

Postrelease mortality in istiophorid billfish

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Abstract: Meta-analysis (inverse-variance, random-effects model) involving 46 studies was used to estimate the effect size of postrelease mortality (F_r) in six istiophorid billfish species (black marlin (*Istiompax indica*), blue marlin (*Makaira nigricans*), longbill spearfish (*Tetrapturus pfluegeri*), sailfish (*Istiophorus platypterus*), striped marlin (*Kajikia audax*), and white marlin (*Kajikia albida*)) following release from recreational, longline, and harpoon fishing gears. The studies involved 400 reporting pop-up satellite archival tags and 64 reporting acoustic (ultrasonic) tags. Despite fish being captured, tagged, and released under widely disparate conditions, locations, and gear types, F_r was homogeneous among species. Variability in F_r was principally due to random sampling error within studies with no evident patterns. Fifteen studies (33% of tags) indicated no mortality, and the overall summary effect size for F_r was 13.5% (95% CI: 10.3%–17.6%). Since the random-effects model decomposed to a fixed-effect model when the between-studies variance $T^2 = 0.00$, results were confirmed using exact nonparametric inferential tests and sensitivity analyses. Our results support earlier findings in the Atlantic and substantiate the majority of istiophorid billfish survive when released from recreational and longline fishing gear, clearly implying catch-and-release as a viable management option that permits fishing activity while protecting parental biomass and the fishery.

Résumé : Une méta-analyse (inverse de la variance avec modèle à effets aléatoires) de 46 études a été utilisée pour estimer la taille des effets de la mortalité après remise à l'eau (F_r) chez six espèces d'istiophoridés (makaire noir (*Istiompax indica*), makaire bleu (*Makaira nigricans*), makaire bécune (*Tetrapturus pfluegeri*), espadon voilier (*Istiophorus platypterus*), marlin rayé (*Kajikia audax*) et makaire blanc (*Kajikia albida*)) après leur libération d'engins de pêche sportive, à la palangre ou au harpon. Les études comprenaient 400 étiquettes de collecte de données par satellite détachables et 64 étiquettes acoustiques (ultrasoniques). Bien que les poissons aient été capturés, marqués et relâchés dans des conditions et emplacements très variés et avec un éventail d'engins, F_r était homogène parmi les espèces. La variabilité de F_r était principalement due à l'erreur d'échantillonnage aléatoire dans les différentes études, sans motif évident. Quinze études (33 % des étiquettes) n'indiquaient aucune mortalité et la taille sommaire globale des effets pour F_r était de 13,5 % (IC 95 % : 10,3 % – 17,6 %). Puisque le modèle à effets aléatoires se décomposait en un modèle à effets fixes quand la variance entre études était $T^2 = 0,00$, les résultats ont été confirmés à l'aide de tests inférentiels non paramétriques exacts et d'analyses de la sensibilité. Nos résultats appuient des résultats antérieurs pour l'Atlantique et révèlent que la majorité des istiophoridés survivent quand ils sont relâchés d'engins de pêche sportive ou à la palangre, ce qui indique clairement que la pêche avec remise à l'eau est une option de gestion valable qui permet l'activité de pêche tout en protégeant la biomasse parentale et la ressource. [Traduit par la Rédaction]

Introduction

Mortality is one of the key parameters needed for modelling the population dynamics of any species. Changes in mortality can result in changes in population growth (Ricker 1975; Quinn and Deriso 1999). Because of declines in some pelagic teleost and shark populations (discussed below), reducing the mortality of bycatch species (i.e., nontargeted and incidentally captured fishes) and sublegal size classes is a high priority for management and conservation worldwide.

In fisheries biology, mortality is broken down into natural mortality (M) and fishing mortality (F), which combine to provide the

instantaneous mortality rate (Z). F has two main components: at-vessel mortality or catch (F_c) and postrelease (sometimes referred to as delayed, hooking, noncatch, or fatigue) mortality (F_r) (Muoneke and Childress 1994; Graves et al. 2002; Diaz and Serafy 2005). F_c and F_r are additive, but mutually exclusive, events (i.e., $F = F_c + F_r$). Musyl et al. (2009, 2011a) reported F_c and F_r were correlated in blue shark (*Prionace glauca*) in both Atlantic and Pacific commercial pelagic longline fisheries and hypothesized that many of the factors responsible for F_c were the same for F_r , including variability in handling practices.

High rates of mortality from industrial fishing have the potential to reduce spawning biomass and ultimately the ability of

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stocks to rebound, whether they are target or bycatch species. There is considerable disagreement about the current state of large pelagic fish populations, but the species at greatest risk are large apex predators, particularly sharks and istiophorid billfish, because their life-history parameters make them susceptible to overexploitation (Kitchell et al. 2004, 2006). Moreover, commercial and recreational fishing generally remove the largest and fittest animals (e.g., Sutter et al. 2012). For example, large female blue marlin (*Makaira nigricans*) can release more than 10^7 eggs (Hopper 1990; Sun et al. 2009). Therefore, continued removal over several decades of these large, long-lived, late-maturing predators can substantially reduce spawning biomass and potentially cause heritable changes in life-history traits such as body size, growth, and age-at-maturity (Law 2000; Kuparinen and Merilä 2007; Enberg et al. 2009). Kitchell et al. (2004) estimated that >90% of mortality in blue marlin was caused by commercial longline fishing practices targeting yellowfin (*Thunnus albacares*) and bigeye tunas (*Thunnus obesus*). Cox et al. (2002) estimated blue marlin biomass to have been reduced to ~20% of its abundance prior to industrialized fishing. Though Hinton (2000) suggested a lesser reduction of ~50%, it is clear that the populations have fallen well below historical levels. System-wide mortality caused by indiscriminant fishing practices can also impact the health and sustainability of entire marine ecosystems. In simulations of commercial longline fisheries, Goodear (2001) and Kitchell et al. (2004) demonstrated that fishing practices targeting tunas also dramatically reduced the biomass of blue marlin and other apex predators with low rates of population increase, while increasing biomass of juvenile tunas and other prey species.

The uncertainty as to the true values of F_c and F_r is a major impediment to effective management and resource conservation in many fisheries targeting large pelagic species. For catch-and-release to be a viable strategy, there must be a high likelihood of postrelease survival. The percentage of blue marlin retrieved alive from commercial longline gear appears to be variable, ranging from 50% to 75% (Cramer 1998, 2000; Jackson and Farber 1998; Lee and Brown 1998; Semba and Yokawa 2007). But it is largely unknown whether these fish would survive if released. Options likely to benefit istiophorid billfish populations include maximizing postrelease survival in the recreational fishery (i.e., protecting large individuals within the spawning biomass), minimizing catch in commercial longline fisheries through removal of shallow hooks (Kitchell et al. 2004, 2006; Pine et al. 2008; Beverly et al. 2009), and reducing injury in both commercial and recreational fisheries through the use of circle hooks (Prince et al. 2002a; Horodysky and Graves 2005; Serafy et al. 2009, 2012). Since only a very small fraction of the spawning biomass interacts with the sports fishing sector (Pine et al. 2008), the most effective alternative to protecting spawning biomass and rebuilding stocks might be the promotion of catch-and-release practices in the commercial longline fishery (Kitchell et al. 2004; Piner et al. 2013). Since 2001, a management measure requiring the release of live blue and white (*Kajikia albida*) marlin during haulback of pelagic longline fishing operations was promulgated by the International Commission for the Conservation of Atlantic Tunas (ICCAT 2001a, 2001b). To assess the efficacy of catch-and-release as a viable management strategy, however, both F_c and F_r must be quantified. In Atlantic fisheries, survival data from electronic tagging studies in istiophorid billfish appeared to support the policy decision by ICCAT, but the number of studies and sample sizes were generally small (Table 1). Mitigation strategies could then be optimized by concentrating on species with high rates of F_c and F_r (Carruthers et al. 2009).

Accurate estimates of F_c and F_r (Benaka and Dobrzynski 2004; Carruthers et al. 2009) are also necessary for estimating total fisheries mortality and in turn for producing accurate stock assessments (Kitchell et al. 2004; Kelleher 2005; Pine et al. 2008; Jensen et al. 2010; Piner et al. 2013). Recent population assessments sug-

gest blue marlin populations in the Pacific are close to fully exploited (Su et al. 2012) and that better estimates on F_r would improve assessment models (Kleiber et al. 2003). Owing to the precipitous decline of other istiophorid billfish populations in both the Atlantic and Pacific oceans, there have been extensive discussions about the optimal ways to protect these species from the effects of fishery exploitation (Kitchell et al. 2004; ICCAT 2001a, 2001b, 2010, 2011, 2012). More specifically, Brodziak and Piner (2010), Jensen et al. (2010), and Piner et al. (2013) suggested low spawner abundance indicated striped marlin (*Kajikia audax*) populations in the Pacific were in a depleted condition and that rebuilding of stocks depended on reducing mortality and increasing maternal biomass.

Studies to determine F_r generally require several hundred samples to achieve statistical power at 80% (e.g., Goodear 2002; Kerstetter et al. 2003; Horodysky and Graves 2005; Kerstetter and Graves 2006a, 2008; Musyl et al. 2011a). Although pop-up satellite archival tags (PSATs) and acoustic (ultrasonic) tags have been shown to be appropriate tools for estimating F_r in istiophorid billfish (e.g., Pepperell and Davis 1999; Graves et al. 2002; and references in Table 1), costs associated with both usually preclude application to large number of individuals. As a result, meta-analysis is an ideal statistical methodology for assessing F_r studies in pelagic fisheries because of low statistical power and diversity in approaches. Most interventions (e.g., hook trials, alterations to gear, etc.), monitoring activities (e.g., species diversity, F_c , etc.) or research questions (e.g., age-at-maturity, asymptotic size, etc.) in fisheries biology are tested repeatedly, so instead of examining studies in isolation, it makes sense to systematically and quantitatively examine the entire body of evidence (Hedges and Olkin 1985; Borenstein et al. 2009). Many small studies (with low statistical power) have assessed F_r experimentally in istiophorid billfish (Table 1). If F_r is consistent across studies, then the meta-analysis usually yields a combined estimate that is more precise than any of the individual studies (Hedges and Pigott 2004; Borenstein et al. 2009; Musyl et al. 2011a). By contrast, if the effect size varies across studies, the meta-analysis may allow for the identification of explanatory factors. Owing to uncertainty in the estimates provided by small, individual studies, Musyl et al. (2011a) used meta-analyses to estimate F_r in blue shark released from longline gear and reported increased power and precision in the summary effect size of 15% (95% confidence interval (CI): 8.5%–25.1%), which is very similar to the summary effect size reported herein for istiophorid billfishes.

Materials and methods

Meta-analysis was used to examine heterogeneity in effect sizes of F_r in six istiophorid billfish species (black marlin (*Istiompax indica*), blue marlin (*M. nigricans*), longbill spearfish (*Tetrapturus pfluegeri*), sailfish (*Istiophorus platypterus*), striped marlin (*K. audax*), and white marlin (*K. albida*)) released from recreational, harpoon, and longline fishing gear using published papers, unpublished reports, and ongoing research. To do so, we first needed to evaluate and document reliable methods to measure F_r and then the relevant literature needed to be searched and assembled to ensure it matched our selection criteria. Details of the examination of the heterogeneity statistics and formal meta-analysis models are described below.

Identification of F_r

Musyl et al. (2011a) reviewed the cost:benefit ratio of methods to investigate F_r in large pelagic fishes. Of the direct methods, PSATs and acoustic tags were shown to provide the best options, but both techniques are expensive. PSATs have been chosen specifically for F_r studies (Table 1) because they can be equipped with fail-safe mechanisms (either mechanical or within the device's software) that prevent them from being crushed at depth if the animal dies and sinks over deep water (e.g., Moyes et al. 2006).

Table 1. Data and results of the random effects meta-analysis on effect sizes of postrelease mortality (F_r) from the literature and unpublished sources on istiophorid billfish using pop-up satellite archival tags (PSATs) and acoustic (ultrasonic) tags.

[Study No.] source and study location	Year	Fishing method	Fishing style; hook type	F_r rate %	95% CI	No. of mortalities/ No. of tags reporting	No. of nonreporting tags	Water or deck	Healthy	Ventilated	Notes, tag types, models, time-to-event (mortality)
Striped marlin (<i>Kajikia audax</i>)											
[1] Holts and Bedford 1990; Southern California	1990	Rod and reel		3.8*	0.2–40.3*	0/12*	0	W			Vemco V4P model tags
[2] Brill et al. 1993; Hawaii	1993	Longline	J hook	16.7	2.3–63.1	1/6	0	W	Y	N	Vemco VP-3 model tags; mortality occurred ~4 h after tagging; 4–8 h soak time
[3] Domeier et al. 2000 2003; Baja, California	2000	Rod and reel	Drop back bait; circle and J [‡]	36.7	21.6–54.9	11/30	2	W	N	N	WC PAT model tags rigged with glass beads for fail-safe depth release mechanism with a specified tolerance of 325–375 m; seven reporting PAT tags excluded from analysis in 2000 for lack of data (see Domeier et al. 2003, their table 3); 30 pound test line class (1 lb = 0.453 kg); ~26 min fight times; all mortalities occurred after <~5 days (mean 1.5 days); 1–12 months programmed pop-up times; tag and tether positively buoyant
[4] Domeier et al. 2000 2003 — corrected year 2000				17.2	7.4–35.3	5/29	3				Striped marlin reported to dive to 460 m (Sippel et al. 2011); four tagged fish in 2000 deemed mortalities (Domeier et al. 2003) for reaching threshold depths where fail-safe mechanism presumably engaged (404, >250 and <350, 312, 416 m); one tag excluded in 2000 by Domeier et al. (2003) for releasing at 244 m; Domeier et al. (2003) indicate two dead fish were tagged in 2000 (one tag did not report)
[5] Domeier et al. 2001 2003; Baja, California	2001	Rod and reel	Drop back bait; circle	16.1	6.9–33.4	5/31	10	W	N	Y	30 pound test; ~25 min fight times; all mortalities occurred after <5 days; 26 fish were resuscitated in 2001; tags equipped with new WC RD 1500 depth severing device (i.e., 1500 m, presumably release depth (RD) at which tether severing mechanism engages)
[6] Musyl et al. (in preparation); Hawaii	2003	Rod and reel	Trolling; J [§]			0/1 [†]	0	W	N	N	MT PIT-100 model tags; 80 pound test; ~10 min fight time; tag applied during tournament fishing; tag and tether positively buoyant
[7] Musyl et al. (in preparation); Hawaii	2004	Longline	Circle			0/1 [†]	0	W	N	N	Soak time ~12 h ; tag and tether positively buoyant
[8] Sippel et al. 2007; New Zealand	2003	Rod and reel	Trolling; J	8.3*	0.5–62.2*	0/5*	1		Y		PAT2.5 model tags; 31- to 113-day programmed pop-up periods; 22–60 days retention

Table 1 (continued).

[Study No.] source and study location	Year	Fishing method	Fishing style; hook type	F_r rate %	95% CI	No. of mortalities/ No. of tags reporting	No. of nonreporting tags	Water or deck	Healthy	Ventilated	Notes, tag types, models, time-to-event (mortality)
[9] Holdsworth et al. 2009; New Zealand	2005–2007	Rod and reel		11.8	3.0–36.8	2/17	5	D	Y	Y	PAT4 model tags; 22 fish double-tagged with PAT and WC SPOT4 and SPOT5 tags (four fish tagged with SPOT tags only — not included); time-to-event data were not quantified in report, only that mortality occurred “shortly after release”
[10] Chiang et al. (in preparation); Taiwan	2007–2013	Harpoon				0/1 [†]	2	W	N	N	MT PTT-100 model tags; positively buoyant
[11] Moyes and Musyl (in preparation); Central Pacific	2011–2014	Longline	Circle	12.5	1.7–53.7	1/8	4	W	N	N	MT PTT-100 model tags; 12-month pop-up periods; tag and tether positively buoyant; mortality was probably result of shark predation as evidenced by depth and temperature differences ~5 days after release; soak times ~12 h [‡] ; hooks and trailing gear left in place
Weighted striped marlin summary effect				18.7	10.7–30.7	20/112	24				95% bootstrap CIs and F_r using all raw, unweighted data: 17.9% (10.7%–25%)
Corrected weighted striped marlin summary effect				14.5	8.9–22.6	14/111	25				95% bootstrap CIs and F_r using all raw, unweighted data: 12.6% (7.2%–18.9%)
Blue marlin (<i>Makaira nigricans</i>)											
[12] Yuen et al. 1974; Hawaii	1974	Rod and reel		50.0	12.3–87.7	2/4	1	W	Y	N	Ultrasonic tag but mentions no make or model number
[13] Holland et al. 1990; Hawaii	1990	Rod and reel		7.1*	0.4–57.7*	0/6*	0	W			No model tag specified (refers to other studies)
[14] Block et al. 1992; Hawaii	1992	Rod and reel		16.7	2.3–63.1	1/6	0	W	Y		Vemco V4P4 model tags
[15] Edwards and Gorzelañy 1989; Florida	1989	Rod and reel		6.3*	0.4–53.9*	0/7*	0				
[16] Graves et al. 2002; Bermuda	1999	Rod and reel	Trolling; J					W	N	Y	MT PTT-100 (early model tag) with no fail-safe measures, study excluded from analysis; 5-day pop-up periods [¶] ; 130 pound test; 15–35 min fight times; three fish resuscitated; eight fish survived with one nonreporting tag
[17] Matsumoto et al. 2002, 2003, 2004; Mid- to South Atlantic	2000–2002	Longline		10.0*	0.6–67.4*	0/4*	7	W			MT model tags; no other information given
[18] Kerstetter et al. 2003; Western North Atlantic	2000	Longline	J	16.7*	1.0–80.6*	0/2*	0	W	Y	N	PAT model tags; 30-day pop-up period; 6–35 h soak times (five MT PTT-100 tags excluded from analysis as they had no fail-safe measures)

Table 1 (continued).

[Study No.] source and study location	Year	Fishing method	Fishing style; hook type	F_r rate %	95% CI	No. of mortalities/ No. of tags reporting	No. of nonreporting tags	Water or deck	Healthy	Ventilated	Notes, tag types, models, time-to-event (mortality)
[19] Prince et al. 2005; Dominican Republic	2003	Rod and reel	Trolling; J			0/1†	0	W	Y		MT PTT-100 model tags
[20] Graves and Horodysky 2010; Western North Atlantic	2008–2009	Rod and reel	Trolling bait; J	6.7	1.7–23.1	2/30	0	W	N	Y	MT PTT-100 HR model tags; 10-day pop-up period; 30–130 pound test; 4–55 min fight times; 9 and 12 min fight time for mortalities that occurred <10 days postrelease
[21] Graves and Horodysky 2010; Western North Atlantic	2008–2009	Rod and reel	Trolling bait; circle	1.7*	1.0–21.7*	0/29*	1	W	N	Y	30–130 pound test; 4–55 min fight times
[22] Musyl et al. (in preparation); Hawaii	2001–2011	Rod and reel	Trolling; J§	1.5*	0.1–19.6*	0/33*	9	W	N		MT PTT-100 and PAT2–PAT3 model tags; 50–130 pound test; ~15 min fight times
[23] Musyl et al. (in preparation); Hawaii	2003	Rod and reel	Drop back bait; J§	20.0	2.7–69.1	1/5	1	W	N		130 pound test; ~15 min fight times; most tags applied during tournament fishing; lone mortality was jaw-hooked jaw (hook removed); 17 min fight time; 82 days postrelease mortality
[24] Mourato et al. (unpublished data); Brasil	2006–2013	Rod and reel; longline		12.5*	0.7–73.4*	0/3*	2	W			PAT4 and MK-10 model tags
[25] Musyl et al. (in preparation); Hawaii	2006	Longline	Circle			0/1†	0	W	N	N	Soak time ~12 h
[26] Chiang et al. (in preparation); Taiwan	2007–2013	Harpoon		7.7	1.1–39.1	1/13	12	W	N	N	MT PTT-100, MT x-tag, and PAT MK-10 model tags; mortality <3 h after tagging
[27] Moyes and Musyl (in preparation); Central Pacific	2011	Longline	Circle				1	W	N	N	MT PTT-100 model tags; 12-month pop-up periods; tag and tether positively buoyant; soak times ~12 h
Weighted blue marlin summary effect				10.3	5.6–18.3	7/144	34				95% bootstrap CIs and F_r using all raw, unweighted data: 4.9% (1.4%–8.3%)
Black marlin (<i>Istiompax indica</i>)											
[28] Pepperell and Davis 1999; Northeastern Australia	1992–1995	Rod and reel		16.7	2.3–63.1	1/6	2	W	N	N	Vemco V22 and V32 model tags; 8–27 h duration; moribund fish had stomach everted; ~7 h postrelease mortality; fish size ~100–420 kg

Table 1 (continued).

[Study No.] source and study location	Year	Fishing method	Fishing style; hook type	F_r rate %	95% CI	No. of mortalities/ No. of tags reporting	No. of nonreporting tags	Water or deck	Healthy	Ventilated	Notes, tag types, models, time-to-event (mortality)
[29] Gunn et al. 2003; Northeastern Australia	2000–2002	Rod and reel	Trolling; J and circle	33.3	4.3–84.6	1/3	0	W	Y	N	Four of five PAT1 model tags did not have fail-safe depth release mechanism and were excluded from analysis; two MT PTT-100 model tags had fail-safe measures; 3–64 days-at-liberty
[30] Musyl et al. (in preparation); Northeastern Australia	2002	Rod and reel	Trolling			0/1†	0	W	N	N	MT PTT-100 model tag; ~950 lb fish; 82 days-at-liberty; tag and tether positively buoyant
[31] Chiang et al. (in preparation); Taiwan	2007–2013	Harpoon		5.9	0.8–32.0	1/17	11	W	N	N	MT PTT-100, MT x-tag, PAT MK-10 model tags; mortality <3 h after tagging
Weighted black marlin summary effect				14.1	4.5–36.5	3/27	13				95% bootstrap CIs and F_r using all raw, unweighted data: 11.0% (0%–26.0%)
Sailfish (<i>Istiophorus platypterus</i>)											
[32] Jolley and Irby 1979; Florida	1974–1976	Rod and reel		12.5	1.7–53.7	1/8	0	W/D			Ultrasonic transmitters developed by D. Pincock, University of New Brunswick; Lawson and Carey 1972; shark predation after ~7 h
[33] Hoolihan 2005; Gulf of Arabia	2002–2004	Rod and reel		11.1	1.5–50.0	1/9	0	D			Vemco V16TP model tags; one fished shortly after release
[34] Hoolihan 2005; Gulf of Arabia	2002	Rod and reel		16.7*	1.0–80.6*	0/2*	0	D			PAT2 model tags
[35] Prince et al. 2006; Central America	2000–2004	Rod and reel	Circle	9.4	3.1–25.4	3/32	9	W	Y		PAT2 and PAT3 model tags; 30- to 120-day pop-up periods; three mortalities after 26, 50, 65 days
[36] Hoolihan and Luo 2007; Gulf of Arabia	2001–2005	Rod and reel		3.6*	0.2–38.4*	0/13*	3	D			PAT2 and PAT3 model tags (14 total); two MT PTT-100 tags (two PAT2 tags excluded, as these were reported in Hoolihan 2005)
[37] Kerstetter and Graves 2008; Gulf of Mexico, Florida	2005–2007	Longline	Circle	11.8	3.0–36.8	2/17	0	W	N	N	MT PTT-100 HR model tags; 10-day pop-up periods; both mortalities <~3 h after release “ACCESS” or condition scores indicate healthy fish died; Kerstetter and Graves 2008
[38] Mourato et al. 2014; Brasil	2009–2010	Rod and reel		10.0*	0.6–67.4*	0/4*	0	W			PAT MK-10 model tags; tag and tether positively buoyant
Weighted sailfish summary effect				10.2	5.3–18.8	7/85	12				95% bootstrap CIs and F_r using all raw, unweighted data: 8.2% (2.4%–14.1%)

Table 1 (continued).

[Study No.] source and study location	Year	Fishing method	Fishing style; hook type	F_r rate %	95% CI	No. of mortalities/ No. of tags reporting	No. of nonreporting tags	Water or deck	Healthy	Ventilated	Notes, tag types, models, time-to-event (mortality)
White marlin (<i>Kajika albida</i>)											
[39] Horodysky and Graves 2005; Mid-Atlantic	2002–2003	Rod and reel	Circle**	2.4*	0.1–28.7*	0/20*	0	W	N	Y	MT PTT-100 HR model tags; 5- to 10-day pop-up periods; 20–40 pound test
[40] Horodysky and Graves 2005; Mid-Atlantic	2002–2003		J**	35.0	17.7–57.4	7/20	1	W	N	Y	Mortalities from 0.1 to 64 h; five fish died within 6 h
[41] Prince et al. 2005; Dominican Republic	2003	Rod and reel	Trolling; J	7.1*	0.4–57.7*	0/6*	1	W		Y	PAT3 model tags, documents at-vessel mortality
[42] Kerstetter and Graves 2006a; Mid-Atlantic	2004	Longline	J and circle			0/1†	0	W		N	One PAT model tag (43-day deployment); 27 MT PTT-100 HR model tags excluded from analysis as these tags did not have fail-safe depth release mechanism; one tag excluded from analysis owing to separation from fish after tagging
[43] Saito et al. 2004; Mid- to South Atlantic	2005	Longline		7.1*	0.4–57.7*	0/6*	6				PAT model tags; no other information provided
[44] Graves and Horodysky 2008; Mid-Atlantic	2002–2006	Rod and reel	Circle	2.6	0.4–16.1	1/39	1	W	N	Y	MT PTT-100 model tags; 10-day pop-up periods; 20–30 pound test; 5–30 min fight times; one fish died after 14 min fight time after 5 days; one tag excluded as tag detached <1 day (20 tags on circle hooks were excluded as these were already reported in Horodysky and Graves 2005)
[45] Mourato et al. (unpublished data); Brasil	2006–2012	Rod and reel		33.3	4.3–84.6	1/3	0	W			MK-10 model tag
Weighted white marlin summary effect				11.0	3.1–31.9	9/95	9				95% bootstrap CIs and F_r using all raw, unweighted data: 9.4% (4.2%–15.8%)
Longbill spearfish (<i>Tetrapturus pfluegeri</i>)											
[46] Kerstetter et al. 2009; East Africa	2004	Rod and reel	Circle	50.0	5.9–94.1	1/2	0	W	N	N	PAT4 model tags; mortality after 11 days; 20 min fight time; hooks removed

Table 1 (continued).

[Study No.] source and study location	Fishing method	Fishing style; hook type	F_r rate %	No. of tags reporting	No. of mortalities/ nonreporting tags	Water deck	Healthy	Ventilated	Notes, tag types, models, time-to-event (mortality)
Overall istiophorid billfish effect size			14.2	10.4–19.0	47/465	93			95% bootstrap CIs and F_r using all raw, unweighted data: 10.1% (7.5%–12.9%)
Overall (corrected for Domeier et al. 2003)			13.5	10.3–17.6	41/464	94			95% bootstrap CIs and F_r using all raw, unweighted data: 8.8% (6.3%–11.4%)

Note: For studies, “year” is deployment year (broken down by gear type when possible) with number of mortalities over number of reporting tags also provided. Nonreporting tags were not taken as being synonymous with mortality (Graves et al. 2002; Musyl et al. 2011a, 2011b). “J” refers to J hooks, and “circle” refers to circle hooks. All PSATs are assumed to have been rigged with fail-safe depth release mechanisms unless indicated (see text for more information; also see Musyl et al. 2011a, 2011b). “MT” refers to Microwave Telemetry (Columbia, Maryland, USA) with PSAT models x-tag, PTT-100, PTT-100 HR (high rate). “WC” refers to Wildlife Computers (Redmond, Washington, USA) with PAT model tags PAT1-PAT4, MK10. The last columns indicate whether fish were tagged in the water (W) or on deck (D), with further indication whether the tagged animal was presumably healthy and resuscitated: “Y” = yes; “N” = no.

*In studies with two or more reporting tags where no mortalities were reported (15 studies), a 0.5 continuity correction factor was added to the event and non-event values to derive study F_r weights, SEs, variances, and 95% CIs (Yates 1934; Haldane 1956; Cox 1970; Sweeting et al. 2004).

[†]Seven studies containing one reporting tag (all survivors) were excluded from the formal meta-analysis.

[‡]Domeier et al. (2003) indicate no significant differences in F_r between J and circle hooks in year 2000.

[§]Musyl et al. (in preparation) indicate majority of fish were captured-tagged-released in jackpot fishing tournaments (emphasis on using heavier class lines (80–120 pound test), which favours short fight times and quickly tagging and releasing fish).

[¶]Soak time is indicative of the time hooks are in the water and may not be indicative of the length of time istiophorid billfish spend hooked (i.e., without hook timers, there is no conclusive information).
¶Though the Graves et al. (2002) study was excluded for having released tags with no fail-safe release mechanism (at this time, the technology was unavailable), they were the first to promote programming tags with short pop-up periods (i.e., 5 to 10 days) in F_r studies because a small set of conventional tag returns suggested blue marlin commenced feeding ~5 days after being captured, tagged, and released. Moreover, acoustic tagging studies reviewed in Pepperell and Davis (1999) suggested mortality occurred around 2 days postrelease. The reader is cautioned that longer programmed pop-up periods make it difficult to disentangle influences like tag shedding, tag failure, and natural mortality from fishing mortality (discussed in text; also see Goodey 2002 and Graves et al. 2002).

^{**}Horodysky and Graves (2005) indicate significant differences in mortality between J and circle hooks.

PSATs can also be programmed to detach and begin transmission if they record no substantial pressure changes (e.g., no depth changes greater than ±5–10 m) for a programmable number of days (usually 2 to 4). This situation would occur if the PSAT released before the programmed pop-up date (i.e., a shed tag) and floated at the surface (or occasionally ended up on land) or if the animal died and sank to the bottom at a depth shallower than the depth initiating release (e.g., Swimmer et al. 2006). In other words, it is possible to tell “dead” from “shed” but in both these instances, data transmission is initiated. Recorded depth and temperature data subsequently allow investigators to discriminate PSATs detaching from dead (i.e., sinking) animals or from those shed prematurely (i.e., prior to the programmed release date) from live animals, as well as PSATs presumably ingested by sharks (Kerstetter et al. 2004). Postrelease mortality can also be determined by attaching acoustic (ultrasonic) telemetry tags and following the animal with a tracking vessel and recording movements in real time. The limitation of these studies is that batteries last for only ~96 h, so the duration of observation postrelease is much shorter than with PSATs. But because shed acoustic tags sink at vastly different rates from tags attached to dead sinking animals (Block et al. 1992; Brill et al. 1993; Pepperell and Davis 1999), a mortality event can be reliably distinguished from a shed tag.

Selection of studies and eligibility criteria

The criteria for F_r studies included in our analysis went through several iterations. We first searched for studies using the key words: postrelease mortality, survival, PSAT, acoustic tags, ultrasonic tags, istiophorid, billfish, marlin, longline, rod and reel, fail-safe release mechanism (or software), and positively buoyant; we also searched for studies that did not purposely tag healthy individuals. This search found only one PSAT study (Domeier et al. 2003; Table 1) and one acoustic study (Pepperell and Davis 1999; Table 1) that met our initial stringent criteria. Two things became apparent during our initial literature search. The majority of published F_r studies failed to indicate (i) whether animals were specifically chosen (i.e., triaged) for tagging based on their presumed condition prior to release and (ii) whether PSATs were tested to confirm that they would be positively buoyant with their tethers and anchoring devices attached (i.e., document whether PSATs would float or sink if shed prematurely). Obviously, selection of healthy or moribund individuals could bias F_r estimates. Some studies did attempt to ascertain the health of istiophorid billfish (Kerstetter et al. 2003; Kerstetter and Graves 2008), but five studies reported mortalities even though they attempted to tag mostly healthy fish (Table 1). For example, Kerstetter and Graves (2008) indicated they tagged the first 17 fish captured alive but gave high health condition scores to 82% (14 fish), of which two tagged sailfish subsequently died. Billfish are tagged in water and usually the researcher observes only one side of the body or part of the body, and the presence of blood may indicate only superficial wounds. We interpreted these findings to indicate the extreme difficulty in reliably determining health status of billfish prior to tagging. Because of the contradictions about presumed health prior to release and subsequently observed mortalities, we decided to include all tagged and released fish, as not including them could also potentially bias our results. Resuscitation (i.e., towing the fish alongside the vessel prior to release to force water over the gills as described by Prince et al. 2002b) was not considered a critical factor, as many F_r studies were designed to match fish handling procedures presumed to be most common in the fishery (Table 1).

It is also extremely important in F_r studies that PSATs float if shed prematurely with the attachment tether and anchoring device still attached. This condition must be satisfied to differentiate prematurely shed tags from mortalities (i.e., to differentiate dead from shed). Unlike acoustic tags where sinking rates have been quantified, prematurely shed PSATs that are negatively buoyant

with the tether and anchoring device attached potentially mimic the sinking of dead animals, especially if tags were covered with bio-fouling organisms (Gunn et al. 2003; Musyl et al. 2011b). According to a meta-analysis of PSAT performance (Musyl et al. 2011b), ~82% of PSATs detach before their programmed release date. If most PSATs were not rigged so as to be positively buoyant if shed prematurely, then a reasonable expectation would be high F_r rates across studies, but this was not the case (Table 1). Therefore, except where indicated, we made the implicit assumption that prematurely shed PSATs were positively buoyant. There were, however, studies where 248 PSATs were deployed on striped marlin that could not be included here, because the tethers were purposely rigged to increase retention times and the PSATs were probably not positively buoyant (i.e., they would sink if shed prematurely), yet no mortalities were reported (Domeier 2006).

Data extraction and quality control

Relaxing both our criteria for inclusion based on positively buoyant PSATs with tethers and anchors and the data on the health status of fish prior to release allowed us to include 38 PSAT and eight acoustic studies (Table 1). In addition, we also incorporated published articles and ongoing research results from multiple years or from multiple types of deployments, which we subsequently refer to as “studies”. Occasionally two or more articles describing different aspects of the same PSAT deployments were found. In these cases, we took care to only include the results of these deployments once. Published work that provided full information about the status of tags were selected, but nonreporting tags were not considered synonymous with a mortality and were not used because many factors can cause failure in electronic tags (Goodyear 2002; Graves et al. 2002; Chaloupka et al. 2004; Hays et al. 2007; Musyl et al. 2011b). Though shark predation is considered a component of M , we assumed that predation causing F_r was attributable to the fishing episode (Kerstetter et al. 2004). We also excluded studies and samples where PSATs were not equipped with fail-safe release features (e.g., Graves et al. 2002; Table 1) and those cases where dead animals were tagged (e.g., Domeier et al. 2003; Table 1), as both could bias the F_r and F_c estimates (Campana et al. 2009a, 2009b; Musyl et al. 2009, 2011a).

Meta-analysis

Studies were assumed to represent random samples (i.e., mixtures of samples, tagging conditions, fishing gear, etc.) of some population in which the underlying (infinite-sample) effect sizes have a distribution rather than a single value. We therefore conducted a random-effects meta-analysis on the logit of the proportion of istiophorid billfish that ultimately died using Comprehensive Meta Analysis version 2.2.064 (Borenstein et al. 2009) and Open Meta-Analyst (Wallace et al. 2012). We employed inverse-variance weighting and estimated variability between studies (τ^2) as T^2 by the method of moments (DerSimonian and Laird 1986), which is preferred in simulations when heterogeneity across studies is low and distributions are non-normal (Kontopantelis and Reeves 2012). Cochran’s Q statistic, a measure of the weighted squared deviations between individual study effects and pooled effects across studies (distributed as a χ^2 statistic with k (number of studies) – 1 degrees of freedom), was used to test for heterogeneity. Q was also used in a mixed-effects analysis of variance (ANOVA) design to test F_r within and across subgroups (i.e., species and gear type) (Gurevitch and Hedges 1999), and the Z test used to determine if F_r was significantly greater than zero (Borenstein et al. 2009). We also estimated I^2 , derived from the Q statistic, which is the ratio of the true heterogeneity to the total observed variation (i.e., it is a measure of inconsistency that describes the proportion of observed dispersion that is real). Metaregression using the Q statistic (unrestricted maximum likelihood, mixed-effects model) was performed to test effect sizes against study latitude, and cumulative meta-analysis and sensitivity analysis

(i.e., leave one study out, recalculate the summary effect, etc.) were used to look for trends (Borenstein et al. 2009). Forest plots were used to visually depict variability in studies. In these plots, the area of the boxes for each study are proportional to the inverse of the variance, and any side of the box is proportional to the inverse of the standard error (SE). The 95% CIs (horizontal bars) for each study is proportional to the SE and is related to sample size. The diamonds represent the summary effect size, and the width is proportional to the 95% CI.

Fifteen studies reported zero mortality, and in these instances, a 0.5 continuity correction factor was added to the events (i.e., number dead) and non-events (i.e., number of survivors) (Yates 1934; Haldane 1956; Cox 1970) to calculate study weights, SEs, and variances (i.e., the computations for meta-analysis do not work with zero events). Seven studies reporting only a single event (all survivors) were not used in the formal analysis. To examine potential confounding effects using the 0.5 continuity correction factor in “one-arm” studies, we implemented exact nonparametric inference tests ($R \times C$ Pearson’s χ^2 tests) in StatXact version 10 (Cytel Inc., Cambridge, Massachusetts, USA, 2013) to verify the results because exact tests do not require the continuity correction (Sweeting et al. 2004; Friedrich et al. 2007). Point probabilities (i.e., measure of discreteness) are provided for each test, which are the probability of getting exactly the test statistic observed given the marginals (i.e., row and column totals). If the exact routine failed to converge (one case), we used exact Monte Carlo methods with 10 000 iterations to derive p values and 99% CIs (Mehta et al. 1988; Senchaudhuri et al. 1995). As a comparative measure to calculating point estimates, we employed resampling techniques to construct 95% parametric bootstrap CIs (binomial distribution with 10 000 replicates; Manly 2007) for F_r using the raw, unweighted data.

Results

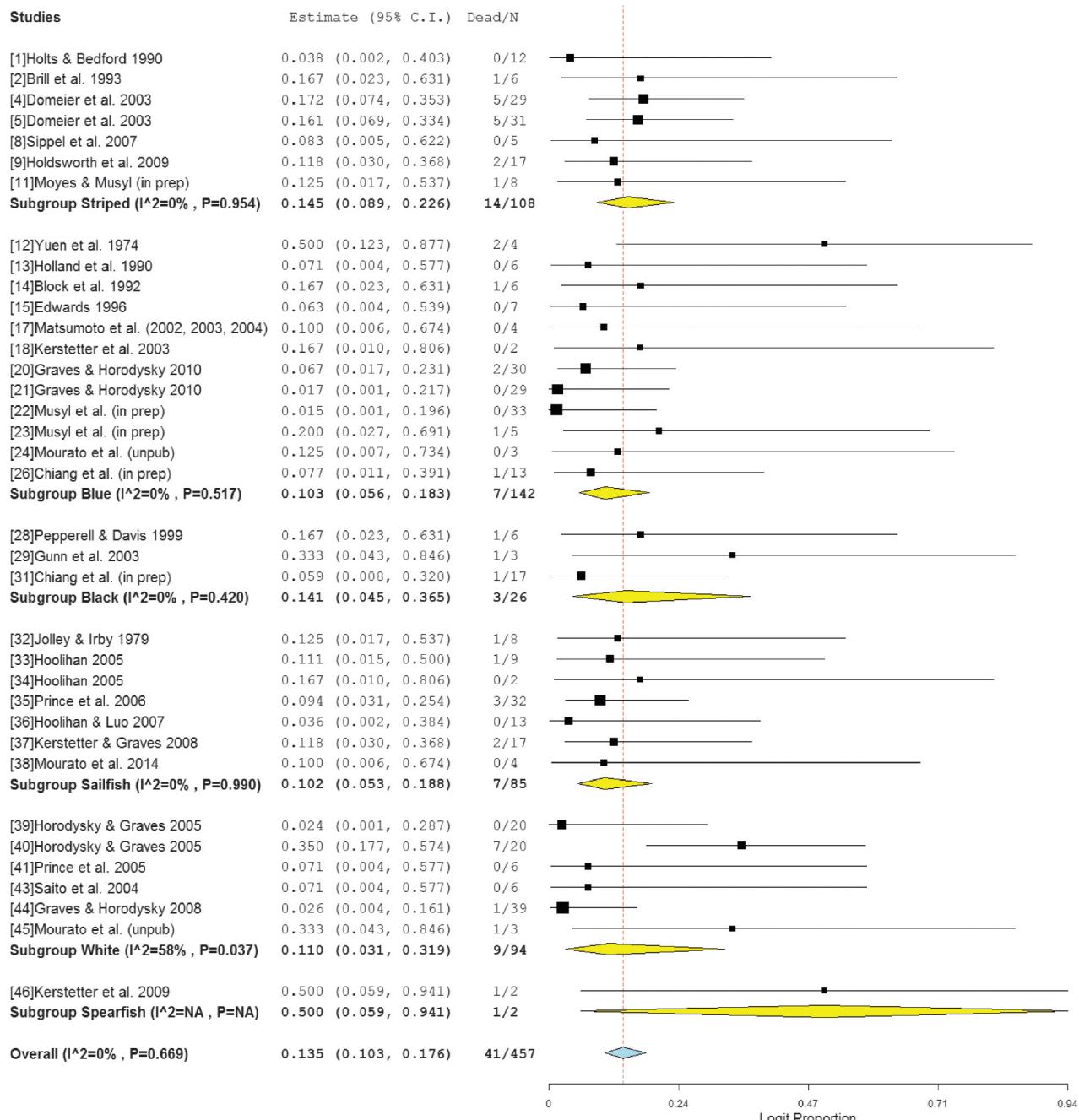
Our metadata included published reports (65% of total, 30 studies) and unpublished reports or ongoing research (35%, 16 studies). Seven (15% of the studies, 1.5% of tag deployments) studies included only single deployments (all survivors) and were excluded from the formal meta-analysis. Fifteen (~33% of the studies) studies had results from 152 tag deployments indicating survival after release, whereas 94 deployments could not be used because the tags did not report. Seven studies (15%) reported results of >29 successful tag deployments, whereas nine studies (~20%) reported results from ≥20 deployments, five studies (11%) reported results from >10 but <20 deployments, while the remaining 25 studies (54%) reported results from <9 deployments. The median number of reporting tags per study was, however, only six (mean = 11, SD = 11, range 1–39). The primary fishing gear used was rod and reel (32 studies, 82% of tags), followed by longline (11 studies, 11% of tags), and harpoon (3 studies, 7% of tags).

Postrelease mortality events were documented in 41 cases. The vast majority (37 tags or 90% of documented mortalities) occurred less than 10 days postrelease. The remaining four cases were three sailfish that died 26, 50, and 65 days postrelease (Study [35], Table 1) and one blue marlin that died 82 days postrelease (Study [23], Table 1).

Striped marlin

The meta-analysis for this species comprised 10 studies, 111 reporting tags, and three gear types. There were no significant differences in F_r among striped marlin studies ($Q_{(6)} = 1.57$, $p = 0.954$, $T^2 = 0.00$, $I^2 = 0.00$), the estimate was significantly greater than zero ($Z = -6.35$, $p \ll 0.001$), and the summary effect size was 14.5% (95% CI: 8.9%–22.6%) when excluding Study [3], which contained errors and substituting a “corrected” version of this study labelled Study [4] (Fig. 1; see below and notes in Table 1). This result was also confirmed by exact χ^2 tests ($\chi^2 = 3.899$, $p = 0.8594$, point probability = 0.0006266). Though the general conclusion is similar ($Q_{(6)} = 8.13$,

Fig. 1. Forest plot for the effect size of postrelease mortality (F_r) in istiophorid billfish released from fishing gear. Study number is provided (in brackets) along with the reference for each study grouped by species (striped marlin, blue marlin, black marlin, sailfish, white marlin, and longbill spearfish). Effect sizes, 95% CIs, and number of tags indicating mortality and total sample size (i.e., dead/N) are provided for each study. I^2 , the amount of variability among studies within species, along with a p value testing for heterogeneity (Cochran's Q), are provided. For studies with zero mortality, a 0.5 continuity factor was added to the events and nonevents (see text). Note especially the much narrower widths of the summary 95% CIs (i.e., diamonds) compared with the individual studies, which indicates more precision in the summary estimates.



$p = 0.229$, $T^2 = 0.19$, $I^2 = 0.26$; $Z = -4.39$, $p \ll 0.001$; $\chi^2 = 12.24$, $p = 0.2166$, point probability = 0.0001103 when excluding Study [4] (i.e., “corrected” Study [3], Table 1) and using the original, uncorrected Study [3] in the analysis, the summary estimate was ~1/5 larger: 18.7% (95% CI: 10.7%–30.7%).

The authors of Study [3] (Domeier et al. 2003), however, used a pressure-activated release mechanism, which may have confounded their interpretation of F_r (Table 1). For PSATs deployed in 2000, glass beads were used on the PSAT tethers, which were

designed to sever the tethers at depths between 325 and 375 m. Striped marlin have subsequently been documented to occasionally descend to 460 m (Sippel et al. 2011), but this had not yet been documented for free-swimming striped marlin when the PSATs were deployed in 2000. Domeier et al. (2003) reported four tagged fish as mortalities when they reached depths where fail-safe mechanisms presumably engaged and concluded these were indicative of what they called “Pattern 2” mortality (i.e., the fish sank to the activation depth of their fail-safe device). In addition,

one tag deployed in 2000 was excluded because it released at 244 m, and the authors indicated that they had tagged two dead fish (from which one PSAT did not report). Reclassifying these six individuals changes the summary effect size estimates, and we consider Study [4] (**Table 1**) to be a more precise and credible estimate for the calculation of F_r in striped marlin (see notes, **Table 1**).

Blue marlin

Blue marlin was the species most commonly included in our meta-analysis, comprising 16 studies, 144 reporting tags, and three gear types. For the 12 studies we included in the analysis, there were no significant differences in F_r among studies ($Q_{(11)} = 10.154$, $p = 0.517$, $T^2 = 0.00$, $I^2 = 0.00$), the estimate was significantly greater than zero ($Z = -6.37$, $p \ll 0.001$), the summary effect size was 10.3% (95% CI: 5.6%–18.3%; **Fig. 1; Table 1**), and the result was also confirmed by exact tests ($\chi^2 = 26.74$, $p = 0.08548$, point probability = 4.6×10^{-5}).

Black marlin

There were only four studies, 27 reporting tags, and two gear types for black marlin. F_r was not significantly different among studies ($Q_{(2)} = 1.737$, $p = 0.420$, $T^2 = 0.00$, $I^2 = 0.00$), the estimate was significantly greater than zero ($Z = -2.84$, $p < 0.005$), the summary effect size was 14.1% (95% CI: 4.5%–36.5%; **Fig. 1; Table 1**), and the result was confirmed by exact tests ($\chi^2 = 2.28$, $p = 0.4885$, point probability = 0.1046).

Sailfish

Of seven sailfish studies (85 reporting tags, two gear types), there were no significant differences in F_r among studies ($Q_{(6)} = 0.862$, $p = 0.990$, $T^2 = 0.00$, $I^2 = 0.00$), the estimate was significantly greater than zero ($Z = -5.99$, $p \ll 0.001$), the summary effect size was 10.2% (95% CI: 5.3%–18.8%; **Fig. 1; Table 1**), and the result was confirmed by exact tests ($\chi^2 = 2.31$, $p = 0.9105$, point probability = 0.00984).

White marlin

For the seven white marlin studies (95 reporting tags, two gear types), F_r was significantly different among studies ($Q_{(5)} = 11.842$, $p = 0.037$, $T^2 = 1.48$, $I^2 = 0.58$), the estimate was significantly greater than zero ($Z = -3.07$, $p < 0.002$), and the summary effect size was 11.0% (95% CI: 3.1%–31.9%; **Fig. 1; Table 1**). Slightly more than half of the variance (58%) was explained between studies, and exact χ^2 tests confirmed the result ($\chi^2 = 22.81$, $p = 0.005482$, point probability = 3.247×10^{-5}). The primary source contributing to the variability in F_r was the use of J hooks in Study [40]. If this study is removed, the results are not significant ($Q_{(4)} = 4.06$, $p = 0.398$, $T^2 = 0.025$, $I^2 = 0.0145$; $\chi^2 = 11.78$, $p = 0.1153$, point probability = 0.04216) and supports the study authors' conclusion that there is less injury and higher survival rates with circle hooks than with J hooks.

Omnibus comparisons

In the absence of grouping, the meta-analysis of F_r among studies was not significantly different ($Q_{(35)} = 30.841$, $p = 0.669$, $T^2 = 0.00$, $I^2 = 0.00$), the estimate was significantly greater than zero ($Z = -11.661$, $p \ll 0.001$), and the summary effect size was 13.5% (10.3%–17.6%; **Fig. 2; Table 1**). This result was also confirmed by exact χ^2 tests using Monte Carlo methods ($\chi^2 = 59.21$, $p = 0.079$, 99% CI for p value = 0.072–0.086).

Grouping studies by gear type did not produce significant differences in F_r among ($Q_{(2)} = 1.189$, $p = 0.552$, $T^2 = 0.00$, $I^2 = 0.00$; $\chi^2 = 1.183$, $p = 0.582$, point probability = 0.0317) or within groups; rod and reel ($Q_{(26)} = 28.867$, $p = 0.317$, $T^2 = 0.096$, $I^2 = 0.10$; $F_r = 13.8\%$ (95% CI: 9.9%–18.9%); longline ($Q_{(6)} = 0.505$, $p = 0.998$, $T^2 = 0.00$, $I^2 = 0.00$; $F_r = 11.7\%$ (95% CI: 5.3%–23.8%)); harpoon ($Q_{(1)} = 0.039$, $p = 0.844$, $T^2 = 0.00$, $I^2 = 0.00$; $F_r = 6.7\%$ (95% CI: 1.7%–23.2%)).

F_r was not significantly different among species ($Q_{(5)} = 3.156$, $p = 0.676$, $T^2 = 0.00$, $I^2 = 0.00$), which was confirmed by the exact

tests ($\chi^2 = 8.228$, $p = 0.1436$, point probability = 2.496×10^{-5} ; **Fig. 1; Table 1**). In the figures, 95% CIs of summary effect sizes (i.e., width of diamond) are much narrower than corresponding intervals for individual studies, indicating increased precision and power in the estimates.

Cumulative meta-analysis, metaregression, and sensitivity analysis

Cumulative meta-analysis (**Fig. 2**) indicated that F_r stabilized at ~13% when ~230 tags are included in the analysis. But when the cumulative meta-analysis was performed sorting studies by sample size (i.e., highest to lowest), a noticeable shift to the right of smaller studies was taken as a diagnostic sign of bias (**Fig. 3**), but these studies had little effect on the summary estimate. Metaregression indicated no significant trends in effect size with study latitude (**Fig. 4**; $Q_{(35)} = 27.86$, $p = 0.799$). Sensitivity analyses (**Fig. 5**) showed that no single study had a significant impact on the estimates.

Discussion

Our meta-analysis indicates ~86% of istiophorid billfish survive after release from fishing gear. In fact, the signal-to-noise ratio was so strong that this could be inferred from examination of the raw data. One way to determine the strength of this signal is the replicate results of independent studies, which was clearly demonstrated, and by definition “replicated results automatically make statistical significance unnecessary” (Carver 1978, 1993). Despite being captured, tagged, and released under a variety of conditions, we could not demonstrate any species-specific differences or patterns in F_r ; rather, variability in F_r can be attributed to random events within studies since by definition the between-studies variance was $T^2 = 0.00$ (Borenstein et al. 2009).

Differences in physiology, metabolism, and reaction to varied levels of stress and stimuli among istiophorid billfish species have been reported (e.g., Daxboeck and Davie 1986; Wells et al. 1986), and it was a reasonable expectation that species-specific differences in F_r would arise, though this was not the case. Species-specific differences in metabolism and physiology in fishes — and presumed stress resulting from capture — have been noted by many authors (e.g., Kieffer 2000; Moyes et al. 2006; Hight et al. 2007; Marshall et al. 2012; Gallagher et al. 2014). But in the case of istiophorid billfishes, these differences do not manifest as species-specific differences in F_r . Our results strongly suggest that animals recover from stress caused by capture and that only a small fraction (~14%) die following release. Holts and Bedford (1990), Holland et al. (1990), and Pepperell and Davis (1999) indicated striped, blue, and black marlin, respectively, swam to deeper depths (generally to just below the maximum depth of the uniformed-temperature surface layer, i.e., ~150–200 m) after being released and would hold station at this depth for several hours presumably to ameliorate the effects of stress (e.g., period necessary to offload excess carbon dioxide and lactic acid caused by respiratory and (or) metabolic acidosis). By contrast, Hoolihan et al. (2011) observed species-specific differences in recovery times for istiophorid billfish released from various fishing gear with PSAT tags and suggested they lasted, on average, 7.5 days ($n = 97$) for four species: blue marlin (8.2 days, $n = 50$), black marlin (23.8 days, $n = 4$), striped marlin (15.8 days, $n = 7$), and white marlin (2.7 days, $n = 15$). Data acquired from PSATs do not have the same resolution as data acquired in real time from acoustic tags, and it is interesting to note recovery time correlates with tag type, which suggests data resolution in PSATs may not be detailed enough to accurately measure and delimit the recovery period. In the studies in **Table 1**, we assume that fish were exposed to different levels of stress. One method in particular thought to contribute to lower stress was tournament fishing, which encourages heavier fishing lines (i.e., 80–120 lb test; 1 lb = 0.453 kg), which results in shorter fight times that enable fish to be more quickly

Fig. 2. Forest plots showing ungrouped studies (left plot) and cumulative plot (right plot) are provided for the effect size of postrelease mortality (F_r) in istiophorid billfish released from fishing gear. Descriptions for the plots follow Fig. 1. For the cumulative meta-analysis (right plot), each study is added to the next one, and the summary effect is calculated at each step and so on. At around 230 tags (Study [40], Horodysky and Graves 2005), the trend stabilizes at $\sim 13\% F_r$.

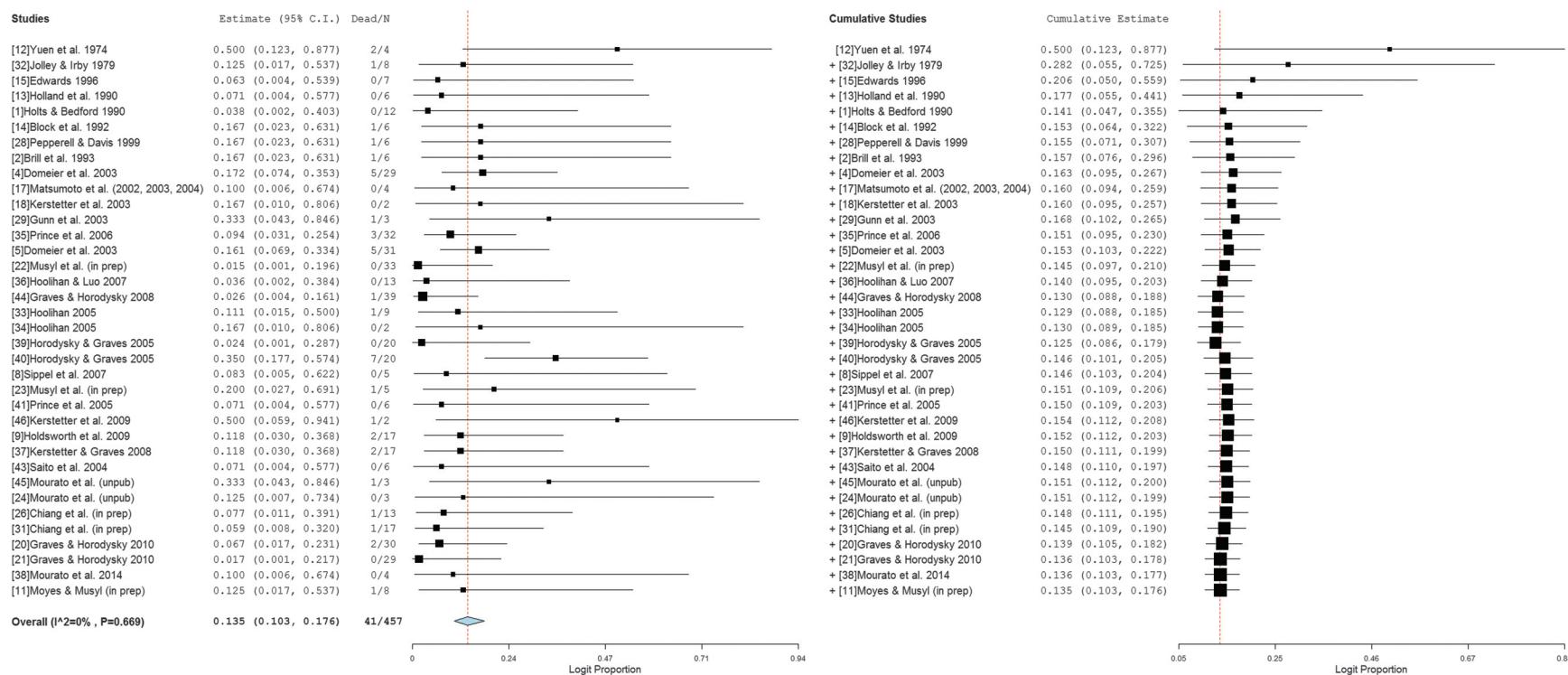


Fig. 3. Cumulative Forest plot arranged by study size, from highest to lowest, is provided for the effect size of postrelease mortality (F_r) in istiophorid billfish released from fishing gear. Descriptions for the plots follow Figs. 1 and 2. At the bottom of the graph (right plot), studies with very small sample sizes shift the summary effect to the right, which is considered diagnostic for bias (Borenstein et al. 2009).

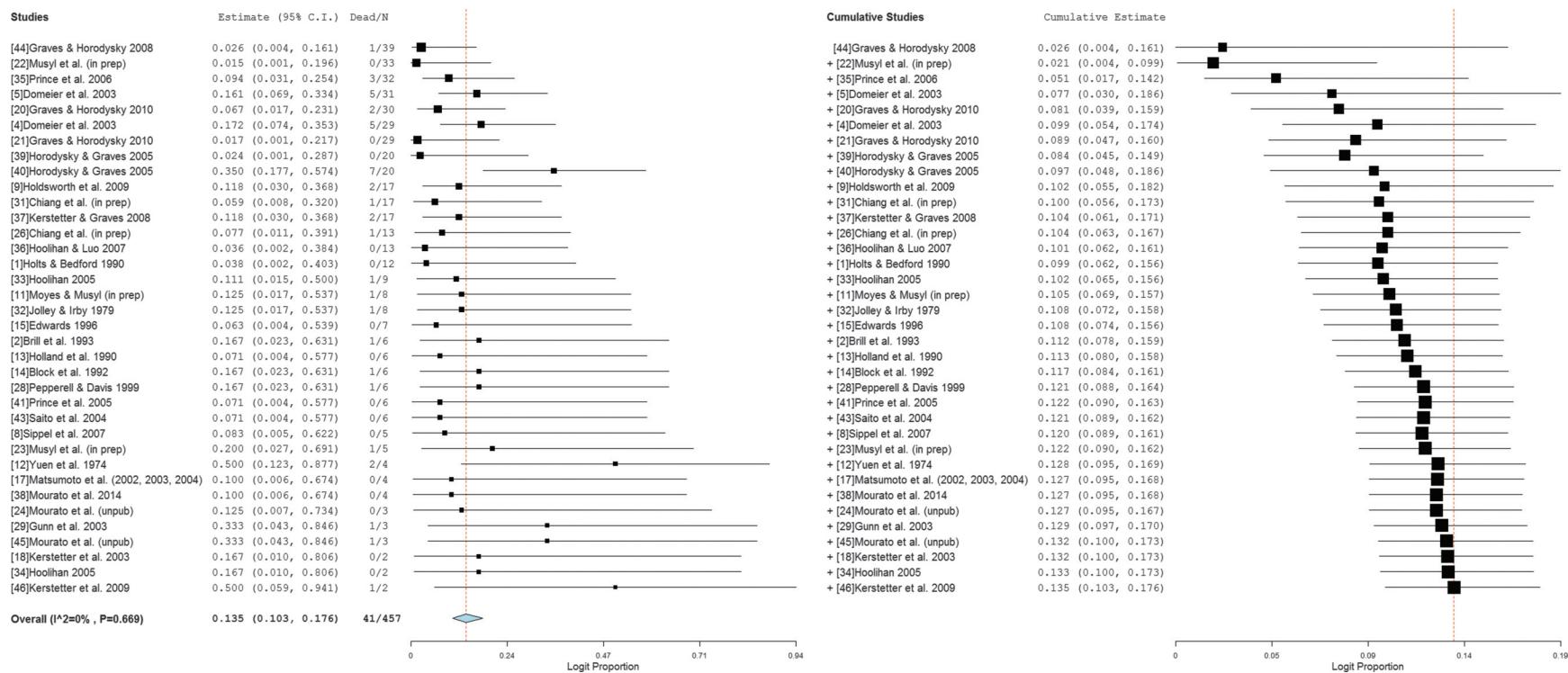
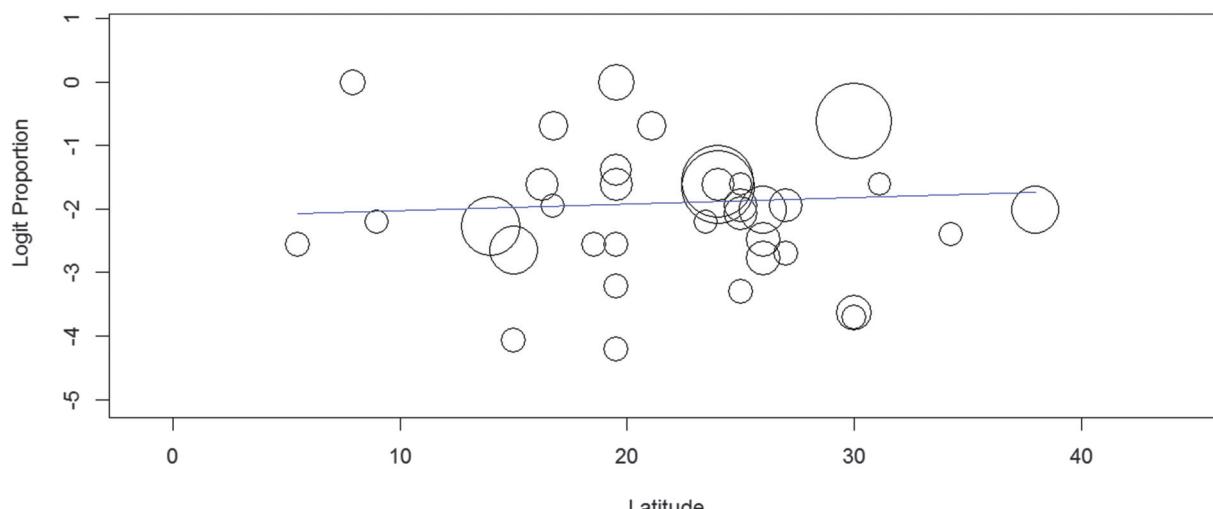


Fig. 4. Metaregression showing effect size of postrelease mortality (F_r) in istiophorid billfish released from fishing gear compared with study latitude. Areas of circles are proportional to the inverse of the variance for each study. No significant trends in effect size with study latitude were found (Fig. 3; $Q_{(35)} = 27.86$, $p = 0.799$); the fitted line is shown.



tagged and released, but this method of fishing produced neither lower nor higher F_r (Table 1, Studies [22] and [23]).

A random-effects model was initially chosen because each study was hypothesized to represent “mixtures” of samples in terms of species, tagging location, body size–age–sex, fishing gear (harpoon, longline, rod and reel), hook type (circle and J), handling practices, whether hooks were removed or not, skill level and aggression of recreational anglers (i.e., high drag settings on fishing reels), fight times or time spent hooked, selection of individuals, resuscitation, predation, stress, injury, and probably many other co-variables such as time out of water and environmental conditions (e.g., capture depth and resultant level of barotrauma, dissolved oxygen, salinity, temperature) unknown in the analysis. Given this variability, we expected highly variable F_r , but this was not observed. As a proxy for temperature, we used metaregression to test F_r effect size against study latitude, but the trend was not significant. F_r estimates presumably can be biased by several factors, but selection of healthy individuals or resuscitation did not appear to influence F_r . Instances of high F_r were rare. Only two studies with appreciable sample sizes indicated $F_r \sim 35\%$, but misinterpretation of events probably affected the estimate in one study (Domeier et al. 2003). In the other (Horodysky and Graves 2005), it was evident the use of J hooks contributed to higher mortality, which has subsequently been confirmed by other investigators (Diaz 2008; Serafy et al. 2009, 2012; Gilman et al. 2012).

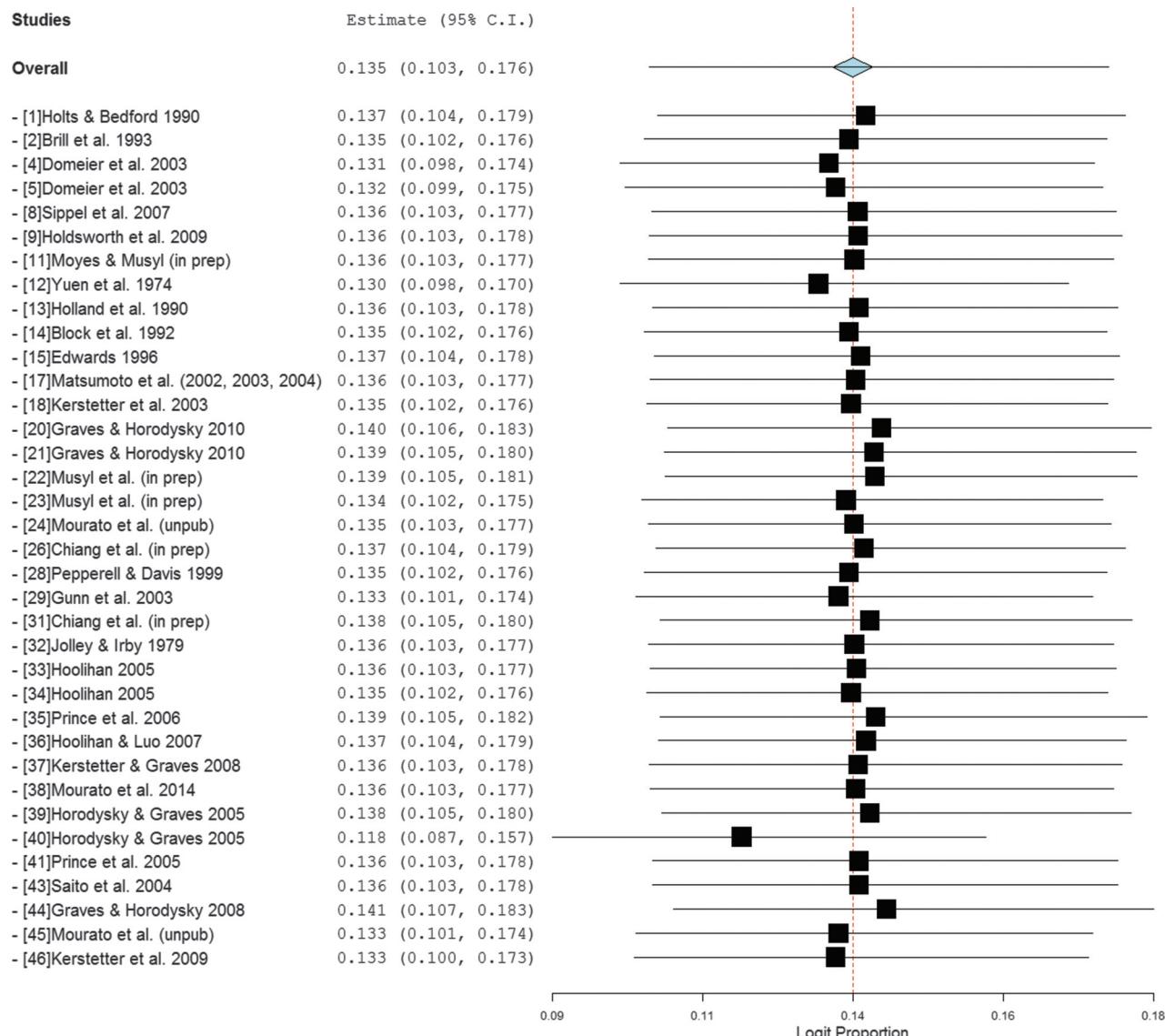
Measurement error does not appear to be a major factor in explaining F_r as only reporting tags were used, and only two studies (Yuen et al. 1974; Gunn et al. 2003) expressed some ambiguity about reporting mortality. These were, however, small studies, and bias in small studies can be seen in the cumulative meta-analysis arranged by sample size from highest to lowest. Because many factors can cause failure in electronic tags, we did not include nonreporting tags in our estimates. For example, PSATs deployed in Taiwan suffered the highest failure rate, but this area is documented to cause interference on the frequency reserved for Argos transmissions (Musyl et al. 2011b and references therein). Other authors have also suggested that classifying nonreporting tags as mortalities could severely bias estimates (Goodyear 2002; Graves et al. 2002; Horodysky and Graves 2005; Musyl et al. 2011a). Finally, it does not seem plausible that affixing electronic tags to monitor F_r in istiophorid billfish actually biases F_r upward, and we argue the presence of a tag probably does not affect nor does it disrupt population level processes (e.g., migration and spawning). For example, Lowerre-Barbieri et al. (2003) surgically implanted

common snook (*Centropomus undecimalis*) with acoustic transmitters, a much more invasive process, but this procedure did not interrupt spawning, as tagged fish were caught multiple times while ovulating.

The 0.5 continuity correction factor for studies with zero mortality events did not alter conclusions, and with $T^2 = 0.00$, the random-effects models decomposed to a fixed-effect model. This allowed us to verify our results from exact nonparametric inference tests, which do not require correction for zeroes. The continuity correction factor did, however, pseudo-inflate the sample size by 15. Although this increase did not affect our conclusions, it did inflate point estimates. The 0.5 continuity correction factor has a more theoretical basis for its use in two-arm study designs (i.e., 2×2 design) than other correction factors (Yates 1934; Haldane 1956; Cox 1970; Sweeting et al. 2004; Friedrich et al. 2007); its use in one-arm studies is not well understood, but it does affect the weighting of studies. In istiophorid billfish, F_r can be characterized as a “rare event”, so it was not possible to exclude studies with zero mortality events unless they comprised single samples; to remove potential bias, we excluded seven studies with only single events (all survivors) from the analysis. However, it is apparent from the high–low cumulative meta-analysis that smaller studies could be biased, although our sensitivity analysis suggested no single study had a dramatic effect on our conclusions. Removing studies with sample sizes less than 5 did not alter the analyses, but this contradicts employing the random-effects model, which places importance on the information contained in small studies.

The problem was not with interpretation of results, however, but rather how to calculate the point estimates. Effect size estimates from the model, even though pseudo-inflated, are preferred because they are conservative and weighted accordingly. Alternatively, we calculated point estimates for F_r from the raw data using all tags with 95% bootstrap CIs (Table 1), and they were similar to model estimates, albeit lower. Other correction factors are possible (e.g., Agresti 2002; Sweeting et al. 2004; Friedrich et al. 2007) as are alternative methodologies (e.g., bootstrap meta-analysis, Adams et al. 1997; or Bayesian meta-analysis, Sutton and Abrams 2001; see also Gurevitch and Hedges 1999). Although Bayesian meta-analysis does not require correction factors for zero mortality rates in studies, it is not clear, however, if the Gibbs sampler would converge with 22 of 46 studies (~34% of tags) indicating zero events unless an enormous number of iterations were used. Although it is allowable to use the summary effect size

Fig. 5. Forest plot showing the sensitivity analysis for the effect size of postrelease mortality (F_r) in istiophorid billfish released from fishing gear. Descriptions for the plot follow Fig. 1. In this analysis, one study is removed and the summary effect is calculated, and then the next study is removed and the summary effect is recalculated and so on. The plot indicated that although there is minor movement, no single study had a significant impact on the summary effect because the 95% CIs overlapped. The analysis does show a nearly 2% drop when the J hook study [40] is removed.



estimate across all studies, as a matter of practical importance, we advocate the use of species-specific effect size estimates weighted by the model.

Fisheries-related factors (e.g., time spent on the hook, leader material, handling procedures, hook type) and fish size can influence the survival of large pelagic teleosts and sharks captured and released from fishing gear (Diaz and Serafy 2005; Kerstetter and Graves 2006a, 2006b, 2008; Carruthers et al. 2009; Campana et al. 2009a). Our working hypothesis was that differences in F_r would be expected by gear type, but this was only demonstrated in one study where the authors compared J and circle hooks (Horodysky and Graves 2005). Istiophorid billfish are obligate ram-jet ventilators, but longline fishing did not produce any differences in F_r when tested against fish captured by rod and reel or when PSATs were placed via harpoon (i.e., the fish was not captured at all). Fish tagged by harpoon (while basking at the surface) were included as outgroups in comparisons as F_r would be ex-

pected to be a random event since the fish experiences no stress or injury attributable to fight time or handling.

There is a general perception that protracted fight time or time spent on a longline hook will reduce the likelihood of survival in istiophorid billfish, but we found little evidence for this conclusion. This practice is generally based on the assumption that larger fish do not survive the trauma of capture and release because of the generally protracted fight times (Muoneke and Childress 1994), although we could not adequately test this hypothesis. In Studies [22] and [23] (Table 1), M.K. Musyl, C.D. Moyes, and R.W. Brill (unpublished data) tagged fish during recreational fishing tournaments, which encourage the release of small (<250 lb or 113 kg) fish, and retention of larger individuals. But no trends were obvious. In general, we conclude that different-sized fish experienced varied levels and periods of stress that comprised the metadata, but fish size was not accurately measured and fight time can be ambiguous unless it is quantified by biochemical

correlates of morbidity and mortality (Moyses et al. 2006; Musyl et al. 2011a). In recreational fishing, total fight time may not be as important as intensity, because long fight times may not necessarily translate into higher stress levels if the fish is not aggressively angled. In a study attaching PSATs to common thresher shark (*Alopius vulpinus*) hooked in the tail from recreational gear, Heberer et al. (2010) reported 26% F_r , and fight times ~85 min delimited survivors from moribund individuals. Stokesbury et al. (2011) and Marcek and Graves (2014) reported 3.4% (2/59 PSATs) and 5% (1/20 PSATs) F_r , respectively, in Atlantic bluefin tuna (*Thunnus thynnus*) released from recreational fishing gear. Aside from the two mortalities that occurred within days after release reported by Stokesbury et al. (2011), Marcek and Graves (2014) recorded only a single mortality after 12 days, presumably due to shark predation.

In the meta-analysis, 90% of the mortalities in istiophorid billfish occurred within 10 days of the capture and release, and many authors report F_r in fish to generally occur within days of release (e.g., Muoneke and Childress 1994; Musyl et al. 2011a), indicating that the detrimental effects of stress are acute. Only four fish (three sailfish and one blue marlin) in the meta-analysis exhibited time-to-event F_r rates >10 days (26, 50, 65, 82 days). Though the juncture between F_r and M is challenging to discriminate, a logical extension suggests that mortality events closer to capture–tag–release would be attributable to the catch incident rather than to events resulting in a natural mortality event occurring later on (Goodyear 2002; Graves et al. 2002). This was the logic Graves et al. (2002) used when they first promoted 5- to 10-day programmed pop-up periods in PSATs to investigate F_r in istiophorid billfish. In other words, longer programmed pop-up periods make it difficult to disentangle influences like tag shedding, tag failure, and M from F_r . Since there was no obvious correlation with F_r and pop-up period, it does not appear F_r was underestimated by using shorter (i.e., 5–10 days) programmed pop-up periods in the PSATs.

When the transition from F_r to M occurs is unknown but when the time from the tagging episode to presumed death is substantial, it is logical to assume that factors other than stress or injuries suffered during capture may have caused mortality. Recently, several authors (Piner and Lee 2011a, 2011b; Lee and Chang 2013) have taken the utility of meta-analysis to synthesize precise estimates of M in istiophorid billfish (0.54–0.38 for striped marlin aged 0–4+ and 0.42–0.22 for blue marlin fish aged 0–4+, respectively), and these estimates are much higher than our estimates of F_r . But our estimates did not contain size or age information. It is unclear what relationship, if any, might exist between M and F_r other than that they are additive. In fish, M has been correlated with factors such as body size and temperature (Pauly 1980; Peterson and Wroblewski 1984; Gulland 1987; Griffiths and Harrod 2007; Gislason et al. 2008), whereas F_r in istiophorid billfishes appears to be invariant for these factors, which further suggests that the variability in this parameter is random.

In the case of presumed F_r after 26–82 days, however, it is possible that biofouling of the PSAT, infection at the tagging site, or both could cause premature tag shedding. Since istiophorid billfishes spend the majority of their time in the epipelagic realm, which overlaps the photic zone, these animals are more likely to exhibit lower PSAT retention times because of increased exposure to fouling and necrotizing organisms (Gunn et al. 2003; Musyl et al. 2011b). If shed PSATs are fouled (which is a reasonable assumption; see Gunn et al. 2003; Musyl et al. 2011b and references therein), then it is possible the added mass could cause PSATs to become negatively buoyant and sink. However, since the PSAT is ~65 g, the sinking rate would not be the same as the sinking rate of a heavier acoustic tag. Moreover, a fouled sinking PSAT influenced by currents could conceivably mimic a sinking animal carcass. Weighted median and mean (\pm SE) retention times of 357 PSATs attached to epipelagic animals were 41 and 60 (\pm 6) days,

suggesting fouling and (or) infection are major factors to explain tag shedding (Musyl et al. 2011b).

The metadata assembled is unquestionably the best source of information of F_r in istiophorid billfish. However, there is a dilemma in interpretation in effect size estimates that contrasts nonsignificance versus practical significance. Another possible interpretation suggests that the absence of significance differences (i.e., type II error) in effect sizes between and within groups (species or gear types) was due to unrepresentative studies or low power, or both. In other words, there is a chance that significant effects, perhaps influenced by moderator variables such as handling practices, gear types, hook type, etc., could have been missed by small studies. One of the most compelling findings was the repeatability of results from studies over dissimilar temporal and spatial scales. Because a certain percentage of false positives (type II errors) can be expected owing to random sampling in null hypothesis significance testing, Carver (1978, 1993) and Ellis (2010) suggested the ability to demonstrate replicated results over temporal and spatial scales was the best test whether the results were real. It follows that if studies are estimating a common effect and if the effect remains constant, then a logical extension is that effect size estimates derived from different studies using similar methodology and measures should be expected to converge (Ellis 2010). If F_r is a random event, the results would be expected to converge, which is what we observed. Furthermore, the similarity of F_r estimates for blue shark and istiophorid billfish determined from separate meta-analysis (also indicating F_r was random) is intriguing and yet to be explained.

Our meta-analysis preserved the magnitude and direction of results from primary studies, but we added improved precision and power to the summary estimates by comparing and aggregating dissimilar studies in a quantitative framework. In the analysis, a significant effect was observed in white marlin studies using J hooks over circle hooks, but this dichotomy was not observed in blue marlin studies where J hooks were also tested (Table 1). The width of the 95% CIs (proportional to SE and correlated to sample size) in the forest plots indicate uncertainty in effect size estimates for smaller studies. The use of CIs, however, do not exclude possible important effects, but they indicate a credible range for what the effect sizes might be. To further explore the issue of type II errors and interpretation of the null hypothesis, post hoc or retrospective power analysis would not shed any insights because the power calculation is based on the observed effect size and there is a 1:1 correspondence between power and p values (Hoenig and Heisey 2001; Ryan 2013). It would be necessary to make the untenable assumption that study-derived effect sizes are identical to the population effect size, which would make the argument circular and therefore pointless. Many authors consider CIs more informative than retrospective power analysis because the estimate and range provides a level of power and precision (e.g., Borenstein et al. 2009; Ellis 2010).

As reviewed in Musyl et al. (2011a), techniques to study F_r in many smaller fish species (e.g., reflex action mortality predictors) are not suitable for istiophorid billfish because of their size, and other techniques are cost-prohibitive (e.g., electronic tags, holding tanks). To assess our effect size estimates and to increase confidence in our mortality estimates, it will be necessary to examine additional samples over time and space and to test which factors are influential. But this information can be achieved as part of regular tagging studies, as no special experimental design is required other than the PSAT fail-safe measures previously indicated. In addition to continually updating the metadata, it will be necessary to develop cost-effective predictors of morbidity and mortality from biochemical or molecular indicators (e.g., Moyses et al. 2006) or possibly from bioelectrical impedance analysis (see Musyl et al. 2011a). It should be mentioned, however, that a small set of subjects would also need to be electronically tagged to serve as known outcome samples for verification and developing mod-

els. Finally, it may be possible to indirectly estimate F_r by examining variability in F_c (Musyl et al. 2011a). If these parameters show significant relationship, it may be possible to develop models to account for this variability and also to examine influential factors. Large sample sizes to examine F_c could be attained from commercial longline fishing operations with the added benefit of making accurate body size measurements and correlating this information to a suite of operational and environmental variables.

As identified by electronic tags in a meta-analysis, F_r appears to be low in istiophorid billfishes released from recreational and longline fishing gear and probably represents stochastic events. Our results imply catch-and-release can be a viable management option that permits fishing activity while protecting parental biomass and the fishery. When F_r occurs, it is generally within days of the initial capture event. Instances of high F_r appear to be study-specific and are rare events. No definitive conclusions about F_r in the meta-analysis could be drawn with regard to fish body size, fight time, temperature, resuscitation, and stress in istiophorid billfish, and these relationships warrant further study. Though the benefits of using circle hooks over J hooks have been clearly demonstrated by many authors, except for white marlin, hook type did not greatly alter any of the main conclusions in this report. Clearly, more samples and detailed information are warranted in fisheries to verify our initial assessment of F_r and what specific factors influence F_c and F_r rates.

Fisheries science is a discipline that contains a plethora of effect sizes. We argue that investigators need to examine historical data in proper context, not only to derive more precise parameter estimates, but also to investigate putative factors responsible for variability and to design better studies. Journal editors and reviewers need to be particularly vigilant and require authors of postrelease mortality studies to provide as much detail as possible, including reporting effect sizes. It appears the tools and techniques for differentiating and discriminating F_r have become refined, and the design of fishing methods and practices (e.g., circle hooks and elimination of shallow hooks) should focus on reducing F_c in istiophorid billfish to protect parental biomass. Meta-analysis on F_c would be an ideal place to start, which we plan on implementing.

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