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FROM THE *TORREY CANYON* TO TODAY: A 50 YEAR RETROSPECTIVE OF RECOVERY FROM THE OIL SPILL AND INTERACTION WITH CLIMATE-DRIVEN FLUCTUATIONS ON CORNISH ROCKY SHORES

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ABSTRACT

The *Torrey Canyon* was wrecked in 1967 with 117,000 tons of crude oil on board. The Plymouth Laboratory of the Marine Biological Association (MBA) of the UK was mobilized to deal with this environmental catastrophe. Many of the rocky shores affected by the spill and unaffected control sites had been studied by staff from the MBA, with A.J. and E.C. Southward charting fluctuations of rocky shore fauna and flora from the early 1950s – particularly barnacles – in relation to climate. Thus a baseline existed to help judge recovery of rocky shores from the beached oil and application of toxic first generation dispersants. A reminder is given of the initial acute impacts of the oil and its treatment by dispersants, and the first ten years of observations on recovery of shore communities. Subsequent follow-up work in the 1980s and 1990s suggested recovery took up to 15 years on the shore (Porthleven) subject to the most severe dispersant application. In contrast, recovery occurred in 2-3 years at Godrevy, a site where dispersants were not applied due to concerns about the impact on seals. The dispersants killed the dominant grazer, limpets of the genus *Patella*, leading to massive subsequent colonisation by seaweeds. The resulting canopy of fucoid algae (“rockweed” or “wrack”) facilitated dense recruitment of limpets. These subsequently grazed the seaweeds down, before the starving limpets largely died off after migrating across the shore in search of food. This reduction in limpet numbers and grazing pressure then prompted a further bloom of algae. There was then a return to normal levels of spatial and temporal variation of key species of seaweeds and limpets fluctuations charted at Porthleven from the mid 1980s to 2016. Comparisons are made with other oil spills for which long-term recovery has been assessed. Lessons learnt from observations stretching back 60 years, both

before and after the spill, for rocky shore monitoring are highlighted – especially the need for broad-scale and long-term monitoring to separate out local impacts (such as oil spills) from global climate-driven change.

INTRODUCTION

The *Torrey Canyon* was wrecked on 18th March 1967 on the Pollard Rock of the Seven Stones reef, 15 miles (25 km) from Land's End, Cornwall, southwest England, UK (Figure 1). The 970 foot (300 m) tanker was bound for oil refineries at Milford Haven with 117,000 tons of Kuwait crude oil. She struck the rocks at 17 knots, tearing open six of her 18 storage tanks and less severely damaging the others. Salvage attempts failed. The ship progressively broke up over the next six weeks due to storm damage and bombing on the 28th, 29th and 30th March in an attempt to burn the oil. She was officially declared to contain no more oil towards the end of April 1967 (Smith 1968). Around 150 km (90 miles) of Cornish coast were affected with a similar extent of severe pollution in the other side of the English Channel in the Channel Islands (particularly Guernsey) and Brittany, France.

The *Torrey Canyon* oil spill attracted much media attention and political intervention. The Prime Minister at the time, Harold Wilson, took a personal interest. He had a holiday home on the Isles of Scilly, seven miles to the southwest of the wreck. It was also the first spill involving the first generation of super-tankers. Furthermore, it was treated – excessively in many instances – by the first generation of dispersants. These were in effect industrial cleaning agents – euphemistically called detergents at the time (e.g. Smith 1968). More damage was done by the dispersant applied than by the oil itself that came ashore in west Cornwall (Nelson-Smith 1968, Corner et al. 1968, Bryan 1969).

Fifty years on from the wreck, our paper briefly summarises the acute impacts and response to the oil spill, from the perspective of the Plymouth Laboratory of the Marine Biological Association of the UK (MBA) - all of whose staff were mobilised to deal with the spill for six weeks (Smith 1968). MBA scientists were subsequently involved in long-term studies of recovery of rocky shores for the next ten years or so (Southward 1979, Southward and Southward 1978), continued by S.J.H. since 1980 in concert with Alan and Eve Southward at one of the worst affected shores – Porthleven (Hawkins et al. 1983, Hawkins et al. 2002, Hawkins and Southward 1992, Hawkins et al. in press, in prep.) and more recently (since 2002) with N.M..

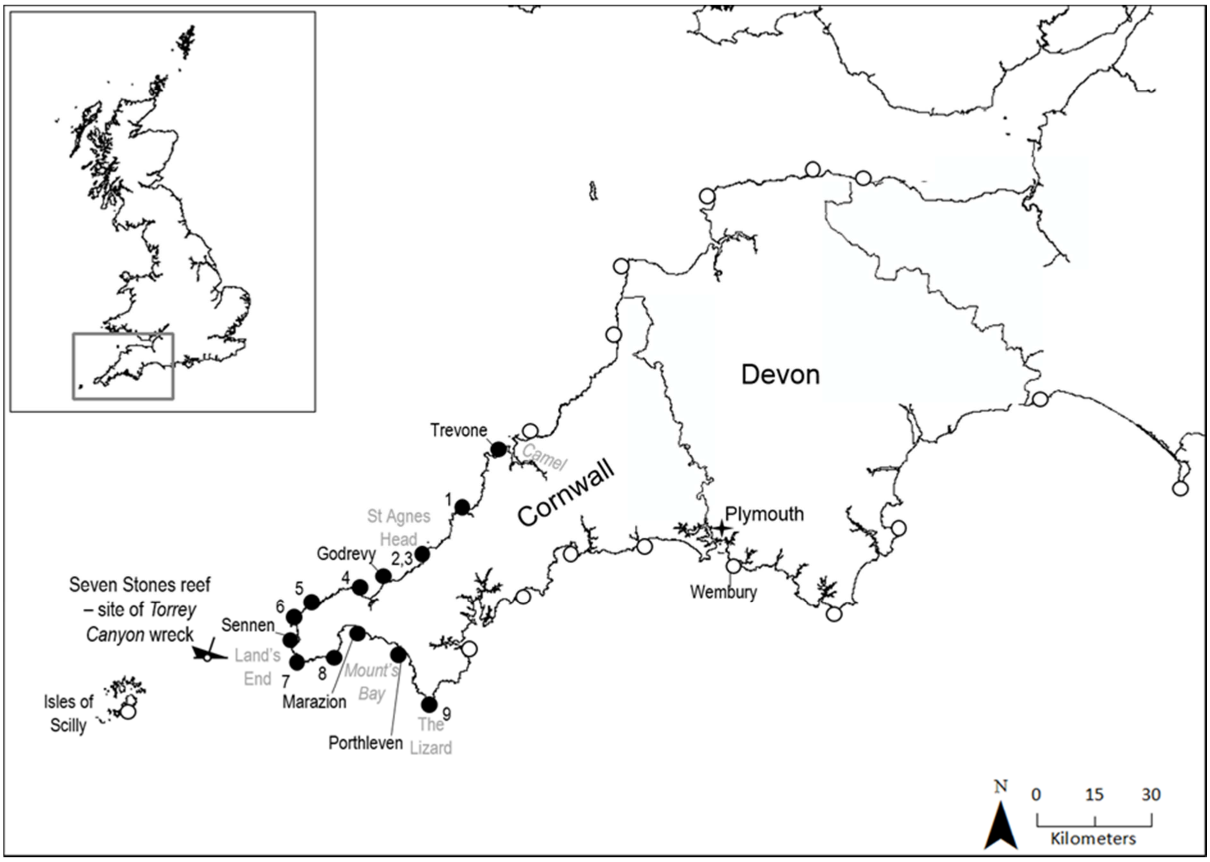

Figure 1 Long-term study sites in southwest England monitored since the 1950s by A. J. Southward and E. C. Southward, and more recently by S. J. Hawkins, Nova Mieszkowska and colleagues from the MBA. Closed circles represent sites affected by the *Torrey Canyon* oil spill and clean-up operation. Open circles represent sites not affected by the incident. Numbered sites are: 1, Newquay;

2, Chapel Porth; 3, Porthtowan; 4, St. Ives; 5, Pendeen; 6, Cape Cornwall; 7, Porthgwarra; 8, Lamorna Cove and Mousehole (very light oiling); 9, Lizard Point.

A network of shores had been studied in the southwest of England for over a decade before the spill (Southward 1967; Figure 1), primarily to understand the influence of climatic fluctuations on intertidal species, particularly barnacles (Southward and Crisp 1954). These observations were subsequently maintained by Southward (e.g. Southward 1991, Southward et al. 1995) and continued or re-started by Hawkins, Mieszkowska and co-workers (e.g., Hawkins et al. 2003, 2008, 2009, Mieszkowska et al. 2006, 2014a,b). The trajectory of recovery following the *Torrey Canyon* oil spill is discussed in relation to its interaction with climate fluctuations and other sources of chronic pollution such as Tributyltin from anti-fouling paints (Bryan et al. 1986, Spence et al. 1990). The *Torrey Canyon* is put into context of other selected spills, in terms of treatment and recovery times. In the discussion, we consider what recovery means and reflect briefly on how oil spill response has changed over the years since the *Torrey Canyon* incident.

THE ACUTE PHASE – INITIAL IMPACTS AND RESPONSE

This brief summary is largely based on the detailed account in Smith (1968) and discussions with former MBA staff who were present at the time of the spill. Following oil becoming stranded ashore, there was, on both sandy and rocky shores, massive application of highly toxic first generation dispersants (see Nelson-Smith 1968, Smith 1968 for details). Around 14,000 tons of oil came ashore, upon which 10,000 tons of dispersant was applied. The most commonly applied dispersant was BP1002 (Smith 1968), with several other proprietary products also used all contained between 66-85% organic solvent with a high proportion of aromatics (up to 85%), a surfactant (often an ethylene oxide condensate) and a stabilizer such as coconut oil diethanolamide (Smith 1968). The armed forces had been mobilised to deal with the oil coming ashore. The priority was to preserve the amenity value of the seashores around Cornwall, one of the UK's premier tourist destinations. There was much less concern about the consequences for marine life.

On pebble and sandy shores, spraying of dispersants was combined with attempts at mechanical oil recovery. Temporary quick sands were produced by the oil-dispersant mixture lasting up to a month. The use of dispersant caused the oil to sink deeply in some beaches. There was evidence at the time that the dispersant killed oil-degrading bacteria, especially at high concentrations (Smith 1968; see Kliendiest et al. 2015 for recent research). Fortunately, there was very little life in the exposed coarse-sediment beaches of west Cornwall, but dispersant application appeared to hinder rather than help the clean up. In France, where oil was deposited some time later, lessons were quickly learned from the experience in Cornwall and a much more nuanced approach was adopted, with minimal use of dispersants on sandy beaches, including the use of straw and gorse ("brush-wood") to aggregate oil for subsequent collection and disposal.

On rocky and boulder shores, a thick layer of oil came ashore in most places between the Lizard and the Camel Estuary (Figure 1). Vast amounts of dispersant were either sprayed on the oil, or in the case of more remote and inaccessible beaches, applied by rolling drums of neat dispersant over the cliff edge to rupture on the rocks below. Particularly heavily treated areas included Porthleven, Sennen, Cape Cornwall, St. Ives and Trevone. Godrevy was one site where dispersant was not applied because of concerns about seals from its owner, the UK conservation charity The National Trust.

At sites where oil was stranded but not treated, or observations were made for a few days before dispersants were applied, there was little mortality of seashore plants and animals. Damage was particularly minimal on steeply sloping rocks. Limpets (*Patella* spp.) seemed to browse on the oil, helping to clear the rock surfaces (Smith 1968). In contrast, on shores with heavy dispersant application, there was widespread mortality of algae (seaweeds), invertebrates, such as snails and crabs, and shore fish. Extensive mortality of algae was observed, especially adjacent to dispersant spraying at mid and high shore levels. Amongst the invertebrates, gastropod molluscs (limpets of the genus *Patella* in particular) were very vulnerable and died in large numbers. The differences were stark in the region between Porthtowan and St. Agnes Head. At Porthtowan, which was heavily sprayed with dispersant, there were bright green rocks in July and August 1967, due to proliferation of ephemeral green algae in the absence of grazing molluscs, particularly limpets. To the north in the National Trust-owned Chapel Porth, which had not been sprayed, the rocks had a normal flora and fauna, being dominated by barnacles and grazing limpets.

LONG-TERM AND BROAD-SCALE OBSERVATIONS OF RECOVERY ON ROCKY SHORES

The summary below is based on previous work on recovery of shores from the *Torrey Canyon* incident (Southward and Southward 1978, Southward 1979, Hawkins et al. 1983, 1994, 2002, Hawkins and Southward 1992). Furthermore, we have re-analysed archived data and photographs (e.g. Figure 2), plus new data collected since 1990 (see also Hawkins et al. 2017, and in prep.). Trajectories of recovery are put into the context of broader-scale work on responses of rocky shore biota to climate fluctuations and more recent rapid climate change (Southward and Crisp 1954, 1956, Southward 1967, 1991, Southward et al. 1995, 2004, Hawkins et al. 2003, 2008, 2009, Mieszkowska et al. 2006, 2014a,b, Poloczanska et al. 2008) at a network of sites both affected by the *Torrey Canyon* oil spill and on unaffected shores in the region (Figure 1). Keeping such time series going is challenging; there are inevitably a few gaps in the data.

Southward and Southward (1978) charted the first ten years of recovery following the *Torrey Canyon* incident (see also Hawkins et al. in press) on shores subject to different levels of dispersant applications. Death of grazing limpets due to dispersant application led to a flush of ephemeral, mainly green, algae (seaweeds) in the first 12 months (Figure 2B). This had been shown previously (Jones 1948, Southward 1964) and subsequently (Hawkins 1981a,b, Hawkins and Hartnoll 1983a, Jenkins et al. 2005, Coleman et al. 2006) in small-scale removal and exclusion experiments. Massive recruitment of *Fucus* species (“rockweed” or “wrack”) then followed (Figures 2B and 3A), as also occurred in experimental limpet removals or exclusions. A dense canopy of seaweed (*Fucus*) followed for up to five years. Under this canopy, any surviving barnacles died due to a combination of smothering by algae, predation by the dogwhelk (or “drill”), *Nucella lapillus*, or by being plucked off the rock when large plants that were directly attached to barnacles were dislodged by wave action (Hawkins and Hartnoll 1983a,b, Hartnoll and Hawkins 1985). Recruitment of barnacles from the plankton was also reduced by sweeping of *Fucus* fronds (Hawkins 1983, Jenkins et al. 1999).

Dense canopies of the seaweed *Fucus* provide an ideal nursery ground for limpets and the following year a very heavy recruitment via larvae from adjacent uncontaminated sites occurred. Fucoid algae do not normally occur on very wave-exposed shores. Even Sennen, one of the most exposed rocky shores in England (Figure 1), became covered by fucoids demonstrating that limpet grazing, not wave action, prevents establishment of these species. Subsequent experiments have confirmed that limpet grazing prevents establishment of fucoids, but persistence is determined by dislodgement by wave action (Jonsson et al. 2006). The *Fucus* phase lasted longest on the most heavily dispersant-treated shores (Porthleven, Trevone), but was probably abbreviated at Sennen due to wave action. This phase of high cover by seaweeds was erroneously reported by some as recovery (e.g. Mellanby 1972). With time, the seaweed canopy cover declined (Figures 2B and 3A). This was due to a combination of *Fucus* being lost due to dislodgement and also the direct grazing activity of the huge population of limpets under the canopy, munching away at the *Fucus* holdfasts and fronds (Notman et al. 2016).

At Porthleven, the shore was particularly bare without seaweeds from 1973-1978 due to overgrazing by the massive population of limpets (Figures 2B and 3). The starving limpets abandoned their normal homing behaviour leaving their home-scars, migrating in a lemming-like front across the shore before many of them died. This dense population of adult limpets also inhibited recruitment of juveniles (Hawkins et al. 1983, Hawkins and Southward 1992) due to severe inter-age class competition (Boaventura et al. 2003). Following this bare phase, there was a subsequent burst of *Fucus* recruitment in the early 1980s due to low numbers of limpets (Figure 3). Since the 1980s, at Porthleven there have been periods with little *Fucus*, interspersed with pulses of *Fucus* recruitment (Figure 3A). The largest occurred in the early 2000s. This probably represents recovery in 13-15 years to natural fluctuations in the balance between limpet grazing and *Fucus* recruitment (Hawkins and Hartnoll 1983b). Similar recruitments of *Fucus* have been seen on other shores in the southwest of England since broader-scale observations resumed in 2002 (Hawkins and Mieszkowska unpublished observations).

Southward and Southward (1978) proposed that recovery following the *Torrey Canyon* incident would occur via aphasic damped oscillations between the dominant grazer and fucoid algae, the dominant seaweed on the shore.

Recovery processes also interacted with climate fluctuations (see Figure 4) driving the relative abundance of both barnacle (northern cold-water *Semibalanus balanoides* and southern warm-water *Chthamalus* species) and limpet (northern *Patella vulgata* and southern

P. depressa) species (Southward et al. 1967, 1991, Southward et al. 1995, Hawkins et al. 2008). *Patella depressa*, a warm-water species, was particularly slow to recover, with lower abundances in the cooler 1960s and 1970s (see Figure 3B) than in the warmer 1950s (Southward et al. 1995, Kendall et al. 2004, Hawkins et al. 2008, 2009). Since the late 1980s, air and sea temperatures have risen in southwest England (Figure 4) and *P. depressa* is much more common than in the early 1980s (Figure 3B) – the end of the cool period. This species does not thrive under *Fucus* clumps, unlike *P. vulgata* (Hawkins and Hartnoll 1983a, Burrows and Hawkins 1998), which aggregates under *Fucus* and disperses or dies when the canopy is removed (Moore et al. 2007). Thus, recovery of this species was impeded by dense fucoid cover on *Torrey Canyon* impacted shores probably favouring *P. vulgata*, coupled with the colder climate of the 1960s and 1970s reducing recruitment in the region as a whole.

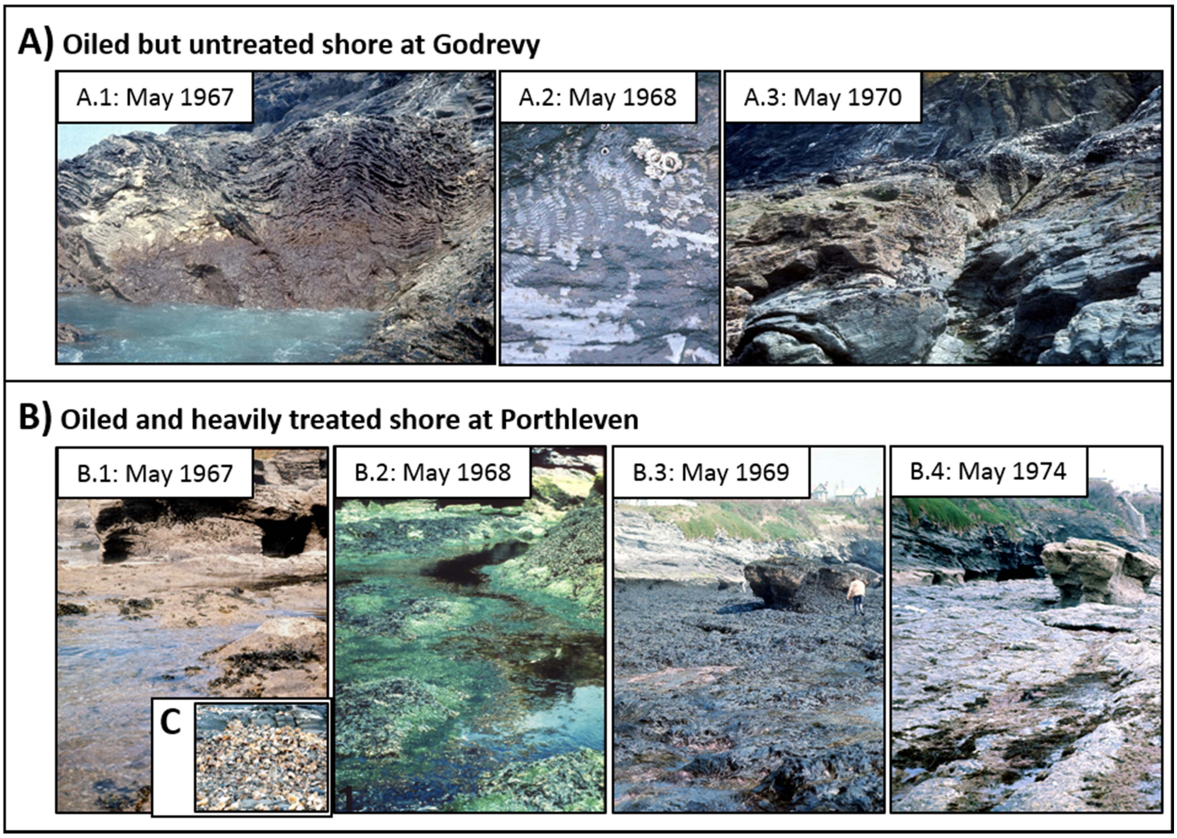

Figure 2 Time series photographs of rocky shores at (A) Godrevy (oiled but untreated with dispersants) and (B) Porthleven (heavily treated). (C) Pile of mollusc shells, including limpets, at

Trevone taken in December 1967. Godrevy received moderate drifting oil in late March 1967 (oiled rock face shown in A.1). In 1968 limpet tooth marks on this rock face indicated that limpets were feeding on the dried oil, helping to clean up the rocks (A.2). Three years later the shore was back to normal appearance (same rock face shown in A.3). In contrast, at Porthleven, which was heavily sprayed with dispersants, killing most of the limpets, a massive bloom of green seaweeds occurred due to lack of grazing (B.2). This was followed by dense growth of brown fucoid seaweeds ("rockweed" or "wrack") in 1969 (B.3), and then a very bare phase in 1974 (B.4) due to overgrazing by a massive recruitment of limpets under the fucoid canopy. The photograph of Porthleven in 1967 (B.1) was taken in May 1967, soon after dispersant application and shows the natural patchiness on the shore – originally covered by barnacles with small patches of fucoids. Images: A.J. Southward and E.C. Southward.

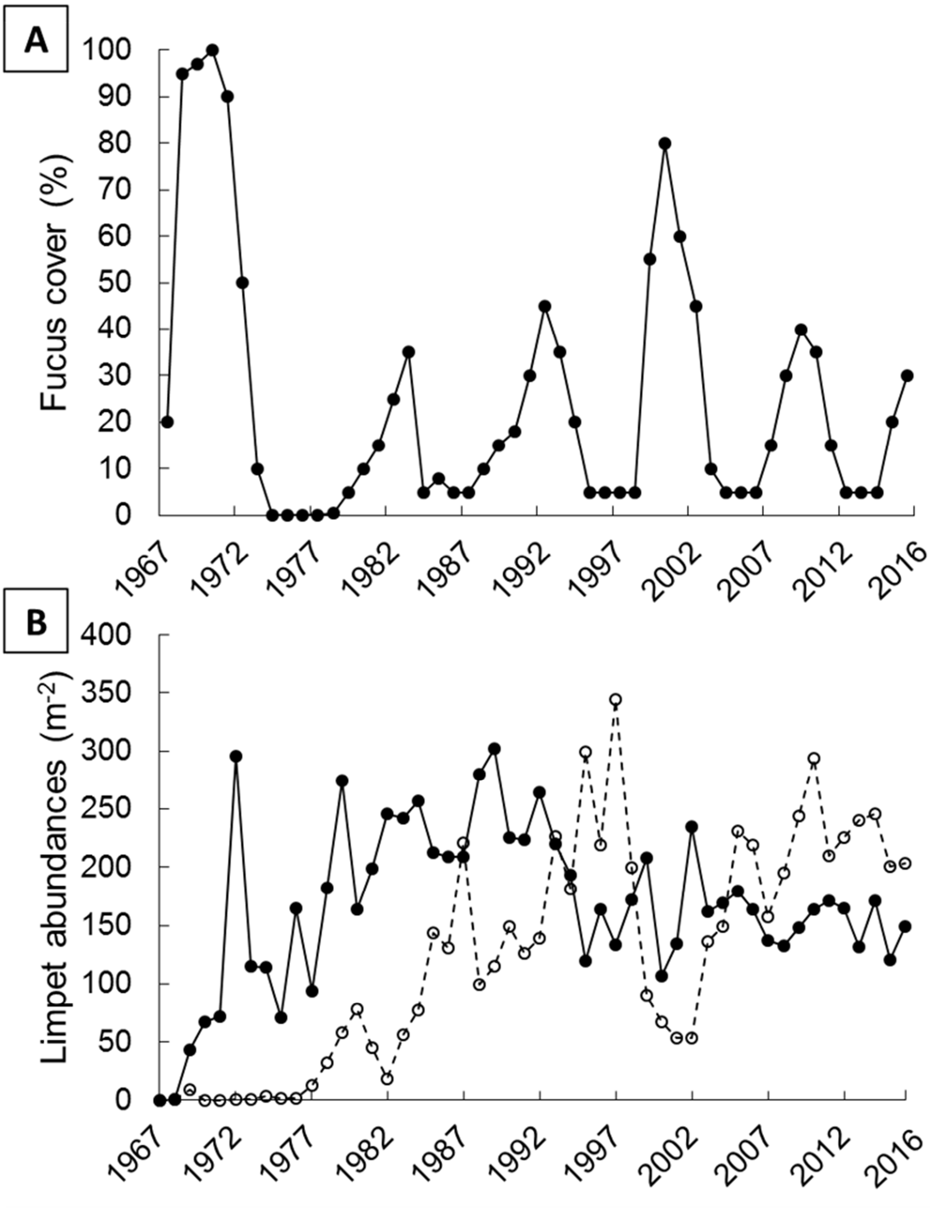

Figure 3 Fluctuations during recovery in (A) *Fucus* ("rockweed" or "wrack") canopy cover and (B) cold-water limpets *Patella vulgata* (solid line) and warm-water limpets *P. depressa* (dashed line) at Porthleven between 1967 and 2016. Adapted from Hawkins and Southward 1992, Southward and Southward 1978, Hawkins et al. 2017; updated with new data.

In stark contrast, the shore at Godrevy that received no treatment by dispersants, recovered within two to three years. There was no major flush of ephemeral algae followed by massive fucoid recruitment. The shore swiftly returned to normal appearance (Figure 2A, Southward and Southward 1978, see also Hawkins et al. in press).

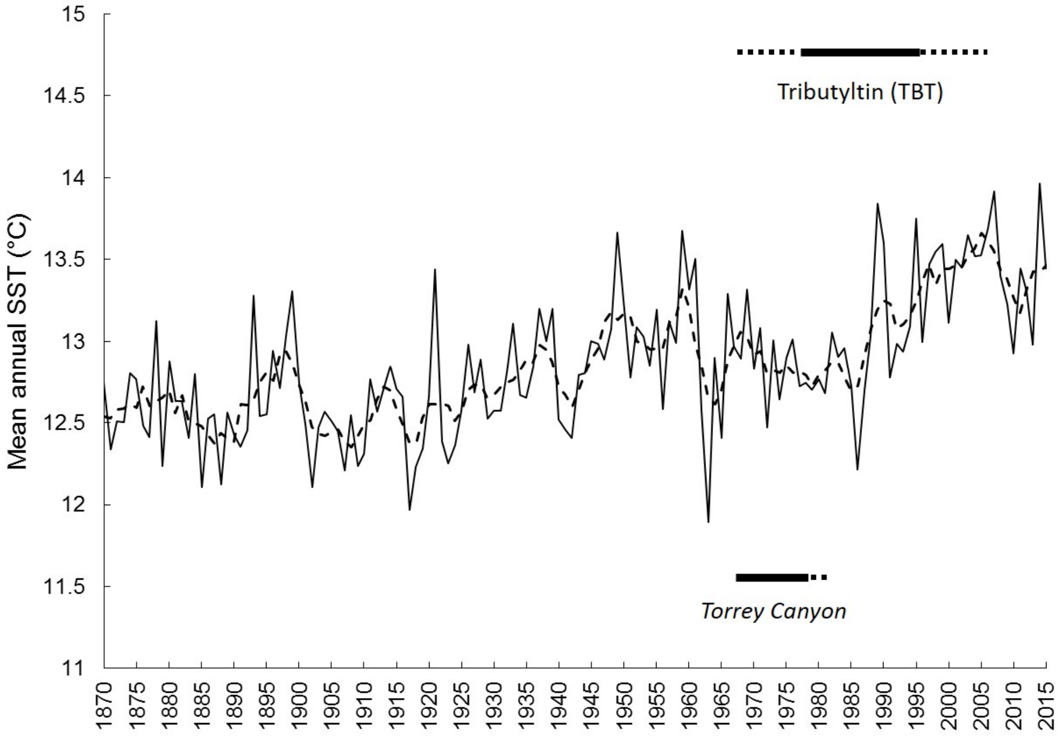

Figure 4 Mean annual Sea Surface Temperature (SST) 1870-2015 off Plymouth, UK (data from UK Met Office Hadley Centre) (solid line: annual mean temperature; dashed line: 5-year running average). Duration of acute pollution from the *Torrey Canyon* oil spill and chronic pollution from Tributyltin (TBT) based antifouling paints is indicated by bars (solid bar: greatest impact; dotted bar: onset or recovery). Modified from Hawkins et al. (2017).

One species that was badly affected by the oil spill in Mount's Bay was the hermit crab, *Clibanarius erythropus*. This warm-water species first appeared in southwest England during the warm spell of the 1950s (Southward and Southward 1977). Subsequently there was little recruitment in the much colder 1960s and 1970s and the populations at Marazion (Figure 1), affected by the oil spill, and populations at a non-impacted control site, Wembury (Figure 1), eventually died out (Southward and Southward 1988). No recruitment of *C. erythropus* occurred even during the warm 1990s and 2000s. This was perhaps due to shortage of shells as a result of ‘imposex’ in dogwhelks induced by Tributyltin (TBT) pollution that had led to local extinctions (Spence et al. 1990) in the preferred shell of the hermit crab. In 2016, *C. erythropus* was re-discovered in west Cornwall, presumably recruiting from France in 2014 and/or 2015. This species is an example of recovery from an oil spill being delayed by climate fluctuations and possibly chronic regional scale pollution – such complex interactions can only be revealed by sustained observations (Hawkins et al., 2017).

COMPARISON WITH OTHER SPILLS

The magnitude and time-scale of rocky shore impacts from the *Torrey Canyon* response have few parallels. Spills of diesels and other light oil products with high aromatic content (e.g. 1957 *Tampico Maru* spill on the Pacific coast of Baja California) have had devastating local effects, but rarely so extensively and intensively on sessile fauna and flora (Auris 1994, Sell et al. 1995). Further, where long-term impacts on rocky shores have been demonstrated, they have largely resulted from persistent smothering of tar residues (e.g. 1986 *Vivita* spill, Curaçao) or considerable physical disturbance and consequent instability (e.g. 1978 *Esso Bernicia*, on boulder shores in the Shetland Islands) (Moore 2006a). Without continued impact, the time scales of recovery are a product of natural ecological processes and the rates of growth and maturation of affected species (Kingston 2002). Mostly the recovery time is short (e.g. 1993 *Braer* spill, Shetland Islands, aided by much natural dispersion by storms).

The literature shows that for almost all oil spills, most of the biodiversity recovers quickly, with a small proportion of the worst affected occasionally taking a lot longer (Moore 2006a).

Studies of rocky shore community recovery following the 1989 *Exxon Valdez* (Alaska) and 1996 *Sea Empress* (South Wales) spills did describe some similar features to those of *Torrey Canyon*. Following the *Exxon Valdez* spill, like the *Torrey Canyon* incident, the impacts of the oil were made worse by the clean-up response – in this case deluge with large volumes of warm water (see account in Houghton et al. 1997). The treatment resulted in severe losses of natural rocky shore plants and animals, including most of the fucoids ("rockweed"). Recolonisation and growth of all the typical species occurred gradually over the first three years, by which time much of the mid and upper shore was densely covered in fucoids, all of a similar age. However, many of these plants then died two years later, presumed to be at the end of their natural life, with consequent loss of associated animals. Another cohort of fucoid germlings replaced them the following year and started to grow, accompanied by gradual recolonisation by the associated animals. It was presumed that this pronounced cyclical change in the fucoid cover, akin to that described by Southward and Southward (1978) for *Torrey Canyon*, would continue until a more natural mixed age class structure was re-established. Some authors suggested that could take many years (Integral Consulting 2006), but no published survey data are available since 1997.

Following the *Sea Empress* wreck in 1996, a section of exposed rocky coast was severely oiled by a fresh light crude which caused more than 50% mortality of limpets and striking consequential effects to the associated populations of algae and animals (Crump et al. 2003). The expected flush of ephemeral algae duly occurred and was followed by a substantial growth of fucoid algae that are not normally present on such wave-exposed shores. Rapid recruitment and growth of juvenile limpets, followed by disappearance of the ephemeral algae, also took place, and limpet densities had returned to high levels by the end of 1998.

Meanwhile, fucoid algae (particularly the bladderless form of *Fucus vesiculosus*), which had reached blanket cover in spring 1997, remained dense until 1999, but then reduced rapidly and returned to pre-spill levels. In 2001, 5 years after the spill, the shore seemed to be very similar to that prior to the spill, with high densities of small limpets (Crump et al. 2003).

DISCUSSION

What constitutes recovery?

Recovery of a biological community or an ecosystem from an acute (pulse) or chronic (press) disturbance can be defined and measured in various ways. Return to previous conditions can be difficult to assess in highly variable coastal marine ecosystems. Such fluctuations are often driven in the short-term by weather-related changes in disturbance regimes, such as extreme storms or temperatures (e.g. Crisp 1964, Firth et al. 2015), coupled with variation in recruitment regimes of key species that, acting together, influence the outcomes of biological interactions between species. On longer time scales, climatic fluctuations and recent rapid climate change can influence population dynamics and interactions between species (e.g. Moore et al. 2007, Poloczanska et al. 2008, Firth et al. 2009, Mieszkowska et al. 2014a). Given the intrinsic spatial and temporal variability of rocky shores, reference conditions can be difficult to define. In the Northeast Atlantic, shores moderately-exposed to wave action can be particularly variable (Hawkins and Hartnoll 1983b, Hartnoll and Hawkins 1985) in contrast to shores of either extreme of exposure, which tend to be more stable. Thus for the rocky shores impacted by the *Torrey Canyon* oil spill and subsequent clean-up, recovery has been defined as return to normal levels of spatial and temporal variation in key species such as canopy-forming fucoid seaweeds and herbivorous limpets (Southward and Southward, 1978, Hawkins et al. 1983, Hawkins and Southward 1992). These key elements control the functioning of the middle of the rocky shore ecosystem fucoids being not only the major primary producer, but also forming a habitat for many other species (Hawkins et al. 1992, Thompson et al. 1996). Limpets control establishment of the fucoid vegetation and hence control the balance of primary and secondary production by filter feeders such as barnacles. A return to normal conditions is to an “envelope” of conditions rather than to a baseline. Such a definition is in keeping with an emerging emphasis on recovery being return to conditions that would have occurred if there had been no oil spill (Sell et al. 1995).

There are alternative approaches such as whole assemblage-level analysis of species richness, relative abundance and diversity. Such an approach is useful for offshore, subtidal and intertidal benthos collected by grabs or coring. It works less well on rocky shores where non-destructive sampling can be used to quantify a suite of dominant species. It has, however, been successfully applied to judge condition of rocky shores by sampling habitat providing sub-components such as kelp holdfasts (Smith 2000) or fauna associated with mussel beds (Crowe et al. 2004).

The *Torrey Canyon* oil spill in context

Fortunately, both during and since the *Torrey Canyon* oil spill, much has been learned. In France and in Guernsey (British Channel Islands), when *Torrey Canyon* oil arrived a few weeks later in 1967 much less damage was done by excessive dispersant application, learning from the earlier excessive response in Cornwall. In subsequent spills, dispersants have been used largely at sea and much more sparingly on shores and in a more targeted and proportional manner (Table 1). Dispersants in use have increasingly been improved to become much less toxic than those used in 1967. Table 1 is an attempt to summarize recovery rates of selected spills in comparable temperate settings. For rocky shores, we have found very few published studies of more than 10 years duration (but see work on the *Exxon Valdez*, Shigenka 2014; the *Sea Empress*, Archer-Thompson 2016; and the *Esso Bernicia*, Rolan and Gallagher 1991, Moore 2006a). Sheltered non-bedrock shores composed of boulders and cobbles, such as those in Prince William Sound impacted by the *Exxon Valdez*, have been observed to take much longer to recover than more exposed bedrock shores, partly due to oil being trapped and also due to disturbance during clean-up operations (Short et al. 2004, Moore 2006a). Shores in South Wales affected by the *Sea Empress* spill seemed to be well on the way to recovery after 5 years (Crump et al. 2003), even on shores that received some dispersant treatment. Population structure of the limpet, *Patella vulgata*, had returned to normal in terms of size, if not age structure (Crump et al. 2003, Moore 2006b).

What has certainly emerged during the *Torrey Canyon* oil spill itself, and subsequently, is that on most wave-exposed rocky shores letting nature take its course and relying on natural dispersal by waves and microbial degradation ("doing nothing") is usually the best option. Such shores are least vulnerable to spills (Baker et al. 1990), reflected in Environmental Sensitivity Index scores used worldwide in maps as part of oil-spill contingency planning. Pressure to be seen to be "doing something" should be resisted on exposed shores.

Table 1 Summary of selected well-documented major oil spills from tankers and estimated recovery times of rocky shores (various sources including International Tanker Owners Pollution Federation (ITOPF) database).

Ship	Location / Date	Amount of oil spilt (Tonnes)	Amount on shore / Length of coastline affected	Treatment on shore	Estimated recovery time	Key references
TORREY CANYON	Cornwall, UK 18/03/1967	117,000 (of which 20,000 burnt/ evaporated)	Cornwall: 14,000 tonnes, 150 km coastline France & Channel Islands: 21,000 tonnes, >60 km coastline	Dispersants (>10,000 tonnes), high pressure water washing	2-3 years on untreated rocky shores, 10-15 years on heavily oiled and treated shores	Smith 1968 Holme 1969 Southward & Southward 1978 Hawkins & Southward 1992 Hawkins et al. 2002
AMOCO CADIZ	Brittany, France 16/03/1978	223,000	>60,000 tonnes, 360 km coastline	Mechanical, high pressure hot water washing of rocky shores, other shores left to recover naturally	Approx. 3 years on untreated rocky shores, 7-8 years on treated shores	Bellier & Massart 1979 Gundlach et al. 1983 Auris 1994 Sell et al. 1995
EXXON VALDEZ	Valdez-Cordova, Alaska 24/03/1989	38,000	>7,000 km^2 of slicks, 800 km coastline (2000 km including islands/inlets)	Mechanical, high pressure cold and hot water washing	3 years on untreated shores, >9 years on treated shores	Peterson 2001 Peterson et al. 2003 Short et al. 2004 Payne et al. 2008 Boehm et al. 2014 Shigenaka 2014
SEA EMPRESS	Pembrokeshire, UK 15/02/1996	72,000	15,000 tonnes, 200 km coastline	Dispersants (12 tonnes), mechanical and manual cleaning, trenching, beach washing, sorbents	5 years, but majority of biological populations returned to former abundances after 2 years	Crump et al. 1999, 2003 Law & Kelly 2004 Moore 2006b Archer-Thomson 2016
ERIKA	Bay of Biscay, France 12/12/1999	20,000[a]	400 km coastline (water-in-oil emulsion formed due to duration at sea, significantly increasing volume & viscosity)	High pressure, hot water treatment on rocky shores, other shores left to recover naturally	>5 years on slow growing communities, or those heavily treated	Kerambrun & Laruelle 2001 Poncet et al. 2003 Jézéquel & Poncet 2011
PRESTIGE	Galicia, Spain 13/11/2002	63,000[a]	1,900 km coastline	Manual cleaning	>2 years (monitoring did not continue long enough to establish recovery)	Albaigés et al. 2006 Castège et al. 2014

[a] Heavy fuel oil

CONCLUDING COMMENTS

Any acute environmental impact should be treated as an experiment. Lessons can be learnt even during the course of an oil spill (i.e. contrast British over-reaction with the more subtle French approaches to the *Torrey Canyon* spill). Experiments need proper ‘controls’ (multiple unimpacted reference sites). Observations need to be made for an extended period – beyond the initial acute phase and the first phase of recovery. It is crucial to secure funding for this unglamorous work as part of any compensation package following a spill. Minor investment in structured “long-thin” scientific study not only allows impacts and recovery to be assessed objectively, but also enables adaptive management and better response to the next incident. Fortunately, since the *Torrey Canyon* spill, great advances have been made in responding to and cleaning spills. Contingency plans are in place worldwide. Dispersants are less toxic and used mostly at sea. Tanker accidents are also less frequent. But there still remains a lack of commitment to longer-term measurement of recovery.

Our study of recovery and subsequent natural fluctuations on rocky shores affected by the *Torrey Canyon* oil spill has shown the importance of long-term and broad-scale observations. Without the broader network of observations, themselves curtailed by large gaps (1987-1997) due to forced early retirement of key staff and funding issues, interpretation of the timescales of recovery and the underlying mechanisms would not have been possible. Our interpretation of recovery has been aided by much manipulative experimental work on the interactions between the key species (summarised in Hawkins et al. 1992). Certainly, such knowledge enables more targeted monitoring of recovery of key elements of the assemblage. Recovery to the condition that would have occurred if a spill had not occurred has to be judged both in the context of climate fluctuations and chronic pollutants as well as considerable short-term natural variability.

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