Rigs-to-reefs: will the deep sea benefit from artificial habitat?

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As a peak in the global number of offshore oil rigs requiring decommissioning approaches, there is growing pressure for the implementation of a "rigs-to-reefs" program in the deep sea, whereby obsolete rigs are converted into artificial reefs. Such decommissioned rigs could enhance biological productivity, improve ecological connectivity, and facilitate conservation/restoration of deep-sea benthos (eg cold-water corals) by restricting access to fishing trawlers. Preliminary evidence indicates that decommissioned rigs in shallower waters can also help rebuild declining fish stocks. Conversely, potential negative impacts include physical damage to existing benthic habitats within the "drop zone", undesired changes in marine food webs, facilitation of the spread of invasive species, and release of contaminants as rigs corrode. We discuss key areas for future research and suggest alternatives to offset or minimize negative impacts. Overall, a rigs-to-reefs program may be a valid option for deep-sea benthic conservation.

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Offshore rigs and platforms (hereafter collectively referred to as "rigs") for oil and natural gas extraction have increased in abundance throughout the world's oceans in recent decades. Estimates put the existing number of offshore rigs worldwide at >7500 (Parente *et al.* 2006) and analysts predict that this number will continue to rise over the coming decades, as demand for petroleum products increases. The finite nature of hydrocarbon supplies means that many existing rigs, particularly fixed rigs (ie those with hard structure affixed to the seafloor) in shallow waters, are now approaching the end of their production life and are due for removal (ie decommissioning).

Despite international legislation concerning procedures for rig decommissioning (eg the 1958 Geneva Convention on the Continental Shelf, the 1982 United Nations Law of the Sea Convention, and the 1989 International Maritime Organization Guidelines and Standards), there is little international consensus on best practices for decommissioning. Central to the decommissioning debate is the issue of disposal of rig materials (ie conductors, jackets, pipes, topsides), which represents the most expensive and challenging phase of the decommissioning process. International treaty provisions currently stipulate complete deconstruction and removal of the installations and associated components; however, exceptions can be made to allow disposal of obsolete rigs in the sea if they fulfill some other "legitimate" purpose, such as reef creation for biological conservation (Osmundsen and Tveteras 2003).

The rigs-to-reefs (RTR) program was developed by the former Minerals Management Service (which, after the 2010 *Deepwater Horizon* explosion and spill, was reorganized into the Bureau of Ocean Energy Management, Regulation and Enforcement) of the US Department of the Interior to convert decommissioned offshore rigs (namely the large steel jacket portion of fixed rigs; Figure 1) into artificial reefs. The program operates under a "win–win" premise, whereby obsolete rigs are recycled as artificial reefs to (1) assist with benthic habitat conservation and fishery management (under the assumption that rigs increase the amount of hard substrate for reef-dwelling organisms and enhance fishery resources) and (2) provide substantial cost savings for the oil and gas industry. Since the first planned RTR conversion took place in 1979 off the coast of Florida, similar programs have been implemented throughout Southeast Asia and in Mexico, and related discussions are ongoing in North Sea countries.

So far, RTR programs have only been considered for sites in relatively shallow marine waters; however, in light of habitat degradation attributable to fishing and other anthropogenic activities, we suggest that it is timely to consider RTR programs in deep-sea (defined here as depths >500 m) locations. There are several options for RTR conversion (Figure 2), and here we discuss – from an ecological viewpoint, as opposed to an ethics perspective – the option of relocating obsolete rigs from shallow to deep waters. We begin by using shallow-water examples

In a nutshell:

- Though relatively rare in the deep sea, natural reefs are critical for ecosystem functioning and are increasingly threatened by human activities
- Artificial reefs are used to restore and/or enhance marine communities, particularly in degraded coastal environments, but empirical evidence for associated ecosystem-level benefits is limited
- With more than 6500 offshore oil and gas rigs due for decommissioning by the year 2025, the "rigs-to-reefs" program provides an opportunity to create deep-sea artificial reef complexes on unprecedentedly large scales

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Figure 1. *Steel jacket being towed to offshore waters for establishment of an offshore rig.*

to outline the potential ecological costs and benefits of adding artificial structures to the marine environment, with special attention given to the "attraction versus production" hypotheses. We then consider the applicability of these findings to the deep sea by discussing aspects that are unique to deep-sea ecosystems. Finally, we offer suggestions for future research to inform policy.

Do artificial structures enhance ecosystem function?

Proponents of the RTR concept have built their case largely around the reported benefits of artificial structures for fish and fisheries. If fish populations are limited by the amount of available habitat, then the addition of suitable artificial habitat increases the environmental carrying capacity, resulting in a sustained increase in population biomass (the "production" hypothesis; Bohnsack 1989). However, fish observed on artificial reefs may simply have been attracted to those locations from surrounding habitat (the "attraction" hypothesis; Bohnsack 1989). Attraction is usually considered detrimental to fish populations, as otherwise sparsely distributed resources can be concentrated, making them easier to exploit (Bohnsack 1989). Theory and research associated with these hypotheses have primarily been concerned with fish; however, we also consider evidence for invertebrates in this section.

Evidence for enhanced production on artificial structures

Debate about whether artificial reefs can achieve the goal of increased production is largely due to the lack of evidence that fish populations are generally limited by available habitat, and the difficulty in demonstrating regional increases in population biomass after artificial reef installation.

The current and widely held view is that fish populations are primarily limited by the survival, dispersion, and settlement of larvae (recruitment limitation; Doherty 1982). However, fish populations can also be limited by the availability of suitable habitat (resource limitation; Shulman 1984), which can affect predation risk (Holbrook and Schmitt 2002), food availability (Robertson 1991), and reproductive output (Thresher 1983). Furthermore, these limiting factors can vary among (Doherty and Fowler 1994) and even within (Jones 1990) species, making it difficult to predict how a given assemblage will respond to increased habitat availability.

If a population of fish is habitat-limited, then the addition of suitable habitat should result in a sustained increase in regional population biomass. Only one study has investigated population biomass at spatial and temporal scales sufficient to directly test whether regional production occurred after the addition of artificial reefs, while also controlling for other sources of variation. Polovina and Sakai (1989) showed that regional catch per unit effort of the Pacific giant octopus (*Octopus dofleini*) increased after the addition of artificial reefs in northern Japanese waters, while flatfish (Pleuronectidae) populations demonstrated no such increase, despite apparent aggregation at artificial reef sites. The authors suggested that the octopus population was habitat-limited, whereas flatfish were possibly recruitment-limited because they exhibited substantial fluctuations in year-class strength irrespective of available habitat.

Because organisms with relatively immobile adult lifestages – including many marine invertebrates – cannot be "attracted" to artificial reefs, colonization and growth of such organisms will likely represent biomass production to some degree. Macroalgae and nearly all major invertebrate taxa, including corals, anemones, hydroids, sponges, sessile bivalves, intertidal mollusks, and polychaetes, have been observed on artificial reefs (Reed *et al.* 2004; Bulleri *et al.* 2005; Chapman 2006; Page *et al.* 2008). Artificial reefs could potentially intercept some propagules that would otherwise have settled on natural reefs; therefore, not all propagules that settle on artificial reefs represent an increase in regional biomass production. However, propagules that settle on artificial reefs in locations relatively isolated from natural reefs would likely not have found suitable natural habitat before perishing. In this case, artificial reefs could potentially increase biomass production by increasing settlement.

In contrast to production, there is considerable direct evidence of fish attraction during the first few years after artificial reef installation (Bohnsack and Sutherland 1985), although we suggest that this should not constitute a body of evidence against production because of the short time scales involved. Observed increases in the abundance of large fish around artificial reefs within days to months after reef installation are clearly the result of attraction, but initial attraction does not preclude the possibility of later production, which may occur over several decades. As a result of the logistical difficulties involved in monitoring regional fish populations over long time scales, it is not surprising that some have taken the approach of measuring the underlying processes of production as proxies – as demonstrated in the following case study.

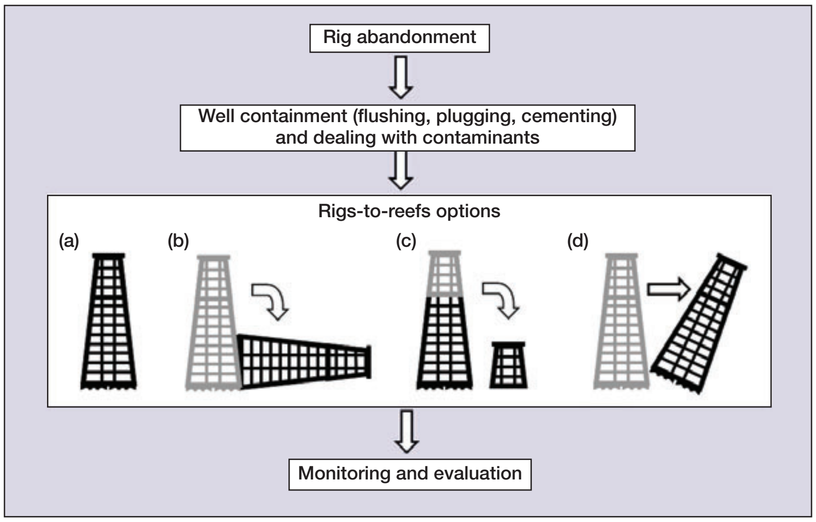

Figure 2. *Decommissioning phases and the different options for rigs-to-reefs (RTR) conversion. Options for RTR conversion include: (a) leaving the rig unaltered in its current location; (b) toppling the entire structure in its current location; (c) partially dismantling the rig in its current location (usually through "topping" – the removal of only the upper portion of the rig); or (d) relocating the rig to another location (eg the deep sea).*

Case study: fish associated with southern Californian rigs

Evidence for production on rigs is limited. Although no published studies have evaluated the success of RTR conversions from an ecological perspective, Love and colleagues provided data that support the beneficial role of fixed rigs for southern California's bocaccio rockfish (*Sebastes paucispinis*) populations. Love *et al.* (2006) estimated that, of the average number of juveniles that survive annually across the geographic range of the species, approximately 20% (equivalent to ~430 000 individuals) were supported by eight southern Californian rigs. Love and York (2005) suggested that, in addition to the rigs themselves, areas surrounding associated underwater oil and gas pipelines might act as nurseries for bocaccio rockfish, based on observed size frequencies of fish and an apparent lack of predation in the vicinity. Furthermore, bocaccio rockfish were approximately twice as common on rigs as compared with natural habitats (Love *et al.* 2005, 2009), and growth-rate measurements suggested that the ecological performance of juvenile rockfish around rigs off southern California was better than that of their counterparts from nearby natural reefs (Love *et al.* 2007). Rigs did not reduce recruitment of bocaccio rockfish to local habitat either (Emery *et al.* 2006). Love *et al.* (2005) also predicted that the loss of a single rig structure from southern California would be equivalent to removing as much as 13 ha of average-producing natural habitat in southern California for cowcod (*Sebastes levis*) and 29 ha of fish-producing biomass for bocaccio rockfish. These estimates contrast with previous suggestions that existing rigs would not have any detectable impact on regional fish stocks in southern California (Holbrook *et al.* 2000).

Artificial reefs as tools for habitat conservation and rehabilitation

Although most attention has focused on their promotion of fisheries production, artificial reefs are increasingly and effectively being applied in mitigation efforts for natural systems – including their use as physical barriers to discourage illegal trawling in seagrass beds in Western Europe (Gonzalez-Correa *et al.* 2005), and also to passively enforce marine parks and fishery-protected areas in Hong Kong (Wilson *et al.* 2002).

Rigs themselves have been described as "de facto marine protected areas" (Schroeder and Love 2004), because they exclude trawl fishing and their large internal spaces (Figure 1) offer shelter to fish and other organisms. Deep-sea communities in particular may benefit from trawl protection afforded by reef addition because their "K-selected" life-history characteristics (eg longevity, slow growth, late reproduction, low fecundity; Koslow *et al.* 2000) make them highly vulnerable to exploitation. If rigs are converted to reefs in the deep sea, well-advertised exclusion zones must be established around their deployment sites to inform fishermen of their location.

Artificial reefs are also used for habitat rehabilitation, to restore depleted reef communities; however, communities that develop on artificial reefs are often different from those on natural reefs (Burt *et al.* 2009). For example, coral assemblages may differ from those found on natural reefs, even 30 years after installation (Burt *et al.* 2009). Differences are usually due to structural dissimilarities between natural and artificial substrates (Perkol-Finkel *et al.* 2006). In situations where habitat degradation is more extreme, and closely approximating natural communities is less important, artificial reefs are likely to be useful in rejuvenating reef communities to some degree (eg Clark and Edwards 1999).

■ "Rigs-to-reefs": considerations and possible implications

Nearly all research on the ecological performance of rigs and other artificial reefs has been conducted in relatively shallow water (< 200 m deep; but see Love and York

2005); consequently, it is difficult to predict how deep-sea communities will respond to the addition of reefs through RTR programs. Furthermore, evaluation of the success of reef additions is likely to vary with stakeholder expectations. In this section, we discuss considerations and possible implications of adding structure to the deep sea.

The suitability of rigs as habitat in the deep sea

Because of their structural design and steel composition, rigs would provide a specific type of artificial reef habitat in the deep sea, which may be suitable for some taxa but not others. Rigs are complex structures, involving numerous crossbeams and large interstitial spaces (Figure 1), which are likely to support high reef-fish diversity and abundance (Luckhurst and Luckhurst 1978; Hixon and Beets 1989). They contain few small interstitial spaces, however, which may reduce the number of small fish and invertebrates using the habitat (Hixon and Beets 1989), at least until epifaunal (encrusting) communities develop. Research into the response of deep-sea communities to habitat complexity is required, because current knowledge is based on experiments in water < 40 m deep.

Concrete or stone appears to have been the most common construction material for artificial reefs in the past decade; however, steel reefs (including oil rigs) have also been found to provide suitable habitat for invertebrate assemblages. Settlement of shallow-water corals was higher on painted steel than on concrete (Fitzhardinge and Bailey-Brock 1989), and numerous sessile macroinvertebrate taxa were found to be common on oil rigs in California (Page *et al.* 2008), indicating that the steel composition of rigs is suitable for invertebrate colonization and growth. Indeed, discoveries of colonies of the deep-water coral *Lophelia pertusa* on recently decommissioned oil rigs in the North Sea indicate that such structures may afford suitable habitat for the development of coral reefs in deep waters (Bell and Smith 1999).

Contribution of rigs to the total amount of deep-sea reef

One question that has arisen for artificial reef (including RTR) programs concerns the amount of structure necessary to provide a benefit to marine populations. Although a typical rig may have an area equivalent to a football field and stand several hundred meters in height (Figure 1), they are likely to only ever represent a small fraction of the total amount (eg > 500 000 whale skeletons [Smith and Baco 2003]; ~200 000 seamounts [Hillier and Watts 2007]) of natural deep-sea reefs (eg rock outcrops, hydrothermal vents, cold seeps, whale carcasses). Nevertheless, because natural deep-sea reefs are relatively rare in terms of the vastness of the sea (< 4% of the seafloor; Glover and Smith 2003), a relatively small amount of structure in the deep sea may still support regionally substantial fish densities and larval sources, as has been shown for shallower systems (Love *et al.* 2005, 2006).

■ The importance of artificial reefs for deep-sea connectivity

Deep-sea reefs vary greatly in terms of their geographical distribution, dynamics, and geological composition; consequently, they harbor distinctive macrofaunal communities and often represent biodiversity hotspots (eg Baco and Smith 2003). Population persistence in the deep sea relies heavily on connectivity between deep-sea communities on isolated reefs (Cowen and Sponaugle 2009). Over large distances, small, isolated reefs may act as "stepping stones" within an inhospitable matrix of soft sediment. For instance, bathymodiolin mussels (and their symbionts) currently inhabiting deep-sea hydrothermal vents are thought to have descended from ancestors associated with shallower marine environments, which over time colonized deeper waters by relying on habitat patches of organic matter, such as whale carcasses (Lorion *et al.* 2009). The addition of artificial reefs in the deep sea is likely to increase ecological connectivity, which will have important biogeographical consequences. These may include increased genetic homogeneity and reduced opportunity for allopatric speciation (when biological populations of the same species become isolated as a result of geographical changes), because rig structures may remove isolating barriers to long-range dispersal. Depending on the species, this could be a positive or negative outcome.

Placement of rigs

Whereas the positioning of new rigs is determined by the location of oil reserves, RTR programs provide an opportunity to place decommissioned rigs in locations that will maximize ecological benefits. Knowledge of larval dispersal trajectories (Cowen and Sponaugle 2009) could allow the strategic placement of rigs to increase recruitment success and help retain larvae that would otherwise be "lost" to inhospitable substrates (Thomson *et al.* 2003). For example, Atchison *et al.* (2008) showed that the genetic affinity of coral populations decreased with distance from natural source habitats, which led to the determination of the minimum distance (< 65 km) of rig placement to intercept larval recruits from natural sources. However, the addition of artificial structures to the aquatic environment will alter natural flow regimes and dispersal patterns; although probably minor, these effects should be assessed.

Environmental costs associated with relocating rigs

Potential environmental costs of rig relocation from shallow to deep waters include:

(1) Physical disturbance of natural communities

Damage to benthic marine communities will occur from direct physical impact (including smothering) within the "drop zone" of the rig. Therefore, localized loss of benthic assemblages should be considered in related cost–benefit considerations.

(2) Contaminant release and movement into the food chain

Substantial amounts of contaminants are known to accumulate within the seabed surrounding rigs (eg mounds of waste generated by drilling into the seabed); however, this issue arises independently of the disposal method. For rigs that undergo reef conversion, contaminant release may result from inadequate removal of potentially harmful substances (eg hydrocarbons) prior to relocation, or corrosion of the rig at its final location. Little is known about whether contaminants enter the food chain and bioaccumulate, although Breuer *et al.* (2004) suggested that contaminant levels remain unchanged within the sediment surrounding rigs unless disturbed. Bioturbation by crabs, polychaetes, and other infaunal organisms may bring contaminated sediments to the surface of the seabed or transport contaminants beyond the physical footprint of the RTR structure. Further research is required, and it may be necessary to develop contingency plans regarding the long-term fate of disintegrating rigs – including policies for site cleanup and whether to replace degraded rigs.

(3) Facilitating the establishment and spread of invasive species

If encrusting or fouling organisms attached to rig surfaces are not removed before rig relocation, then the risk of spreading invasive species becomes a serious concern. Indeed, there are reports of invasive species associated with rigs (Page *et al.* 2006). Even "clean" rigs could potentially facilitate the spread of invasives by functioning as "stepping stones" to promote dispersal. This issue needs to be considered on a case-by-case basis, because it depends on the organisms present on a particular rig, the transport path to the deployment site, and the physical and biological conditions of the deployment site. Surveys for potential invasive species could be conducted on rigs by divers or remotely operated vehicles before removal and relocation. Rigs that are (1) found to harbor potentially invasive species or (2) destined for deployment in locations that may be particularly sensitive to the introduction of invasive species should not be used for RTR conversion. However, the alternative, shore-based decommissioning, still involves potential spread of invasives through transport to coastal areas.

(4) Potential adverse changes in natural food-web dynamics and community structure

Although direct impacts of artificial reef addition on native communities will probably be limited to the immediate vicinity (Ambrose and Anderson 1990), there is the potential for more widespread, indirect effects. For instance, the addition of more than 20 000 individual reefs in offshore sedimentary areas of Alabama (US) resulted in regional increases of red snapper (*Lutjanus campechanus*) populations, raising concerns among scientists that diversity and abundance of native, soft-bottom communities might be negatively affected (Gallaway *et al.* 2009). Whether these changes were considered "adverse" depended on individual stakeholder expectations; from a fisheries perspective, increased catches of red snapper were considered a positive outcome.

We suggest that robust monitoring programs (involving pre- and post-deployment surveys) could greatly reduce the risk of encountering the aforementioned environmental costs.

Toward the future: research priorities

Recommended areas for future research – in the application of RTR programs for the deep sea, for the purpose of enhancing fisheries and biodiversity – include:

- Longer term (decadal) investigations of the effects of rig deployment on communities in waters deeper than 200 m, including community-scale investigations of trophic interactions around deep-water rigs. To date, almost all work has been performed in waters < 100 m (with the exception of Love and York [2005], whose study extended to 235 m) and over time frames too short to account for population fluctuations.
- Further understanding of the importance of connectivity for maintaining populations of deep-sea biota. Developments in fish otolith (ear-stone) microchemistry, stable isotope techniques, population genetics (eg microsatellite markers), and three-dimensional oceanographic models offer new possibilities.
- Accurate estimates of abundance, species composition, and size/age classes of fauna across vertical and horizontal profiles. This will allow determination of important structural features of rigs as habitat and their potential for increasing production of population biomass, and improve the understanding of how faunal assemblages vary with time since rig deployment, as well as with location and time of year.
- Tissue analysis of sampled fauna for the presence of contaminants. This will help to determine the risks and improve estimating the spatial scale of chemical pollution associated with disintegrating rigs.
- Assessment of the risk of spreading marine invasive species during rig relocation from shallow to deep waters. This will assist decisions on whether or not the level of risk is acceptable.
- Determination of the feasibility of "cleaning" rigs (to remove contaminants and any unwanted fauna) before relocation to the deep sea. For each cleaning method (eg onshore versus in situ), cost–benefit analyses and associated carbon footprint calculations should be per-

formed. The fate of organisms dislodged from rigs during the cleaning process also needs to be considered.

Conclusions

Opinions on human impacts in the deep sea vary. Some predict that the deep sea will remain relatively unaffected by anthropogenic activities and climate change by the year 2025, relative to the rest of the planet (Glover and Smith 2003); others suggest that the deep sea is already severely affected by such disturbances and call for further action to protect deep-sea ecosystems (Davies *et al.* 2007). We suggest that a RTR program in the deep sea, in conjunction with the establishment of marine protected areas, may offer a means of conserving deep-sea communities. Partnerships between scientists and industry (eg The SERPENT project, www.serpentproject.com) will improve the capacity for further research, and we recommend that industry savings from an RTR program should support independent research and monitoring programs to evaluate the effectiveness of rigs in fulfilling their intended purpose as artificial reefs in the deep sea. Environmental impact assessments carried out by independent bodies and overseen by representatives from a variety of stakeholders (eg government, community, industry) will ensure control and transparency during a RTR program, especially given that the program is expected to represent a financial windfall for industry.

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