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Valuing Nature Waste Removal in the Offshore Environment Following the Deepwater Horizon Oil Spill

Travis W. Washburn†, David W. Yoskowitz and Paul A. Montagna*

Harte Research Institute for Gulf of Mexico Studies, Texas A&M University Corpus Christi, Corpus Christi, TX, United States

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***Correspondence:**
*Travis W. Washburn
travis.w.washburn@duke.edu;
Buff2216@yahoo.com*

†Present address:
*Travis W. Washburn,
Division of Marine Science and Conservation, Nicholas School of the Environment, Duke University, Beaufort, NC, United States*

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The offshore and deep-sea marine environment provides many ecosystem services (i.e., benefits to humans), for example: climate regulation, exploitable resources, processes that enable life on Earth, and waste removal. Unfortunately, the remote nature of this environment makes it difficult to estimate the values of these services. One service in particular, waste removal, was examined in the context of the Deepwater Horizon oil spill. Nearly 5 million barrels of oil were released into the offshore Gulf of Mexico, and 14 billion dollars were spent removing about 25% of the oil spilled. Using values for oil spill cleanup efforts, which included capping the wellhead and collecting oil, surface combustion, and surface skimming, it was calculated that waste removal, i.e., natural removal of spilled oil, saved BP over $35 billion. This large amount demonstrates the costs of offshore disasters, the importance of the offshore environment to humans, as well as the large monetary values associated with ecosystem services provided.

Keywords: deep sea, ecosystem services, biodegradation, oil removal, cleanup costs, oil fate

INTRODUCTION

This study examines the ecosystem services provided by the offshore marine environment, which is comprised mostly of the deep sea (>200 m) (Gage and Tyler, 1997), in the Gulf of Mexico. The term ecosystem service (ES) has been defined different ways (Fisher et al., 2009); however, a commonly used description comes from the Millennium Ecosystem Assessment (MEA, 2005) which defines ES as "the benefits that people obtain from ecosystems." Ecosystem services are divided into services that benefit humans directly (e.g., fisheries, tourism, transportation) and services that benefit humans indirectly (e.g., climate regulation, nutrient regulation, waste removal) (Fisher et al., 2009; Luisetti et al., 2011).

"Waste removal" which is the ability of the environment to process and remove contaminants introduced by humans will be the focus of this assessment. The removal of pollutants by the marine environment is generally considered an indirect service. Waste removal studies have primarily focused on wetland communities, where organic waste is assimilated into the environment and converted to harmless or useful ecological products (Kazmierczak, 2001). Microbial communities with resistant strains have also been shown to bioremediate heavy metals associated with sewage sludge (Watanabe, 2001).

The offshore and deep-sea environment, which is the largest habitat on Earth, plays a major role in global waste removal in several ways. Pollutants reach the deep sea via sinking of large water masses, adsorption onto larger sinking particles or marine snow (Dachs et al., 2002; Daly et al., 2016), dense shelf water cascades (Canals et al., 2006), or direct dumping by humans

(Glover and Smith, 2003). Once in the deep sea, pollutants may be deposited and buried, where they remain for very long periods of time. Macrobenthic organisms on the deep-sea floor assimilate and chemically alter many wastes through bioturbation as well as remove waste from the system through burial (Solan et al., 2004). The level of bioturbation also regulates the amount of wastes exposed to oxidizing and reducing environments which determines rates of decomposition and sequestration (Armstrong et al., 2010). On the other hand, the pollutants may be detoxified through biotic or abiotic processes in the deep sea, which is considered a regulating service (Thurber et al., 2014).

It is difficult to quantify the benefits humans receive from the offshore environment, such as waste removal following dumped or accidentally spilled waste. Galparsoro et al. (2014) suggested that there is a gradient of services in relation to depth with humans deriving more benefits from coastal benthic habitats, and benefits decreasing with depth. However, this may not reflect actual benefits provided by the deep sea as not only is there a lack of data for this habitat but also a lack of market equivalents. There are several ways to value ecosystem services. The simplest valuation method uses market prices; however, this only works for goods and services directly used by humans (e.g., food and raw materials) and can also be problematic if market conditions are not optimal (Hussen, 1999). When markets for services are not available, monetary values must be estimated through other methods, such as avoided costs, replacement costs, mitigation costs, and restoration costs (EPA, 2009; TEEB, 2010; National Research Council [NRC], 2012). Willingness to pay is one approach to estimate replacement costs (i.e., money required to replace a service should the environment no longer provide it) and avoidance costs (the money saved by not providing a service performed by the environment) (Farber et al., 2002). However, it is likely that few people would be willing to pay for conservation or protection of the deep-sea because they never experience the offshore environment.

An early estimate of the global value of ecosystem services found that coastal areas provided more services than deeper areas. Even though the coastal zone covers 8% of the planet's surface, it provides 43% of total global ecosystem service values (Costanza et al., 1997). However, the study relied on literature reviews that were dominated by studies on terrestrial and coastal ecosystem services. Without economic valuations of deep-sea environments, it is difficult for decision-makers, or for the public to understand why the deep sea is important.

The Deepwater Horizon (DWH) oil spill provides an opportunity to value a benefit obtained from the offshore environment by providing a direct monetary equivalent in the form of cleanup costs compared to the natural degradation of hydrocarbon pollutants. In April 2010, the DWH blowout occurred, and in the subsequent months approximately five million barrels of oil were released (Peterson et al., 2012). A deep-water bloom in bacterial biomass followed the DWH blowout, and the majority of hydrocarbon mass in the deep-water underwater plume was respired by bacteria (Du and Kessler, 2012). This is one mechanism by which waste removal occurs offshore.

The current study quantifies the potential benefits of the deep-sea environment to humans by focusing on waste removal in the offshore Gulf of Mexico following the DWH spill. Avoided costs were estimated using values for the cost of cleanup efforts by BP and oil that remained in the Gulf.

MATERIALS AND METHODS

To quantify the amount of money saved by natural processes that removed hydrocarbons from the DWH spill, the amount of oil that was actually removed from the environment by anthropogenic means was first calculated. British Petroleum (BP) undertook three major activities to remove oil spilled from the Maconda 252 wellhead: skimming oil from the sea surface, capturing oil from the wellhead with a capping device, and burning oil at the surface (BP, 2010). It is estimated that approximately 4.9 million barrels of oil were released into the deep sea (Griffiths, 2012), although the United States District Court found approximately 3.19 million barrels were released (DWH NRDA, 2016). Information regarding the amount of oil recovered from cleanup efforts following the DWH blowout was obtained from BP annual business reports (BP, 2010, 2011) as well as several independent studies (Lubchenco et al., 2010; Ramseur, 2010; USCG, 2011; Ryerson et al., 2012).

After the quantity of hydrocarbons removed by human activities was determined, the cost of cleanup was examined. British Petroleum annual business reports were examined to identify the amount of money spent during cleanup operations (BP, 2010, 2011). The BP annual business reports for 2010 and 2011 provided information on money spent on legal claims, money put into a trust for future expenditures regarding the DWH spill, and money spent on efforts to respond to the spill.

The costs for specific activities are necessary to identify how much money spent on cleanup operations was spent specifically removing oil from the environment. Several private and federal organizations were contacted to try to obtain this information, which included data on specific cleanup efforts (i.e., surface skimming, burning, dispersant application, and capping at depth), and efforts to stop the wellhead from leaking (i.e., relief wells and top-kill efforts). Inquiries on costs were sent to British Petroleum, the Assessment and Restoration Division of NOAA, the National Pollution Fund Center (NPFC) under the United States Coast Guard, and Freedom of Information Act (FOIA) office.

RESULTS

To determine the amount of money saved by natural waste removal by the deep Gulf of Mexico following the DWH spill, the avoided costs method was used. Avoided costs are the costs society avoided paying to remove the waste due to natural services (Farber et al., 2002). British Petroleum was responsible for funding cleanup efforts. British Petroleum posted a $41 billion dollar loss in 2010 solely related to the DWH oil spill. Of this $41 billion, it has been estimated that BP spent approximately $14 billion directly in spill response operations (BP, 2010;

Ramseur, 2010). In addition, BP paid an estimated \$15 billion to federal, state, and local governments for economic claims and response costs (Ramseur, 2016), approximately \$1.5 billion of which was recorded in FOIA redacted documents (USCG, 2010/2016). However, the reimbursement costs to federal and state governments for cleanup efforts were likely included in the \$14 billion BP spent on cleanup operations (Ramseur, 2016).

While BP spent a total of \$14 billion dollars on spill response, spill response operations included not only efforts to capture and remove released oil, but also efforts to stifle the spill from the wellhead such as the drilling of two relief wells and top-kill efforts (BP, 2010). Details of the costs of halting the spill were not in financial reports. Unfortunately, after requesting information from several federal agencies no additional information on costs associated with the DWH response could be obtained. Data provided to the government only concerned reimbursements to the government by the Oil Spill Liability Trust Fund (OSLTF) on work done by federal organizations (FOIA office, person comm.). Thus, the only available number for cleanup costs was the original \$14 billion dollars estimated by BP, and this entire cost was used as an estimate for total cleanup costs in this study, because of a lack of other available information.

The total amount of oil removed by these cleanup efforts must also be determined before calculating the cost of removing a barrel of DWH oil. The United States Coast Guard estimated that approximately 25% of the oil released during the DWH spill was captured, dispersed, or burned. It was estimated that 17% (830,000 barrels) of the oil was captured from capping mechanisms on the riser or blowout preventer, 8% (400,000 barrels) was dispersed either at the wellhead or sea surface, 5% (250,000 barrels) was burned, and 3% (150,000 barrels) was skimmed from the surface (**Table 1**; USCG, 2011). The USCG estimate for oil removal was very similar to those provided by BP; however, BP estimated 828,000 barrels of oily liquid were skimmed from the surface, much more than the 150,000 barrels found by the USCG (**Table 1**). This discrepancy was most likely due to the fact that BP counted the total amount of liquid captured, which would include sea water, but the USCG counted only oil captured (BP, 2010; USCG, 2010/2016). Because oil that was chemically dispersed was still left in the system, this fraction was included in the amount of oil naturally removed or buried.

The cost associated with removing, or cleaning, one barrel of oil released by the DWH blowout (\$/barrel) was calculated as the total amount spent on BP oil spill response (SP_t) divided by the total amount of oil cleaned (O_c):

$$(\$/\text{barrel}) = SP_t/O_c$$

For the DWH spill, the total cost of cleanup was estimated at \$14 billion, and the total amount of DWH oil removed from the GoM during cleanup efforts was estimated to be 25% of the spilled amount (17% captured at depth, 5% burned, and 3% skimmed) or 1.225 million barrels. Thus the estimated amount of money spent to remove one barrel of DWH oil from the Gulf was:

$$\$/\text{barrel} = (\$14{,}000{,}000{,}000)/(1{,}225{,}000 \text{ barrels}) \text{ or } \sim\$11{,}400/\text{barrel}$$

Once the cost of removing one barrel of DWH oil was calculated, the total amount of oil remaining in the deep Gulf of Mexico was required to achieve a value for natural oil removal. Unfortunately, the fate of hydrocarbons released during the DWH spill is still not fully understood and there are several conflicting reports. Ryerson et al. (2012) estimated that 5% of the total spill mass evaporated into the atmosphere, 10% formed surface slicks, and 25% was removed mechanically or burned. A deep-water plume at approximately 1200 m depth also formed containing approximately 35% of the total spill mass. Lubchenco et al. (2010) estimated removal efforts to have captured 25% of the total oil released in addition to 25% which was evaporated or dissolved, 24% which was dispersed, and 26% unaccounted for or residual. The federal government had the same estimate for captured oil but found 29% of the oil to be dispersed,

TABLE 1 | The estimated values for the fates of oil (% of total) released during the Deepwater Horizon oil spill in 2010.

Fate	BP, 2010	Lubchenco et al., 2010	Ramseur, 2010	Ryerson et al., 2012	USCG, 2011
Cleaned	39	25	25	26	25
Captured at depth	17		17		17
Skimmed at surface	[c]17		3		3
Mechanically recovered				20	
Burned	5		5	6	5
[a]**Naturally degraded/removed**	61	75	75	74	75
[b]Chemically dispersed		8	16		8
Naturally dispersed		16	13		
Dispersed		24	29		
Evaporated/dissolved		25	24	5	
Sheens/slicks				10	
Residual/unaccounted		26	22	[d]24	
Underwater plume				35	

[a]*Naturally degraded/removed oil was not listed in BP, 2010 or USCG, 2011. For these numbers, the percentages given for cleaned oil were subtracted from 100, and the remainder listed.* [b]*Chemically dispersed oil was not considered cleaned as it still remained in the marine environment.* [c]*This number represents "oily liquid" collected which would include seawater.* [d]*Residual amounts were not given in Ryerson et al. (2012). For these numbers the percentages given were subtracted from 100, and the remainder listed.*

16% chemically and 13% naturally (Ramseur, 2010). They found slightly lower numbers for evaporated or dissolved hydrocarbons (24%) and residual oil (22%) (**Table 1**).

The total value of natural removal of oil (NV_r) by the Gulf of Mexico was calculated as the cost of cleaning one barrel of oil ($/barrel) multiplied by the number of barrels of oil naturally degraded or removed (O_r):

$$NV_r = (\$/\text{barrel}) \times (O_r)$$

For the DWH spill, the cost of removing one barrel of oil from the GoM was estimated to be $11,400 in this study, and the total amount of oil remaining after cleanup efforts was estimated at 75%. However, 5% of the oil was estimated to have been evaporated while 10% formed sheens and slicks (Ryerson et al., 2012). Hydrocarbons that entered the atmosphere or reached the shore would not have been processed by the offshore Gulf. While most of the oil did not reach the coastal environment, this study conservatively estimated that half of the oil that formed sheens and slicks (or 5% of the total oil released) washed inshore equating to 10% of the DWH oil either entering the atmosphere or coast leaving 65% or 3.185 million barrels in the offshore GoM. Thus the estimated amount of money saved by BP by not having to remove the remaining DWH oil in the offshore Gulf is:

$$NV_r = \$11{,}400/\text{barrel} \times 3{,}185{,}000 \text{ barrels or } \sim\$36.3 \text{ billion}$$

This is a very conservative cost estimate because the oil removed was easily captured as it was concentrated at the surface, leading to cheaper engineering and removal costs than at depth. The uncaptured oil was dispersed over a very large area at great depths by the deep-sea plumes and the marine oiled snow events. Thus, it would have taken considerably more effort and expense to capture this oil in the deep sea.

Calculations in the present study include only oil released during the spill, but there was a substantial amount of natural gas released as well. Nearly all the natural gas released from the DWH oil spill never reached the water surface or even left the deep sea. Natural gasses including methane, ethane, and propane concentrations were several orders of magnitude higher in waters below 800 m compared to shallower depths (Valentine et al., 2010). It was estimated that as much as 200,000–500,000 tons of C_1–C_5 natural gasses were released (Joye et al., 2011; Reddy et al., 2012). Replacement costs for natural gasses removed naturally by the deep-sea environment are not possible to calculate because cleanup efforts were solely focused on observable oil. However, it is likely that humans benefited from the degradation of these gasses before they entered the atmosphere.

While the current analysis focuses on the removal of liquid hydrocarbons released into the environment by human activities, there was also approximately 8 million liters of dispersant intentionally added to the marine environment. Over 5 million liters of the dispersant COREXIT® EC9500A were applied to the sea surface while an additional 2.9 million liters were injected directly at the wellhead to prevent hydrocarbons from reaching the coastline (Kujawinski et al., 2011). COREXIT has been shown to be toxic to many different organisms, especially larval forms (Goodbody-Gringley et al., 2013; Almeda et al., 2014). The presence of COREXIT was also found to inhibit hydrocarbon-degrading bacteria, possibly hindering the environment from regulating wastes (Hamdan and Fulmer, 2011). Regardless of the pros and cons of dispersant usage during the DWH spill, the GoM was forced to regulate 8 million liters of an artificial chemical. The removal of dispersants from the system was undoubtedly a benefit to humans.

DISCUSSION

The natural processes in the offshore and deep-sea Gulf of Mexico provided BP over $35 billion dollars in value by the removal of oil released during the DWH spill either through burial, dispersion, or removal processes (e.g., bacterial degradation). The removal of wastes, such as oil, from the environment is considered an ecosystem service, and often termed waste removal (Farber et al., 2006). The values of hydrocarbon degradation presented here do not capture the entirety of hydrocarbon removal by the Gulf because they do not include oil released by other drilling activities, runoff, boats, or other spills/leaks.

The DWH spill was unique because it released hydrocarbons directly into the deep sea. There are several mechanisms by which human wastes may reach the deep sea. While mostly banned now, munitions and radioactive wastes were actively dumped into the deep sea up until the mid-to-late twentieth century (Glover and Smith, 2003). Pollutants from land enter the marine environment via runoff into the continental shelf where dense shelf waters cascade along with sediments into the deep sea (Armstrong et al., 2010). Waste particles can also attach to elements of marine snow and sink through the water column as oil particles did after the Deepwater Horizon spill (UAC, 2010; Daly et al., 2016). Values obtained for oil removal in the deep GoM are an important first step in understanding the benefits of deep-sea ecosystem processes following human-made disasters.

Unlike many coastal and terrestrial services, a large number of benefits provided by the deep sea to humans do not pass through the economy (which assigns monetary values to goods and services) but are provided indirectly to humans. These services, such as the removal of wastes by the environment, cannot be measured by market values and in many cases are not evident to the people benefiting from them (Costanza et al., 1997). The DWH spill provides a unique opportunity to examine the value of deep-sea oil degradation. During and after the spill, a known quantity of money was spent cleaning a known quantity of hydrocarbons. Using the concept of avoided costs, the amount spent on oil cleanup can be used to calculate the amount of money saved on natural storage and degradation of oil. Avoidance costs are used when services provided by nature can be replaced with man-made systems (Farber et al., 2002).

Most studies that focus on the value of waste removal in the marine environment are performed in wetlands and based on values per hectare of wetland, instead of the amount of wastes removed (Kazmierczak, 2001; Patton et al., 2013; Zhang et al., 2014). Studies that examined waste removal in the offshore marine environment were also often focused on wastewater.

Using replacement costs, Murillas-Maza et al. (2011) estimated a cost of 1,216 euros ($1,300) to eliminate one ton of biochemical oxygen demand (BOD) contained in wastewater. Mangi et al. (2011) estimated a cost of 2,100 pounds (2,500 euros or $2,700) to remove one ton of BOD in wastewater. The present study estimates that it cost BP approximately $80,000 to remove one ton of DWH oil from the ocean.

The calculations in the present study do not take into account environmental damages associated with the spill. Previous studies have illustrated that the DWH spill caused extensive damages in the deep-sea ecosystems, affecting soft-bottom benthic infauna and deep-sea corals (Montagna et al., 2013; Fisher et al., 2014; Washburn et al., 2016). Any damages that would result in a decrease of value of other ecosystem services would reduce the value of waste removal calculated in this study. Another possible source of error in the calculations performed in this study is the total costs associated with the oil response that were not directly related to the removal of oil (e.g., relief wells and top kill efforts). These costs were unavailable, and any amount of money spent from the $14 billion of cleanup on activities not associated with oil removal would decrease the total value of natural oil removal.

While the values calculated for this study may be larger than the actual savings provided by the offshore GoM, they are likely to be conservative for several reasons. Values from the present study on waste removal do not include the savings associated with the removal of natural gasses released from the spill nor the removal of introduced dispersants. As much as 500,000 tons of natural gasses were released during the DWH spill, and nearly all of these gasses were bacterially respired before reaching the surface (Joye et al., 2011). Methane is also created throughout the ocean floor via methanogenesis, which has been estimated to produce between 85 and 300 Tg CH_4 annually (85–300 billion tons), and microorganisms associated with the seafloor consume more than 90% of this methane (Knittel and Boetius, 2007). Anaerobic oxidation of methane in the seafloor results in minimal efflux (<2% of global flux) of methane from the ocean to the atmosphere (Armstrong et al., 2012). If the natural removal of methane released during the DWH spill were valued, then it is likely that the value for natural hydrocarbon degradation in the present study would increase.

Cleanup efforts were also focused on areas with high concentrations of easily collected oil. As removal efforts move to areas with lower hydrocarbon concentrations, the cost per unit of oil removed from the Gulf of Mexico will increase. These removal activities do not take into account possible cleanup efforts after the spill was stopped. Oil removal activities are often performed for extended periods of time in coastal areas following shallow or surface water spills (Teal and Howarth, 1984). Work in the deep sea is also generally much more expensive than work in shallow waters because of obvious limitations to offshore access.

The DWH spill was the first of its kind, but previous spills and subsequent cleanup activities can be used to compare costs associated with a spill in the deep Gulf of Mexico to spills in shallower areas and different water basins. On March 24, 1989 the tank vessel *Exxon Valdez* grounded in Prince William Sound, Alaska and released roughly 260,000 barrels of oil (Exxon Corporation, 1993; Exxon Trustee Council, 1995). Exxon Mobil was estimated to have spent $2 billion on cleanup activities that removed approximately 10% of the oil released or 26,000 barrels (Exxon Corporation, 1993; Exxon Trustee Council, 1995). Using avoided costs it can thus be estimated that roughly $80,000 were spent on the removal of one barrel of oil following the *Exxon Valdez* spill, or seven times the cost to remove a barrel of DWH oil. Much of this money was spent on shoreline cleanup suggesting that additional cleanup efforts following the DWH spill would greatly increase the costs associated with removing a barrel of oil from the shore or deep seafloor.

The present study estimated the avoided costs provided by an ecosystem service in the offshore marine environment. The avoided cost and replacement cost techniques rely on best available data in relation to the bio-physical changes in the system and the most appropriate cost equivalents (National Research Council [NRC], 2012; Pollack et al., 2013). The extensive research into cost of removal of oil for this study more than meets the customary expectations and has minimized any "subjectivity" in the estimates. The technique itself is no more "subjective" than any other valuation technique that is dependent upon human action and decision making (EPA, 2009; National Research Council [NRC], 2012). We have noted that results are dependent upon available cost estimates and that avoided cost estimations can change as more information becomes available.

Services are not provided uniformly throughout the water column. While the 35% of oil released that was trapped in the underwater plume at 1,200 m (Ryerson et al., 2012) was most likely removed entirely in the deep sea (equating to a savings of ~$20 billion provided solely by the deep sea), some of the oil that reached the surface was removed via evaporation, biodegraded at the surface, or transported to shallow or coastal areas. The estimates here excluded oil that left the marine environment, but did not differentiate between oil removed in the deep-sea vs. surface waters, nor the cost of cleanup efforts at depth vs. at the surface. Thus, the entire value of natural oil removal was not provided by the deep sea alone.

The exact amount of oil removed just by deep-sea processes is unknown; however, the natural release of nearly 70,000 tons of oil annually into the Gulf of Mexico through natural seepage (Ocean Studies Board and Marine Board [OSBMB], 2003) has created a deep-sea environment adapted to the input of oil. A large portion of the $40 billion worth of oil removal likely occurred in the deep GoM because nearly half of the oil that remained in the system (35%) was trapped in a deep-sea plume and only 20–25% was cleaned at the surface, evaporated, or formed surface slicks (**Table 1**). While the services provided by humans from deep-sea processes generally do not directly benefit humans, the DWH spill provides an example of the deep-sea environment directly mitigating a man-made disaster by preventing much of the oil from affecting valuable coastal and terrestrial services and thus impacting humans more directly. Offshore stakeholder workshops have found that services associated with market values (e.g., fisheries and oil/gas extraction) are generally the services most greatly valued. However, other services such as waste removal were also considered important to humans (Yoskowitz et al., 2016).

Human life is dependent on functions in the deep-sea that drive global biogeochemical cycles (Cochonat et al., 2007). Thus, knowledge of the services provided by the deep, as well as values for these services, is imperative when making policies concerning activities in this environment. The DWH event is one example of human impact on the deep sea. Impacts of this spill are still being examined, but the natural burial, dilution, and degradation of hydrocarbons from the spill will reduce these impacts and enable the recovery of the offshore environment. Most people do not have contact with or receive direct benefits from the offshore marine environment. Information on the value of offshore services will help scientists and the community in general to better understand the importance of these systems.

AUTHOR CONTRIBUTIONS

TW conceived the idea, collected all the data, wrote the first draft, and applied the revisions. PM and DY provided the funding and assisted with manuscript writing and edits.

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