There are some general patterns in kelp habitat structure across the UK, primarily due to the preferred environmental conditions of different kelp species. In general, UK kelp forests are dominated by *L. hyperborea*, with species such as *A. esculenta* often more common in the north of the UK where average seawater temperatures can be almost 3°C lower than in the south (Smale *et al.* 2016). In the somewhat warmer south-western waters of the UK, from the Isle of Wight to Lundy Island, the warmer-water kelp *L. ochroleuca*, which was first reported in the UK in 1948, can be found (Parke 1948a; Smale *et al.* 2015). Given that climate change is expected to drive increases in seawater temperatures around the UK in the coming decades, kelp species that prefer cooler temperatures are expected to become less common and can be considered 'climate change losers', while warm-water kelps such as *L. ochroleuca* are likely to become more common and can be considered 'climate change winners' (Smale and Moore 2017). It has been suggested that by 2100, southern regions of the UK may be too warm for any kelp species to survive (Brodie *et al.* 2014), with poleward shifts in the distribution of many species likely (Assis *et al.* 2022).

Storms, which are expected to increase in both number and severity, have also impacted kelp habitats around the UK. For example, in 2021, Storm Arwen, which was characterised by northerly wind gusts of over 90 kph and wave heights of over 7 m, impacted *L. hyperborea* forests along the coast of south-east Scotland and north-east England, significantly reducing the kelp canopy cover as well as the structure of both the kelp forest and the understorey seaweed and invertebrate communities beneath the canopy (Earp *et al.* 2024a), although natural unassisted recovery is anticipated in the coming years. Along the coast of West Sussex, a once extensive kelp bed, estimated to cover 177 km^2 (HR Wallingford 2023; Williams *et al.* 2022; Worthing Borough Council 1987) was

damaged by a violent extratropical cyclone in 1987 known as the Great Storm, where wind gusts reached up to 185 kph (Met Office 2023). Following the storm, significant amounts of kelp were washed ashore, resulting in a much thinner or less dense kelp bed, which have been further degraded by anthropogenic activities (see Box 1 for further information) (Sussex IFCA 2020).

There has also been an increase in the presence of the invasive kelp species, *Undaria pinnatifida*, around the UK coast. This species was first recorded along the south coast in 1994 and it is now established at a number of locations including natural shores and artificial substrates, particularly in southern areas of the UK (Farrell and Fletcher 2006; Oakley 2007; Smale *et al.* 2013). Given that this species has the capacity to tolerate a wide range of environmental conditions, it has the potential to become more prevalent around the UK in the coming decades.

BOX 1

CASE STUDY

Localised kelp habitat decline in Sussex

Along the coast of West Sussex, a once extensive kelp bed, estimated to cover 177 km^2 (the size of over 20,000 football pitches) (Worthing Borough Council 1987), comprised of predominantly *S. latissima*, has declined in recent decades. The decline is believed to be the result of multiple factors but was likely triggered by damage from the 'Great Storm' of 1987 whereby a significant quantity of kelp was washed ashore. Following this, the development of new fishing technology allowed trawlers to tow their nets through the smaller, thinner kelp beds, and declines in seawater quality caused by sediment dumping and pollution running-off the land are believed to have caused further degradation and prevented the kelp recovering to its previous extent. By the late 2010s, less than 5% of the original kelp habitat remained (6.28 km^2) (Sussex IFCA 2020) (Figure 3). Consequently, the wildlife associated with the kelp declined and the valuable ecosystem services the habitat provided have been lost.

In March 2021, the Sussex Inshore Fisheries and Conservation Authority (IFCA) Nearshore Trawling Byelaw came into force which prohibited trawling along large sections of the Sussex coastline covering ~300 km^2 of nearshore habitats (Sussex IFCA 2019). The objective of this Byelaw is to use ecosystem based management to improve the quality and extent of essential fish habitat, including the historic kelp beds, to promote the recruitment and abundance of commercially important fish and shellfish species including European sea bass, black seabream, edible crab, European lobster, and cuttlefish, as well as other non-commercially important species, both inside and outside of the managed area, to support ecosystem recovery and sustainable fisheries into the future.

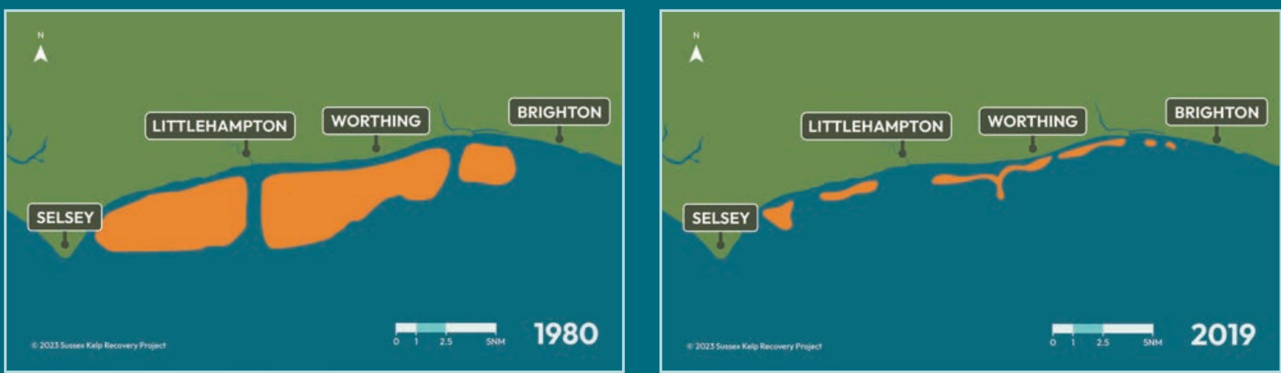


Figure 3: Extent of kelp beds in Sussex nearshore waters 1980-2019. Source: Sussex Kelp Recovery Project

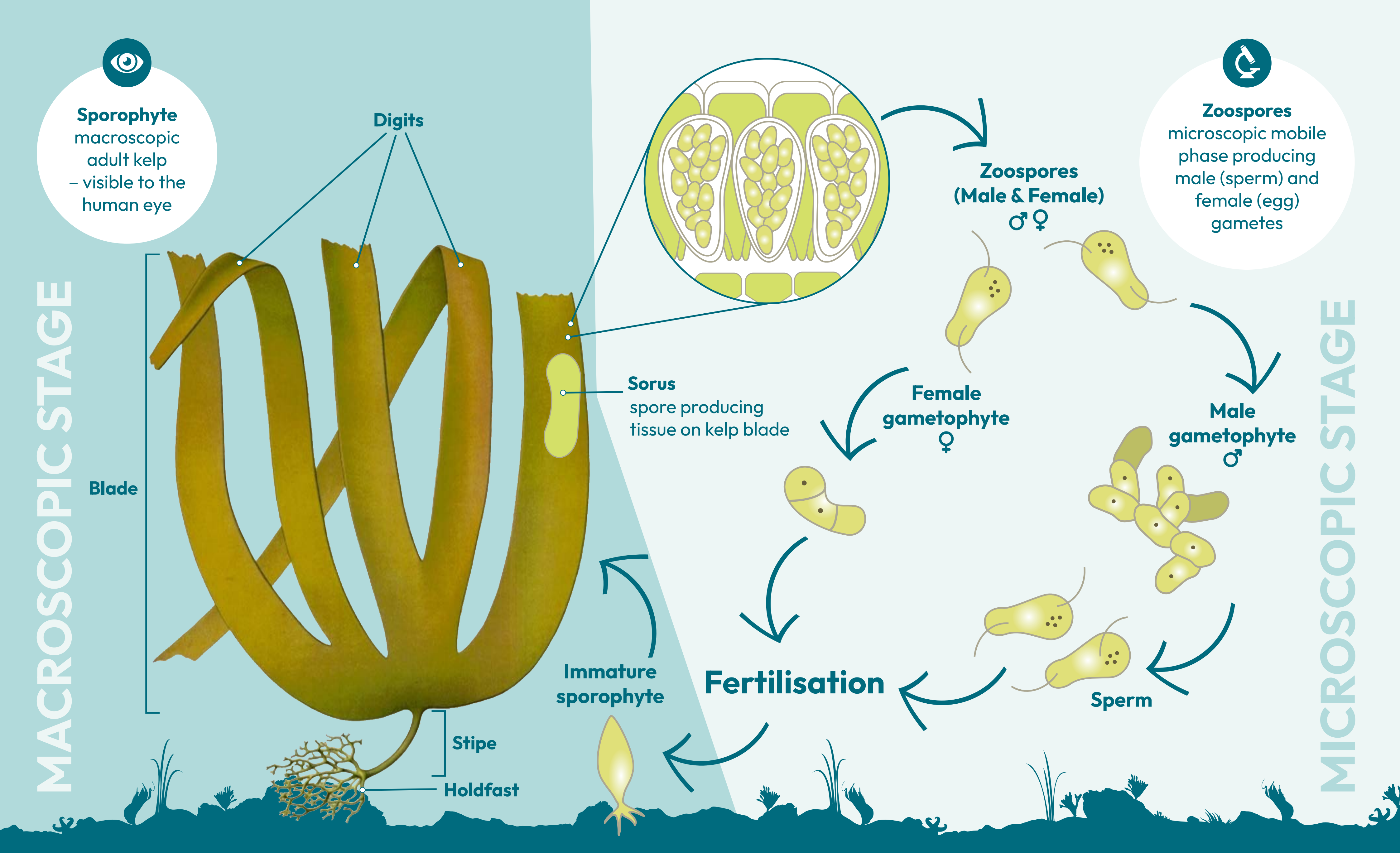
UK KELP SPECIES, LIFE CYCLE AND DISTRIBUTION

The UK is home to seven of the 13 species of kelp found in European waters: *A. esculenta*, *L. digitata*, *L. hyperborea*, *L. ochroleuca*, *S. latissima*, *U. pinnatifida*, and *Saccorhiza polyschides* (although the latter is not a 'true' kelp of the order *Laminariales*) (Birkett *et al.* 1998).

UK kelp species have two different phases in their lifecycle (Figure 4), the one we are most familiar with is the macroscopic adult **sporophyte** phase (that can be seen by the human eye) which reproduces asexually by releasing millions of tiny spores. These spores are released from **sori** that form either on the vegetative blade of the kelp, on **sporophylls**, or occasionally on the stipe and holdfast depending on the kelp species (Akita *et al.* 2016). These spores can move over relatively short distances and eventually settle and attach themselves to a suitable rocky seafloor or hard artificial structures.

Here, the spores develop into microscopic **gametophytes** (whose size is measured in micrometres - on the same scale as the width of human hair) that are either male or female. The male and female gametophytes produce sperm and eggs that reproduce sexually by binding together and developing into a sporophyte. The sporophyte eventually matures and the cycle is complete. The location of spore release on the kelp and the timing of reproduction, however, varies across the different kelp species (Table 1), as does their distribution and physical appearance.

The next section provides a description of each kelp species found in the UK based on information provided in Birkett *et al.* (1998), Smale *et al.* (2013), Burrows *et al.* (2014) and the corresponding species pages on The Marine Life Information Network (MarLIN: www.marlin.ac.uk). Information on one other macroalgae, *S. polyschides*, is also included given that it is common in the UK and can form large canopies similar to kelp forests that have similar ecological roles.



Kelp Life Cycle

Figure 4: The lifecycle of a Laminarian kelp.
Source: Sussex Kelp Recovery Project/Blue Marine Foundation 2023.

Alaria esculenta Dabberlocks / winged kelp

Common names: Dabberlocks / winged kelp

IUCN national Red List status (2021): Endangered (A2c)

Structural features: *A. esculenta* is a relatively distinct kelp species, characterised by a small holdfast, a short stipe, and a long, flexible blade between 30 cm – 1.5 m in length. The blade has a prominent midrib, similar to that on the leaf of a terrestrial plant, although at times, the blade may be worn away, leaving only the midrib.

Lifecycle: Adult individuals have flat, finger-like structures that grow on the stipe during winter-spring (October – May). These structures are known as sporophylls which contain the reproductive tissue where spores are produced.

Lifespan: *A. esculenta* is a perennial species that typically lives for 4-10 years. Growth is usually greatest in spring.

Range: *A. esculenta* is considered an Arctic cold-temperate species. Globally, it is found in the North Atlantic from Iceland to Novaya Zemlya (Russia) and south to Brittany, as well as from Greenland to the Bering Strait. It can also be found in the Bering Sea and Sea of Japan in the North Pacific. Around the coast of the UK, it is found from the Shetland Islands, along the western coast of the UK to the south-west coast of England, and along the east coast of the UK to Flamborough Head (Figure 5). Although populations of *A. esculenta* have declined along the south-west coast of England (Mieszkowska *et al*. 2006).

Habitat preference: It is most common on exposed shores from the low tide line to depths of approximately 8 m, although it has been reported at depths in excess of 40 m in Rockall (Scotland). However, it may also be present on less-exposed shores although it is usually outcompeted by other kelp species.

Alaria esculenta Dabberlocks / winged kelp

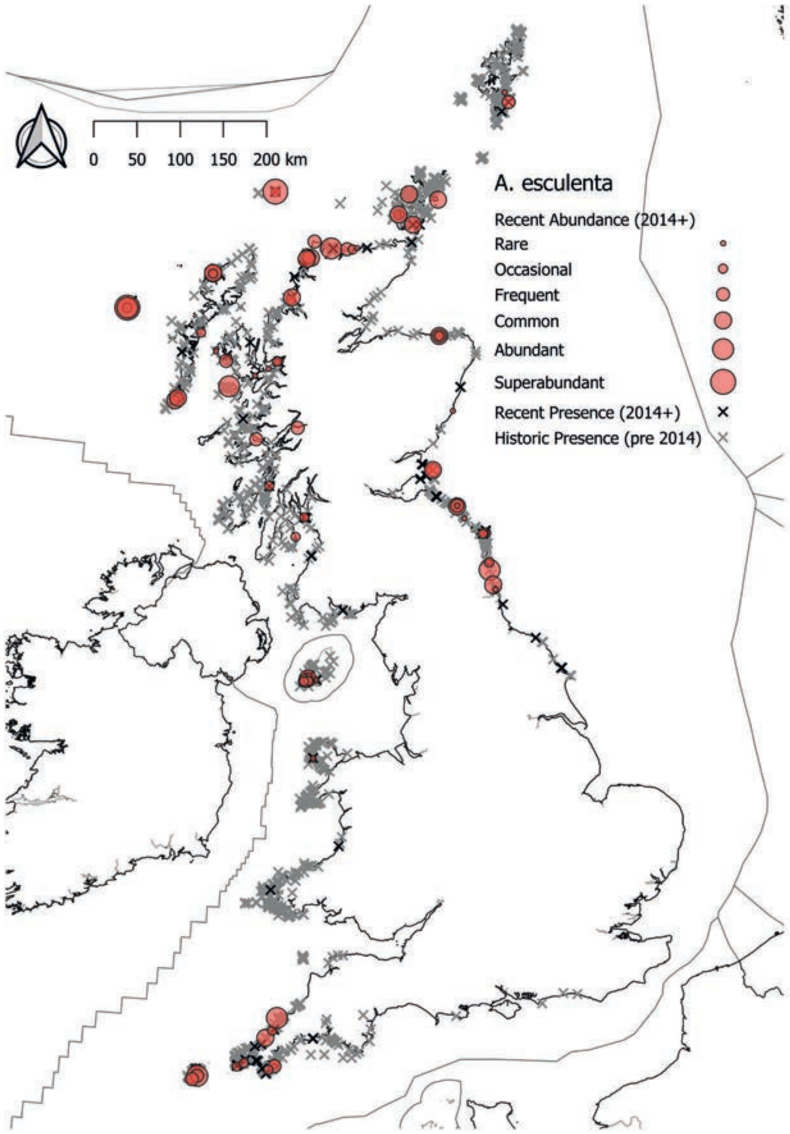


Figure 5:. *Alaria esculenta* historical and recent distribution around the UK. Historical records (grey X) span from 1788 to 2014. Recent records (2014–2020) are displayed using the Marine Nature Conservation Review (MNCR) SACFOR abundance scale: Rare = 1–5% cover, Occasional = 5–9% cover, Frequent = 10–19% cover, Common = 20–39% cover, Abundant = 40–79% cover, and Super-abundant = >80% cover. Recent records since 2014 without MNCR abundance data are shown as a black X. Source: Data compiled from multiple sources as used in the red list assessment of British seaweeds (Brodie *et al*, 2023).

Laminaria digitata — Oarweed

Common name: Oarweed

IUCN national Red List status (2021):
Vulnerable (A2b)

Structural features: *L. digitata* has a dome-shaped holdfast from which a flexible stipe that is oval in cross-section emerges. The stipe is smooth, does not snap easily, and red seaweeds do not usually grow on the stipe. The blade is dark brown in colour, flat, thick, and leathery to touch, lacks a mid-rib, and usually splits into 5-12 strap-like fingers or digits. The number and length of the digits varies with environmental conditions, with fewer, shorter digits often found on individuals in sheltered locations.

Lifecycle: Reproductive tissue called sori from which spores are released, appear on the blades year-round with a peak in July-August and November-December. Young sporophytes can be seen year-round but are most common in spring. These young individuals are easily confused with younger individuals of *L. hyperborea*.

Lifespan: *L. digitata* is perennial and can live for 4-10 years and reach a length of 2-4 m, although in some regions, for example south-eastern England, they are commonly much smaller (Yesson, personal communication). Growth is greatest between February to July and is on average approximately 1.3 cm per day. A new blade grows below the old blade from around November-time, resulting in a distinct collar region between the old and new blades (Figure 6) until the old blade is shed in spring.

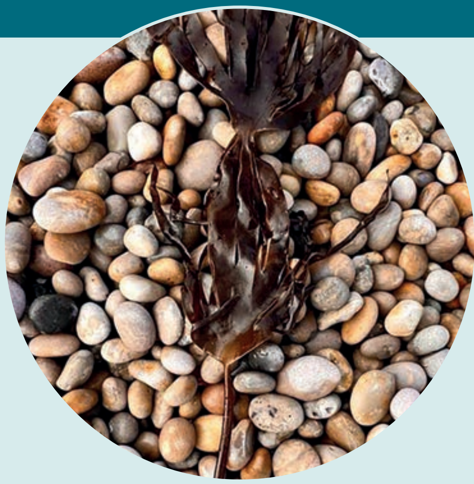


Figure 6: *L. digitata* showing collar between old and new growth.

Range: *L. digitata* is considered a North Atlantic Arctic cold-temperate species. Globally it is found along the east coast of the USA (from the Hudson Strait to New York) and Canada, southern Greenland, along the coastline of Europe to Novaya Zemlya (Russia). It is found as far south as the Canary Islands and the Black Sea. Across the UK, *L. digitata* is relatively common, but is known to be absent from Liverpool Bay, the Severn estuary and along the east coast of England between the Great Ouse and Thames estuaries due to the murky nature of the water and/or lack of suitable rocky or hard substrate (Figure 7).

Habitat preference: *L. digitata* is successful in areas that are exposed to wave action or with strong currents. In Europe, it can be observed on the low intertidal zone and is outcompeted by *L. hyperborea* in the shallow subtidal. On some coastlines, it may also be found in low-mid intertidal rockpools.

Laminaria digitata Oarweed

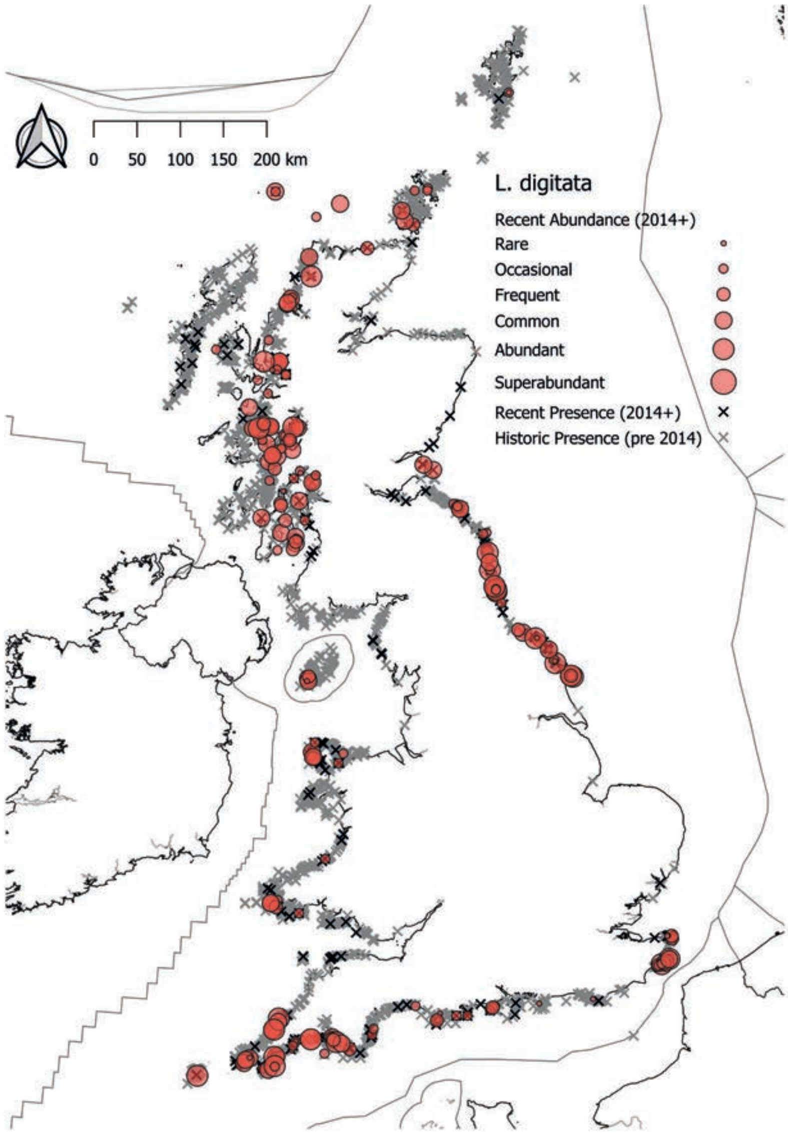


Figure 7:. *Laminaria digitata* historical and recent distribution around the UK. Historical records (grey X) span from 1788 to 2014. Recent records (2014–2020) are displayed using the Marine Nature Conservation Review (MNCR) SACFOR abundance scale: Rare = 1–5% cover, Occasional = 5–9% cover, Frequent = 10–19% cover, Common = 20–39% cover, Abundant = 40–79% cover, and Super-abundant = >80% cover. Recent records since 2014 without MNCR abundance data are shown as a black X. Source: Data compiled from multiple sources as used in the red list assessment of British seaweeds (Brodie *et al*, 2023).

Laminaria hyperborea — Tangle / cuvie / forest kelp

Common name: Tangle / cuvie / forest kelp

IUCN national Red List status (2021):
Near Threatened (A2b)

Structural features: *L. hyperborea* has a large, conical holdfast that has many intertwined branching **haptera** (finger-like structures) (Figure 8). The stipe is stiff and rigid, standing erect when out of the water. It is also circular in cross section and snaps when bent. The rough texture of the stipe means it is often has small seaweeds and animals growing on it. The blade is golden brown to dark brown in colour, broad, flat, thick, and leathery to touch, lacks a mid-rib, and usually splits into 5-20 strap-like fingers or digits. The number and length of the digits varies with environmental conditions, with fewer, shorter digits often found on individuals in sheltered locations. In exposed locations, the stipe is generally thicker.

Lifecycle: The reproductive sori from which spores are released appear on the blades over a 6-7 week period in winter, with young sporophytes most commonly observed in spring.

Lifespan: *L. hyperborea* is a perennial species that can live for 5-20 years and reach a length of up to 3.5 m. Growth is generally greatest in winter and is approximately 1 cm per day.

Figure 8: *L. hyperborea* holdfast close up.

Range: *L. hyperborea* is considered a European North Atlantic cold-temperate species. Globally it is found from Iceland to Russia (near Murmansk), south to mid-Portugal and as far north as Norway and the Faroe Islands. It is notably absent from the Bay of Biscay. Around the UK, it is found on the majority of coasts but is scarce along the south-east coast of England due to a lack of suitable hard substrate (Figure 9).

Habitat preference: *L. hyperborea* can be seen from the extreme low water mark down to ~40 m depth depending on light availability, but most commonly forms forests at depths of 10-20 m. It inhabits moderately exposed to exposed coasts and is generally not found in sheltered areas.

Laminaria hyperborea — Tangle / cuvie / forest kelp

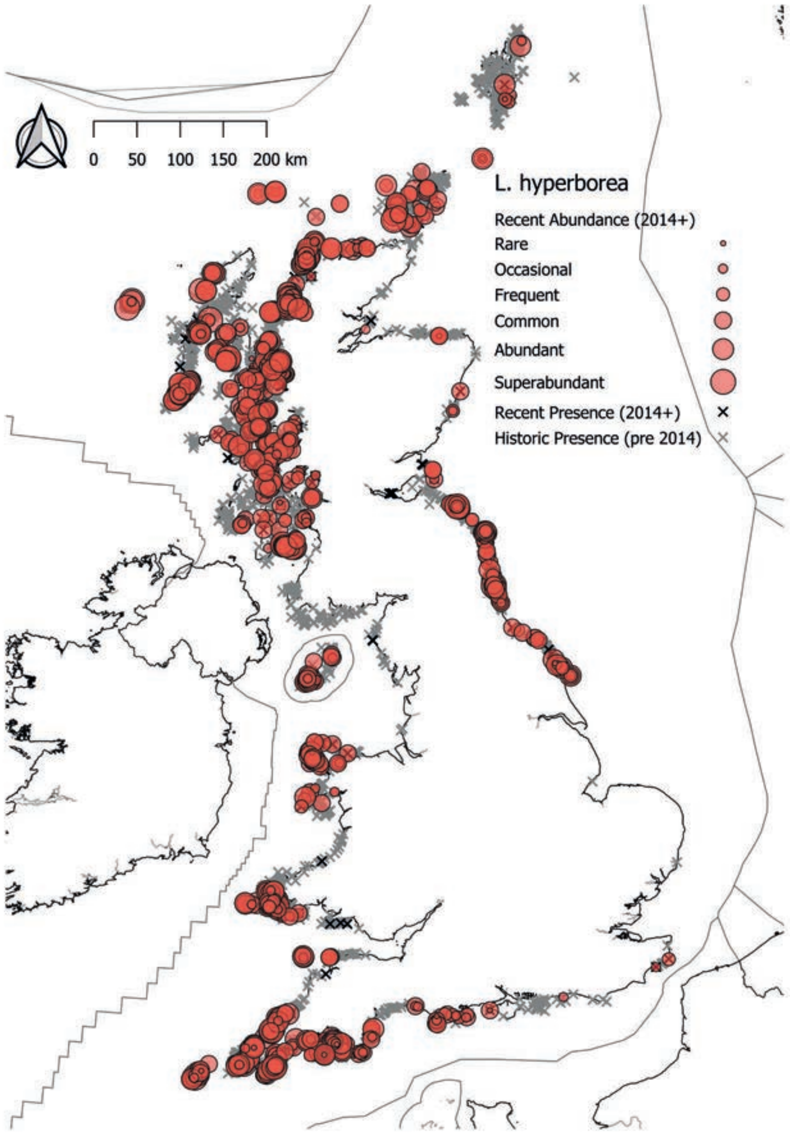


Figure 9: *Laminaria hyperborea* historical and recent distribution around the UK. Historical records (grey X) span from 1788 to 2014. Recent records (2014–2020) are displayed using the Marine Nature Conservation Review (MNCR) SACFOR abundance scale: Rare = 1–5% cover, Occasional = 5–9% cover, Frequent = 10–19% cover, Common = 20–39% cover, Abundant = 40–79% cover, and Super-abundant = >80% cover. Recent records since 2014 without MNCR abundance data are shown as a black X. Source: Data compiled from multiple sources as used in the red list assessment of British seaweeds (Brodie *et al*, 2023).

Laminaria ochroleuca — Golden kelp

Common name: Golden kelp

IUCN national Red List status (2021): Near Threatened (A2c)

Structural features: *L. ochroleuca* is similar in appearance to *L. hyperborea* but can be distinguished by a distinct yellow halo at the junction between the stipe and blade. Its stipe is relatively smooth and red seaweeds do not grow on it.

Lifecycle: *L. ochroleuca* exhibits continuous growth throughout the year with peak growth at the beginning of summer (Pessarrodona *et al.* 2019). Little is known about its reproduction around the UK, although in Portugal the reproductive season lasts from April-May to November-December.

Lifespan: *L. ochroleuca* is a perennial species that can reach up to 1.5 m in length (John 1969).

Range: *L. ochroleuca* is considered a warm-temperate Lusitanian species. Globally, it is found in the northeast Atlantic and the Mediterranean (Franco *et al.* 2018). Since 1940, it has been found on the south coast of England including Lundy Island, the Isles of Scilly and coasts of Devon and Cornwall (Figure 10). This extension in its distribution is believed to represent a slow northward expansion of warmer seawater. More recently, a small population has been observed on the coastline of Belmullet in western Ireland (Schoenrock *et al.* 2019), however the origins of this population are unknown.

Habitat preference: In the UK, *L. ochroleuca* is often found in mixed beds with *L. hyperborea*, however it is not believed to offer the same type of habitat and ecosystem services as *L. hyperborea* (Smale and Vance 2016; Teagle and Smale 2018). In the Isles of Scilly, a stand of *L. ochroleuca* has been found at 25 m depth (Smirthwaite 2007).

Laminaria ochroleuca Golden kelp

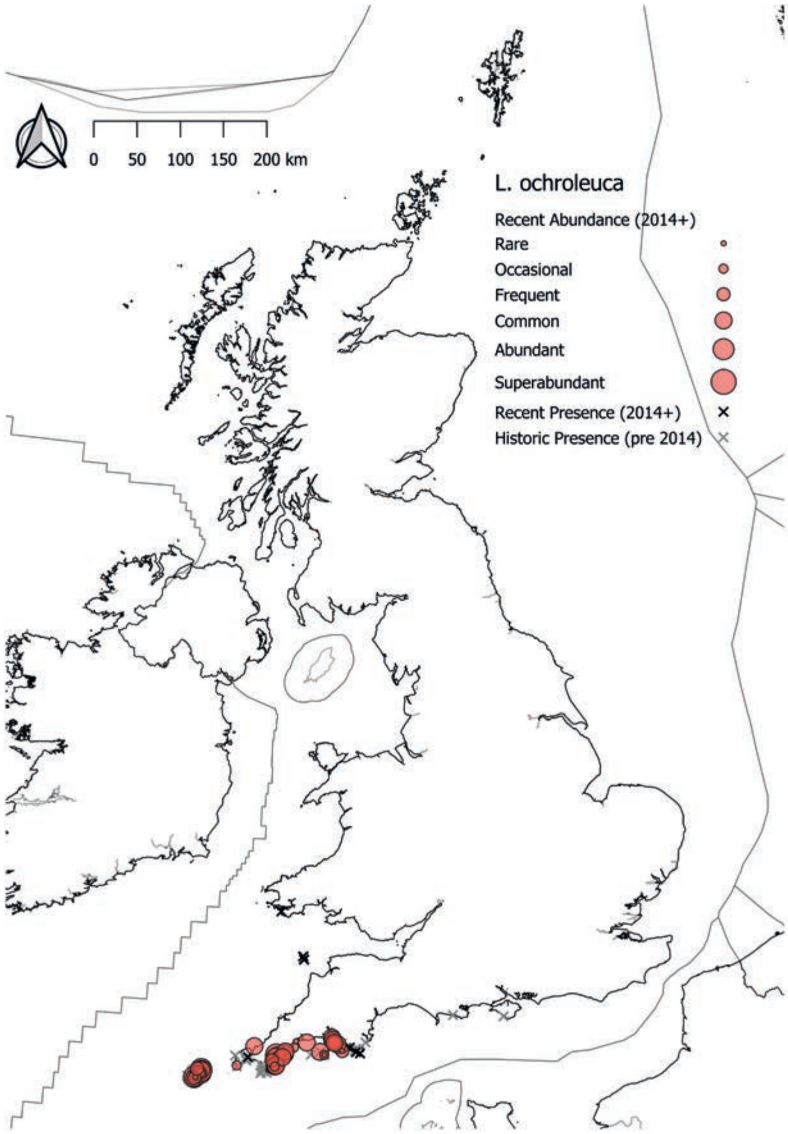


Figure 10: *Laminaria ochroleuca* historical and recent distribution around the UK. Historical records (grey X) span from 1788 to 2014. Recent records (2014–2020) are displayed using the Marine Nature Conservation Review (MNCR) SACFOR abundance scale: Rare = 1–5% cover, Occasional = 5–9% cover, Frequent = 10–19% cover, Common = 20–39% cover, Abundant = 40–79% cover, and Super-abundant = >80% cover. Recent records since 2014 without MNCR abundance data are shown as a black X. Source: Data compiled from multiple sources as used in the red list assessment of British seaweeds (Brodie *et al*, 2023).

Saccharina latissima — Sugar kelp / sea belt

Common name: Sugar kelp / sea belt

IUCN national Red List status (2021):
Near Threatened (A2b)

Structural features: *S. latissima* is a large kelp that is characterised by a single, undivided, golden-coloured blade that lacks a midrib and has a wrinkled surface and frilly margin. It has a short, flexible stipe that is not usually overgrown by other seaweeds and a small, compact holdfast. The shape of the frond and stipe can vary with environmental conditions.

Lifecycle: The reproductive sori from which spores are released appear on the blades between October-April.

Lifespan: *S. latissima* can live for 2-5 years but in some areas may also grow as an annual opportunistic species. It can reach up to 4 m in length and grows fastest from late winter to spring at approximately 1.1 cm per day, although rates of 4.8 cm per day have been recorded.

Range: *S. latissima* is considered an Arctic-cold-temperate species. Globally it is found in the North Atlantic from the west coast of the USA to Europe and from Novaya Zemlya (Russia) in the north to northern Portugal in the south. It is also found in the North Pacific from the east coast of the USA to the Bering Strait and Japan. In the UK, it can be found on all coasts (Figure 11).

Habitat preference: *S. latissima* can occur from the low intertidal zone to depths of 30 m and occasionally in rockpools. It is more common in sheltered areas and can attach to unstable rocks.

Saccharina latissima Sugar kelp / sea belt

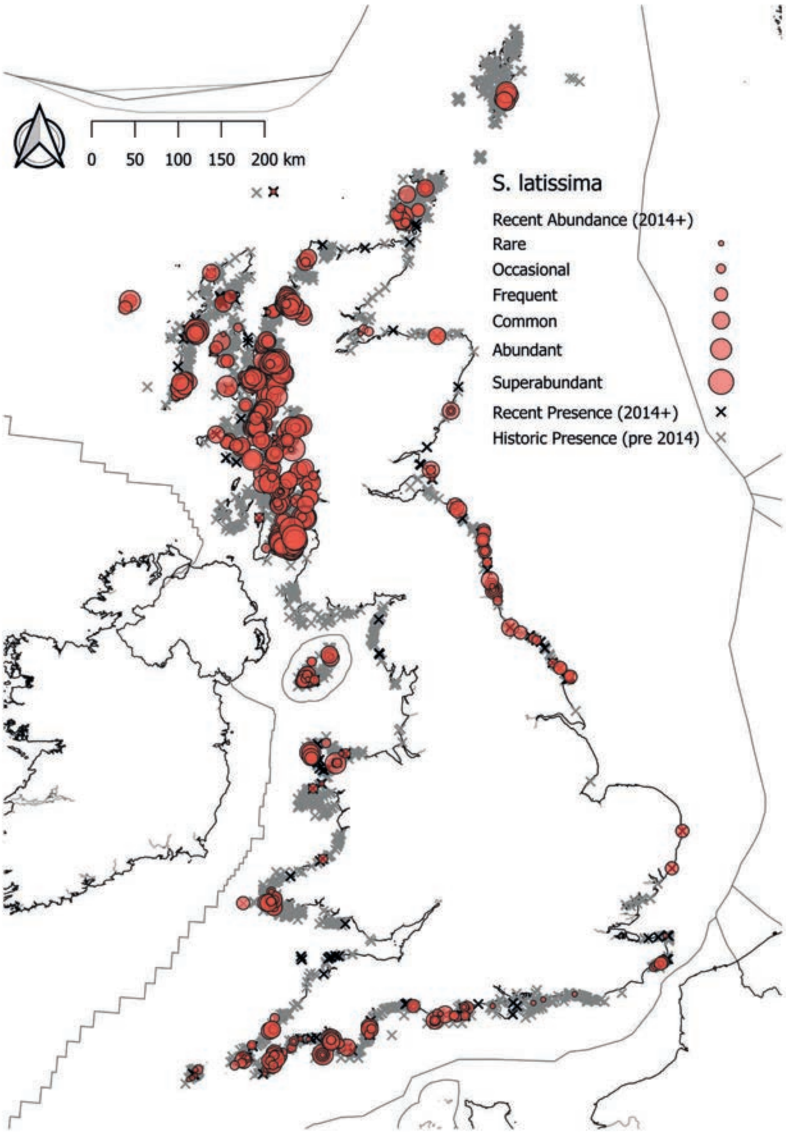


Figure 11: *Saccharina latissima* historical and recent distribution around the UK. Historical records (grey X) span from 1788 to 2014. Recent records (2014–2020) are displayed using the Marine Nature Conservation Review (MNCR) SACFOR abundance scale: Rare = 1–5% cover, Occasional = 5–9% cover, Frequent = 10–19% cover, Common = 20–39% cover, Abundant = 40–79% cover, and Super-abundant = >80% cover. Recent records since 2014 without MNCR abundance data are shown as a black X. Source: Data compiled from multiple sources as used in the red list assessment of British seaweeds (Brodie *et al*, 2023).

Saccorhiza polyschides Furbellows

Common name: Furbellows

S. polyschides is a 'pseudo-kelp' from the order Tilopteridales as opposed to a 'true kelp' from the order Laminariales. However, it is considered a kelp here because it has characteristics similar to Laminarian kelps.

IUCN national Red List status (2021):
Least Concern (A2bc; B2ab(ii))

Structural features: This species has a bulbous, warty holdfast that supports a tough, flattened stipe with frilly edges. The blades do not have a midrib and are broad, flat, and divided into digits that range from 3-30 in number.

Lifecycle: It follows a typical Laminarian kelp lifecycle whereby the base of the blades, the stipe frills and the bulbous section of the holdfast contain the sori that release spores between October to May.

Lifespan: *S. polyschides* is a fast growing, opportunistic, pseudo-annual species that can live between 12-18 months and can reach up to 4 m in length (Fernández *et al.* 2022). The peak growth season is late-spring and during this time, individuals may grow up to 6.5 cm per day.

Range: *S. polyschides* is an Atlantic species that is found from Ghana to Norway and in the Mediterranean around Greece and Italy. In the UK, it has been recorded on western coasts from south-western England to the Shetland Islands, however it is not consistently found along the east coast of the UK, although populations are found on the Farne Islands and adjacent Northumberland coast (Figure 12).

Habitat preference: *S. polyschides* is primarily found in areas that are moderately exposed or sheltered from wave action, and it is not found in areas where salinity may be reduced (e.g., near river mouths). The presence of this species has also been noted in 'mixed' habitats, comprised of bedrock, boulders, and sand, suggesting that it may be able to colonise and survive in sandier areas than true kelp species. *S. polyschides* competes with *L. hyperborea* for space and is often found below the zone of *L. hyperborea*, but it can be observed between the low tide line to depths of 35m.

Saccorhiza polyschides Furbellows

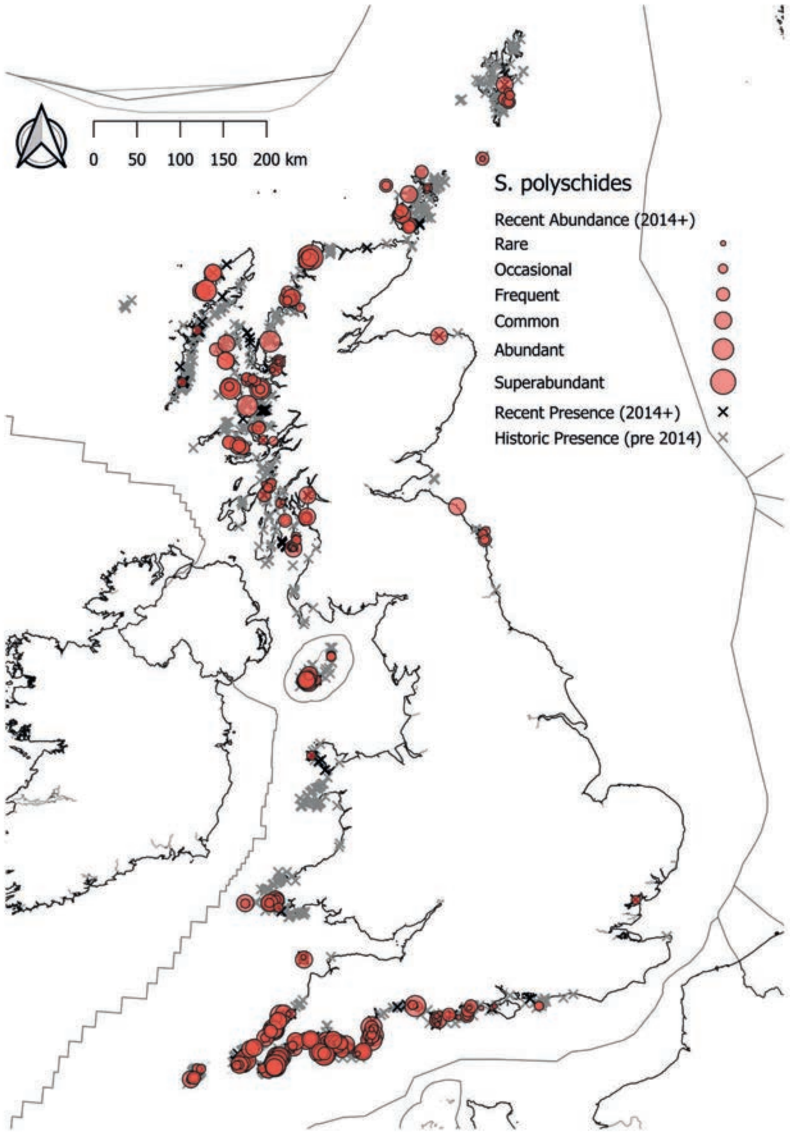


Figure 12: *Saccorhiza polyschides* historical and recent distribution around the UK. Historical records (grey X) span from 1788 to 2014. Recent records (2014–2020) are displayed using the Marine Nature Conservation Review (MNCR) SACFOR abundance scale: Rare = 1–5% cover, Occasional = 5–9% cover, Frequent = 10–19% cover, Common = 20–39% cover, Abundant = 40–79% cover, and Super-abundant = >80% cover. Recent records since 2014 without MNCR abundance data are shown as a black X. Source: Data compiled from multiple sources as used in the red list assessment of British seaweeds (Brodie *et al*, 2023).

Undaria pinnatifida Wakame

Common name: Wakame

IUCN national Red List status (2021):
Not Evaluated (Non-native species).

Structural features: *U. pinnatifida* has a branching holdfast and a short stipe of approximately 10-30 cm that has a wavy/corrugated appearance, especially near the holdfast (this can be used to distinguish it from *A. esculenta*). The blade has a distinct midrib and is broad, flat, brown in colour and tapers to a point. In older plants, the blade tissue can split horizontally to the midrib to form strap-like structures.

Lifecycle: Adult individuals develop reproductive structures known as sporophylls on their stipe, primarily in autumn. These structures contain the sori.

Lifespan: *U. pinnatifida* is an annual species, and individuals can reach a length of 3 m.

Range: *U. pinnatifida* is not a native UK kelp species and was first recorded in 1994 (Farrell and Fletcher 2000). This species is native to the northwest Pacific (China, Japan, Korea) and was brought to Europe accidentally through the movement of shellfish and on the hulls of boats, as well as deliberately for aquaculture purposes. In Europe it can be found along the west coast of Spain, the French Mediterranean and Brittany. In the UK it is found on the southwest coast of England, as far east as the Isle of Wight, to the Isle of Wight, as well as in ports in Milford Haven and Anglesey (Wales), Belfast (Northern Ireland), Glasgow and Edinburgh (Scotland) (Figure 13).

Habitat preference: In its native habitat, *U. pinnatifida* forms dense stands at depths of up to 15m, however in the UK, it is primarily found on man-made structures such as pontoons, although it has colonised natural reef in some areas of southwest England where it more commonly settles on vertical substrates, which native kelps do not (Heiser *et al.* 2014).

Undaria pinnatifida Wakame

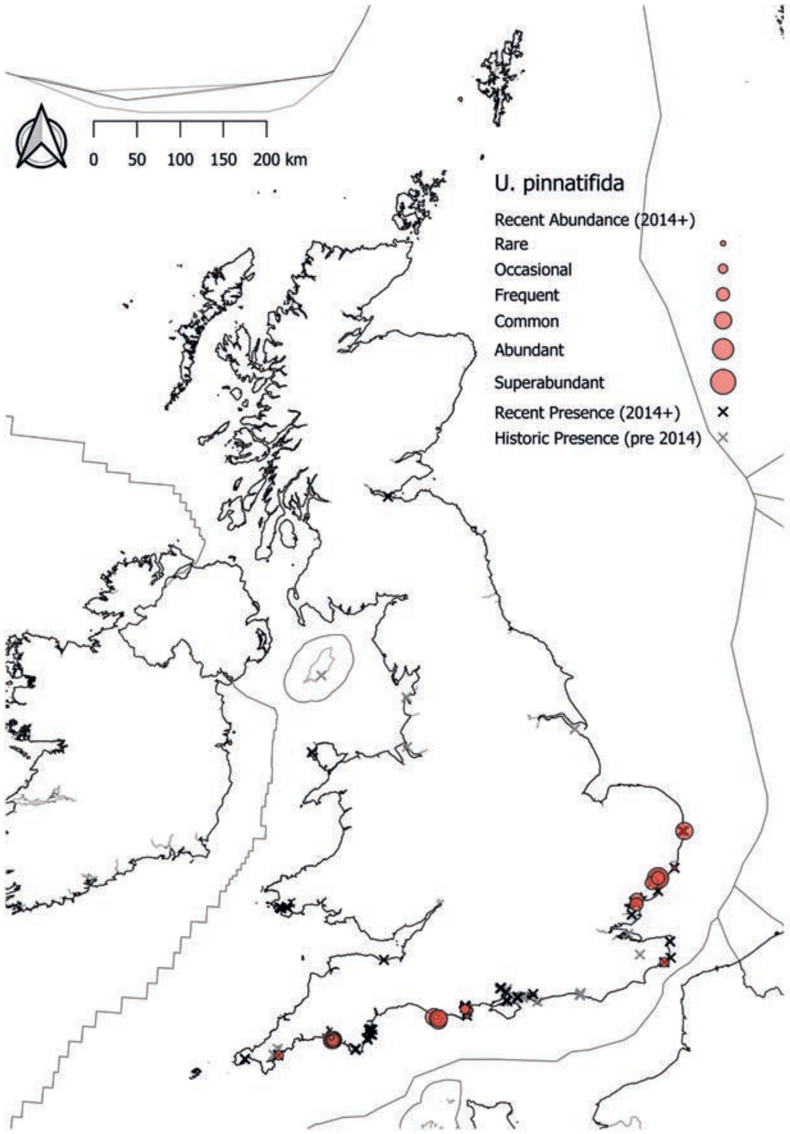


Figure 13: *Undaria pinnatifida* historical and recent distribution around the UK. Historical records (grey X) span from 1788 to 2014. Recent records (2014–2020) are displayed using the Marine Nature Conservation Review (MNCR) SACFOR abundance scale: Rare = 1–5% cover, Occasional = 5–9% cover, Frequent = 10–19% cover, Common = 20–39% cover, Abundant = 40–79% cover, and Super-abundant = >80% cover. Recent records since 2014 without MNCR abundance data are shown as a black X. Source: Data compiled from multiple sources as used in the red list assessment of British seaweeds (Brodie *et al*, 2023).

Photos: © M D Guiry seaweed.ie
Source ref: Smale et al. 2013 and Algaetraits 2022
Lengths typical for Sussex/Depth ranges for N Atlantic.

Figure 14: Fact file and key identification features for kelp species that are known to occur in Sussex waters.
Source: Sussex Kelp Recovery Project/Blue Marine Foundation 2023.

Species	Spore production	Location of reproductive tissue	Young sporophytes appear	Maximum growth period	Age to fertility	Life expectancy
Alaria esculenta *Order: Laminariales*	October-May	Sporophylls on the upper stipe, towards the base of the blade.	Early spring	Spring	8 - 14 months	Perennial 4 - 10 years
Laminaria digitata *Order: Laminariales*	Year round with peaks in July - August and November - December	Sori on the blade	Year round with peaks in spring and autumn	February - July	18 - 20 months	Perennial 4 - 10 years
Laminaria hyperborea *Order: Laminariales*	Between September-April but with a peak in January	Sori on the blade	Year round with a peak in spring	November - June	2 - 6 years	Perennial 5-20 years
Laminaria ochroleuca *Order: Laminariales*	Unknown in UK	Unknown in UK	Unknown in UK	Throughout the year with a peak at the beginning of summer	Unknown in UK	Perennial Unknown in UK
Saccharina latissima *Order: Laminariales*	October - April	Sori on the blade	Winter – spring	Late winter – spring	8 - 20 months	Perennial or annual 2 - 5 years
Saccorhiza polyschides *Order: Tilopteridales*	October - May with a peak in March	Sori on the base of the blade, the stipe frills, and the holdfast bulb	Spring-summer but can be year-round	Late spring	8 - 22 months	Annual 8 - 16 months
Undaria pinnatifida *Order: Laminariales*	Spring – summer	Sporophylls on the stipe	Year round but mainly autumn	Unknown in UK	8 - 10 months	Annual 10 - 14 months

Table 1: Key growth and reproductive information for UK kelp and other similar canopy-forming macroalgae. Information represents the broadest range and is based on Birkett *et al.* (1998), Pessarrodona *et al.* (2018), and the corresponding species pages on The Marine Life Information Network (MarLIN: www.marlin.ac.uk).

ECOSYSTEM SERVICE VALUE OF UK KELP SPECIES

Ecosystem services is a term used to describe a varied collection of benefits natural ecosystems such as kelp habitats provide to humans. These services are divided up into four broad groups:

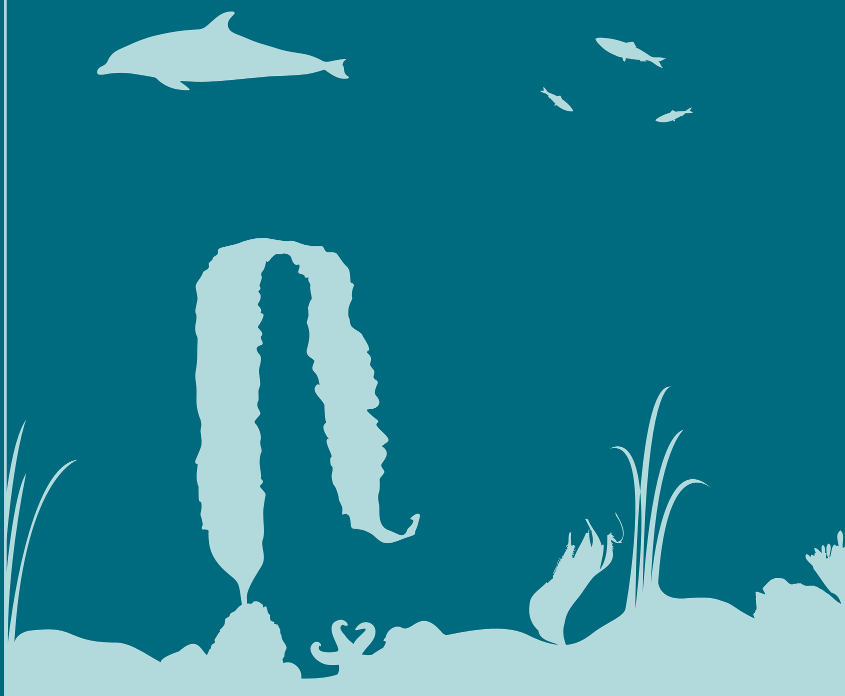
Provisioning services – these are products that people can take from the ecosystems, for example food, fuel, and materials.

Regulating services – these are processes that occur within the ecosystem that benefit people, such as climate regulation, carbon storage and protection from storms.

Cultural services – these are non-material ways in which ecosystems can benefit people's health and wellbeing, for example through recreation and education.

Supporting services – these are the basic natural processes that take place in an ecosystem in order to sustain life, for example photosynthesis, nutrient and water cycling. Without supporting services, we would not have provisioning, regulating and cultural services.

Kelp habitats provide a range of ecosystem services, including primary production, shelter, foraging and breeding/nursery areas for an array of marine species (Figure 15), protecting the coast from storms and erosion, storing carbon, and providing jobs through activities such as tourism (Figure 16).



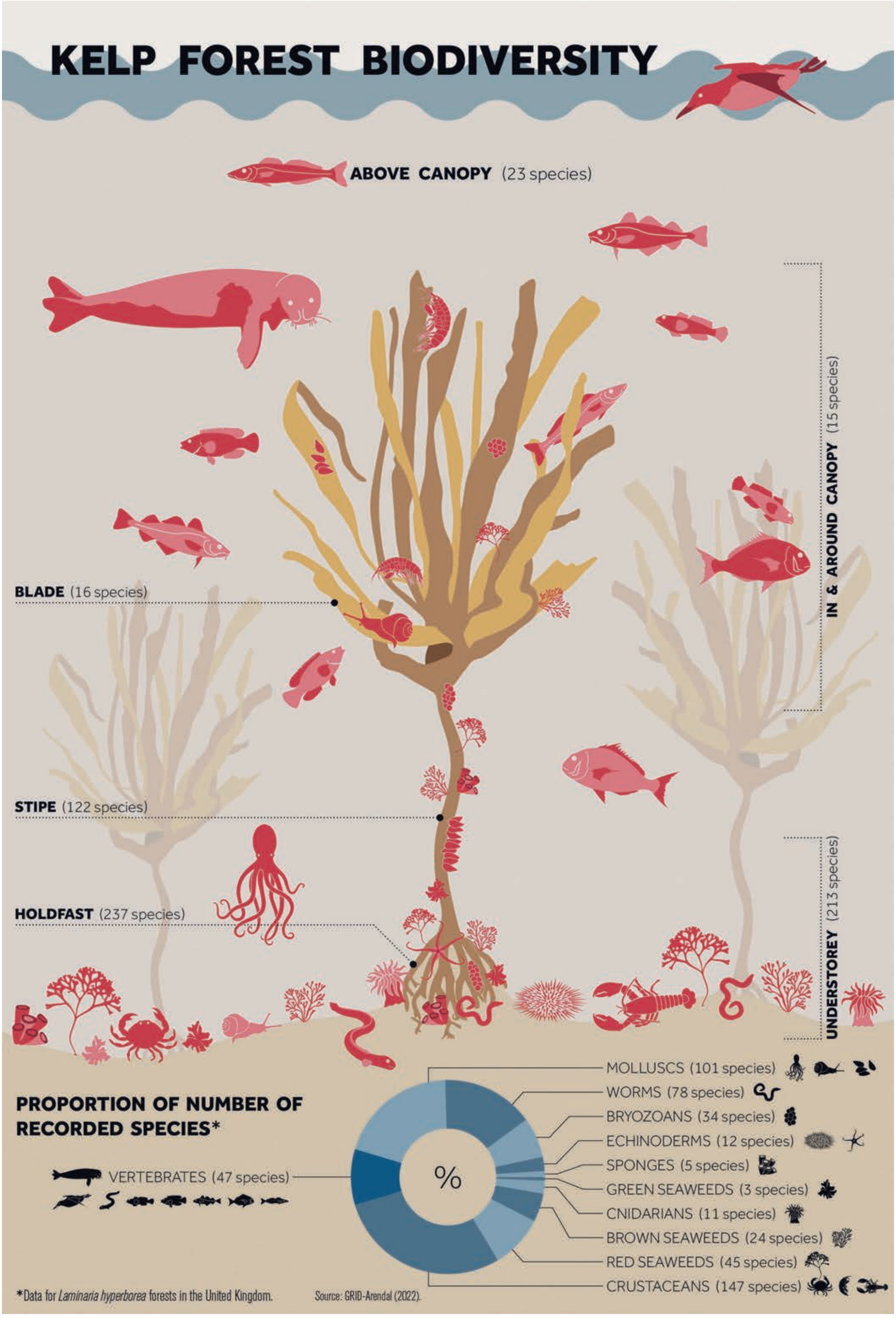


Figure 15: Example of the biodiversity value of the United Kingdom's kelp forests.
Source: UNEP (2023)/GRID-Arendal, Norway.

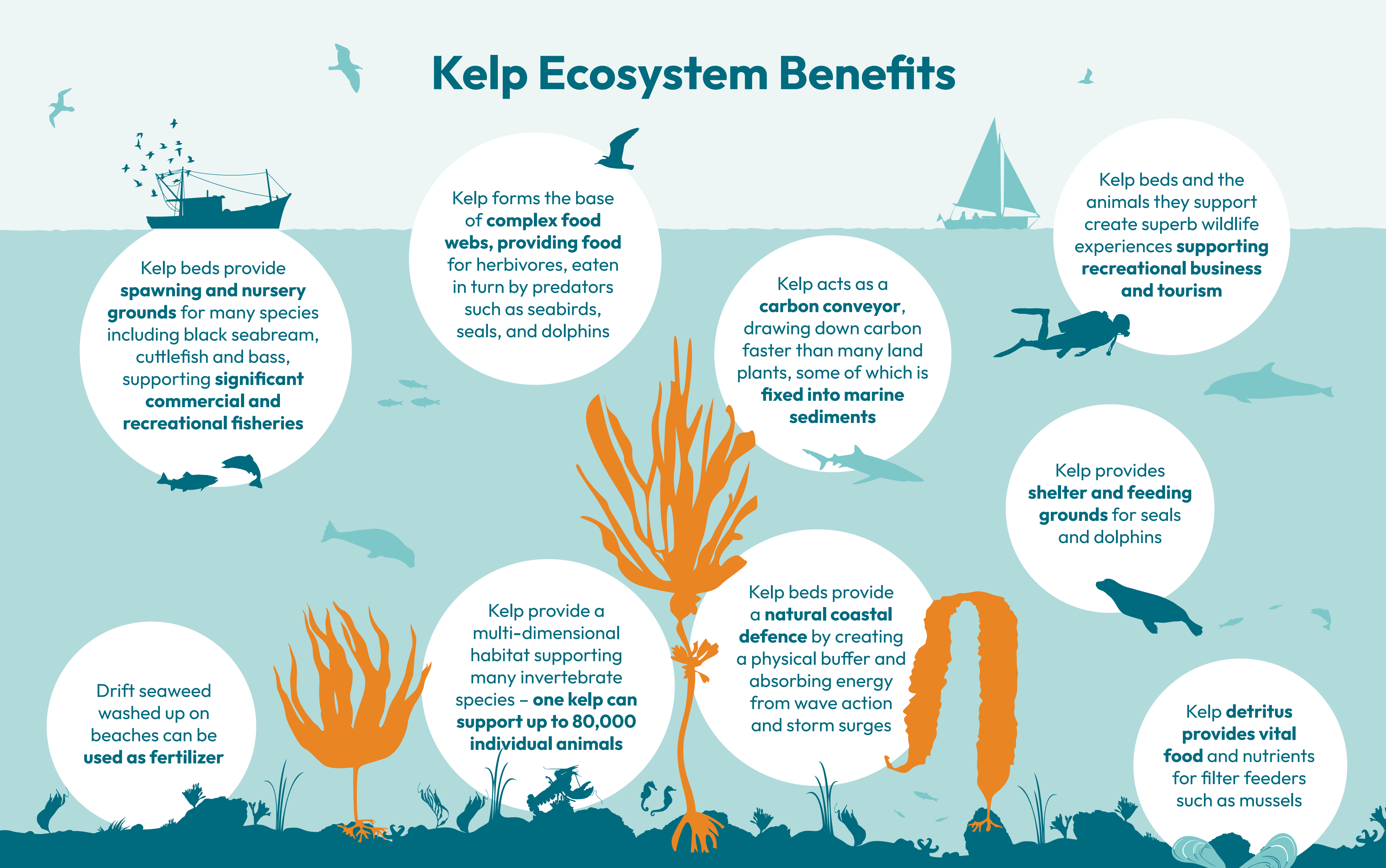


Figure 16: Key ecosystem services provided by kelp in the UK.
Source: Sussex Kelp Recovery Project/Blue Marine Foundation

Fish nursery and essential fish habitats

Kelp are ecosystem-engineers that form an intricate, three-dimensional habitat that alters local environmental conditions including the availability of light, the movement of seawater and sediments, and the availability of nutrients. This unique environment enables other species of flora and fauna to thrive.

Firstly, the kelp themselves provide shelter and a nursery environment for thousands of creatures, many of which are important for food-webs and fisheries. The small gaps within the kelp holdfast are a home for thousands of tiny organisms such as worms, snails, and starfish. Other species, including sea mats, sea squirts and some red seaweeds live on the kelp stipe and blades. These species, particularly red seaweeds attached to the kelp stipe, provide shelter for other small organisms. In the UK, scientists have discovered over 260 different species living in the holdfasts of *L. hyperborea* (Teagle *et al.* 2018) and over 130 different species associated with *L. hyperborea* stipes (King *et al.* 2021), while the number of individuals per kelp can be over 80,000 for this species (Christie *et al.* 2003) (UNEP 2023). However, the number of organisms associated with an individual kelp depends on factors including the season, local environmental conditions, as well as the kelp species and its age, with older, more structurally complex kelp and/or kelp forests likely to host a greater number of individuals (Anderson *et al.* 2005; Christie *et al.* 1998).

In some areas, a layer of small, often red seaweeds, forms on the seafloor between individual kelp which is similar to the small understorey plants and grasses that grow in a forest on land. These understorey seaweeds provide an additional living space as well as a source of food for many animals. Recent research has found almost 180 species living in understorey seaweeds beneath *L. hyperborea* forests in the UK (Earp *et al.* 2024b). Kelp forests are also a home for larger creatures including sea urchins, crabs, and lobsters, some of which, for example the European lobster (*Homarus gammarus*) are highly prized by fishers (Smale *et al.* 2022).

Some species, including some squid and sharks use kelp forests as breeding grounds, attaching their eggs to kelp stipes and holdfasts (Rosenfeld *et al.* 2014). While some fishes, such as Atlantic cod (*Gadus morhua*) and pollock use kelp forests as a nursery ground (Jackson-Bué *et al.* 2023).

Other fishes feed within kelp forests, for example several wrasse species feed on the small organisms that live within the kelp forest (Norderhaug *et al.* 2005), and in turn, they attract larger fish-eating species such as conger eels (*Conger conger*), birds, otters, and seals. Many of the fish found within kelp forests, including cod, pollock, seabream and European sea bass (*Dicentrarchus labrax*), are also valuable and targeted by commercial and recreational fishers.

Food provision for fishery resources

Kelp is highly productive, with the Giant Kelp, *Macrocystis pyrifera*, that grows along the Pacific coast of the Americas and along the coastline of South Africa and southern Australia, believed to be one of the fastest growing organisms on Earth – growing up to 60 cm a day and reaching up to 65 m in length. As such, kelp forests are considered one of the most productive ecosystems on Earth (Steneck *et al.* 2002). Globally, the primary production of brown seaweeds on rocky areas is estimated to be around 900 million tonnes of carbon per year (the weight of 6 million blue whales!) and rivals that of ecosystems on land (Duarte *et al.* 2022). In UK coastal waters, it is estimated that kelp ecosystems may be responsible for at least 45% of primary production (Smale *et al.* 2013).

Some of this primary production (i.e. kelp material), is eaten by creatures that live within the kelp habitat, such as the blue-rayed limpet (*Patella pelluicida*). However, a large quantity of kelp material is lost when the kelp dies back, damaged, or removed by wave action. This material is called 'detritus' and it is very important in marine food-webs. Some detritus remains within the kelp habitat, but it is estimated that 80% leaves the kelp areas and can either be washed-up on the shoreline, transported to other ecosystems, or carried out into deeper waters, with reports of kelp detritus being found at 420 m in a Norwegian fjord (Filbee-Dexter *et al.* 2018). Wherever it ends up, the kelp material can be either broken down by microscopic organisms releasing important nutrients into the ecosystem, or it is eaten by small creatures. For example in Chile, kelp detritus forms almost 70% of the food eaten by the sea urchin, *Tetrapygus niger* (Rodríguez 2003). The creatures that feed on kelp detritus release nutrients back into the ecosystem when they excrete, but are also considered food by larger creatures, and form an important link in coastal nutrient cycles and food-webs.

Commercial harvest

Kelp is harvested around the world, both commercially and artisanally, for a wide range of purposes including: as food for both humans and animals (Buschmann *et al.* 2008; Wernberg *et al.* 2019), as a fertiliser (Craigie 2011; Epstein *et al.* 2021), for extracting components such as alginates that are used in the food and pharmaceutical industries (Vásquez *et al.* 2014a), and potentially as a biofuel (Kraan 2013). In some countries, kelp is harvested at an industrial-scale, for example up to 300,000 dry tonnes of wild kelp (valued at over US$ 70 million) can be landed each year in Chile which represents almost 40% of the global brown seaweed harvest (Gouraguine *et al.* 2021; Lotze *et al.* 2019; Vásquez *et al.* 2014a). In the UK, kelp along with other brown seaweeds, were historically harvested and burned to produce soda ash that was used in glass, for making soap, for bleaching linen, for the extraction of iodine, and to produce gelling agents known as 'hydrocolloids' (Capuzzo 2022). Although the UK's seaweed harvesting industry (both red and brown species) is smaller than other neighbouring countries (such as France and Norway), over the last decade, it has grown considerably and now includes both wild-harvested and farmed kelp, of which *L. digitata* and *S. latissima* are among the most commonly targeted species. There are currently no records of how much kelp is harvested in the UK each year, however with the demand for seaweed-products expected to increase in the future, kelp production and harvesting will likely also increase (Capuzzo 2022; Smale *et al.* 2013). While there is some evidence to suggest that the rapid recruitment and growth of some kelp species can allow for sustainable, large-scale harvesting, the potential impact on other kelp-associated services, for example fisheries, may be significant.

Nutrient cycling and water quality maintenance

Kelp absorb nutrients including nitrogen and phosphorous from seawater in order to grow. In coastal areas where human activities have resulted in an increase in the concentration of nutrients in seawater, kelp represent an important and natural means of removing some of these nutrients and preventing eutrophication and/or the development of harmful algal blooms (Jiang *et al.* 2020). In the Falkland Islands, the value of nutrient cycling by kelp forests is estimated to be £2.4 billion per year (Bayley *et al.* 2021), while nutrient cycling by kelp forests along Australia's southern coast, known as 'The Great Southern Reef' which supports forests of giant kelp (*Macrocystis sp.*) and spiny/leather kelp (*Ecklonia radiata*), has an estimated value of over £80 billion per year (Bennett *et al.* 2016). Due to the efficiency of kelp in removing nutrients from seawater and thus improving water quality, many fish-farms and aquaculture facilities include kelp within their systems. For example, in the Bay of Fundy (Canada), waste nutrients from salmon aquaculture are removed from the seawater by mussels and kelp (*S. latissima* and *A. esculenta*) which are then also sold commercially (Reid *et al.* 2011). However, it is important to note that if the concentration of nutrients in seawater is considerable, it can result in a decline in kelp and an increase in small turf algae (Filbee-Dexter and Wernberg 2018).

Carbon sequestration and transfer

More recently, kelp habitats have been suggested to help reduce the impact of climate change (Figure 17). During photosynthesis, kelp absorb the greenhouse gas carbon dioxide (CO_2) and convert it into carbohydrates and sugars that support the growth of kelp tissue. Some kelp will be consumed by animals and the carbon incorporated into tissue or shell, or respired and converted back into CO_2. When kelp is eroded, damaged, removed or dies, some of this carbon-containing kelp material can be carried away from the kelp habitat and sink into the deep sea where it is locked away or '**sequestered**' in the sediment, forming what we call a '**carbon sink**'. The carbon that is stored within a marine ecosystem (including habitats such as kelp forests and the deep sea) is known as '**blue carbon**'. A coarse estimate suggests that globally, kelp habitats - along with other brown macroalgae - could together be responsible for the storage of over 173 million tonnes of carbon per year, of which approximately 90% becomes stored in the deep sea (Krause-Jensen and Duarte 2016) - this is equivalent to almost half the UK's CO_2 emissions in 2021 (Department for Business 2022). The fate of kelp carbon depends on the kelp species in question and where the detritus is transported, deposited or consumed, meaning sequestration rates can vary significantly, and are the focus of several ongoing studies (Gregg *et al.* 2021; Queirós *et al.* 2022; Williamson and Gattuso 2022).

Kelp and the Carbon Cycle

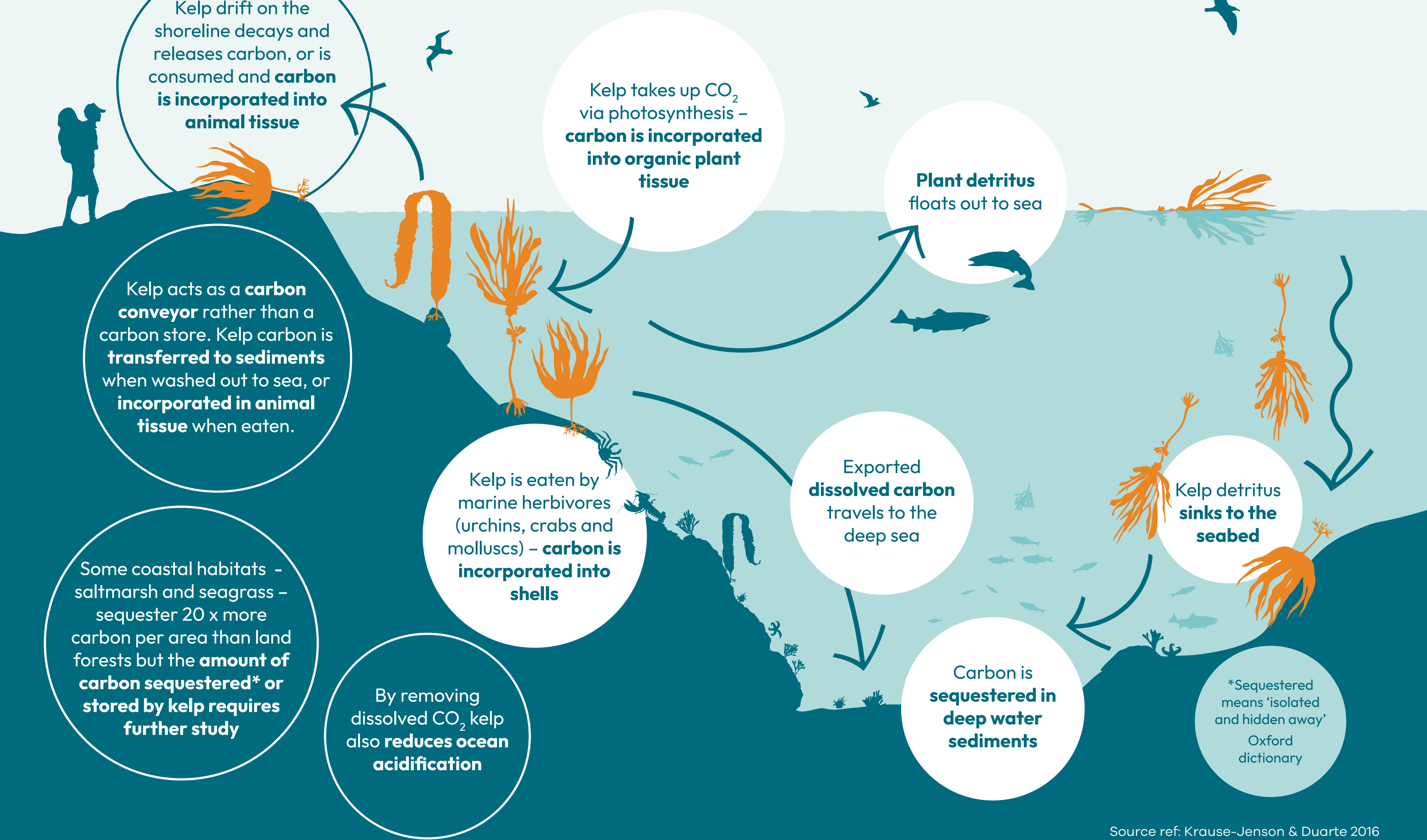


Figure 17: Kelp and the Carbon Cycle

Coastal defence

Climate change is expected to pose significant threats to humans living in coastal areas, through rising sea levels that may cause flooding, as well as an increase in the number and severity of storms (Knutson *et al*. 2010; Young *et al*. 2011). Kelp forests (and cultivated kelp farms) reduce the impact of some of these threats for example through wave attenuation. Dense kelp forests provide a physical barrier that reduces wave speed and energy and thus the impacts on land (Zhu et. al. 2022). For example, a study in Norway found that *L. hyperborea* forests can reduce the force of waves reaching the coast by up to 60% (Mork 1996). By reducing the size and speed of waves, kelp forests protect the coastline from erosion and prevent sand and pebbles being moved away from beaches. The degree of coastal protection offered by kelp forests depends on a variety of factors including the physical structure of the kelp species, the size and density of kelp, and whether there are any understorey seaweeds beneath the forest (Morris *et al*. 2020a; Smale and Vance 2016). While the degree of coastal protection offered by kelp forests is less than that of other marine ecosystems such as coral reefs and seagrass meadows (Narayan *et al*. 2016), given that kelp forests are found along a large proportion of the UK coastline (~60% where there is suitable substrate; Smale *et al*. 2013; Yesson *et al*. 2015), they are an important natural coastal defence system that is likely to play a vital role as climate change continues.

Tourism and recreational value

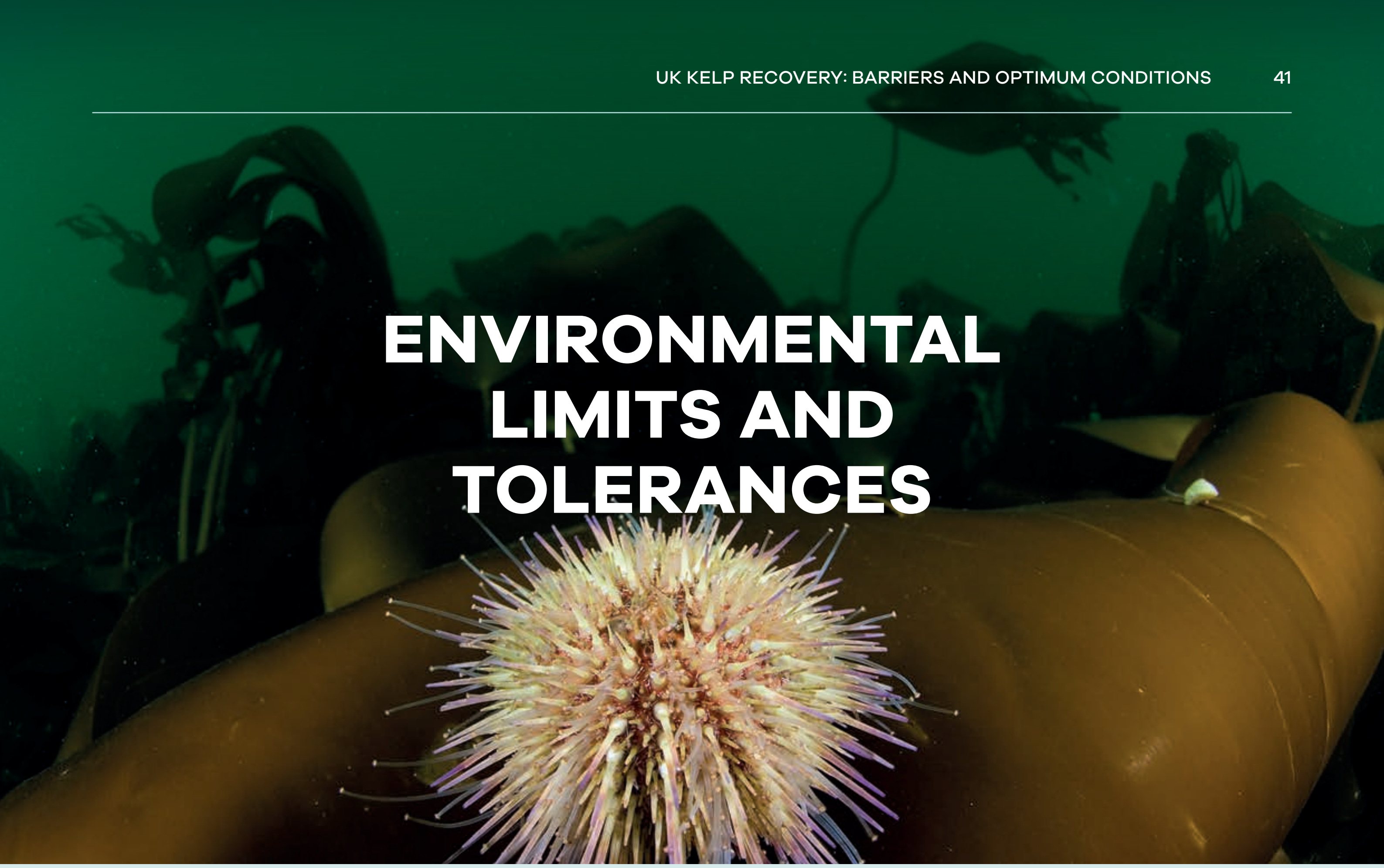
In some areas, the diverse marine life that lives within or frequents kelp forests, attracts people through recreational activities, with scuba-diving and snorkelling, kayaking, wildlife watching and photography increasing in popularity in recent years. These activities can significantly benefit human physical and mental wellbeing, as well as providing an income for local communities. Yet despite kelp-associated leisure and tourism activities attracting many participants, the value of these activities remains largely unquantified relative to ecosystems such as coral reefs. However, recent estimates have shown that tourism associated with kelp forests along The Great Southern Reef off the south coast of Australia, may represent a multibillion dollar industry (Bennett *et al*. 2016), while marine ecotourism associated with kelp forests in South Africa is valued at over US$100 million per year (Blamey and Bolton 2018), and scuba-diving on kelp-dominated rocky reefs in Lyme Bay (south coast of the UK) was estimated to generate over £1 million across the 10 dive operators based there (Rees *et al*. 2010).

Existence and cultural value

Kelp also has a non-use or 'existence value' associated with the presence of natural assets. The wide variety of species associated with kelp forests is a key factor of interest and information for the scientific community (Vásquez *et al*. 2014a). The high diversity found in kelp forests creates resilience to climate change as more species or variants increase the chance of resilient ones persisting and thriving through the changes in environmental conditions associated with climate change. High levels of diversity also means that kelp forests could contain species that may help develop new medicines in the future. In some areas, kelp forests or marine environments more broadly, hold important cultural, historical, or religious values for coastal communities. For example, in the Pacific Northwest, many tribes have myths, stories and traditions centred around kelp forests (Naar 2020). Furthermore, kelp forests may provide a 'feel-good' value, or inspire artists and educators (Wernberg *et al*. 2019). These non-use values, however, remain challenging to quantify.

Ecosystem service valuation

The value of kelp habitat ecosystem services depends on the condition of the kelp, with healthier habitat likely to have higher values. Recent estimates suggest that globally, fisheries production and nitrogen removal by kelp could generate between US$ 465 to 562 billion per year (Eger *et al*. 2023). A modelling approach has provided initial estimates of the ecosystem service value of Sussex kelp under three different scenarios; historic kelp extent (1987 – 177 km^2), current extent (2019 – 6.28 km^2), and a hypothetical maximum extent (167 km^2) based on bathymetry and suitable substrate (Williams *et al*. 2022; Williams and Davies 2019). The model estimated a decline in the value of ecosystem services from over £3 million in 1987 to ~£79,000 in 2020 as a result of the decline in habitat extent, although this value could increase to over £3.5 million should the kelp beds re-establish/be restored (Williams *et al*. 2022; Williams and Davies 2019).



ENVIRONMENTAL LIMITS AND TOLERANCES

The structure, function and health of kelp forests is influenced by a range of abiotic (physical) and biotic (biological) factors (Figure 18).

Abiotic factors

Substrate

Kelp are most frequently found attached to stable rocky substrate including bedrock and artificial structures, but where water movement is limited (tidal currents as opposed to wave action), it can also be found attached to stable boulders and cobbles (Birkett *et al.* 1998). Some species, including *S. latissima* can survive on relatively unstable boulders and cobbles because its flexible stipe reduces the drag on the boulder/cobble upon which it is attached and thus reduces the chance it will be moved or overturned (White and Marshall 2007).

As such, *S. latissima* has been successfully restored in pilot sites in Norway using the 'green gravel' technique which involves aquarium seeding and rearing of kelp spores on gravel which are later outplanted in the field (Fredriksen *et al.* 2020), and this technique is now being tested on a range of species and across a range of environmental contexts (www.greengravel.org). If kelp colonise unstable substrate, they are often considered temporary or 'ephemeral' and can be lost during extreme weather or when the blade size is large enough to cause movement of the substrate upon which the individual is attached (Birkett *et al.* 1998). Generally, kelp are not found in sandy areas as they cannot attach or anchor to small sand grains and would also be subject to scouring (Stamp and Lloyd, 2022).

The type and rugosity (measure of roughness or unevenness) of the substrate may also influence the settlement and survival of kelp, although these factors have been relatively understudied. Rock type was found to influence the health of the kelp *Ecklonia radiata*, with individuals seeded onto limestone rock experiencing severe tissue bleaching compared to those on basalt and laterite (Alsuwaiyan *et al.* 2022). In the UK, there is little evidence to suggest that kelp settlement and survival is influenced by rock type, with kelp species found on a variety of rock types including chalk (JNCC 2023). Increased substrate rugosity can however, improve the strength of attachment of kelp (Eger *et al.* 2022a), and recent studies have found that kelp settlement was greater on rock with large-scale surface rugosity (cm) compared to rock with smaller-scale (mm) rugosity (Muth 2012).

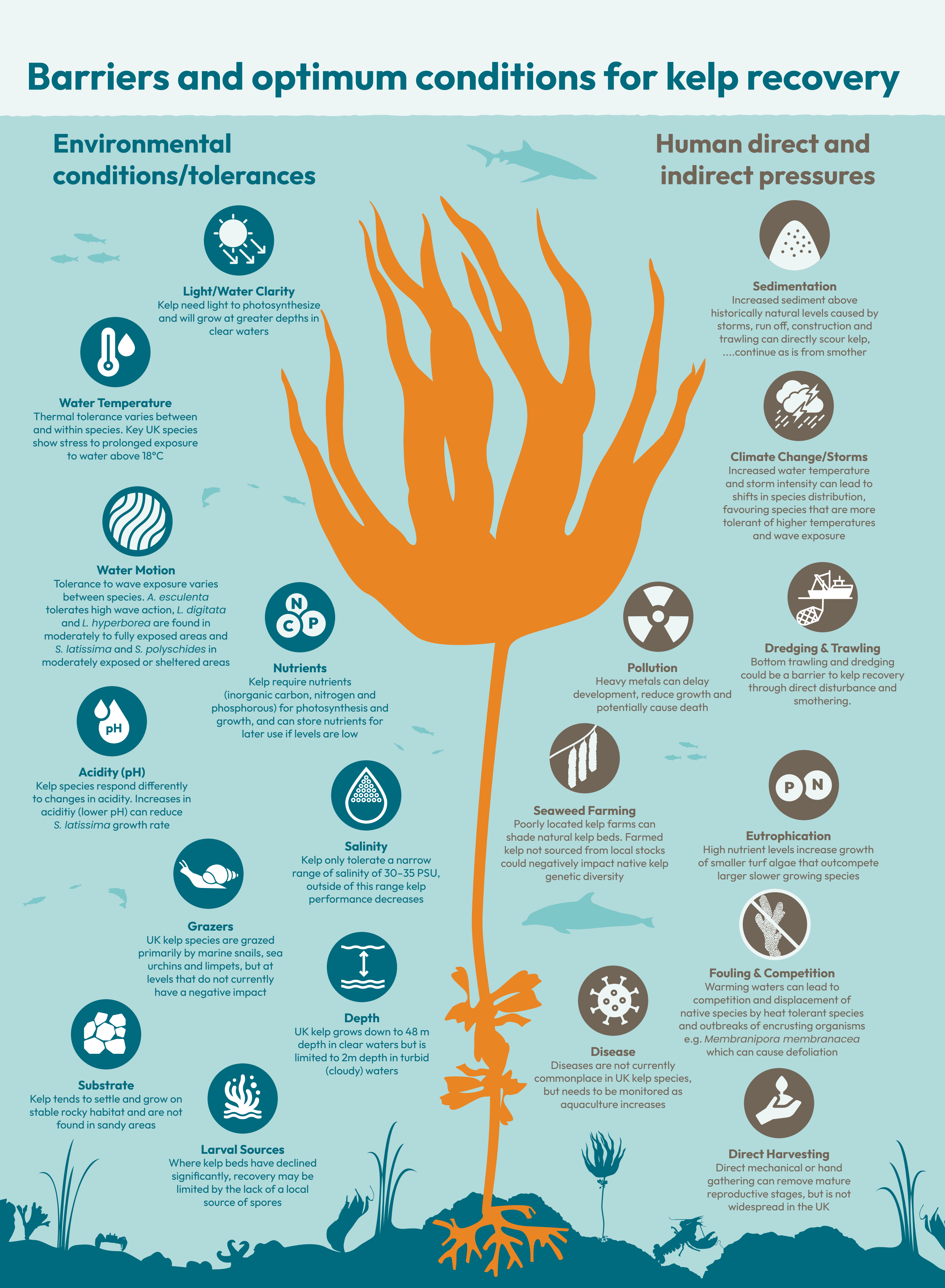


Figure 18: Environmental conditions and human pressures affecting kelp settlement and growth.

Light

Kelp are photosynthetic organisms, meaning light is an essential component of their growth and survival. As such, kelp are only found in areas where their light requirements are met, meaning they can be found deeper in clearer waters where light can penetrate further, and shallower in turbid waters where light cannot penetrate as far. In mature laminarian kelp, light saturation for photosynthesis is around 10-150 micromole photons per square metre per second (µmol photons m^{-2} s^{-1}), while younger individuals and gametophytes which are often found in lower light conditions beneath the kelp canopy are photoacclimatised to lower light conditions with growth possible at 1 µmol photon m^{-2} s^{-1} (Egan *et al.* 1989; Han and Kain 1996; Lüning 1979).

The light requirement and adaptations to light availability does however, vary across kelp species, with some able to survive well where others could not. For example, *Laminaria solidungula* grows in the Arctic where there are periods of low light/darkness for long periods of time over winter, however it is specially adapted to these conditions and able to survive by using energy reserves generated during the lighter summer months (Filbee-Dexter *et al.* 2019). Other laminarian species can grow at depths where light levels are reduced to 1% of incident light at the surface (Birkett *et al.* 1998).

Despite light being essential for kelp, too much light can reduce photosynthesis, damage cells, and potentially result in death (Kerrison *et al.* 2015). Some kelp species are able to employ techniques to increase/reduce their absorption of light, for example adjusting the number of photosynthetic pigments in their blades, depending on local environmental conditions (Blain *et al.* 2020; Delebecq *et al.* 2013). In the UK, *L. digitata* is likely the most tolerant species to high light intensity given that it is often found on the low intertidal zone which is regularly exposed to sunlight, whereas high light intensity is believed to reduce photosynthesis in *L. hyperborea* which may explain why it is somewhat restricted to subtidal areas (Tyler-Walters 2007).

Depth

The depth at which kelp is found varies considerably and is driven by light availability, water quality, and the requirements of different species. In areas of high water quality, light can penetrate further meaning kelp can be found at greater depths, for example *Eisenia galapagensis* is found at depths of 60 m around the Galapagos (Graham *et al.* 2007) and *Laminaria rodriguezii* has been reported at depths of 260 m in the Adriatic Sea (Žuljević *et al.* 2016). However, where water is turbid or loaded with organic matter, light cannot penetrate as far meaning kelp are found only in shallower waters. In the UK, kelp can be found from the low intertidal zone to depths of up to 48 m (Birkett *et al.* 1998). Along parts of the southeast coast of England, the Bristol Channel, Liverpool Bay and the Severn estuary where water is often turbid, kelp may be absent or limited to depths no more than 2 m (Birkett *et al.* 1998).

Oarweed

Laminaria digitata

Sedimentation/turbidity

Sediment loads in the marine environment are quite variable and are driven by factors including river discharges, coastal erosion and runoff, resuspension of already-present sediment during stormy weather, as well as factors associated with human activity such as bottom-towed fishing, construction, and waste disposal (e.g. dredge spoils or mining waste). Sediments can have significant negative effects on kelp habitats through the direct physical influence of sediment particles on kelp individuals, or indirectly by changing the clarity of the water and influencing the availability of light (Airoldi 2003). Firstly, increased sediments can reduce the availability of hard substrate for the settlement of kelp spores, while sediment burial can influence their survival and growth (Arakawa 2005; Devinny and Volse 1978; Matsumoto *et al.* 2020; Watanabe *et al.* 2016). The accumulation of fine sediments on rocky substrate can have significant negative effects on kelp recruitment should the smothering event be prolonged or coincide with the main reproductive period of a specific kelp species (Moy and Christie 2012).

The response of kelp early-life stages to sedimentation will likely vary across species, as well as on the quantity and nature of the sediment (e.g. particle size or whether they contain any pollutants) and the duration of the smothering (Devinny and Volse 1978; Watanabe *et al.* 2016). Furthermore, several studies have found that increasing sediment loads inhibit kelp species and promote turf-forming seaweeds which can then proliferate and create unfavourable environmental conditions that prevent the kelp from returning (Eriksson and Johansson 2005; Filbee-Dexter and Wernberg 2018; Gorgula and Connell 2004). Smothering by fine sediment is unlikely to cause significant damage to semi-mature and mature kelp, although species that form a mucus layer on the blade may attract and adhere sediment which could block light and weigh the blades down (Glascott, personal communication).

Secondly, increased sediment loads can increase the turbidity of seawater which reduces the distance light can penetrate through the water – in some cases, this is referred to as 'coastal darkening' (Blain *et al.* 2021). This reduces the amount of light reaching the kelp which can impact photosynthesis, growth, reproduction, and survival. Recent research has shown that reduced light as a result of increased turbidity can result in a 95% reduction in kelp productivity which has implications for carbon cycling (Blain *et al.* 2021).

Temperature

Seawater temperature is one of the main factors that controls the global distribution of kelp, which primarily inhabit cool-temperate and sub-polar waters. Globally, sea surface temperatures (SST) are rising, and the waters around the UK are no exception. In the NE Atlantic, SST have increased by ~0.3-0.8°C per decade over the last ~25 years (Lima and Wethey 2012). In 2020 the average SST in the UK was 11.9°C, which is 0.5°C greater than the 1981-2010 average, and between 2011-2020 temperatures were 0.7°C higher than the 1961-1990 average (Met Office 2021). Furthermore, nine of the ten warmest years on record have occurred since 2002 (Met Office 2021), and recent predictions estimate that the sea around the UK may warm by more than 3°C by 2100 (National Oceanography Centre 2023).

Generally, kelp can withstand a range of temperatures within a 'thermal tolerance limit'. These limits vary both across species and within species, for example *Eisenia cockeri* along the coastline of Peru can tolerate seawater temperatures of over 25°C but would likely not survive in colder Arctic waters where the kelp *Laminaria solidungula* is found, and vice versa (Bolton and Lüning, 1982). The position of a kelp within its thermal tolerance limit, determines how they may respond to changes in temperature as well as other environmental stressors. For example, the resilience of *Ecklonia radiata* to stressors (e.g. storms) is believed to be affected by temperature, with populations in southern areas of Western Australia exhibiting greater resilience compared to populations in northern areas where seawater temperatures are 2-4°C warmer (Wernberg *et al.* 2010). Furthermore, increases in seawater temperature in the northeast Atlantic are likely responsible for the poleward range expansion of the warm-water tolerant kelp *L. ochroleuca*, and a range contraction of the cold-water kelp *A. esculenta* (Smale *et al.* 2015; Williamson *et al.* 2015), while around Japan, increasing temperatures have resulted in losses of *Ecklonia cava* (Tanaka *et al.* 2012).

Aquarium experiments have found that temperature variations impact kelp individuals, with reductions in the growth rate and tissue strength, and increases in tissue damage and loss rates for *S. latissima* and *L. digitata* from Nova Scotia subjected to temperatures of 14°C and 18°C for two weeks, with total mortality occurring at 21°C (Simonson *et al.* 2015). More recently, researchers have found that within some species of kelp, there are groups known as '**ecotypes**' that are better adapted to certain environmental conditions. For example, thermal ecotypes of *L. digitata* have been identified between cooler northern and warmer southern regions of the UK (King *et al.* 2019). In Tasmania (Australia) where seawater temperatures are rising, warm water tolerant ecotypes of the kelp *Macrocystis pyrifera* have been identified within local populations and these individuals are being trialled as restoration candidates in areas where seawater temperature increases have caused a decline in kelp abundances (Layton and Johnson 2021).

Furthermore, temperature can influence the reproduction and early life-stages of kelp (Bartsch *et al.* 2013; de Bettignies *et al.* 2018; Le *et al.* 2022). For example, temperatures over 22°C reduced the growth of *Ecklonia radiata* gametophytes in Tasmania by over 50%, and no sporophytes developed (Mabin *et al.* 2013). Temperature increases may also indirectly reduce the amount of light available to kelp, as phytoplankton can proliferate in warmer temperatures, which lead to algal blooms. These blooms use light to grow, and reduce light penetration through the water column by increasing particulate matter within the water column (HR Wallingford 2023).

pH

The average pH of seawater is currently 8.1 (basic or alkaline), ranging from 7.5 to 8.5 depending on local conditions. However, as the ocean absorbs carbon dioxide from the Earth's atmosphere, the pH decreases and becomes more acidic. The oceans absorb about 30% of the carbon dioxide in the atmosphere and over the past two centuries, as carbon dioxide levels have increased, the pH of ocean surface waters has reduced by 0.1 pH unit. While this doesn't sound much, the pH scale is logarithmic, so this change represents a 30% increase in acidity (National Oceanic and Atmospheric Administration 2020). Ocean acidification can negatively impact many marine organisms, particularly those that have hard calcium carbonate skeletons or shells such as corals or oysters. For such species, low pH can prevent the formation of calcium carbonate structures or cause existing structures to dissolve. The impact of pH on soft-tissued kelp is varied, suggesting that the response is species specific. For example, at a lower pH, the growth of *Nereocystis luetkeana* increased, while that of *E. radiata* did not change, and that of *S. latissima* declined (Falkenberg *et al.* 2013; Swanson and Fox 2007). More recently, research has revealed that kelp forests have a capacity to ameliorate local effects of ocean acidification, and that they could act as important pH refugia in the future for species such as sea urchins that are more susceptible to ocean acidification (Ling *et al.* 2020).

Salinity

The salinity of seawater has not varied much over the past 600 million years (Birkett *et al.* 1998) and is approximately 35 Practical Salinity Units (PSU), but it can vary from less than 15 PSU at the mouth of rivers to over 40 PSU in the Dead Sea. For the most part, kelp can only tolerate a narrow range of salinity, usually between 30-35 PSU and values beyond this can result in death (Birkett *et al.* 1998; Davis *et al.* 2022), although in some areas, kelp may have adapted to local environmental conditions, forming special ecotypes that are able to tolerate salinities beyond the normal tolerance range (Kerrison *et al.* 2015). UK kelp species are considered fully marine with the exception of the non-native *U. pinnatifida* which can tolerate a wider range of salinities and thus can be found in more estuarine environments (Oakley 2007). *S. latissima* has been found in Danish fjords where salinities are between 22-24 PSU (Middelboe and Sand-Jensen 2000), and salinities of 20-55 PSU were found not to significantly impact the photosynthetic performance of Arctic *L. digitata* (Karsten 2007), suggesting that ecotypes of some UK kelp species may be tolerant to wider ranges of salinity.

Sugar Kelp
Saccharina latissima

Nutrients

The marine environment has a remarkable capacity to absorb and recycle waste products, both naturally occurring (e.g. waste from marine creatures) as well as those from human activities (e.g. sewage and agricultural fertilisers). These waste products often contain high concentrations of inorganic nutrients or organic material. Around the UK, seawater nutrient concentrations exhibit a degree of variation, due to the variable nature of anthropogenic stressors, rainfall and runoff (Smale *et al.* 2016, 2020b). Concentrations also, in the absence of human activities, often follow seasonal cycles (Roleda and Hurd 2019).

Kelp requires nutrients, primarily inorganic carbon, nitrogen and phosphorous for photosynthesis and/or growth. Throughout the year, kelp uses nutrients directly, but also stores them in reserves for use in seasons when nutrients are scarce. Cultivation research has estimated the optimum nutrient concentrations for European macroalgae species (*L. digitata*, *S. latissima*, and *S. polyschides*), with the ideal conditions for the three species collectively given as; nitrate + ammonium >5 µM L^{-1}, phosphate >0.3 µM L^{-1} (Kerrison *et al.* 2015). If, however, the concentration of a specific nutrient is low and the kelp does not have a reserve, the growth of the kelp may be limited. This is described by Liebig's Law of the Minimum which states that '*the nutrient available in the smallest quantity relative to the requirements of the plant will limit its rate of growth*'.

Too many nutrients can also have negative effects on kelp. Along the coast of several European nations, increased nutrient concentrations in coastal waters have been linked to a process called '**eutrophication**'. Here, the increased nutrients are rapidly used by turf algae species with high growth rates that compete with the slower growing kelp (and usually win) (Filbee-Dexter and Wernberg 2018). For example, the large-scale disappearance of *S. latissima* and shift to a turf algae dominated environment in Norway is believed to have been driven in part, by eutrophication (Moy and Christie 2012). Increased nutrients can also be used by fast-growing microscopic phytoplankton which reduces seawater clarity and in turn the amount of light reaching the kelp, further reducing their growth and/or survival (Birkett *et al.* 1998).

Pollution

Some waste products that reach marine environments are toxic, for example crude oil and pesticides. These pollutants can have impacts on kelp both directly and indirectly. Direct smothering of kelp and kelp-associated species by crude oil can severely affect the structure and functioning of the ecosystem. For example, while some kelp are covered with a layer of slime that may protect it from smothering by oil, researchers found that applying crude oil to *L. digitata* and *Macrocystis sp.* reduced the rate of photosynthesis (Birkett *et al.* 1998; O'Brien and Dixon 1976). Oil smothering and the subsequent decline and/or loss of important kelp associated fauna such as sea otters can indirectly impact kelp by reducing the number of predators, thus allowing herbivorous species to increase in number and potentially overgraze the kelp (Peterson *et al.* 2003). Similar impacts are likely to occur if toxic pollutants, such as polychlorinated biphenyls (PCBs) which were used in many industrial and commercial materials up until the 1970s and 1980s when their use was banned, which are known to build-up in marine food chains, become concentrated in top kelp forest predators (e.g. sea otters) and impact their reproduction and survival (Nakata *et al.* 1998).

Heavy metals are also a pollutant in marine environments and their concentration has increased beyond naturally occurring levels due to human activities such as industry and mining (Bandara and Manage 2023; Nriagu and Pacyna 1988). Depending on their concentration, these metals can impact the growth, reproduction and survival of marine organisms including kelp. The impact of increased heavy metal concentrations varies across kelp species, but the effects can include a decrease in overall size, a reduced number of blades, delayed development, and potentially death of the kelp, as well as reduced diversity of kelp-associated fauna (Contreras *et al.* 2007; Jara-Yáñez *et al.* 2021; Oyarzo-Miranda *et al.* 2020). Pollution can also have negative effects on the kelp lifecycle that may be greater than the impacts of climatic stressors, for example copper pollution has been found to inhibit the development and growth of kelp gametophytes (Leal *et al.* 2018). In the UK, the abundance and impact of heavy metals on kelp is currently unknown, however research is underway along the NE coast of England to determine the impact of heavy metals (including aluminium from historic mining) on *L. hyperborea* forests (Catherall, personal communication).

Water motion

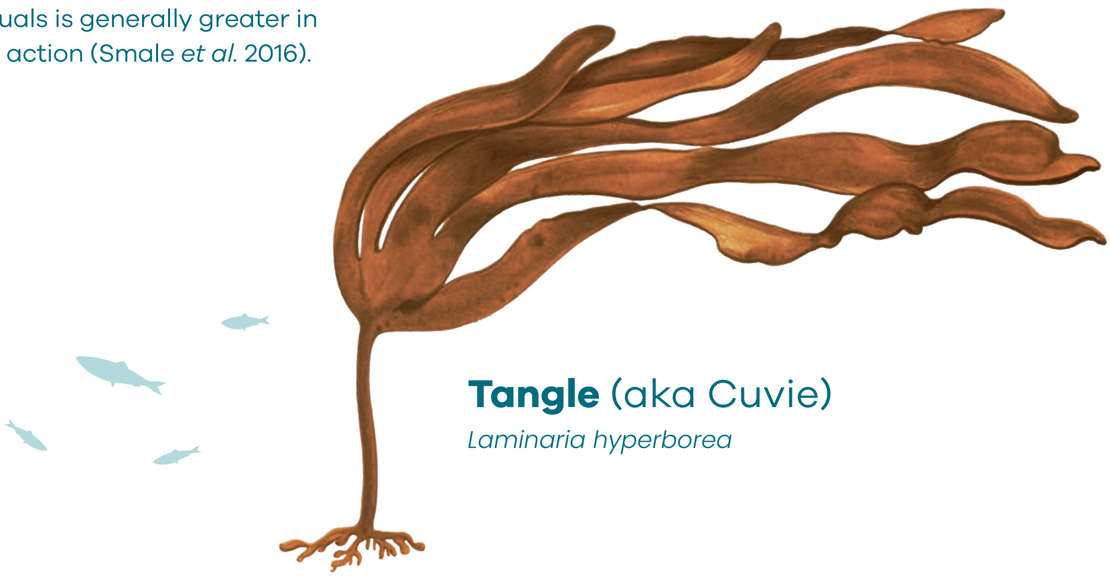
Water movement is essential to kelp development as increases in water motion reduce the thickness of **boundary layers** on the kelp surface that can limit the supply of carbon dioxide and nutrients for photosynthesis. However, water motion also has a range of effects on the structure of kelp habitats, including the species that are present, the physical appearance of the species, the dispersal distance of spores, and the nature of understorey seaweeds. Water movement is highly variable depending on tidal flows, ocean currents and exposure to wave action.

As kelp are primarily subtidal, tidal heights have little effect on kelp beds, although some individuals found low on the shore may be exposed on occasion and therefore subject to drying out, bleaching whereby parts of the blade turn white, and potentially die. In areas sheltered from wave action, tidal currents can promote the development of very large, long-lived kelp individuals. The tidal currents remove silt from the kelp blades which increases productivity by removing shading and maintaining concentration gradients for the uptake of nutrients by the kelp (Birkett *et al.* 1998).

The effect of wave exposure is well known to influence kelp, with certain species more tolerant or better adapted to life in high-energy environments. For example, in the UK, species such as *A. esculenta*, are found in areas subject to high wave action, whereas *L. digitata* and *L. hyperborea* are found in areas moderately to fully exposed to wave action, and *S. latissima* and *S. polyschides* are found in areas sheltered from or moderately exposed to wave action (Smale *et al.* 2016; Smale and Moore 2017; Stamp and Tyler-Walters 2015; White 2008) . For *L. hyperborea* the density, biomass, morphology, and the age of individuals is generally greater in sites exposed to wave action (Smale *et al.* 2016).

Generally, species or individuals that inhabit wave exposed shores are smaller in size and tougher (Wing *et al.* 2007), potentially with larger holdfasts (Bekkby *et al.* 2014), which is due to them investing energy in strengthening their structure and attachment to prevent being removed by wave action, rather than increasing their length (Kregting *et al.* 2016). However, prolonged and/or more frequent exposure to wave action beyond 'normal' conditions (e.g. as a result of storms) may increase sediment scouring and/or dislodge individuals, preventing growth to maturity (Birkett *et al.* 1998; Earp *et al.* 2024a).

The appearance of kelp plants is considered 'plastic' meaning they are able to change their appearance if their environmental conditions change (Fowler-Walker *et al.* 2006). For the most part, the impact of wave exposure on kelp is species and area specific, for example wave action had no impact on the growth rate of *L. hyperborea*, whereas *L. digitata* in areas of both high and low water motion had lower growth rates, with optimal growth rates occurring in areas with currents flows of between 0.6 - 1.5 metres per second (Kregting *et al.* 2013, 2016). While wave action in some areas can resuspend sediment off the seafloor and into the water column, reducing the clarity of the water and the availability of light which can impact growth rates, in other areas, it may cause significant movement of the kelp canopy and allow light to pass through gaps to the sub-canopy and increase the growth of juvenile or smaller kelps.



Tangle (aka Cuvie)

Laminaria hyperborea

Biotic factors

Kelp density and biomass

Kelp density and biomass is naturally variable both among locations and species, primarily as a result of environmental conditions (e.g. light availability, temperature), with the density and biomass of kelp individuals further influencing environmental conditions and how the forest functions (Dayton *et al.* 1992; Flukes *et al.* 2014; Smith *et al.* 2021). For example, in Australia, research has shown that thinning (i.e. reducing the biomass) of *E. radiata* altered the structure of communities within the understorey (Flukes *et al.* 2014), while reductions in forest extent and the density of adult *E. radiata* reduced the recruitment, growth and survivorship of juvenile *E. radiata* (Layton *et al.* 2019). This could be due to the fact that greater kelp biomass and/or densities may reduce the impact of grazing in areas with herbivore populations (Hambäck and Englund 2005). Increased densities may also increase chemical communication by individuals impacted by grazing that stimulates the production of defensive chemicals in nearby kelp to discourage herbivores, thus improving survival (Rohde *et al.* 2004; Toth and Pavia 2000).

In addition, some kelp species in the North Pacific are known to exhibit 'density dependent growth' meaning their growth rates are somewhat regulated by the density and/or biomass of nearby kelp. At higher densities and/or greater biomass, there will be more competition among individual kelp for resources such as light and space, meaning individuals may receive fewer resources and thus their growth may be limited (Reed 1990). Currently, little is known about the optimum density and/or biomass for UK kelp species (Kerrison *et al.* 2015).

Grazing pressure

Kelp are eaten or grazed by an array of herbivores including sea urchins, snails, and small crustaceans. The number of grazers is controlled by predators such as fish, starfish, and otters, however, declines in the number of predators can lead to booms in the population of grazers which can damage and destroy kelp and allow the forest to switch to a new type of ecosystem. For example, in Alaska, increased killer whale predation (which had already been significantly reduced by human hunting) on sea otters reduced the size of the sea otter population and in turn reduced the number of sea urchins that were being removed from the kelp forest (i.e., eaten by the sea otters). As such, the sea urchin population overgrazed the kelp causing a complete collapse of the kelp forest ecosystem (Estes *et al.* 1998). Similarly, declines in bull kelp (*Nereocystis luetkeana*) were driven in part by Sea Star Wasting Syndrome which reduced populations of the Sunflower Star (*Pycnopodia helianthoides*), an important urchin predator (Harvell *et al.* 2019; Rogers-Bennett and Catton 2019).

With limited predators, populations of the Purple Urchin (*Strongylocentrotus purpuratus*) increased and fed aggressively on the kelp, forming barrens in some areas (Harvell *et al.* 2019; Rogers-Bennett and Catton 2019). Similar processes have been reported in other areas including California, Tasmania, Japan and Norway (Agatsuma *et al.* 2019; Hagen 1983; Ling and Keane 2018; Watanabe and Harrold 1991), and as a consequence, the removal of sea urchins is suggested as a technique to promote the recovery of kelp forests that have been damaged by grazing (Carlsson and Christie 2019; Duggins 1980; Ling *et al.* 2010; Miller and Shears 2022; Piazzi and Ceccherelli 2019; Watanuki *et al.* 2010). Furthermore, herbivores have been found to graze on kelp gametophytes, which could further limit the recovery of kelp if the spores are unable to survive digestion (Henríquez *et al.* 2011; Santelices *et al.* 1983; Veenhof *et al.* 2022).

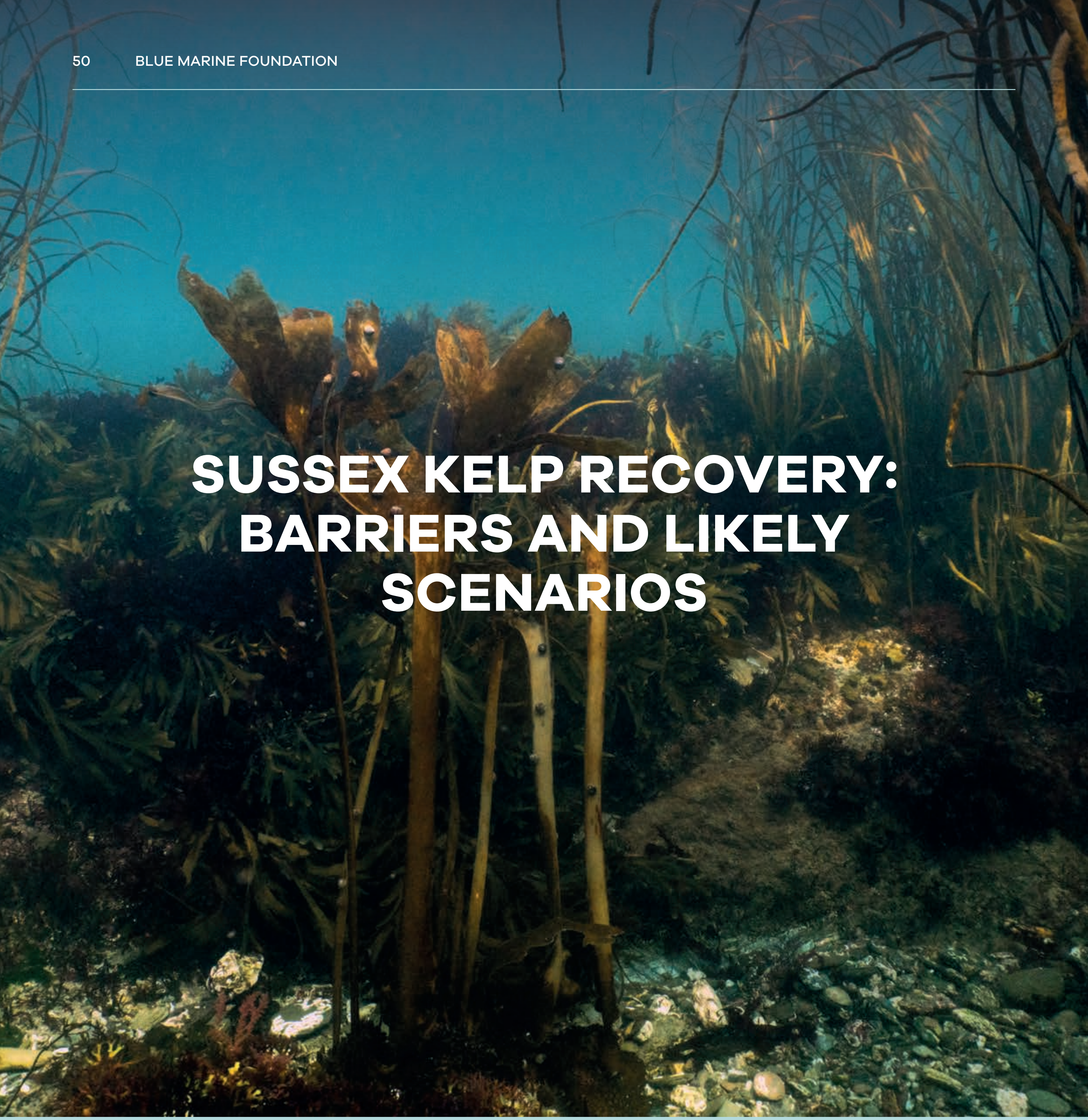
UK kelp are grazed by a variety of species including the sea urchin *Echinus esculentus*, the blue-rayed limpet *Patella pellucida* and various other small organisms, however the impact of herbivorous grazing on kelp habitats in the UK is believed to be small (Hereward *et al.* 2018; Smale *et al.* 2020a), with small urchin barrens observed in a limited number of environments (Jones and Kain 1967).

Invasive species and disease

Globally, marine ecosystems are being impacted by a range of introduced, non-native species, some of which can have significant effects on the physiology and population dynamics of native species. For example, the outbreaks of an introduced epiphytic (a nonparasitic organism that grows on a host for physical support) bryozoan (a tiny organism that grows in a colony to form a mat-like structure; *Membranipora membranacea*) to the Pacific coast of the Americas has resulted in significant defoliation of native kelps.

Dense colonies of the bryozoan causes kelp blades to become brittle and increases their susceptibility to breakage, particularly during storms (Saunders and Metaxas 2008; Scheibling and Gagnon 2009; Watanabe *et al.* 2010). It was also shown to negatively impact spore release from fertile kelp blades (Saier and Chapman 2004). Field and laboratory studies found that higher temperatures can lead to the earlier formation and increases in size of *M. membranacea* colonies (Saunders and Metaxas 2008; Scheibling and Gagnon 2009). *M. membranacea* is a common species on UK coasts and is often observed on kelp blades, however it is not currently known to cause significant defoliation, although if seawater temperatures continue to increase in the future and colonies become larger and/or form earlier, it may begin to impact on UK kelp beds.

The effect of diseases in marine ecosystems has become increasingly apparent in recent years, and like any other living organism, kelp can be impacted by diseases and pathogenic microorganisms such as viruses. However, these diseases and viruses have been somewhat overlooked, and their role within kelp systems remains largely unknown. Although in Australia and New Zealand, the white or 'bleached' patches observed on *E. radiata* have been linked to viruses (Beattie *et al.* 2018; Easton *et al.* 1997). While in China, diseases including hole-rotten disease and red-spot disease have been reported in *Laminaria japonica* which is commercially cultivated (Sawabe *et al.* 1998; Wang *et al.* 2008; Zhang *et al.* 2020). While no evidence of increased disease in kelp nearby to aquaculture facilities was found, with kelp aquaculture on the rise, the risk and/or prevalence of kelp diseases and viruses may increase in the coming years and will require further research. In addition, diseases can indirectly affect kelp habitats if they reduce or remove key predators of kelp-grazers. This was the case in northern California whereby Sea Star Wasting Syndrome reduced the urchin-grazing Sunflower Star (*Pycnopodia helianthoides*) population, which in turn allowed Purple Urchin (*Strongylocentrotus purpuratus*) populations to increase that then overgrazed the bull kelp, *Nereocystis luetkeana*, resulting in the formation of urchin barrens in some areas (Harvell *et al.* 2019; Rogers-Bennett and Catton 2019).



SUSSEX KELP RECOVERY: BARRIERS AND LIKELY SCENARIOS

Marine biodiversity is highly variable through space and time due to complex interactions between biotic and abiotic processes (Beas-Luna *et al*. 2020; Bell *et al*. 2015; Fraschetti *et al*. 2005; Lamy *et al*. 2018; Stark *et al*. 2020; Westerbom *et al*. 2008). Understanding how these processes influence the structure and distribution of populations is a fundamental objective in ecology and a prerequisite for conservation, management and restoration initiatives (Bremner 2008; Courchamp *et al*. 2015).

In Sussex, the exclusion of bottom trawling (a fishing method that tows heavy nets or chains along the seabed) from a significant area where dense kelp beds once existed should facilitate natural recovery of the kelp, however current and future environmental conditions (e.g., sedimentation, seawater temperature) alongside biological factors (e.g. larval dispersal, recruitment and genetic components), may influence kelp recovery in the area. This section assesses the potential barriers and conditions that could hinder natural kelp recovery in Sussex and the expected trajectory for kelp recolonisation if conditions are favourable.

Environmental conditions affecting recovery

Sediment loading

Declines in water quality as a result of sediment loading and increased nutrients has resulted in degradation and/or declines in both kelp and macroalgae in many regions (Filbee-Dexter and Wernberg 2018). Sediment loads in Sussex have been the focus of much attention as they are believed to be one of the main factors that might limit kelp recovery (Figure 19). HR Wallingford published a report commissioned by the Blue Marine Foundation on sediment, sources, sinks, and trends in the Sussex area (HR Wallingford 2023). Briefly, they stated that the sediment regime of the area lies within the wider sediment regime of the English Channel which is characterised by an eastward movement of sediment in the region of 2-70 M tonnes/year, while more local sources of fine sediment include cliff erosion (about 290,000 tonnes per year), wash out from beach nourishment projects, river inputs and offshore activities including aggregate dredging and wind farm installation.

The harbours and marinas along the Sussex coast trap and act as sinks for fine sediment (both sand and mud), which is maintained in the nearshore system by removal and deposition at local nearshore disposal sites through licenced maintenance dredging. This may cause localised increases in suspended sediment with acute effects where dredge disposal is frequent and close inshore. Chemical contaminants present in the sediment may be released into the water column when the sediment is dredged, but the potential impact of sediment contaminants on kelp has not yet been studied.

In a 2022 survey of sea users in the Sussex area, 67% of respondents (n=129) had noticed a change in the amount of sediment in one or more coastal environments (in the water, on the seabed, in rockpools) of which 90% noted an increase. Silt was the most common type of sediment observed (Sussex Kelp Recovery Project 2022).There is, however, no clear published evidence of long-term changes in sediment loads around the Sussex coastline (HR Wallingford 2023), and it is unclear how this may change in the future as a result of the Nearshore Trawling Byelaw and other sediment management activities (e.g. saltmarsh restoration in local estuaries that could trap some sediment coming down river). Sediment management activities are however unlikely to mitigate the large sediment loads from cliff erosion, which may increase in the future due to rising sea levels, or the resuspension of sediment during storms which are predicted to increase in frequency and intensity as our climate changes.

Given that there is no long-term data regarding sediment loading/turbidity in Sussex, and it is unclear how it may change in the future, it is challenging to state the specific impacts sediments may have on local kelp recruitment and growth. Literature from other areas has reported that impacts of large, or increased sediment loads could include reductions in the availability of suitable substrate for kelp settlement and the burial of kelp spores (Arakawa 2005; Devinny and Volse 1978; Matsumoto *et al.* 2020; Watanabe *et al.* 2016), as well as reductions in water clarity (and therefore light penetration) that can negatively impact kelp productivity and survival (Blain *et al.* 2021). Negative feedback loops could also hinder kelp recovery, for example, turf algae can often survive and potentially thrive in areas subject to sedimentation, and if these species become established, they can compete with kelp for resources, and prevent/inhibit spore settlement and/or growth (Filbee-Dexter and Wernberg 2018).

Further information and examples of sedimentation impacts on temperate reef assemblages (including kelp) are summarised by Airoldi (2003). However, kelp forests are known to persist in areas with increased sediment loads, for example Port Phillip Bay (Australia; Kriegisch *et al.*, 2019), so it is also possible that the kelp species that may recolonise the Sussex area will be those that have a higher degree of resilience to high sediment loads/greater turbidity such as *S. polyschides*. Moreover, it may be possible that other marine species may colonise the area and stabilise the substrate (e.g., mussels) and make the environment more suitable for kelp colonisation. Further insights into the influence of sedimentation on kelp in Sussex, particularly the sediment budget and the impact of sedimentation on kelp growth, will be obtained through PhD research being conducted at the University of Sussex (Glascott, personal communication).

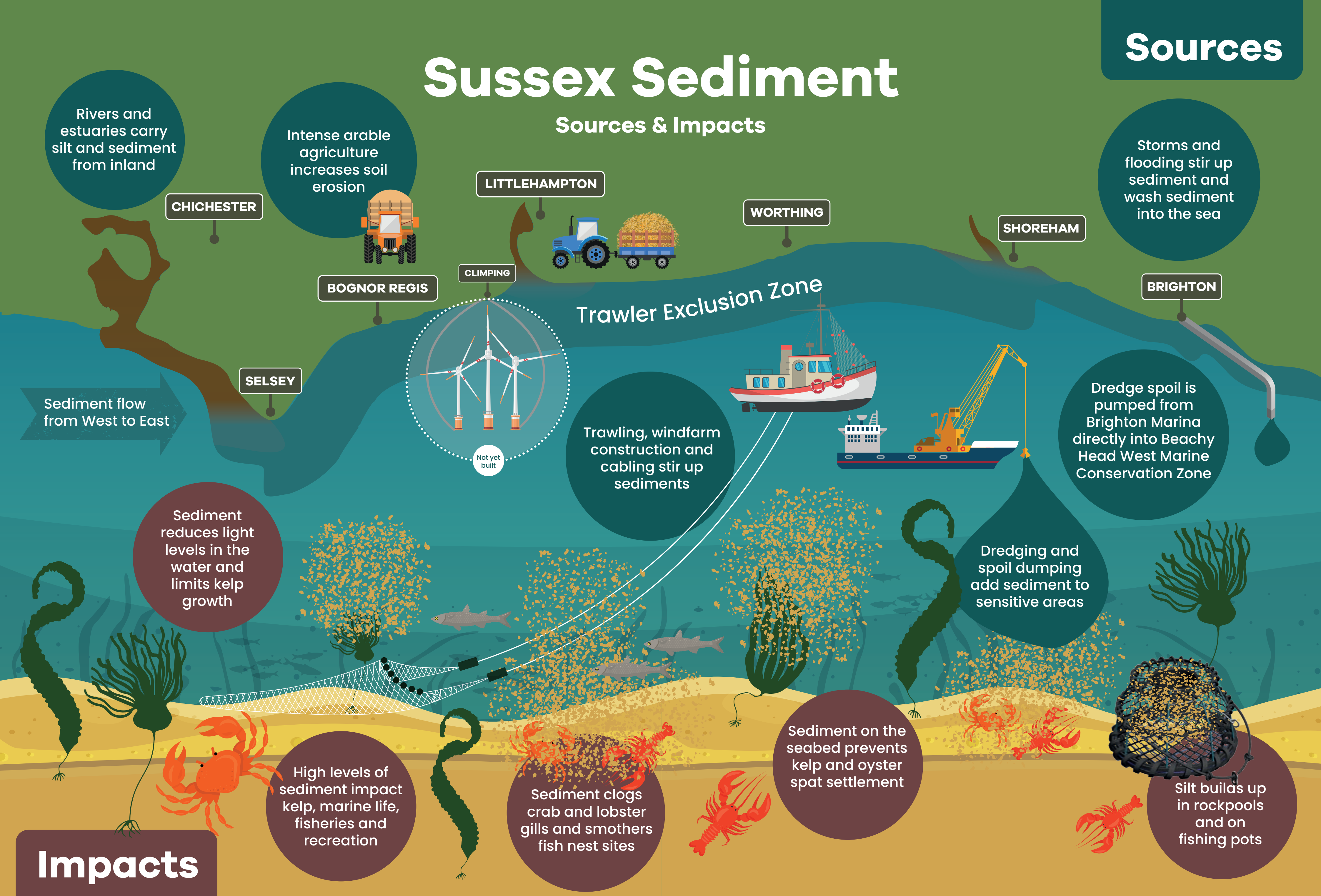


Figure 19: The sources and impacts of sedimentation in Sussex.

Substrate

To date, habitat maps for the Sussex coastal waters and imagery from dropdown cameras showed the presence of soft sediment in many areas (Sussex IFCA, 2020; Yesson, unpublished; experience.arcgis.com/experience/e43daa493bc64083a8b9d024bf7ad4f3/) which is less likely to support dense stands of kelp. While sublittoral and circalittoral rock are also present to a lesser extent, a proportion of this is comprised of chalk which may also be unsuitable for kelp – although *L. hyperborea* is known to be associated with chalk at Flamborough Head (North Yorkshire) (JNCC 2023). However, habitat maps and the use of underwater imagery can be misleading when identifying suitable areas for marine organisms. For example, sediment can obscure bedrock which would then not be identified in habitat assessments. However, in Lyme Bay Marine Protected Area (MPA), following towed demersal fishing gear being banned from 206 km^2 of seabed, reef associated species started to appear indicating the presence of rocky habitat beneath a sediment veneer (Sheehan *et al.* 2013a). As such, only seabed penetrating surveys could fully determine the availability and suitability of habitats within the Sussex area.

Temperature

Rising sea surface temperatures (SST), which could be up to 3°C warmer in the UK by the end of the century (National Oceanography Centre 2023) may also influence the recovery and composition of kelp beds along the Sussex coast. Currently, temperatures in the area are likely to be within the thermal tolerance limit of all kelp species historically known to the area. However, temperatures over recent years have been increasing (Figure 20) and data published by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS 2023) shows that sea temperatures across the south and east of England hit record-breaking levels in 2022, with temperatures in Sussex above 20°C in August and September.

Models predicting habitat suitability up to 2100 under Representative Concentration Pathway (RCP) 8.5 (i.e. a predicted climate change for a worst-case scenario) suggest that the Sussex coastline would become too warm for *A. esculenta*, *L. hyperborea* and *L. digitata*, with these species' ranges shifting northwards. At the same time, *L. ochroleuca* and *S. polyschides* ranges are expected to expand along the English Channel coastline into Sussex and beyond (Assis *et al.* 2018). In the short to medium term as waters warm, kelp populations are likely to persist in Sussex waters, but there may be changes in the relative abundance of warm- and cold-tolerant species as has been observed in southwest England (Smale *et al.* 2015; Smale and Moore 2017).

At present, there is no data to suggest that marine heatwaves have negatively impacted UK kelp populations, although aquarium trials involving *L. digitata*, *L. hyperborea* and *L. ochroleuca* collected on the southwest coast of the UK found that under low light conditions, summertime marine heatwaves caused significant declines in the biomass, blade surface area and photosynthetic efficiency of the cool-water kelps *L. digitata* and *L. hyperborea*, compared to springtime heatwaves or heatwaves under high light conditions (Bass *et al.* 2023).

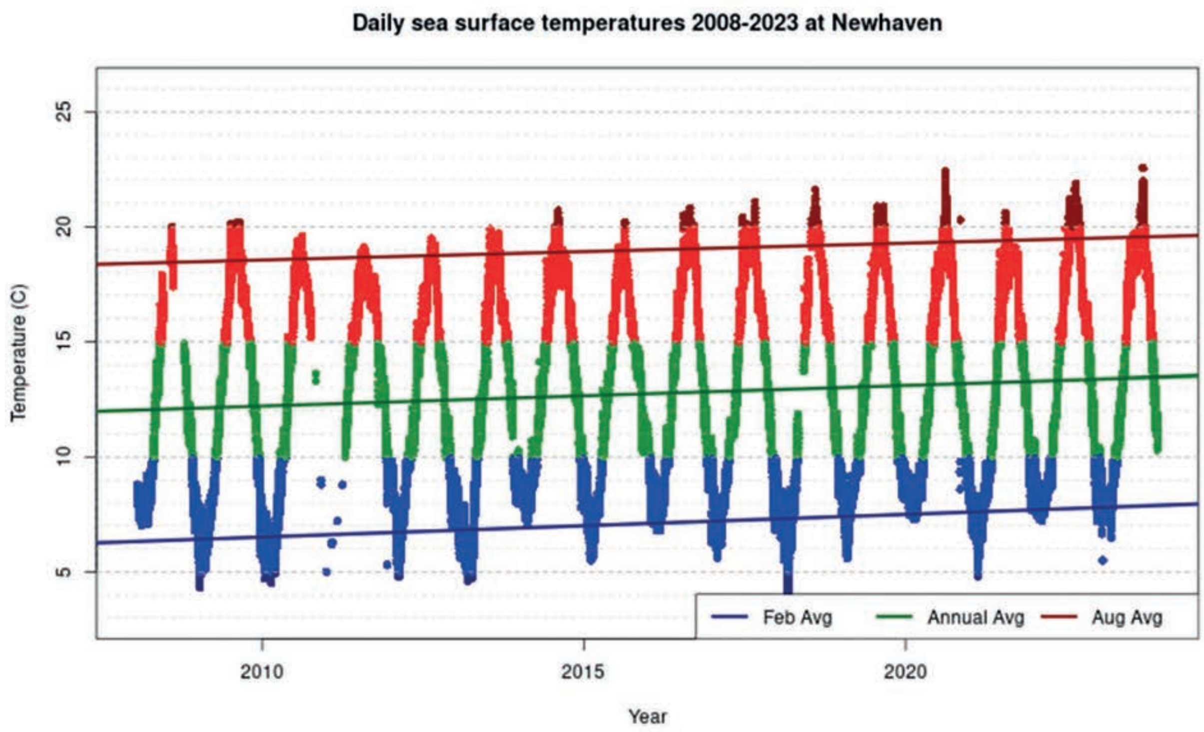


Figure 20: Daily in-situ sea surface temperatures from the In Situ TAC of the Copernicus Marine Service (http://marineinsitu.eu/) for buoy #6201014 (situated approx. 2km south of Newhaven, Sussex). Lines show trend in average monthly / annual temperatures.

Water motion

Water motion in coastal waters also has the potential to influence turbidity through the stirring and resuspension of fine particles/ sediment, which in turn can influence the light environment for kelp. The combined effect of different types of water motion (i.e. waves, tidal cycles, and currents) on turbidity is challenging to predict, and varies both seasonally and annually, making it difficult to determine how they will influence the light availability for kelp in the Sussex area.

Winds in Sussex are generally from the southwest, although there is some variability in direction and strength, likely as a result of the North Atlantic Oscillation (NAO) (Earl *et al.* 2013). As such, waves in the Sussex area generally travel in an easterly direction, often increasing in size with **fetch** (HR Wallingford 2023). Similarly, residual currents in the English Channel, although rather weak, generally occur in an eastward direction (Guillou *et al.* 2015). It is therefore plausible that kelp spores may be carried in an eastward direction, and that kelp recovery in Sussex may occur from west to east.

However, incident waves closer to the shore are influenced by bathymetry and the shape and orientation of the coastline, with the inshore wave climate along the Sussex coast considered to be relatively energetic (HR Wallingford 2023). Furthermore, in the absence of wind, the presence of headlands and islands along the coast can cause recirculation of the residual tidal flow (that generally travels in an easterly direction) and in Sussex, this has led to the formation of a series of gyres, some of which travel in westerly and northeasterly directions (Guyard 2000; HR Wallingford 2023). The addition of wind, however, could influence the flow/effect of these residual tidal flows. As such, kelp recovery along some areas of the Sussex coast may not occur in the predicted easterly direction, and the strength of water motion is likely to further influence where and which kelp species are able to recover/recolonise different areas.

Nutrients and pollution

Increased nutrient concentrations may also impact kelp recovery in Sussex. Intense arable farming adjacent to the coast may use fertilisers that runoff via rivers into coastal marine areas. The nutrients in these fertilisers can be taken up by phytoplankton and opportunistic algae such as turfs that can proliferate and impede kelp recovery. Coastal nutrient enrichment is known to be problematic around the UK and northern France and has resulted in macroalgal blooms in the Channel Manche region (RaNTrans Project rantransproject.com), Budle Bay (Northumberland; LIFE WADER Project tweedforum.org/our-work/life-wader), and Milford Haven (SW Wales; Joniver 2022). Nutrient concentrations in Sussex waters have not been monitored and therefore it is difficult to determine whether elevated nutrient concentrations could inhibit kelp recovery.

Biotic factors

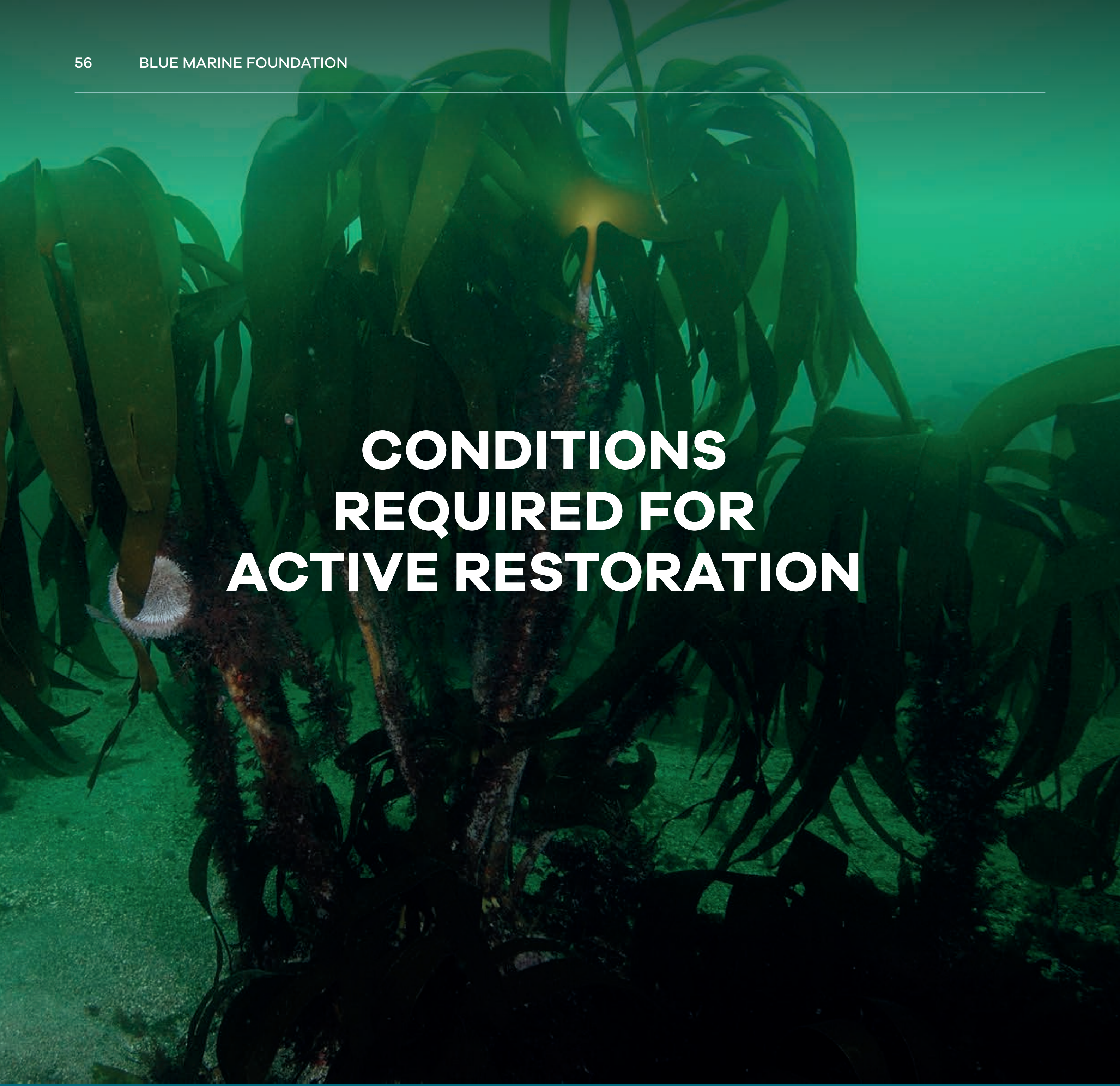
Biotic factors such as larval dispersal and recruitment, genetics and local adaptation of both kelp and important kelp-associated species (e.g. urchins), as well as disease could further influence the recovery and composition of kelp beds in Sussex. However, at present, limited information exists regarding these factors and thus it is challenging to state what their impacts may be. Although AECOM Ltd (2020) state that propagule limitation is likely to be a key issue to recovery of kelp beds along the Sussex coast. While pockets of kelp habitat have persisted in Sussex at Bognor Rocks and near Worthing and Selsey, this may not be sufficient to seed widespread recovery. More extensive kelp habitat is observed around the Isle of Wight and may be important for recovery in a system dominated by eastward water movement (Yesson, personal communication), although the level of connectivity between populations is currently unknown, but could be assessed through population genetic analyses.

It is important to note that there has been an increase in kelp farming along the southeast coast, including a kelp farm test site off Pagham Special Protection Area (Balchin, personal communication). This could potentially increase the risk of disease in natural kelp populations (Sawabe *et al.* 1998; Wang *et al.* 2008; Zhang *et al.* 2020), although the potential for this is limited and poorly understood.

Potential recovery scenarios

Kelp habitat recovery in Sussex, should it occur, will likely be influenced by complex interactions between all these factors and thus it is challenging to predict what a trajectory of recovery may look like. Recent kelp clearance experiments along the coasts of south-west England and Wales found that following the removal of *L. hyperborea*, areas were recolonised in the first year by *S. polyschides* and *S. latissima* with some small *L. hyperborea*, however over two to three years both *S. polyschides* and *S. latissima* declined and *L. hyperborea* became dominant again (Smale and Moore, unpublished). This experiment showed that kelp is successfully able to recolonise cleared areas and that in some cases, a succession of kelp species may occur during a process of staged recovery. It would therefore be plausible for kelp recovery in Sussex to undergo similar successional patterns. However, it is important to note that this recovery experiment was conducted in an area adjacent to a healthy source of kelp spores, and the area was known to be a suitable environment for kelp colonisation and survival. Initial reports from Sussex suggest that recolonisation may be occurring within the Nearshore Trawling Byelaw area, with mermaids tresses/sea lace (*Chorda filum*) and blue mussels (*Mytilus edulis*) found during surveys in 2022 (Sussex Kelp Recovery Project 2023).

It is also important to note, that even when drivers of degradation and/or loss are removed, recovery is a complex process, and it will likely take time for any changes in kelp populations to be observed. However, Layton *et al.* (2020) highlighted that there is only one known example of passive restoration achieving long-term kelp restoration – this was in relation to *M. pyrifera* on an artificial reef in California (Reed *et al.* 2006, 2017).



CONDITIONS REQUIRED FOR ACTIVE RESTORATION

The restoration of kelp forests has a long history, spanning 300 years and 16 countries (Eger *et al.* 2022b; UNEP 2023). The process of improving environmental conditions to assist the recovery of kelp forests is often known as passive restoration, while active restoration involves introducing kelp material, including whole individuals, reproductive material and/or spores, to an area where kelp have declined in number or have disappeared.

It is important to acknowledge however, that 'prevention is better than cure' and that prior to commencing active restoration of kelp habitats, every effort should be made to reduce stressors that caused the initial decline and/or loss and improve environmental conditions so that kelp may recover naturally (Bekkby *et al.* 2020).

The Society for Ecological Restoration (SER) defines restoration as *"the process of initiating or accelerating the recovery of an ecosystem that has been degraded, damaged or destroyed"*.

There has been increasing interest in the restoration of a range of habitats in the UK, including kelp forests. A recent report highlights the restoration potential of kelp around the UK coastline (Johnson *et al.* 2023), but it is important to note that in most of these areas there are currently healthy kelp populations and therefore restoration is not required (Wilding *et al.* 2023).

It is possible therefore, that passive restoration alone may not be sufficient to facilitate recovery of the kelp beds in Sussex, for example if there is not a healthy source of kelp spores nearby that can reach areas where kelp has been lost. If this proves to be the case and natural recovery is not evident within five years of trawling management, active or passive restoration may need to be considered (Fanshawe, personal communication). Active restoration, however, is often costly and is not recommended if environmental conditions may still challenge kelp survival (Eger *et al.* 2022b). For kelp restoration, both passive and active, to be successful, a number of factors need to be considered, for example the proximity of nearby kelp habitats which is a key predictor of restoration success (Eger *et al.* 2022b), or the role of herbivory. These factors are outlined in the Kelp Restoration Guidebook and the UNEP Into the Blue Report.

Active restoration of kelp forests has been trialled around the world, involving a range of species and techniques, although success is variable and not guaranteed (see Earp *et al.* 2022 for a review). As such, restoration is somewhat of a 'trial and error' process, with success often influenced by factors such as the nature of the site (e.g. environmental conditions), the restoration species, the timing of the restoration activity and the restoration technique.

Any active restoration proposals will need to be assessed on a case-by-case basis and it is recommended that pilot studies are conducted to test site, species and technique suitability and gain support for the work before they are scaled-up.

Any kelp restoration or recovery initiatives in Sussex should not aim to recreate the habitats that were previously present, but instead to create an environment where kelp may survive and form self-sustaining populations that will in turn, attract a diverse array of kelp-associated species and provide a variety of valuable ecosystem services. Given that kelp beds in this area were previously comprised of *L. digitata*, *L. hyperborea* and *S. latissima*, these species are the most appropriate candidates for initial active restoration activities and information on their environmental requirements/tolerances are outlined in Table 2. Identifying the most appropriate sites for restoring these species in Sussex is challenging, but sites should only be selected if environmental conditions appear suitable for the survival and growth of either of the three kelp species (Table 2) and thus monitoring of environmental conditions at restoration sites will be required prior to commencing restoration activities. To restore any of the three kelp species, a range of techniques are possible and are outlined below and in Table 3, however it is important to note that novel restoration techniques are always being developed and tested, and so the techniques listed below are not exhaustive.

Table 2: Physical and biological tolerances for the three kelp species historically found in Sussex waters. Information is based on Birkett *et al.* (1998), Kerrison *et al.* (2015), the MMO (2019) and the corresponding s pecies pages on The Marine Life Information Network (MarLIN: www.marlin.ac.uk) alongside additional articles where referenced.

Species	*L. digitata*	*L. hyperborea*	*S. latissima*
Depth	Low intertidal but sometimes in rockpools	Low intertidal – 40 m but in general forests are found no deeper than 15-20 m along the coast of southern England and Wales	Low intertidal – 30 m. Sometimes in rockpools
Temperature (°C)	Optimum 5-15 but can tolerate 0-23 (Liesner *et al.* 2020b)	~3-20 (Kain 1964; Lüning 1980; Sjøtun *et al.* 1993)	Optimum 5-15 but can tolerate 2-21 (Andersen *et al.* 2013)
Salinity (PSU)	Optimum 30-40 but can tolerate 15-30	Optimum 30-35 but can tolerate 16-40	Optimum 25-40 but can tolerate 15-24
Substrate	Stable hard substrate including bedrock, boulders, cobbles, pebbles, and artificial structures	Stable hard substrate including bedrock and boulders	Hard substrate including bedrock, boulders and unstable hard substrate including cobbles and pebbles
Exposure (waves/ currents)	All areas but more common in moderately to highly exposed areas and areas with strong currents	All areas but more common in moderately to highly exposed areas and areas with moderate currents	Most common in sheltered to moderately exposed areas. May appear as an annual species in exposed areas
Light	Limited knowledge Adult sporophytes light saturated at around 150-200 µmol m^{-2} s^{-1} (Kerrison *et al.* 2015)	Limited knowledge	Limited knowledge Adult sporophytes light saturated at around 215 µmol m^{-2} s^{-1} (Kerrison *et al.* 2015)
Nutrients	Nitrate & nitrite - Optimum >10 mmol/m3 but can tolerate 4-10 (MMO 2019)	Limited knowledge Intermediate tolerance – although found near sewage outflows in Isle of Man	Nitrate & nitrite - Optimum >10 mmol/m3 but can tolerate 4-10 (MMO 2019)
Grazers	Urchins, small invertebrates, some fish	Urchins, small invertebrates, some fish	Urchins, small invertebrates, some fish

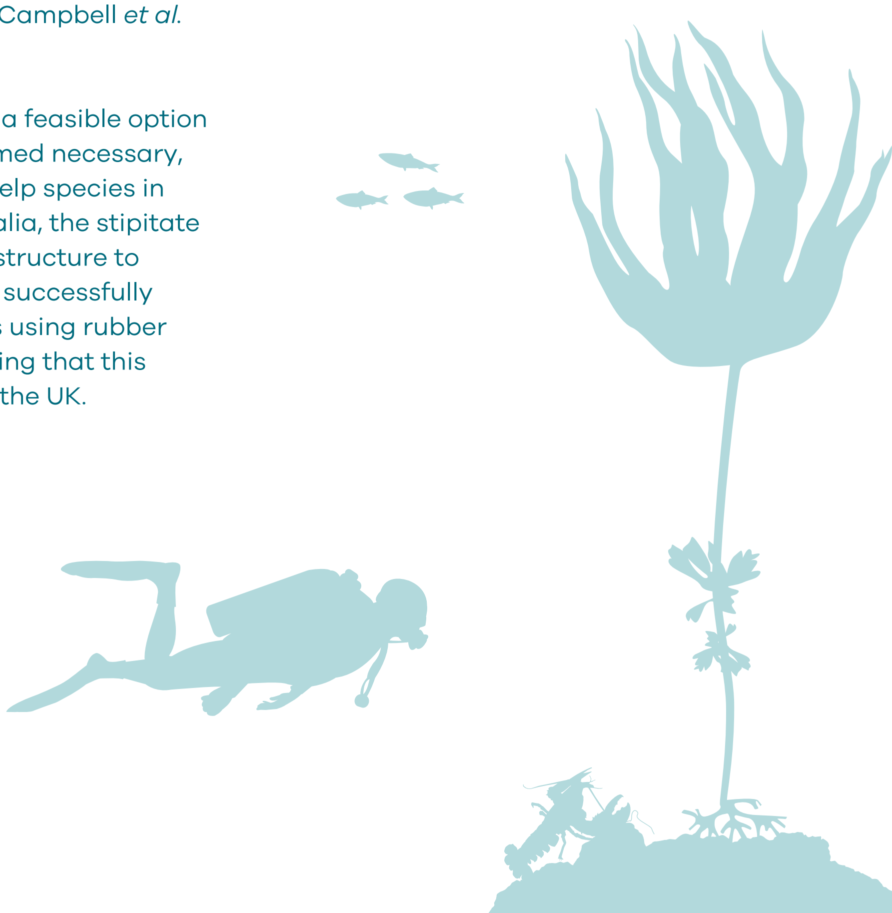
Transplantation

Transplanting involves deploying adult or juvenile kelp from donor populations, beach cast individuals or aquarium cultured specimens to areas where kelp has been degraded or lost. Transplants can be secured onto a range of substrates including; concrete blocks, plastic mesh, shells, ceramic tiles, rocks, rope and old holdfasts, using a range of methods including; glue, epoxy putty, cable ties, rubber bands, chains, mesh and bolts (Earp *et al.* 2022). Transplantation is one of the most commonly used kelp restoration techniques and has been trialled across a range of species and environmental contexts with varying levels of success (Earp *et al.* 2022; Eger *et al.* 2022b; Morris *et al.* 2020b). The advantages of this method are that the transplants can influence local environmental conditions and create a suitable environment for the settlement of spores and the growth of new recruits, as well as the fact that transplants can be precisely placed within restoration areas (Eger *et al.* 2020, 2022a; Layton *et al.* 2019). While limitations include potentially negative impacts on donor populations, being relatively labour intensive, and there being no guarantee that the transplants will survive and attach to the bedrock (Eger *et al.* 2022a). The permanent attachment of transplants to the bedrock however, is not necessarily a requirement of restoration as long as the transplants survive long enough to reproduce and seed the area – this was the case with Fucalean seaweed transplants in Australia (Campbell *et al.* 2014).

In Sussex, transplantation may be a feasible option for active restoration if this is deemed necessary, with success reported for similar kelp species in other areas. For example, in Australia, the stipitate kelp *E. radiata* (which is similar in structure to *L. digitata* and *L. hyperborea*) was successfully transplanted onto concrete blocks using rubber bands (Layton *et al.* 2021), suggesting that this technique may also be possible in the UK.

Transplantation using green gravel

A transplantation technique known as 'green gravel' has been successful for *S. latissima* in Norway (Fredriksen *et al.* 2020). This technique involves seeding small rocks with kelp, rearing them in an aquarium and then outplanting them at restoration sites. Although relatively high costs are associated with aquarium rearing, this technique does not require intensive field installation as the rocks can be deployed from the side of boats. As such, the technique is scalable and research is currently underway to assess its applicability across a range of environmental contexts and species as part of the Green Gravel Action Group (www.greengravel.org/action-group). This has included investigations into using its suitability as a technique for exposed intertidal areas in northeast England using different rock sizes (Earp *et al.* 2024c), and trials are due to commence in Germany using *L. hyperborea* (Stahl, personal communication). Furthermore, green gravel could be seeded with selected kelp genotypes that are resilient to specific stressors (e.g. temperature) in order to restore environmentally tolerant habitats (Coleman *et al.* 2020; Institute for Marine & Antarctic Studies 2020; Layton and Johnson 2021), although it is important to consider the ethical concerns around manipulating the genetics of wild organisms for conservation (Filbee-Dexter and Smajdor 2019).



Seeding

Seeding involves enhancing kelp recruitment at restoration sites by either installing reproductive bodies (i.e. sorus tissue), or dispersing laboratory cultured early life stages. Advantages of this technique are that it minimises damage to donor populations as only a piece of reproductive kelp material as opposed to the entire plant is removed. Drawbacks of the technique include the high mortality of early life stages, the fact that there is little control over where spore settlement will occur, and it can be labour intensive to install bags of reproductive tissue. In addition, it could also result in reduced genetic diversity, and in turn resilience if the source material is from a small kelp population. While seeding has been somewhat successful for restoring kelp (Earp *et al.* 2022), success is most likely in areas where adult conspecifics are present (Layton *et al.* 2019) and where competition is limited (Hernandez-Carmona *et al.* 2000). As such, it may be beneficial to include this technique as a method to assist kelp recovery in Sussex, however it would be best used in areas adjacent to adult populations (either naturally occurring or transplants).

Other techniques

While a suite of other techniques for restoring kelp forests exist (e.g. herbivore and competitor exclusion/removal, the installation of artificial substrates), their applicability to the Sussex context is limited. For example, grazing pressure within kelp habitats and the formation of extensive urchin barrens is relatively limited in the UK (Hereward *et al.* 2018), meaning herbivore exclusion is likely to have little impact on kelp restoration/recovery in Sussex. While the presence and extent of turf algae and other kelp competitors in Sussex is unknown, their exclusion/removal is likely not a feasible option across large scales. Both these techniques are also reliant on a source of kelp spores to recolonise the exclusion/removal areas which may not be available in Sussex.

Installing artificial habitats that are suitable for kelp colonisation, growth and survival, in the strictest sense is not considered restoration, but instead 'afforestation' (Eger *et al.* 2022b). This approach is not considered as a feasible kelp restoration strategy in Sussex as it involves replacing a habitat as opposed to restoring a natural habitat. There are however, some existing and planned artificial structures along the Sussex coast that may be suitable for kelp, for example the pilings of offshore wind farms, but further information on these structures is required to assess their suitability for kelp colonisation and survival.

In summary, there is currently only one known academically led kelp restoration experiment in the UK which involved seeding green gravel with *S. latissima* and outplanting them along the northeast coast of England (Earp *et al.* 2024c), and as such there is little evidence to support the use of specific restoration techniques or species in a UK context. However, green gravel (or similar aquarium seeding/rearing/outplanting, for example on tiles that could be attached to the substrate in the field; De La Fuente *et al.* 2019), is likely the most promising assisted recovery or active restoration technique that could be employed in Sussex using any of the three historically present species, although pilot experiments would be beneficial to explore this in the first instance. In addition, transplantation of adult individuals of the three species (including a variety of age classes) may also be beneficial, although experiments would need to be conducted in Sussex to determine the best method of attachment depending on the resources and substrates available. Further information on all these techniques can be found in the Kelp Restoration Guidebook.

Table 3:. Definition of restoration techniques and examples of use. Adapted from Earp *et al.* (2022).

Technique	Examples	References
Transplantation involves the installation of adult and/or juvenile individuals from either a donor population, a laboratory culture, or opportunistic drift/beach cast individuals. Transplants can be installed at restoration sites using an array of techniques.	Mesh devices bolted or tied/cable-tied to substrate.	Correa *et al.*, 2006; Marzinelli *et al.* 2009.
	Chains with tethers.	North 1976.
	Elastic/rubber bands to attach transplants to: – Natural substrates. – Artificial substrates. – Stumps of clear-cut macroalgae. – Longlines. – Plastic grids. – Buoys suspended above the substrate.	Westermeier *et al.* 2014, 2016. Layton *et al.* 2021. Hernández-Carmona *et al.* 2000. Westermeier *et al.* 2013. Westermeier *et al.* 2014. Wilson, Haaker & Hanan, 1977.
	Adhesive glues.	Serisawa *et al.* 2003; Westermeier *et al.* 2014, 2016.
	Epoxy putty to attach: – Transplants directly to the substrate. – Exorcised rock fragments hosting naturally occurring individuals to the substrate.	Susini *et al.* 2007; Tamburello *et al.*, 2019; Vásquez & Tala, 1995. Gao *et al.* 2017; Sales *et al.* 2011; Whitaker, Smith & Murray, 2010.
	Cable ties to attach: – Transplants directly to pre-installed plastic mesh. – Substrates hosting individuals to pre-installed plastic mesh.	Campbell *et al.* 2014. Vásquez *et al.* 2014.
	Deployment of substrates hosting laboratory reared individuals. – Bolted to the substrate. – In pens or loose on the substrate.	De La Fuente *et al.* 2019. Fredriksen *et al.* 2020.
Seeding involves enhancing the recruitment potential at restoration sites through the installation of translocated reproductive tissues/bodies, and the dispersal of early life stage cultures.	Installation of translocated reproductive tissues/bodies.	Choi *et al.* 2000; Collier & Machovina, 2005; Ford & Meux, 2010; Hernández-Carmona *et al.* 2000; Verdura *et al.* 2018; Westermeier *et al.* 2014.
	Installation of desiccated, translocated reproductive tissues/bodies.	Vásquez & Tala, 1995.
	Distribution of laboratory spore culture.	North 1976; Vásquez & Tala, 1995; Yu *et al.* 2012.
Artificial habitat creation involves installing structures on the seabed that mimic suitable substrate for kelp settlement and growth. They are often used in conjunction with other interventions such as transplantation and/or seeding.	Comprised of natural rocks/boulders.	Dean & Jung, 2001.

Table 3 (contd.): Definition of restoration techniques and examples of use. Adapted from Earp *et al.* (2022).

Technique	Examples	References
Competitor exclusion/removal refers to the removal of a species that would otherwise outcompete forest species for resources or inhibit their recruitment. Often used in conjunction with other interventions such as transplantation and/or seeding.	Clearing of turf algae.	Sanderson 2003; Fredriksen *et al.* 2020.
Herbivore exclusion/removal involves the installation of devices that exclude single or multiple herbivore species, or practices that remove specific herbivore species.	Multiple species exclusion using cages.	Bennett, Wernberg & de Bettignes, 2017; Tamburello *et al.* 2019.
	Multiple species exclusion using epoxy rings coated with anti-fouling paint.	Whitaker, Smith & Murray, 2010.
	Herbivorous fish exclusion using bubble curtains.	Bennett, Wernberg & de Bettignes, 2017.
	Urchin exclusion using plastic pseudo-kelp.	Vásquez & McPeak, 1998.
	Urchin removal by: – Collection and relocation. – Crushing with iron pipes. – Killing with quicklime (CaO).	Collier & Machovina, 2005; Ford & Meux, 2010. Taino 2010. Wilson, Haaker & Hanah, 1977.
Nutrient enrichment involves releasing nutrients to stimulate the growth of algae. Often combined with other interventions in mixed-method approaches (e.g. Yu *et al.* 2012).	Bags of steelmaking slag + compost (released iron humates).	Yamamoto *et al.* 2010.
Pollution mitigation involves the treatment of wastewater discharge.	Removal of suspended solids and biological treatment (including nitrification-denitrification process) of sewage outflow.	Diez *et al.* 2013.
Multiple techniques can be employed in restoration experiments and often involve a combination of active techniques to increase the number of individuals and passive techniques to provide a suitable environment for the individuals.	Seeding of and transplanting of individuals to artificial structures and pools.	Dean & Jung, 2001; Terawaki *et al.* 2001; Yu *et al.* 2012.
	Seeding of substrates transplanted to elevated positions in the water column to minimise sedimentation.	Carney *et al.* 2005.
	Excluding/relocating herbivores from areas containing transplants or that have been seeded.	Bellgrove *et al.* 2010; Collier & Machovina, 2005; North 1976; Vásquez & McPeak, 1998.
	Installing additional materials to protect transplants from desiccation and wave action.	Whitaker, Smith & Murray, 2010.
	Removal of competitors from areas with transplants.	Hernández-Carmona *et al.* 2000.

RECOMMENDATIONS FOR RESEARCH AND MONITORING

Monitoring is a fundamental requirement to determine whether natural kelp recovery is occurring, and also, the potential feasibility and effectiveness of any restoration activities being considered.

Establishing baselines, tracking change through continued monitoring, and ongoing research are vital to understand whether environmental conditions are suitable for kelp recovery/restoration, to assess potential barriers to kelp settlement and growth, to track ecosystem changes and to inform potential management initiatives.

Monitoring of a wide range of indicators as summarised below should ideally be undertaken on a regular basis (e.g. annually, seasonally, or monthly depending on the factor) and conducted using scientifically sound protocols that are consistent, replicable, and include comparison to reference or 'control' areas where possible/appropriate using before-after control-impact (BACI) designs and best practice guides.

The Kelp Forest Alliance and Ocean Wise published 'Monitoring Kelp Forest Ecosystems: A Guidebook to Quantifying Biodiversity' in 2024, providing a comprehensive overview of the different methodologies for monitoring the extent, health, and associated benefits of kelp forests (kelpforestalliance.com/knowledge-hub Knowledge Hub - Kelp Forest Alliance). The Kelp Forest Alliance guidelines will be updated as the field grows with new technologies and research (Eger *et al.* 2024).

Benthic monitoring

Substrate

While habitat maps exist for many areas, it would be beneficial to gain a better insight into the nature of these often dynamic habitats. For example, it is important to determine whether rocky habitats are comprised of bedrock, boulders and/or pebbles, as well as the rock type, as this may influence the species that may recolonise the area, as well as informing the most appropriate potential restoration techniques. Such monitoring can be conducted using towed arrays of high-definition cameras which can cover an extensive area, or through SCUBA diver surveys. In areas where sediment is present, it may also be beneficial to use ground penetrating techniques to identify whether this is truly sediment, or a veneer on bedrock.

Benthic species

Monitoring benthic species is beneficial for several reasons. Firstly, it could identify areas where species that may compete with kelp (e.g. turf algae) and thus present a barrier to recovery are prevalent. Secondly, it could identify areas where recolonisation and/or succession of benthic species is occurring that could ultimately lead to kelp recovery. It may also identify areas of suitable substrate for kelp should reef associated species be observed in areas otherwise considered unsuitable. This was the case in Lyme Bay where bedrock was found to underly soft sediment due to the presence of reef associated species which has been released from trawling disturbance (Sheehan *et al.* 2013a). Such monitoring could be conducted using towed HD cameras, drop down cameras and diver surveys.

Potential grazers

Understanding the abundance of key kelp associated species/grazers such as sea urchins could determine whether such species are overgrazing the kelp and present a potential barrier to recovery.

Water quality

Sedimentation

Monitoring of sediment transport and settlement within and adjacent to extant kelp beds as well as at potential restoration sites would generate further insights into sediment loading in the area, and potentially the tolerance of local kelp to sediments. Such monitoring could include the deployment of sediment traps as well as settlement plates (note: data loggers for other variables such as light and temperature could also be attached to the traps.

Turbidity and light

It would be beneficial to monitor turbidity and light adjacent to extant kelp populations and potential restoration sites in order to gain an insight into how water clarity may influence kelp morphology and growth in the area. Turbidity can be measured using a Secchi disk, while light could be monitored by deploying light loggers.

Nutrient and pollution concentrations

Both nutrients and pollution have the capacity to inhibit kelp recovery and allow for the proliferation of turf algae. As such, monitoring these parameters, including in the vicinity of extant kelp populations, as well as along gradients from potential sources such as river mouths and arable land (particularly after rainfall) could identify nutrient/pollution sources, and also provide an insight into the tolerance of local kelp to variation in these factors. Quantifying concentrations of nutrients/pollution could be done using SONDES probes or by taking water samples. Additionally, nutrient sources can at times be determined by blooms of opportunistic green algae such as *Ulva* spp. on the coastline.

Monitoring existing kelp habitats

Monitoring the extent and structure of kelp habitats alongside environmental metrics provides information needed to identify how kelp habitats are affected by different pressures and thus inform which areas may have the best potential for restoration.

Kelp habitat mapping

Identifying the location and extent of existing kelp areas is necessary in order to establish a baseline and subsequently monitor any expansion/losses, but also to identify potential connectivity between patches to determine whether propagule supply is a factor that may limit recovery of certain areas. This provides an idea of the distance propagules would need to travel to potential recovery sites. Such work may be supported by citizen science such as diver surveys (e.g. Seasearch).

Genetics and genomics

It may also be important to understand the genetic diversity and structure of extant kelp populations to conserve this diversity, identify source locations for expanding populations and investigate how genetic components may influence restoration success (Wood *et al.* 2020). This would initially involve taking small samples of kelp fronds from extant populations and sequencing targeted sections of DNA such as microsatellite markers (Guzinski *et al.* 2016; Liesner *et al.* 2020a).

Density, morphology, biomass, growth, and survival

Understanding the current structure and functioning of kelp habitats is important to provide a baseline against which to detect change in response to natural recovery, or to compare change as a result of adopting different restoration interventions. Diver surveys are the most cost effective and accurate method to monitor these factors. Density can be determined using quadrat and/or transect surveys, although drop down video and remotely operated vehicles could be used to monitor this factor (Burrows *et al.* 2014). Morphology and density can be determined by sampling a proportion of individuals per population and measuring factors such as stipe length, blade length, age, and biomass, as well as growth determined using the hole punch method. Protocols for monitoring kelp density and morphology are outlined in Smale *et al.* (2016) and Smale and Moore (2017), and the hole-punch method for monitoring growth is described by Parke (1948b).

To effectively monitor and assess the recovery of kelp habitats and associated species in Sussex, a comprehensive and integrated research and monitoring programme is necessary. Some of the monitoring activities identified above are currently being undertaken at the national level by the national kelp monitoring programme established in 2024 (Environment Agency, personal communication) and by regional or local projects led by partners in the Sussex Kelp Recovery Project, academic institutions, and partners in the Crustacean Habitats and Sediment Movement project (CHASM). It is recommended that a gap analysis is undertaken to identify any key indicators of kelp recovery that are not currently being monitored and to address these gaps.

CONCLUSIONS FOR SUSSEX KELP RECOVERY

While this report set out to present available ecological knowledge on the key kelp species historically present in Sussex waters, the optimal environmental conditions for natural kelp recovery, the factors that could limit natural kelp recovery or any potential active restoration activities in the area, and the monitoring and research requirements to track the recovery of kelp habitats in Sussex, much of the information presented and these conclusions are applicable to other UK regions.

Along the coastline of West Sussex, kelp beds, historically composed of *S. latissima*, *L. hyperborea* and *L. digitata* have declined in density and extent over the past 30 years. There is a growing interest in recovering these kelp habitats and their associated ecosystem services. This commenced with the Nearshore Trawling Byelaw 2019 which became enforceable in 2021, prohibiting bottom trawling on 300 km^2 of seabed, with the aim to facilitate the recovery of kelp and other essential fish habitats and their associated assemblages and ecosystem services.

Kelp recovery along the Sussex coast may be limited in part by the supply of kelp spores, and further information regarding the connectivity between areas of extant kelp beds and areas where kelp have declined would be beneficial. Should a source of spores be available, given that water motion along the Sussex coast generally occurs in an eastward direction, it is more likely that kelp spores will be carried in an eastward direction and that kelp recovery would occur in a west to east direction.

Environmental conditions including sedimentation, nutrient concentrations and pollution and increasing temperatures may also impact kelp recovery. Increasing sediment loads along the Sussex coast primarily arise from coastal erosion, land and river runoff and marine activities such as dredging and windfarm installation, and have been the focus of significant recent attention (SKRP 2024). Sediment loading can reduce the availability of substrate for kelp settlement, smother settled kelp spores and reduce water clarity and in turn light penetration that can negatively impact kelp productivity.

Management of some of the anthropogenic inputs may mitigate and reduce sediment loads, however coastal erosion and the resuspension of particulate matter held within the system linked with increased storm intensity and frequency will likely continue to influence kelp habitats in the future. Resilience to sediment varies, favouring species more resilient to high sediment loads such as *S. polyschides* and fast-growing sediment tolerant turf algae. Increased sedimentation could therefore drive a shift in the distribution/composition of kelp species in Sussex or inhibit recovery due to competition from non-kelp species.

Rising sea temperatures may also impact kelp recovery and while temperatures are currently within the thermal tolerance limit of kelp species historically common in the Sussex area, extreme temperatures have been experienced on the south coast of the UK in recent years. Increasing temperatures could have negative impacts for kelp early-life stages, as well as the productivity of mature adults, and may also drive changes in the composition of kelp beds, with warm-water tolerant species (e.g. *L. ochroleuca*) more likely to survive and thrive.

Nutrient and pollution concentrations in Sussex waters can favour proliferation of turf algae and phytoplankton at the expense of kelp – although concentrations of these elements are not currently being widely monitored in Sussex and so their potential impact on kelp recovery remains unknown.

Monitoring along the Sussex coast is a vital requirement to determine whether environmental conditions are suitable for kelp to persist. Monitoring should include: benthic monitoring to determine the substrate type, sedimentation rates and the composition of benthic communities; water quality monitoring to understand local turbidity/light levels; monitoring of nutrient and pollution concentrations; kelp habitat monitoring to determine the extent, density, morphology, growth, survival and genetic composition of kelp populations in the area; and monitoring to understand the abundance and composition of kelp-associated communities (e.g. herbivore populations).

Monitoring should ideally be undertaken once every month or season and conducted using scientifically proven protocols that are replicated and compared to reference areas - using before-after control-impact (BACI) designs where possible and appropriate.

If environmental conditions are deemed suitable for the growth and reproduction of kelp, but natural recovery is limited, active restoration interventions may be required to assess whether, with assisted direct intervention, kelp can settle and grow in sufficient abundance to create a self-sustaining population. Restoration of kelp along the Sussex coast, however, should not necessarily aim to recreate the historic habitats, but instead to create an environment where kelp may survive and form self-sustaining populations that in turn attract a diverse array of associated species and provide a variety of valuable ecosystem services.

Identifying the most appropriate target species for such restoration is challenging but given that kelp beds along the Sussex coast were historically comprised of *S. latissima*, *L. digitata* and *L. hyperborea*, these would be the most appropriate candidates for initial restoration activities. Similarly, identifying the most appropriate sites for restoration is not simple, and environmental conditions at potential sites should be monitored before commencing restoration activities to ensure they are suitable for the target kelp species.

A suite of techniques are available for kelp restoration, however along the Sussex coast, transplanting and seeding are likely to be the most appropriate techniques. Transplantation is a relatively successful restoration technique, and it can be beneficial in enhancing local environmental conditions that promote additional kelp settlement and growth, however it is often labour intensive and can have detrimental impacts on source populations. Transplantation using green gravel (i.e. rock seeded with kelp, reared in aquaria and outplanted at sea) can overcome some of these limitations and is considered the most promising technique for any future potential kelp habitat restoration in Sussex, although high energy environments such as Sussex may lead to large displacement of seeded gravel as seen in other trials (e.g. Marques *et al*. 2024, Earp *et al*. 2024c). The feasibility of seeding, as an option for Sussex kelp restoration, could be enhanced if used in combination with other techniques and conducted in areas where mature kelp are already present, however it is challenged by the high mortality rates of early kelp life stages.

Other restoration techniques including herbivore and competitor exclusion, and the installation of artificial substrates are either less applicable to the Sussex context and/or are not currently cost-effective options at scale.

As there are limited examples of active kelp restoration in the UK, it is important that any efforts in Sussex adhere to international principles and standards, and that scientific literature concerning the target kelp species, restoration technique and restoration of areas with comparable environmental conditions is reviewed. In regards to international standards, Gann *et al*. (2019) sets out a series of principles that underpin ecological restoration relating to the planning and design, implementation, monitoring and evaluation and maintenance of restoration projects upon completion and many points relating to these principles were touched on in this report.

In addition, pilot studies should be conducted to determine the most appropriate kelp species, restoration site, and technique prior to commencing any large-scale restoration efforts.

As with Sussex IFCA's Nearshore Trawling Byelaw, future work would benefit from incorporating the principles of ecosystem-based management (EBM) regarding both the extant kelp beds to the west of Sussex that may provide a source of spores for kelp recovery and to maximise the effectiveness of kelp recovery and any restoration efforts. An EBM approach aims to ensure that the cumulative impacts of human activities are kept within thresholds to ensure healthy and resilient ecosystem conditions that provide the desired ecosystem services (UNEP 2023). EBM approaches are believed to be suitable for kelp ecosystems and recently, Hamilton *et al*. (2022) identified six principles for EBM of kelp forests:

1. Monitoring at biologically relevant spatio-temporal scales
2. Identifying and managing cumulative stressors
3. Managing across spatial and institutional scales
4. Developing and implementing co-management approaches with users
5. Rapid adaptive management
6. Managing food-web connections.

Developing an EBM approach is challenging however, often requiring several cycles of planning and implementation, and should be underpinned by robust monitoring and collaborations. Further information on EBM of kelp forests can be found in the UNEP Into the Blue Report (2023).

There is no clear or guaranteed trajectory for the recovery of kelp habitats along the Sussex coast, and it is possible that active restoration interventions may be required to aid recovery. Any active restoration efforts should involve pilot studies to determine the most appropriate kelp species, restoration sites and protocols before any large-scale efforts are undertaken and should be accompanied by robust monitoring protocols (e.g. BACI designs).

In summary, mitigating stressors that caused the original kelp degradation and declines in the Sussex area or could hinder or prevent recovery, and improving local environmental conditions to optimise the chances of natural kelp recovery or any assisted restoration deemed appropriate in future, should be the priority in the short to medium term.

GLOSSARY

Blades – Flat, leaf-like structures where photosynthesis occurs. These structures may also be referred to as the fronds. Some kelp species have a single blade per individual (e.g. *Saccharina latissima*), which in some species is divided into multiple digits (e.g. *Laminaria hyperborea*), while some species have multiple blades per individual/stipe (e.g., *Macrocystis pyrifera*).

Blue carbon – The carbon captured and stored by coastal and marine ecosystems, particularly algae, mangroves, tidal marshes, and seagrasses. Blue carbon also relates to carbon stored in seabed sediments, fish, and shellfish.

Boundary layers – Thin layers of seawater that form around kelp blades and other marine organisms. These layers affect the chemical and physical environment around the kelp, and can impact the organisms that live on it.

Carbon sequestration – The process by which carbon dioxide is removed from the atmosphere, for example by trees, grasses and algae through photosynthesis, and its long-term storage (>100 years) as carbon in plant biomass, soils, and sediments.

Carbon sink – An area or habitat that absorbs a greater quantity of carbon dioxide from the Earth's atmosphere than it releases, and stores it in the form of carbon, thereby reducing the effects of global warming.

Digits – Strap-like divisions of a single kelp blade (e.g. Laminaria digitata and *Laminaria hyperborea*).

Ecosystem based management – An integrated approach for managing anthropogenic activities that cause cumulative impacts on ecosystems.

Ecosystem services – The varied collection of benefits including goods and services that natural ecosystems provide to humans These include provisioning services (e.g. food, fuel, and raw materials), regulating services (e.g. climate regulation, carbon storage), cultural services (e.g. tourism and recreation) and supporting services (e.g. basic natural processes such as photosynthesis).

Ecotype – A group of organisms that are specifically adapted to local environmental conditions.

Eutrophication – A process by which excessive nutrients enter a water body. This can result in a dense growth of aquatic plants that has a negative impact on the ecosystem.

Fetch – The distance of open water over which the wind blows without obstruction, with larger fetches allowing larger waves to be generated.

Gametophyte – The microscopic, haploid phase of the kelp lifecycle which produces gametes that bind together to form a zygote from which the sporophyte arises.

Haptera – Irregular, branching, root-like structures that intertwine to form the kelp holdfast and attach the kelp to the substrate.

Holdfast – A root-like structure that anchors kelp to rocks or other hard substrate on the seafloor comprised of a complex web of root-like projections called the haptera.

Photosynthesis – The process by which kelp and other plant species use light, carbon dioxide and water to create energy (sugars) and oxygen.

Pneumatocysts – Air-filled bladders that provide buoyancy to the kelp and help them stand up in the water column (e.g. *Macrocystis pyrifera*).

Prostrate kelp – Kelp species that cover the substrate with their fronds (e.g. *S. latissima*).

Stipe – A stem- or trunk-like structure that provides support for the kelp blades. The stipe of some kelp species, for example *L. hyperborea*, may be overgrown with epiphytic organisms such as red algae. Some kelp species only have one stipe per individual (e.g., *L digitata*), whereas some kelp species have multiple stipes per individual and are known as 'multi-stipate' (e.g. *Lessonia trabeculata*).

Sori – Reproductive sorus tissues containing cells known as the sporangia that produce and contain the kelp spores. These tissues can be located either on the blade of the kelp, on sporophylls, or occasionally on the stipe and holdfast depending on the kelp species.

Sporophyll – An additional blade bearing reproductive cells known as the sporangia that produce and contain the kelp spores. This blade is grown solely for the purpose of reproduction in some kelp species (e.g. *Undaria pinnatifida*).

Sporophyte – The adult, diploid phase of the kelp lifecycle which reproduces asexually by releasing spores from reproductive tissue called sori.

Stipitate kelp – Kelp species that generally extend a few metres above the sea floor to form sub-surface canopies, with their blades supported by rigid stipes (e.g. *L. hyperborea* and *L. digitata*).

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