12 Fisheries Bycatch of Marine Turtles

Lessons Learned from Decades of Research and Conservation

Rebecca Lewison, Bryan Wallace, Joanna Alfaro-Shigueto, Jeffrey C. Mangel, Sara M. Maxwell, and Elliott L. Hazen

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12.1 BIOLOGY AND SIGNIFICANCE OF SEA TURTLE BYCATCH

Sea turtles spend the majority of their lives in coastal or pelagic waters, making in-water sources of mortality critical to population viability. Sea turtles have been negatively impacted by a number of human-mediated factors including oil spills (Antonio et al., 2011), contaminants (van de Merwe et al., 2010; Swarthout et al., 2010; Komoroske et al., 2011; Stewart et al., 2011), and other types of marine pollution, namely debris ingestion and entanglement (Lazar and Gracan, 2011; do Sul et al., 2011). Coastal and in-water shoreline development also have been shown to degrade ocean habitat, which can negatively affect resident turtles (Harewood and Horrocks, 2008; Pike, 2008). While all of these factors likely have some negative effect on sea turtle populations, the human activity that has the largest impact on sea turtles is fisheries bycatch (Lewison et al., 2004a; Wallace et al., 2011). Although directed take of turtles is one form of fisheries impact, and in some regions opportunistic take of captured turtles is still prevalent (Alfaro-Shigueto et al., 2011), turtles are generally an

unwanted and unwelcome byproduct of fishing activities. Because fishing is an important source of protein and livelihood for millions of people worldwide, incidental capture, or bycatch, of sea turtles continues to be the most pressing human impact on sea turtle populations globally. In this chapter, we review the current state of knowledge about global marine turtle bycatch, including how characteristics of sea turtle biology and fishing practices interact to result in bycatch, assessments of population-level impacts of turtle bycatch, descriptions of where and how turtle bycatch occurs across distinct fisheries sectors, a summary of techniques and approaches to bycatch reduction, and new ways forward for bycatch research and management.

12.2 UNDERSTANDING HOW SEA TURTLE BYCATCH HAPPENS

Fisheries bycatch occurs at the intersection of sea turtle ecology, behavior, distribution, and fisheries activity (Figure 12.1). Bycatch is a result of an individual's *vulnerability* to capture, which is influenced by behavior, ecological, and intrinsic life history attributes, as well as the *susceptibility* of an individual due to spatial or temporal overlap with fishing gear. The likelihood of capture, or overall sea turtle catchability, is a function of a combination of these two elements.

Vulnerability reflects a combination of ecological characteristics including foraging behavior (e.g., likelihood to chase baited hooks), migratory routes, and distributions at depth (e.g., proportion of shallow vs. deep dives), as well as aggregations of individuals in time and space for breeding and/or feeding. As air-breathers, turtles must return to the surface periodically to replenish oxygen stores. This physiological constraint on diving behavior exposes them to particular bycatch threats, in terms of the depth of the fishing gear as well as in the amount of time that fishing gear is left

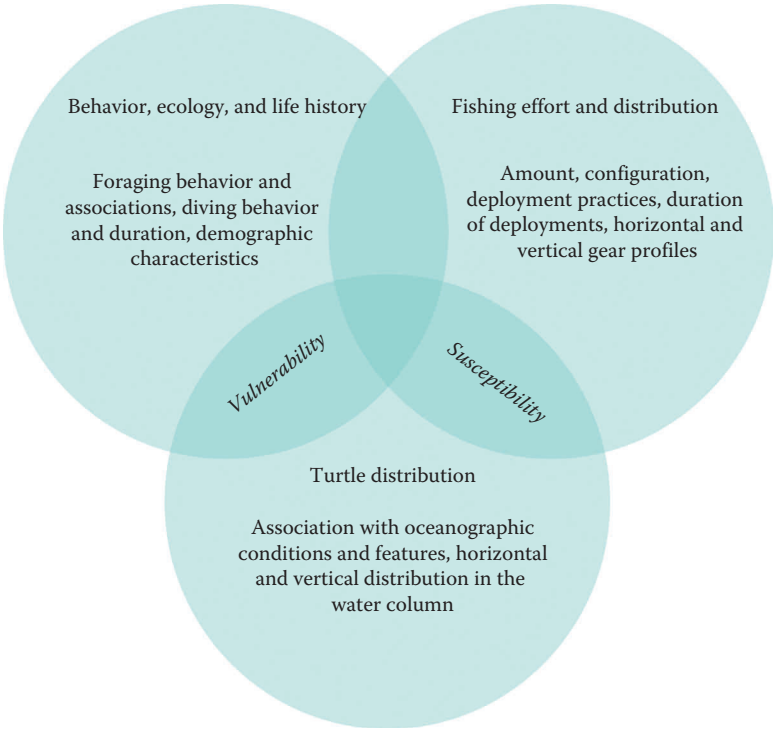

FIGURE 12.1 A conceptual model of the different factors that drive sea turtle bycatch. Vulnerability is primarily driven by ecological and life history attributes and characteristics that govern behavior and distribution. Susceptibility, in contrast, is driven largely by the horizontal and vertical overlap of fishing vessels and sea turtles, and represents the elements in the system that can be managed.

in the water (Poiner and Harris, 1996). The different ecological functions of diving (e.g., foraging, thermoregulation, predator evasion) as well as diel dive patterns, i.e., daily and seasonal patterns of dive frequency and duration, also influence the likelihood of encountering fishing gear (Howell et al., 2010). Satellite telemetry research has demonstrated that sea turtles occupy particular ranges of water temperatures to optimize the efficiency of physiological processes and/or to take advantage of resource availability related to these temperatures (Polovina et al., 2000, 2003, 2004; Wingfield et al., 2011). Foraging sea turtles, including loggerheads and leatherbacks, also exhibit a close association to more productive waters, where they aggregate and forage in thermohaline fronts, convergence zones, upwellings, or mesoscale eddies, where primary productivity is high and turtle prey tend to be aggregated (Kobayashi et al., 2008; McCarthy et al., 2010; Benson et al., 2011; Ferreira et al., 2011; Shillinger et al., 2011; Bailey et al., 2012).

Another dimension of bycatch vulnerability is the demographic sensitivity of sea turtles to bycatch mortality. Because sea turtles have delayed sexual maturity (9–30 years, see Chapter 5), sea turtle populations are most sensitive to impacts that kill individuals from older age classes (Crouse et al., 1987; Heppell, 1998). These individuals have higher per capita reproductive values, where reproductive value (RV) is the number of offspring a member of a given age group can produce between any specific age and their death; RV tends to be highest at the onset of reproductive maturity (Fisher, 1930). Elasticity analyses provide additional insight into the relative contribution of individual age classes to overall population growth rate, or lambda, taking into account the duration of those age classes (Heppell et al., 2000a,b). Elasticity analyses across turtle species have demonstrated that population growth rates depend strongly on the survival of turtles nearing and reaching sexual maturity (i.e., large benthic juveniles, subadults, and adults; Heppell, 1998; Heppell et al., 2000a; NMFS, 2001), which are age classes commonly caught as bycatch (Lewison and Crowder, 2007).

Susceptibility refers to the overlap in space and time of fishing effort with turtle habitats and is an essential element of the bycatch equation. In contrast to the ecological and life history traits that drive vulnerability, susceptibility is driven by factors that can be managed. The level of overlap is largely because fishing fleets, like turtles, favor areas of high productivity. Distributions of many target species, e.g., swordfish, have been shown to closely associate with convergence areas (Hazin and Erzini, 2008). Transition zones and fronts in the Azores, North Pacific, the Costa Rica Dome, off the western coast of Baja California Peninsula, and along the Gulf Stream in the Western Atlantic are examples of areas where sea turtles aggregate, where fishing pressure is intense, and consequently are areas where the probability of bycatch is likely to be high (Polovina et al., 2000, 2003, 2004; Hawkes et al., 2007; Howell et al., 2008; Shillinger et al., 2008; Wingfield et al., 2011; Ferreira et al., 2011). Similar aggregations can be found in continental shelf zones (Casale et al., 2012). As with turtle distribution, fishing activity shifts considerably within and among years, often in response to the same oceanographic features that attract turtles. Because sea turtle movements can be described in three dimensions—i.e., horizontal distribution as well as vertical dive-depth—bycatch susceptibility is also driven by spatial location, depth and vertical profile of gear. The species-specific seasonal and regional dive behaviors that sea turtles exhibit may also account for differences in susceptibility among sea turtle species within and among regions (Godley et al., 2008). Fishing activity can overlap foraging grounds, migration corridors, or areas adjacent to nesting grounds, each with different population-level ramifications.

12.2.1 Differences among Fishing Gears

Sea turtle bycatch occurs in a diversity of fishing gears throughout turtles' broad geographic ranges in the ocean. Vessels from large-scale and small-scale fisheries (SSFs) using trawls (Lewison et al., 2003), gillnets (Murray, 2009), seine nets, pound nets (Gilman et al., 2010), longlines (Witzell, 1999; Watson et al., 2005; Casale, 2010), and many other gears all incur sea turtle bycatch. Sea turtle bycatch has been most widely documented in four broad categories of fishing gear, although

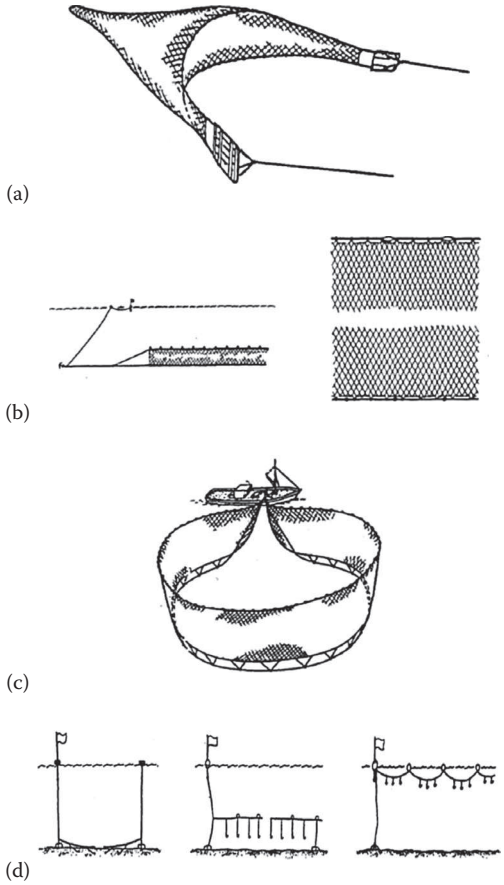

FIGURE 12.2 Illustrations of the general fishing gear in which sea turtle bycatch has been most widely documented. (From FAO Fisheries Technical Paper. No. 222. Revision 1, ftp:/ftp.fao.org/docrep/fao/008/t0367t/t0367t04.pdf). The four gear categories that are shown (a) trawl, (b) nets, (c) purse, and (d) longline represent very broad categories of fishing gear and within each category is a wide diversity of fishing gear types. For more information on fishing gears, go to http:/www.fao.org/fishery/topic/1617/en.

within each of these categories there is a wide diversity of gear types (see http:/www.fao.org/fishery/topic/1617/en for more detailed gear descriptions, see Figure 12.2 for illustrations). These include the following:

Trawls: Trawl vessels typically pull one or more large funnel-shaped nets through the water where the target species are captured in a bag at the end of the net, termed a cod-end. Trawls can be deployed at different depths depending on the target species. For sea turtles, coastal or shallow bottom trawls used to capture shrimp and other coastal flatfish can result in high bycatch (Finkbeiner et al., 2011). Once sea turtles enter the cod-end, they are unable to escape and will die if the duration of a trawl operation exceeds the physiological capacity for a sea turtle to remain submerged without surfacing to breathe. There also may be sublethal effects to sea turtles from trawl capture and recapture (Caillouet et al., 1996).

Nets: Nets are another broad gear category of fishing gears that are vertically oriented in the water column either tethered to the substrate or left to drift. Gillnets are one common type of net gear, comprising panels of nets that are used to form walls of nets of varying lengths. They catch a wide assortment of species based on the mesh sizes. The primary threat to sea turtles is entanglement in the net mesh, which can result in injury or death from drowning. Another type of net gear,

pound nets, are stationary nets usually supported by poles pounded into the substrate. Pound nets corral migrating fish through a series of funnels into a holding pen. Turtles may become entangled in a leader net, which is set perpendicular to shore to divert fish to the mouth of the pound net. In some regions, the holding pen is open (i.e., has no roof) and in others, it is enclosed. If turtles enter a pen that is enclosed, they are unable to reach the surface to breathe and drown.

Purse seines: Purse seines consist of a wall of netting that is set in a circle around a school of targeted fish. The bottom of the net is pulled shut, or pursed, to form a bag, and the catch is hauled on board the ship. Purse seiners often set nets around natural floating debris and fish-aggregating devices (FADs, Fonteneau et al., 2000) because fish species aggregate at these objects. Smaller size classes of turtles can become entangled in the FADs' tethered ropes, buoys, or floats. Existing data suggest that FAD setting has resulted in an increased bycatch of sea turtles (Gilman and Lundin, 2009).

Longlines: Longlines are a series of hundreds or thousands of hooks that hang off a mainline of variable length set at discrete depths to target fish species, often tuna and swordfish. Much of the bycatch of sea turtles occurs when the lines are set shallowly (0–100 m), a depth range where all sea turtle species dive extensively. Sea turtles can be hooked while trying to ingest bait from baited hooks or become entangled when their flippers encounter the hooked branch or mainlines. Bottom set longlines can also lead to bycatch (Jribi et al., 2008).

12.2.2 Bycatch Rates and Mortality among Gears

Bycatch rates vary widely within and among gears, fleets, and fishing areas. Bycatch rates vary substantially, in part, because of different gear configurations and fishing practices but also because of turtle and fishing vessel movement. Lewison and Crowder (2007) compared published bycatch rates for a single gear type, pelagic longlines, and found that even among four different longline fleets deploying tuna (deep) sets in the Pacific, maximum bycatch rates of leatherbacks for each fleet ranged from 30% to 60% of the highest overall rate see references in Lewison and Crowder 2007. In a more detailed comparison, Wallace et al., 2010a synthesized reported sea turtle bycatch records and fishing effort in gillnets, longlines, and trawls by major fishing regions (see Table 2 in Wallace et al. [2010a]). This comprehensive data compilation confirmed what previous studies have asserted, i.e., bycatch rates are highly variable within and among gears and regions.

Sea turtle mortality is not synonymous with bycatch across gear types. Whereas in some gear, turtles die as a result of becoming captured or entangled, in other gear types, a turtle can be released within little or no injury depending on the type of gear and the type of interaction. If mortality is not directly observed during gear retrieval, it may occur after the turtle is released. Although post-capture mortality estimates are essential to understanding the impact bycatch may be having on sea turtle populations, it is a major knowledge gap. While it is difficult to estimate and compare post-capture mortality rates across gears and among sea turtles species, the existing estimates suggest that post-capture mortality varies substantially among gear types and sea turtle species, reflecting likely variation among sea turtle populations, oceanographic conditions in which bycatch occurs, and gear-related differences.

In general, existing mortality estimates suggest that sea turtle mortality is higher in net and trawl gear than in longlines. Henwood and Stuntz (1987) published some of the earliest estimates of mortality in shrimp trawl vessels in the southeastern U.S. waters, estimating overall mortality rate for the Gulf of Mexico is 29% (34%, 22%, 38% for the eastern, central, western Gulf, respectively). For the U.S. Atlantic coast, these authors estimated a mortality rate of 21% reflecting the shorter average duration of trawl tows on this coast. Sea turtle mortality in trawls in the Eastern Tropical Pacific Ocean was estimated at 37% without the use of bycatch reduction devices (Arauz et al., 1998). A study examining artisanal drift gillnets in the Caribbean found that 27% of leatherbacks caught were hauled on board dead (Lum, 2006), similar to estimates for gillnets in the Mediterranean of 20%–30% of loggerheads caught (Gerosa and Casale, 1999). Forty per

cent of turtles caught in drift gillnets in the northeast Atlantic were recorded as dead, and this was considered to be largely a function of soak time (Murray, 2009). Direct mortality estimates from longlines vary from 8% to over 30%, and are related to factors such as hook type, set depth, and whether the turtle was hooked in the mouth, stomach, or externally (Chaloupka et al., 2004; Casale et al., 2008). Tagging studies of turtles caught in longlines indicated that mortality was greater for individuals that swallowed or ingested the hook (referred to as deep-hooked individuals), and some data suggest that, with proper hook removal, lightly hooked turtles may not experience a reduction in annual survival (Sasso and Epperly, 2007).

12.3 INTERPRETING THE BYCATCH LANDSCAPE

12.3.1 Characterizing Bycatch

There are two basic data types needed to characterize sea turtle bycatch. The first essential data type is direct reports of observed bycatch. Bycatch data are typically collected in two ways: (1) by data recorded by trained observers on fishing vessels (termed observer data) by resource agencies and independent scientists, or (2) data collected during dockside interviews and surveys. Information on bycatch is usually reported in the form of a bycatch rate, or bycatch per unit effort (BPUE). Bycatch rates are generally calculated as the number of turtles captured relative to the associated amount of fishing effort observed. Comparisons among bycatch records are hindered substantially by the diversity in fishing effort metrics used to report bycatch (see Table 1 in Wallace et al. [2010a]). This lack of conformity can be overcome (see Wallace et al., 2010a), but it presents a substantial challenge to comparing or assessing bycatch effects among fisheries, gear types, or ocean regions.

Observer bycatch data have been shown to provide high-resolution information by providing a more accurate and precise estimate of the number of turtles caught as well as locations where bycatch occurred. Although observer data are an essential ingredient to characterizing and quantifying bycatch, the precision of the data is influenced by the amount of fishing effort upon which the data are based (Tuck, 2011). Sims et al. (2008) found that high or low bycatch rates of sea turtles in gillnets in the northwest Atlantic Ocean tended to occur where relatively low fishing effort were observed, illustrating potential biases in bycatch rates based on relatively low levels of observed fishing effort. This finding was confirmed with a similar assessment using global-scale bycatch data across geographic regions and different gear categories (Wallace et al., 2010a).

Observer data are collected primarily in large-scale fisheries; however, observers typically monitor small proportions of a fishing fleet's total effort (typically <5% with some exceptions; Finkbeiner et al., 2011). Fisher interviews have been used effectively in many SSFs, which are typically data-poor, to capture bycatch occurrences and spatial extents of fishing activities (Moore et al., 2010; Alfaro-Shigueto et al., 2007, 2011). The costs of implementing observer programs in developing countries are often prohibitive, especially given that SSFs consist of large numbers of boats distributed diffusely (as opposed to in centralized ports) along the coasts (see Section 12.4.2). In the absence of empirical datasets, researchers have increasingly relied on the knowledge of local fishermen to characterize bycatch in this fishing sector (Moore et al., 2010). Despite the limitations of social survey data (Kennelly, 1999; Huntington, 2000; Gilchrist et al., 2005), structured interviews have provided useful information about marine mammal and sea turtle bycatch in both small- and large-scale fisheries when observer data were limited or not feasible to collect (Moore et al., 2010; Alfaro-Shigueto et al., 2011).

The second kind of information that is needed to evaluate fisheries impacts is the amount of fishing gear deployed, or fishing effort. Data on the intensity and spatial locations of fishing effort are needed to quantify and monitor bycatch risk for sea turtles and other nontarget species (Bellman et al., 2005). The most commonly reported measure of fisheries production is the amount of catch (Maunder and Punt, 2004). This is due in part to relative ease of data collection; catch data can be collected at ports or landing sites. While catch data provides important information on the quantity

(i.e., number or biomass) of target species harvested, it does not necessarily provide information on the expended effort, which is likely to be a better indicator of bycatch of nontarget species like sea turtles (Caillouet et al., 1996).

Although these two data types form the foundation of bycatch assessments for sea turtles, the vulnerability/susceptibility framework in Figure 12.1 demonstrates the complex suite of factors that impact bycatch occurrence for sea turtle species. Collecting data on these other axes of influence continues to be a priority to provide an accurate characterization of species and location-specific bycatch likelihoods.

12.3.2 Mapping the Bycatch Landscape

Maps provide a visual representation of processes and patterns, highlighting relationships between map objects, themes, and regions (Nelson and Boots, 2008). Creating maps of the bycatch landscape is challenging given data gaps and nonstandard data reporting. However, mapping bycatch data as well as fishing effort distribution provides an important tool to analyze spatial patterns, reveal areas where bycatch data are lacking, and to identify fishing areas where multinational efforts or regional oversight are needed (*sensu* Small, 2005).

Maps of fishing effort have been hindered by lack of data reporting; many agencies report catch, not effort (see Section 12.2.1). There have been a number of attempts to directly map fishing effort in the context of bycatch in large ocean regions (Tuck et al., 2003; Lewison et al., 2004b; Stewart et al., 2010; Waugh et al., 2011). Even with inherent imprecision in these mapping exercises, these studies can serve as the foundation for spatially explicit bycatch risk assessments (Waugh et al., 2011). Fishing effort mapping exercises also provide gross estimates of total fishing effort (Lewison et al., 2004b; Stewart et al., 2010), which by itself can help frame the potential risk bycatch poses to sea turtle populations in particular fishing areas.

Given the strong effect that spatial distribution of fishing vessels and sea turtles has on bycatch, spatial analyses are an important part of bycatch characterization. Analyzing spatial patterning and extent of sea turtle bycatch at the scale of a fleet can be used to inform management and develop strategies designed to reduce bycatch (Gardner et al., 2008; Sims et al., 2008; Lewison et al., 2009; Kot et al., 2010). However, sea turtle bycatch also occurs at spatial scales far larger than that of a single fleet. At larger scales, mapping bycatch becomes hampered by the nonstandard bycatch metrics used within and among fishing areas and fleets. One way to overcome the obstacle of bycatch metric variability is to use expert opinion to create relative ranks for bycatch records. Using a comprehensive sea turtle bycatch database from 1990 to 2008 (see Wallace et al., 2010 for citations), Lewison et al. (in review) used independent bycatch experts to rank bycatch records on a standard scale (from low to high severity). The resultant map demonstrates the diverse bycatch landscape (Figure 12.3). Although some of the variability among data records may reflect effective bycatch mitigation strategies employed by some but not all fleets, the differences among records demonstrate that even within gear categories, sea turtle bycatch is highly variable. Furthermore, spatial variation in bycatch in different gear types could reflect regional differences in fishing gears used, distributions of observer coverage, or reporting biases.

Some of the newer and more innovative bycatch reduction measures acknowledge this variability and are based on more complex maps that capture the dynamic nature of sea turtle catchability. Howell et al. (2008) developed a software product, TurtleWatch (http:/www.pifsc.noaa.gov/eod/turtlewatch.php), which is based on extensive research that has identified an association between the geographic distributions of loggerheads and sea surface temperature (SST) isotherms, and data showed that seasonal habitat use tends to track these temperature boundaries (Polovina et al., 2001, 2004; Kobayashi et al., 2008). TurtleWatch maps changing conditions in SSTs and the associated likelihood of loggerhead turtle presence in fishing areas, and provides this information to help fishermen avoid turtle bycatch. When its recommendations are heeded, TurtleWatch has been effective at reducing loggerhead bycatch in the Hawaii-based pelagic longline fishery (Howell et al., 2008).

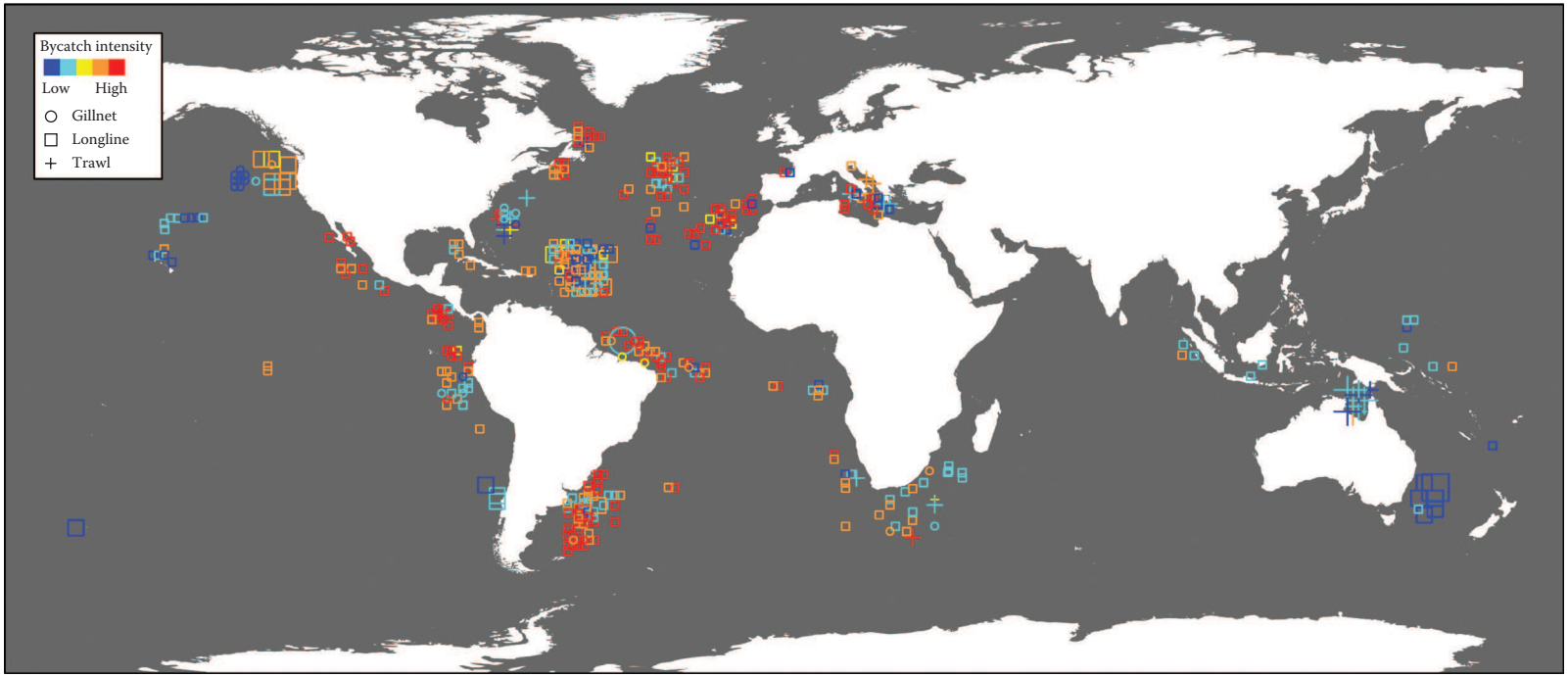

FIGURE 12.3 Map of global documented bycatch records of sea turtles from 1990 to 2008, across gillnets (○), longlines (□), and trawls (+) where bycatch intensity of each record is ranked from high (red) to low (blue). Symbol size corresponds to the amount of fishing effort for each data record. (From Lewison et al., in review.)

12.4 ASSESSING POPULATION-LEVEL IMPACTS OF BYCATCH

To assess population-level impacts of bycatch within and across fishing gears, several constituent pieces of information are necessary, and must be considered together. As discussed in Section 12.2.1, some measure of the frequency or magnitude of bycatch is needed, which is usually in the form of BPUE. However, the fact that bycatch occurred does not *de facto* demonstrate mortality has occurred, i.e., bycatch rates only indicate the number of turtles caught. Specific information on mortality rates (i.e., the proportion of turtles caught that die as a result of bycatch interactions, see Section 12.1) is required to estimate the number of turtle deaths due to bycatch, which is more directly useful to population projections. Another critical element needed to assess the population-level impacts of bycatch is the relative "importance" of turtles taken as bycatch, namely the RV of the turtles caught. Using RVs as a scalar for absolute bycatch numbers can allow for comparisons of relative impacts of different fisheries on sea turtle populations (Wallace et al., 2008). Finally, but perhaps most importantly, information on population viability is necessary as a foundation for interpreting the aforementioned variables in a population context. Specifically, estimates of population abundance and trends, as well as other characteristics that might make a population more or less vulnerable to bycatch (and other threats)—e.g., geographic distributions, feeding ecology, life history traits—provide a "common denominator" for comparisons of different bycatch impacts across sea turtle populations. Effective assessments of population-level impacts of bycatch for purposes of identifying conservation priorities in different gears, regions, or for different populations require a combination of all of these pieces of information—bycatch rates, mortality rates, RVs, and population characteristics.

A far more detailed understanding of the affected populations is required to identify the drivers of observed population trends, create conservation targets, and to prioritize limited conservation resources to reduce bycatch and leverage the greatest recovery outcomes (Wallace et al., 2010a). This type of threat assessment must be conducted at biologically appropriate scales to permit population-relevant evaluations and subsequent management responses. To this end, Wallace et al. (2010b) established regional management units (RMUs) for sea turtles worldwide to provide an appropriate biogeographic and population framework for such assessments. Within this RMU context, expert evaluation of available data was used to assess the conservation status of all marine turtle RMUs by evaluating population viability and relative impacts of various threats (Wallace et al., 2011). In this assessment, bycatch was identified as the highest threat for sea turtles globally (Table 1 in Wallace et al. [2011]) and was determined to be a moderate or high threat for more than three-fourths of all sea turtle RMUs globally. Furthermore, this evaluation demonstrated that different gear types were driving the RMU-specific bycatch threats across regions and species (Wallace et al., 2011).

A more detailed analysis of the Wallace et al. (2011) results reveals differences in the relative impacts of bycatch among species and gear types (Table 12.1). Loggerheads, olive ridleys, and leatherbacks had the highest average bycatch scores, with 80% of loggerhead RMUs, 75% of olive ridley RMUs, and 50% of leatherback RMUs scored as high bycatch RMUs. The average bycatch scores for other species were moderate, and no other species had more than 30% of its RMUs scored as high bycatch. Gillnets were identified as a gear of primary concern most frequently for leatherbacks, green turtles, and hawksbills, while longlines were identified for loggerheads, and trawls for olive ridleys. These interspecific differences in which gears have highest impacts might be explained by variations in life histories and habitat use, as well as in different fishing gears operating in individual RMUs (see Section 12.1). Looking across all RMUs for all species, gillnets were identified as the primary bycatch gear for 18 RMUs, followed by trawls (13 RMUs), longlines (10 RMUs), and others (2 RMUs), suggesting that nets may be the gear category of highest conservation concern for sea turtles globally. Although these results point to some general patterns in sea turtle bycatch at broad species-level and global scales, bycatch reduction strategies are not "one size fits all." The strategies must take into account biological (e.g., RMU, nesting stock), geographical factors (e.g., proximity to nesting beaches, high-density feeding areas), and fisheries sectors (large vs. small scale) to ensure long-term population recoveries (see Section 12.5).

TABLE 12.1
Bycatch Scores by Species Based on RMU-Specific Assessments by Wallace et al. (2011)

Species	No. RMUs (No. Scored)[a]	No. RMUs Scored "High Bycatch"	Average Bycatch Score (Low to High, 1–3)	Gear Types Identified for "High Bycatch" RMUs (No. RMUs in Which Each Gear was Mentioned)
Loggerheads	10 (10)	8	2.80	Longlines (7), trawls (5), gillnets (5), IUU[b] (1)
Olive ridleys	8 (8)	6	2.63	Trawls (6), gillnets (3), longlines (2)
Leatherbacks	7 (6)	3	2.50	Gillnets (3), longlines (1)
Kemp's ridleys	1 (1)	0	2.00	NA
Flatbacks	2 (2)	0	2.00	NA
Green turtles	17 (16)	5	1.97	Gillnets (5), trawls (2)
Hawksbills	13 (13)	2	1.69	Gillnets (2), bomb fishing (1)

Relative impacts of bycatch (and other threats) were assessed for each RMU as "low," "medium," or "high" (scores of 1, 2, or 3) based on expert evaluation of available data and the likelihood of an RMU going extinct in the future if current levels of bycatch continue unabated (see Wallace et al. [2011] for details).

[a] Two RMUs received scores of "data deficient" for bycatch impacts.

[b] Illegal, unreported, and unregulated fisheries.

12.5 BYCATCH IN DIFFERENT FISHERIES SECTORS

Like fishing gear types, variability among fishing sectors also can underlie differences in sea turtle bycatch rates and associated mortality. Although differentiation between large-scale and small-scale fishing sectors can be imperfect and imprecise (Ruttan et al., 2000), the generalizable characteristics of the two sectors correspond to recognizable patterns in sea turtle bycatch.

12.5.1 Bycatch in Large-Scale Fisheries

Large-scale fisheries are commercial operations commonly involving at-sea processing or extensive storage, enabling fishing activities to continue without the need to offload landings frequently at port. Information on bycatch from large-scale fisheries varies greatly from region to region, as well as fishery to fishery, with some fisheries within a jurisdiction collecting high-resolution bycatch data and others collecting virtually none. In the most data-rich fisheries, dedicated observers record information such as gear configuration, catch and bycatch coordinates, species composition, gear set or soak times, as well as date and volume of catch. Large-scale, industrial fisheries are a recognized source of bycatch and mortality for sea turtles, as well as other marine megafauna, including seabirds, sharks, and marine mammals (Brothers, 1991; Baum et al., 2003; Lewison et al., 2004b). Indeed, a number of these fisheries have been implicated in contributing to dramatic declines in sea turtle populations (Chan and Liew, 1996; Spotila et al., 2000; Fujiwara and Caswell, 2001). Because of the high amounts of fishing effort that large-scale fleets exert, even relatively low bycatch rates from vessels in this sector can have high cumulative effects on sea turtle populations due to the sheer magnitude of total interactions across all fishing operations, e.g., in a single year, pelagic longline fleets from 40 nations set an estimated 1.4 billion hooks in the water, which is equivalent to ca. 3.8 million hooks every day (Lewison et al., 2004b). The cumulative nature of the effects from large-scale fisheries as well as the management infrastructure and oversight has led to a high level of scrutiny and action to reduce sea turtle bycatch in many regions in this sector (Gilman et al., 2011).

12.5.2 Bycatch in Small-Scale Fisheries

In recent years, attention has shifted to bycatch in SSFs, which has been identified as an equally important source of sea turtle mortality (Lewison and Crowder, 2007; Soykan et al., 2008; Wallace et al., 2010a). SSFs, also often called "artisanal" fisheries, use a wide range of fishing methods including set and drift nets, pound nets, trawls and seines, surface, midwater or demersal gear, longlines, and traps. Most attempts to define SSF focus on fleet characteristics such as their general reliance upon manual labor, relatively small vessel or engine size and storage capacities, dispersed vessel ownership, and relatively coastal fishing locations. Despite restricted local scales of individual SSFs, the aggregated SSF sector has economic importance globally, and serves as a source of food and employment for *ca*. 1 billion people (Béné, 2006). Small-scale fleets are particularly common in developing countries where they often form the mainstay of the fisheries sector (Béné, 2006). What distinguishes SSFs from the industrial fisheries described earlier is the low degree of capital investment, smaller vessel size, limited mechanization, and the decentralization of effort and resources.

Despite being defined as small-scale, SSF fleet sizes can be vast, with many thousands of vessels operating in a country or region (Alfaro-Shigueto et al., 2010; Stewart et al., 2010). These fleets are often spread along long stretches of coastline, operating out of remote coastal communities. The fleets themselves are often dynamic, switching between gear types throughout the year to target seasonally abundant species. These communities are often economically and politically marginalized, which typically means that few bycatch reduction measures and limited enforcement of existing bycatch mitigation measures exist in SSFs. Furthermore, bycatch monitoring and management are often hard to assess due to the nature of SSFs themselves, i.e., diffuse effort, remote landing sites, and political and economic marginalization (Chuenpagdee et al., 2006).

Research in recent years has shown that SSF fleets can have high, possibly unsustainable, levels of sea turtle bycatch (Godley et al., 1998; Lewison and Crowder, 2007; Peckham et al., 2007; Gilman et al., 2009; Alfaro-Shigueto et al., 2011; Casale, 2011). Sea turtle bycatch by SSFs has been reported for many nations and regions around the globe, including Trinidad and Tobago (Lum, 2006), Brazil (Gallo et al., 2006), Tunisia (Echwikhi et al., 2010), the Mediterranean (Godley et al., 1998; Casale, 2011), Peru (Alfaro-Shigueto et al., 2011), and parts of Africa and Asia (Chaloupka et al., 2004; Moore et al., 2010), and likely includes all species of sea turtles (Chaloupka et al., 2004; Limpus, 2007; Gilman et al., 2009; Wallace et al., 2010a; Casale, 2011). It is also clear that bycatch occurs in many of the different gear types employed by SSFs, including longlines, demersal gillnets, driftnets, pound nets, and trawls (Arauz et al., 1998; Peckham et al., 2007; Gilman et al., 2009; Alfaro-Shigueto et al., 2011; Casale, 2011, also see refs in Lewison and Crowder, 2007; Wallace et al., 2010a). Small-scale gillnet fisheries in particular are a source of growing concern, given their high observed bycatch and mortality rates (Peckham et al., 2007; Gilman et al., 2009; Alfaro-Shigueto et al., 2011), and a number of studies have highlighted assessments of sea turtle bycatch in SSF as an urgent research priority (Salas et al.; 2007; Gilman et al., 2009; Casale, 2011; Wallace et al., 2011).

Estimates from SSFs suggest that the amount of sea turtle bycatch in SSF may be comparable to bycatch levels in industrial fleets (Lewison and Crowder, 2007). In a study of sea turtle bycatch by SSFs operating in Baja California, Mexico, Peckham et al. (2007) estimated an annual bycatch of ca. 1000 loggerheads and suggested that this value is similar in magnitude to the Pacific-wide industrial longline fleet. Similarly, Alfaro-Shigueto et al. (2011) estimated that ca. 5900 sea turtles are taken annually in Peruvian SSFs operating out of just three ports, but suggested that the true total likely numbers in the tens of thousands of sea turtles caught each year if cumulative impacts of the numerous and widespread Peruvian SSFs is considered. However, many bycatch studies in SSFs are based on a relatively low amount of observed effort, which typically correspond to low-confidence bycatch estimates, and/or could reflect a reporting bias, wherein researchers are more likely to report high bycatch rates than low or absent bycatch rates (see Sims et al., 2008; Wallace et al., 2010a). Nonetheless, even in cases where bycatch rates may be low, the vast number of boats

that operate in SSFs can lead to large numbers of total interactions (Peckham et al., 2007; Alfaro-Shigueto et al., 2011; Casale, 2011). Moreover, SSFs sometimes have high observed mortality rates (Peckham et al., 2008; Echwikhi et al., 2010) or some of the incidentally caught turtles, while captured alive, may be used for human consumption (Peckham et al., 2008; Alfaro-Shigueto et al., 2011). For all of these reasons, we echo previous calls for enhanced and urgent efforts directed toward observation, monitoring, management, and reduction of sea turtle bycatch in SSF.

12.6 BYCATCH REDUCTION

Despite many remaining challenges, there have been major improvements and developments in sea turtle bycatch reduction in the past decade. The best strategies to reduce bycatch integrate sea turtle ecology with fishing patterns or practices to minimize overlap and entanglement risk with fishing gear, with minimal impact on target species yield (Gilman et al., 2011). Modifications to gear, bait types, set locations, and timing and duration of sets have all been explored as possible bycatch reduction measures (Gilman et al., 2007). Some bycatch reduction measures have been shown to be relevant and effective across both large-scale and SSFs. However, given fundamental differences in the management framework and infrastructure between the two fishery sectors, reduction efforts vary according to fishery-specific circumstances.

12.6.1 Bycatch Reduction in Large-Scale Fisheries

Direct gear and fishery modifications such as changes to bait type, modifying gear to make it less visible or attractive to sea turtles, making gear less likely to cause direct mortality, or changing the way that gear is deployed are all examples of bycatch mitigation techniques that have been employed to reduce sea turtle bycatch in trawl, passive net, and longline large-scale fisheries. Here, we outline the range of techniques, highlighting the bycatch reduction achievements within each gear. However, considerable work remains to be done to further reduce bycatch across gears, and bycatch reduction strategies that have been successful in one fishery or one region may not work well in a similar fishery in a different part of the world. Mitigation techniques need to be tested and tailored to the specific fishery in which they are being utilized (Cox et al., 2007; Read, 2007).

Trawls became the focus of sea turtle bycatch reduction efforts in the 1980s, a focus that continues today. Shrimp fisheries in the Gulf of Mexico have been historically one of the largest sources of sea turtle bycatch in U.S. waters, as bycaught turtles would be held underwater and drowned over the duration of a multi-hour tow (Finkbeiner et al., 2011). Bycatch of large juvenile and adult loggerheads, in particular, has been identified as the greatest source of mortality for the southeastern U.S. loggerhead turtle population (Finkbeiner et al., 2011), and stage-based population models showed that reduction of capture in trawl nets was necessary for population recovery (Crouse et al., 1987). To decrease bycatch of loggerheads and other species, particularly Kemp's ridley and leatherback sea turtles, turtle excluder devices (TEDs) were developed to allow turtles to escape from trawl nets. TEDs usually consist of metal bars inserted into the neck of a trawl; when a turtle encounters the bars, it is forced out of an opening in the bottom of the net while shrimp continue through the bars into the bag end of the trawl. In 1991, year-round TED regulations were put into effect in U.S. waters. Subsequent to that action, there was a significant decrease in stranding rates of both species, particularly Kemp's ridleys (Crowder et al., 1995, Lewison et al., 2003, Heppell et al., 2005). The escape opening in TEDs was first increased in some areas and fishing seasons in 1994 to accommodate for the larger-size turtles like leatherbacks and adult loggerheads (Federal Register, 1994). A second increase was mandated in 2002 when predicted bycatch reductions were not realized (Epperly and Teas, 2002). A number of studies have shown that the effectiveness of TEDs is more complex than simply mandating their use in key areas and during key times of the year; shifting effort of trawlers, proper use of installed TEDs, limited requirement of TEDs with enlarged escape openings, and, particularly, compliance of TED use are critical for the recovery of turtle

populations (Epperly and Teas, 2002; Lewison et al., 2003; Cox et al., 2007; Finkbeiner et al., 2011). However, with full compliance and proper implementation, TEDs can dramatically decrease sea turtle bycatch and mortality, as shown in a multidecade synthesis of sea turtle bycatch in U.S. fisheries (Finkbeiner et al., 2011). Indeed, TEDs are used effectively in other fisheries, most notably Australia's northern prawn fishery and Queensland's east coast trawl fishery (Brewer et al., 2006). Following a World Trade Organization ruling that TED requirements were a permissible requirement for shrimp imported into the United States, TEDs have been implemented in a number of countries, although compliance may be poorly enforced (Alio et al., 2010; Sala et al., 2011).

Sea turtle bycatch in longline fisheries has received substantial scrutiny in several regions, and as a result, a number of effective sea turtle bycatch reduction strategies have been implemented in longlines. Gear depth, set and soak time, and hook type have all shown to be important elements of gear configuration that affect bycatch rates. For example, shallow longlines set less than 50 m deep have higher bycatch rates than deeper sets (Gilman et al., 2006; Beverly et al., 2009); sea turtles are caught more often on hooks closer than 30 m from floats than those further away (Seco Pon et al., 2007); leatherback turtles are caught more often during nighttime longline sets compared to the day; and increased soak times result in higher catches of loggerhead turtles in the U.S. Atlantic longline fishery (Gilman et al., 2006). These differences in bycatch rates among gear deployment practices and gear configurations have driven many of the effective bycatch reduction strategies in longline vessels, which include changing the time of day of sets or setting at depths in the water column less frequently used by sea turtles, changing to bait types less likely to be consumed by turtles, changing hook type, size, and shape to decrease ingestion of the hook, and spatial and temporal management of fishing effort (Polovina et al., 2003; Gilman et al., 2006; Howell et al., 2008; Lucchetti and Sala, 2010; Piovano et al., 2012). Switching from J to circle hooks that tend to decrease the severity of hooking, as well as switching to larger hooks that are more difficult for turtles to ingest, have shown promise in several fisheries, particularly because these fixes have resulted in little impact on catch rates (Watson et al., 2005; Gilman et al., 2006; Read, 2007; Pacheco et al., 2011, Swimmer et al., 2011). Changes in hook and bait type have been successfully regulated or applied voluntarily in a number of fisheries around the world including the Mediterranean, U.S. Atlantic, Pacific and Gulf of Mexico longline fisheries, and in the Western and Central Pacific longline fisheries (Gilman et al., 2006, 2010; Lucchetti and Sala, 2010; Curran and Bigelow, 2011). In one of the most successful examples, the Hawaii-based longline swordfish fishery switched from J hooks with squid bait to large circle hooks with fish bait, which resulted in a significant decline in loggerhead (83%) and leatherback bycatch (90%), and a concomitant increase in swordfish catch (16%) (Gilman et al., 2007).

While fewer direct gear modifications have been made to large-scale gillnet fisheries, set modifications, as well as spatial and temporal restrictions, have been employed to reduce interactions between turtles and gillnets (Murray et al., 2009). In Japan and in the U.S., there also has been some attention focused on developing pound net escape devices (PEDs) to reduce sea turtle bycatch and mortality (Ishihara et al., 2011). For gillnet fisheries in the U.S. Atlantic, latitude, temperature, and net mesh size all were significant predictors of bycatch rates where larger mesh, southern latitudes, and warmer temperatures result in higher catches of loggerhead turtles (Murray, 2009). In addition, increasing the depth of gillnet sets from the surface would decrease the likelihood of capture as the fishing gear would reside outside of the typical range of turtle vertical habitat (Lucchetti and Sala, 2010). Reduction in mesh size and increased rigidity of the net leaders has helped reduce the impact of pound nets to turtles (Gilman et al., 2010).

Time-area closures have been another successful technique for reducing bycatch (Dunn et al., 2011). These may be seasonal or permanent closures based on known areas of high bycatch, or can be more precautionary and dynamic in nature, based on the probability of turtles being present. For example, since 2000, the area off South Padre Island, Texas, has been closed to shrimp trawling from July 15 to December 1 in order to protect nesting Kemp's ridleys (Lewison et al., 2003). A large-scale, annual 3 month closure of the drift gillnet fishery in California and Oregon has resulted in

zero leatherback bycatch in this fishery (Moore et al., 2009). Furthermore, along the U.S. west coast, the drift gillnet fishery may be closed during El Niño events in order to reduce bycatch of loggerhead turtles that move further north on the warm El Niño currents from Mexico into U.S. waters (Federal Register, 2007). Off the coast of central West Africa, Mayumba National Park in Gabon, and the adjacent Conkouati National Park in the Republic of Congo were created as permanent no-take areas to protect leatherback and olive ridley sea turtles from bycatch, with additional seasonal closures in adjacent areas during peak nesting seasons (Witt et al., 2008; Maxwell et al., 2011).

Time-area closures may also be enacted for other purposes, such as when a fishery hits a "bycatch quota" (i.e., an area is closed to fishing when a certain level of bycatch has been reached), or to protect target catch during key times of the year, but these closures may simultaneously protect bycatch species. An example of a bycatch quota forcing a fishery closure is the Hawaii-based shallow-set longline fishery, which is limited to 16 interactions with leatherbacks and 17 interactions with loggerheads in a calendar year; if more interactions occur, the fishery is closed, as it was in 2011 for reaching the leatherback take limit (Federal Register, 2011). Lewison et al. (2003) described closures in Texas to protect shrimp stocks that also resulted in a reduction in sea turtle strandings, even if that was not the intention of the closure. Closures, while effective in many areas, may have unintended negative consequences on bycatch, however, by shifting fishing effort to new areas, potentially ones with higher concentrations of turtles or other species vulnerable to bycatch (Abbott and Haynie, 2012). Being able to anticipate and adapt to fisher's responses to closures is key for successful, long-term bycatch reduction.

12.6.2 Bycatch Reduction in Small-Scale Fisheries

The characteristics that define SSF (e.g., large, dispersed fisheries, economically marginalized, little regulation) present significant challenges to implementation of bycatch mitigation measures. As many of these fisheries operate in impoverished communities, the costs associated with new technologies can be prohibitive. Moreover, mitigation products used in large-scale may not be regularly available to fishers in this sector, requiring the creation of new markets. Given the geographic dispersion of SSF fleets, proper implementation of mitigation and monitoring to ensure compliance can also be problematic. Initiatives such as changes to fishing methods can address some of these challenges (Eckert et al., 2008; Peckham et al., 2009). Fishery certifications or eco-labeling could also provide incentives for SSF to implement bycatch mitigation measures, if obstacles to compliance monitoring could be overcome. Small-scale fishers can directly benefit from sea turtle bycatch reduction; fewer turtles can mean less gear damage, bait loss, and time savings for fishers. There is a clear need to find the opportunities and mutual benefits for fishers to engage in potential bycatch solutions.

Mitigation measures that have been tested in small-scale longline fisheries include the use of circle hooks to reduce hooking rates and severity coupled with dehookers to facilitate hook removal (see references in Read, 2007). Mitigation measures tested in gillnet fisheries include a number of gear changes that are designed to reduce turtle attraction and incidence of entanglement (Gilman et al., 2010). These include net illumination (Wang et al., 2010), eliminating floats from main lines (Peckham et al., 2009; Gilman et al., 2010), alteration to net tie-downs and net height, and removal or reduction of floats (Gilman, 2009). The use of at-sea advisory programs, in which fishers share bycatch information with land-based biologists via radio to facilitate bycatch avoidance as well as safe handling and release of bycaught turtles, have also been used as a way to help fishermen select their fishing areas and minimize the likelihood of bycatch (Alfaro-Shigueto et al., 2012). Developing alternative food sources or conservation incentives has also been proposed as a means to reduce bycatch in SSF (Peckham et al, 2007; Ferraro and Gjertsen, 2009). Switching from higher to lower bycatch gear capable of targeting the same target species is another promising mitigation technique that has been shown to be an effective bycatch reduction strategy in SSFs (Chuenpagdee et al., 2003; Peckham et al., 2009).

12.7 SOCIAL SCIENCE OF BYCATCH

The ability to address the global issue of sea turtle bycatch has been challenged by a number of different factors, some of which relate more directly to facets of social science than biological science, e.g., social capital, the level of ecological awareness, governance structure of management and fisher communities, existence of policies to regulate and mitigate bycatch (Lewison et al., 2011). The multidisciplinary nature of these challenges, coupled with the need to work across local to ocean-wide scales, provides support for the assertion that effective bycatch reduction requires an integrated approach involving researchers from multiple disciplines working with partners from local communities up through international governance regimes (Figure 12.4). Although this level of cross-disciplinary integration has not been achieved, ongoing efforts within these various fields are redefining the ability to effectively address the issue of bycatch in small and large fisheries. In some developing Central and Latin American countries, community involvement, coordination, and collaborations have been established to address bycatch in SSFs (Hall et al., 2007; Peckham et al., 2007; Peckham and Maldonado-Diaz, 2012), yielding promising results. Combining education, outreach, and cooperative fisheries management, these efforts provide a clear model of participatory bycatch assessments and ultimately bycatch mitigation (Hall et al., 2007).

Engaging fishermen, fishing cooperatives, and the communities in which they live may be essential to reducing sea turtle bycatch (Gutierrez et al., 2011). Work by Jenkins (2010) clearly demonstrates that for two large-scale fisheries, U.S. trawl and purse seine, the most effective and successful bycatch reduction technology and strategies were invented and designed by fishers. This evaluation of successful bycatch reduction accounts for both sea turtle bycatch reduction achieved as well as fisher adoption and compliance, two essential elements for meaningful and long-term sea

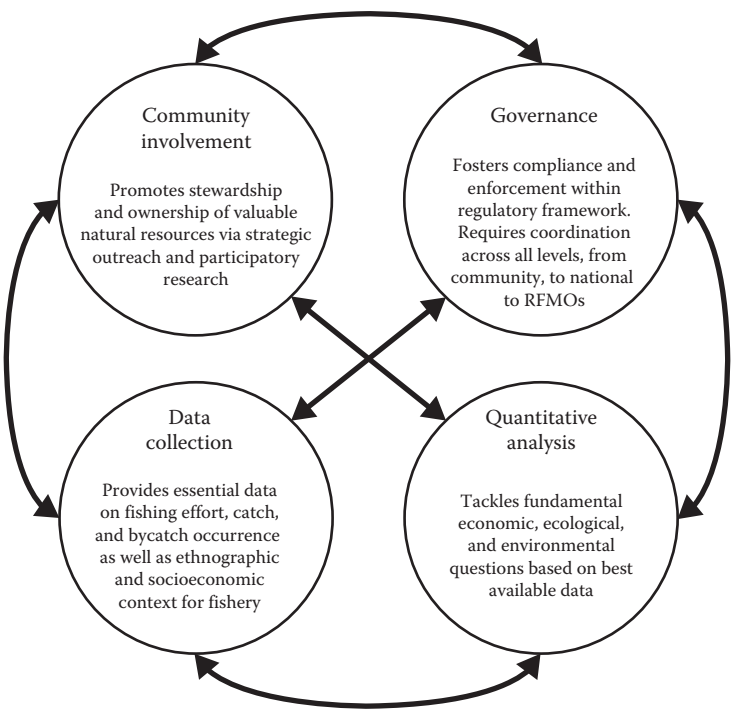

FIGURE 12.4 Cross-sectoral and multidisciplinary framework for bycatch reduction. (From Lewison, R.L., Soykan, C.U., Cox, T., Peckham, H., Pilcher, N., LeBoeuf, N., McDonald, S. Moore, J.E., Safina, C., Crowder, L.B. 2011. Ingredients for addressing the challenges of fisheries bycatch. *Bulletin of Marine Science* 87(2): 235–250.)

turtle bycatch reduction (Jenkins, 2010). For SSFs, in particular, command-and-control approaches, such as fisheries closures and mandated technological fixes, are often impractical and may only provide short-term solutions (Berkes et al., 2001; Hilborn et al., 2005; McClanahan et al., 2006). Numerous studies have shown that engaging fishermen from the outset of bycatch research and reduction initiatives can augment the development and adoption of long-term solutions (Hall et al., 2000; Kennelly, 2007; Campbell and Cornwell, 2008; Jenkins, 2010), in part because investment in the conservation process may increase fishers' subsequent adoption of conservation strategies (Cox et al., 2007; Jenkins et al., 2008). In the context of SSFs, which predominantly occur in developing nations where management and enforcement are limited, engaging fishers and their communities can be particularly important because bycatch mitigation programs are essentially voluntary (McClanahan et al., 2006; Jackson, 2007).

12.8 NEW APPROACHES AND DIRECTIONS IN BYCATCH RESEARCH

There have been substantial advances in the recognition and assessment of the significant threat that fisheries bycatch poses to sea turtle population worldwide. At the same time, the development of bycatch reduction measures also has yielded some promising and effective approaches. The problem of sea turtle bycatch is still largely one of scale; while some fleets require and enforce bycatch reduction measures, the vast majority do not. Although large-scale and SSFs are faced with different challenges in terms of bycatch reduction, both sectors are likely exerting population-level effects on sea turtle populations that, in many cases, are already in decline (Wallace et al., 2011). Innovations, such as at-sea advisory programs that provide real-time information to small-scale fishers on observed bycatch (Alfaro-Shigueto et al., 2012), and tri-national programs that connect small-scale fishers on opposite sides of the ocean to gain a clearer understanding of sea turtle status (Tri-National Fisherman's Exchange, Grupo Tortuguero, Peckham and Maldonado-Diaz, 2012), are creating new possibilities to tackle the daunting issue of sea turtle bycatch in SSFs. Likewise, rapid bycatch assessments, which are interview-based surveys that characterize gear use, fishing effort and obtain semi-quantitative estimates of bycatch, are proving to be a powerful approach to gathering general bycatch information from widely distributed and difficult-to-monitor SSFs (*sensu* Moore et al., 2010).

For large-scale fisheries, technological advances are paving the way to more effective bycatch reduction. A number of new promising approaches serve to integrate multiple factors that drive sea turtle bycatch vulnerability, i.e., insights from sea turtle ecology, life history, and physiology, gained from sea turtle telemetry and tracking. Integration of these data in the context of a dynamic ocean environment will yield a new generation of innovative and effective bycatch reduction strategies. One of the best contemporary examples of this, TurtleWatch (Howell et al., 2008), provides management recommendations to the Hawaii longline fishery that are based on documented seasonal relationships between SST and turtle distribution, with the overall aim of reducing loggerhead bycatch. In the U.S. mid-Atlantic coast gillnet fisheries, managers also use SSTs to enact rolling closures based on the probability that turtles aggregate in predictable temperatures zones (Murray et al., 2009). Comparable studies that have also shown relationships between water temperatures or movement patterns and seasonal distributions of other sea turtle species (McMahon and Hays, 2006; Hawkes et al., 2007; Sherrill-Mix et al., 2007; Gardner et al, 2008; Benson et al., 2011; Shillinger et al., 2011) provide the foundation on which to develop similar bycatch management strategies in other ocean regions.

As the field of bycatch research has developed, new perspectives and definitions of bycatch have emerged. Defining bycatch as "any catch that is unwanted and unmanaged" (Davies et al., 2009), we can consider sea turtle bycatch in an integrated multi-species catch management context. This type of integration of bycatch and catch patterns has been employed by a small number of fleets. In the Eastern Australian longline fishery, managers use a combination of satellite tracking and remote sensing to create forecasting models of where sensitive bycatch species will occur, creating tiered

fishing zones based on predicted distribution of multiple target catch species and bycatch species that also takes into account the potential economic yield given real-time quota levels (Hobday et al., 2011). Because these kinds of approaches require large amounts of high-resolution data on biological and physical oceanography, fleet-specific behavior, and economic parameters, they are difficult to develop and apply widely. However, the synoptic nature of these tools provides a template for how it might be possible to simultaneously reduce bycatch of protected species like sea turtles, while maintaining sustainable catch levels. Given that a third of all fish stocks are overexploited or depleted (Worm et al., 2009) and the ongoing concerns about the viability of many sea turtle populations, creating assessment tools that can consider sea turtle bycatch reduction within the broader context of fisheries sustainability is an essential next step.

Effective bycatch research and mitigation will rely on the continued integration of sea turtle ecology, fisheries management, and social science. As demonstrated in this volume, research on sea turtle ecology over the past decade has transformed our understanding of these species. Likewise, over the past 10 years, quantitative analyses of bycatch data have developed substantially and played an important role in refining our understanding of the population-level effects of bycatch, and the oceanographic variables associated with sea turtle bycatch. More recent programs on education, outreach, and cooperative fisheries management approaches have also provided powerful models of the importance of participatory bycatch assessment and bycatch mitigation. Maximizing the integration of ecological data within an oceanographic, fisheries and social context will be essential in balancing the survival of sea turtles and sustainable fisheries.

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