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Should all fish in mark–recapture experiments be double-tagged? Lessons learned from tagging coastal cod (*Gadus morhua*)

Björn Björnsson[1]*, Hjalti Karlsson[2], Vilhjálmur Thorsteinsson[1], and Jón Solmundsson[1]

[1]*Marine Research Institute, Skúlagata 4, PO Box 1390, 121 Reykjavík, Iceland*
[2]*Marine Research Institute, Árnagata 2, 400 Ísafjördur, Iceland*

**Corresponding Author: tel: +354 575 2000; fax: +354 575 2001; e-mail: bjornb@hafro.is.*

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Cod (*Gadus morhua*) were tagged outside and inside "herds" formed by anthropogenic feeding in an Icelandic fjord. Recapture rates were twice as high for fish double-tagged with one surgically implanted electronic tag and one anchor tag (46.6 and 62.2%) than with fish tagged with only a single anchor tag (20.0 and 29.2%) outside and inside the herds, respectively. The two main reasons for the differences observed in recapture rates were higher detection and reporting rates for the double-tagged fish. In cage experiments, 8% of the fish receiving implanted tags died during the first 2 d after tagging. For double-tagged fish, tag loss was ~10% for both tag types. About 80% of the tags were returned by fishers and 20% by fish processors. The tag detection rate by fishers was estimated at ~45 and ~80% for single- and double-tagged fish, and the reporting rate at ~74 and ~100% for single- and double-tagged fish, respectively. It is proposed for future tagging studies to double-tag all fish routinely, placing one tag dorsally and one ventrally, to enhance the detection rate and to account for tag loss.

Keywords: cod, double-tagging, mark–recapture, tag detection, tag loss, tag reporting.

Introduction

The potential for mark–recapture methods to estimate fish population parameters is well documented (Beverton and Holt, 1957). However, for practical reasons, these studies are rarely used directly in stock assessments, although the importance of estimating mortality rates independently with large-scale tagging has gained increasing attention in recent years (Cadigan and Brattey, 2006). The success of a tagging programme depends largely on tagging-related mortality, tag loss, and the rates of tag detection and reporting, for anchor tags used to estimate exploitation rates and changes in spatial distribution and electronic tags used to investigate fish behaviour. It is therefore important to know the influence of these factors when estimating population size and mortality rates.

In almost all tagging studies, it is a standard procedure to tag fish with a single tag, but in some studies, a subsample has been double-tagged to estimate tag loss (e.g. Otterå *et al.*, 1998; Cadigan and Brattey, 2006). Reporting rates have been estimated with a limited number of high-reward tags or through observers in multiple-component fisheries (Pollock *et al.*, 2001, 2002; Pine *et al.*, 2003). Bayliff and Holland (1986) mention that one of the reasons to double-tag fish is to enhance return rates. However, we know of no study recommending double-tagging all fish in mark–recapture experiments, and little attention has been paid to the effects of double-tagging on fisher detection rates. Tags overlooked by fishers are often detected by fish processors, but usually such recaptures lack the crucial information of accurate date and location.

Our main aim, based on tagging data for coastal cod (*Gadus morhua*) off Northwest Iceland, was to investigate the effects of double-tagging on the fisher detection rate and how it is influenced by conditions at sea. Other factors determining recapture rates, such as tagging-related mortality, tag loss, and the rate of tag reporting, were also estimated. We conclude with a proposal for a tagging procedure intended to improve the rate of tag detection by fishers.

Methods

Tagging

As part of a study of cod ranching (Björnsson, in press), 6005 cod were tagged in Arnarfjördur, Northwest Iceland, in three batches; two outside and one inside four "herds" formed by anthropogenic feeding. The herds were located near the centre of the fjord, two near the north coast (3 km apart), and two near the south coast (3 km apart; Figure 1). For the purpose of the ranching study, commercial fishing was prohibited within a 30-km^2 area around the herds from 15 May 2005 to 29 November 2006. The reserved area was extended west by 1.5 km from 30 November 2006 to 31 January 2007 (Figure 1). Tagging was carried out on board MV "Höfrungur", except on 2 and 3 June 2005 when MV "Bríik" was used; both are shrimp trawlers of 30 grt.

Outside the herds, fish were captured with a shrimp trawl at depths of ~90 m. The trawl was towed for 30–60 min, then lifted at a steady pace of ~20 m min^{-1} to the surface. The fish in the codend were lifted in portions of ~300 kg to recovery tanks, one tank of 1200 l with a false, removable bottom and a few 600-l fish tubs with ample flow of seawater. During tagging of each portion,

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the remaining fish were kept in the trawl belly slightly below the surface. Most fish survived unless they were in the final portions of large catches. Dead and exhausted fish were removed from the tanks, and inflated fish were deflated with a large hypodermic needle inserted posterior to the pectoral fin into the swimbladder. Tagging started a few minutes after the fish had been lifted into the recovery tank, and only fish in good condition were tagged.

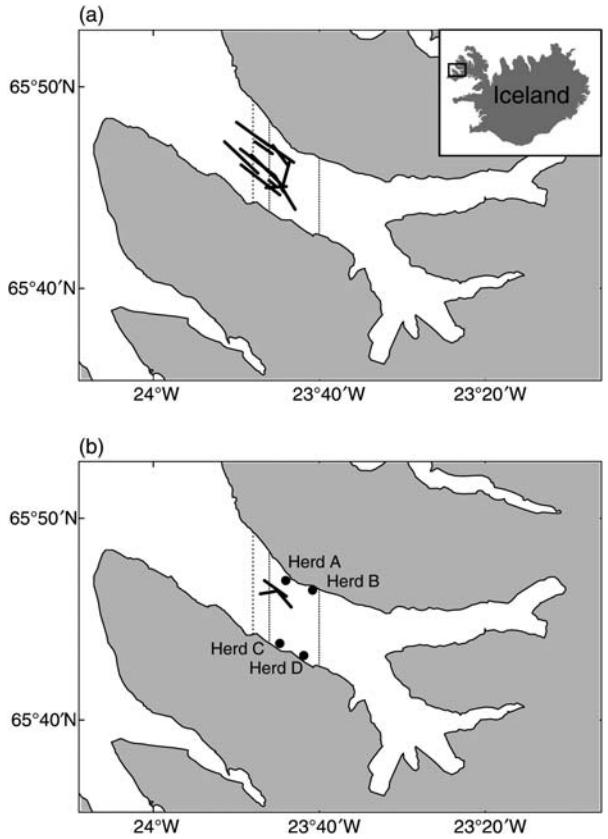

Figure 1. Tagging locations in Arnarfjördur: (a) tows made 2–10 June 2005 with a shrimp trawl (TRAWL-2005); (b) captures in four herds 24–27 July 2006 with a liftnet (HERD-2006, black dots) and tows made on 28 July 2006 with a shrimp trawl (TRAWL-2006, thick lines). The area where commercial fishing was prohibited (heavy dotted lines) established on 15 May 2005 was extended west (light dotted line) from 30 November 2006 to 31 January 2007. Based on Fig. 1 in Björnsson et al., 2010.

Inside the herds, fish were captured with a liftnet at depths of 5–10 m. The liftnet was made from a circular hoop 2 m in diameter and a net bag 2 m long, the lower part lined with canvas to be able to lift the fish in seawater. It was equipped with a bait bag and a video camera attached at the bridle ropes to facilitate capture (Björnsson, in press). Once fish in the herd had crowded above the liftnet, it was raised to the surface in <30 s. Usually, 10–50 fish were captured per lift. No mortality was observed for the fish captured with the liftnet.

Each fish was tagged with an anchor tag (T3313, Hallprint Ltd, Australia; Table 1) placed on the left side of the fish at the base of the first dorsal fin centrally using a tagging gun. Fish suitable for tagging ranged from 20 to 96 cm long, of which 90% were 30–70 cm. Additionally, 95 of the anchor-tagged fish were tagged with one or two electronic tags inserted surgically into the abdominal cavity, each with a coloured tube protruding from the belly centrally between the vent and the tip of the pelvic fin (Table 1). Two types of electronic tag were used; data-storage tags from Star-Oddi, Iceland, and transmitter tags from Vemco, Canada (Table 1). Owing to the large size of the electronic tags, they were only used for tagging fish $\geq$44 cm (842 g), whereas the minimum size of fish tagged with anchor tags only was 20 cm (82 g).

During surgery, each cod was kept on its back in a cradle lined with a soft cloth, and a hose with running seawater was placed in its mouth. A piece of soft cloth was wrapped around the head to block visual stimuli. A cut of 1–2 cm was made on the belly using a scalpel and a suitable dose of antibiotic (0.1 ml Engemycin vet. per kg fish, i.e. 10 mg Oxytetracyclin per kg fish) and vitamin B (0.1 ml Becoplex vet. per kg fish) injected through the cut with a syringe. The cylindrical electronic tag was then inserted into the cavity, one end of the tag sutured to the belly, and the colour tubing attached to the posterior end of the tag threaded through the belly with the help of a large hypodermic needle. Finally, the cut was closed with one stitch. Surgery was performed in compliance with the rules set by the Committee on Welfare of Experimental Animals established by the Ministry of Agriculture, Reykjavík, Iceland. The fish remained calm during the operation and did not show any noticeable reaction to the incision.

Three tagging experiments were performed: (i) 2–10 June 2005 outside the herds (TRAWL-2005), when cod were captured in several hauls, partly outside the reserve area (Figure 1a); (ii) 24–27 July 2006 inside the herds (HERD-2006), when cod were captured within the four herds with a liftnet (Figure 1b); and (iii) 28 July 2006 outside the herds (TRAWL-2006), when cod were

Table 1. Number and size of the different tags used in Arnarfjördur from 2 to 10 June 2005 outside herds (TRAWL-2005), from 24 to 27 July 2006 within herds (HERD-2006), and on 28 July 2006 outside herds (TRAWL-2006).

				Number of tags		
Type of tag	**Length of tube (cm)**	**Colour**	**Weight (g)**	**TRAWL-2005**	**HERD-2006**	**TRAWL-2006**
Anchor tags only	5	O	0.13	3409	1604	897
DST milli (38 × 13 mm)	10	Y	9.2	29	0	0
DST centi (46 × 15 mm)	10	Y	19	10	0	0
V13 (38 × 13 mm)	10	B	11.4	9	3	0
V13P (45 × 13 mm)	10	R	12.4	10	3	0
V13P and DST[a]	10	R	31.4/21.6	0	31	0

Data-storage tags (DST) from Star-Oddi, Iceland (www.star-oddi.com); V13 and V13P from Vemco, Canada (www.vemco.com). Tube coloured orange (O), yellow (Y), blue (B), or red (R). The diameter of the colour tubing was 1.3 mm for the anchor tags (excluding the clear protecting tubing) and 1.7 mm for the electronic tags.
[a]17 DST milli; 14 DST centi.

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captured in three hauls, mainly within the reserve area (Figure 1b). The fish were released in the same area in which they were captured. During TRAWL-2005, 3467 cod were tagged with anchor tags and 58 of the same fish with electronic tags (Table 1). During HERD-2006, 1641 cod were tagged with anchor tags and 37 of the same fish with one or two electronic tags (Table 1), to monitor the horizontal location, depth, and temperature of the fish. A slightly larger cut (2–3 cm) had to be made for fish tagged with two electronic tags taped together with insulation tape. During TRAWL-2006, 897 cod were tagged with anchor tags but none with electronic tags. To minimize tag-shedding variability, all fish (including both tag types) were tagged by a single experienced worker (the second author).

To study post-tagging mortality of the fish tagged with electronic tags in HERD-2006, 36 cod (31 with two electronic tags) were placed in four cylindrical net cages (1.7 m diameter, 2.0 m long with a mesh size of 50 mm) and kept submerged 5 m below the surface close to the four herds for 2 d prior to release. The adaptation cages were equipped with floats at the top and moored from the seafloor up to reduce movement from surface waves. There was little wind (<5 knots) during the cage trial. Tags from the three fish that died in the cages were removed and inserted into three fresh fish, two of them released directly overboard.

Recaptures

Arnarfjördur hosts a commercial fishery for cod and haddock, mainly using Danish seines and longlines. In 2005 and 2006, the registered commercial catches of cod and haddock in the fjord were 551 and 430 t, respectively. As part of the cod-ranching project, there was a substantial experimental fishery from September 2005 to January 2007, when a total of 171 t of cod and 82 t of haddock were captured with a liftnet, a shrimp trawl, and a Danish seine (Björnsson, in press).

For some 20 years, there has been a well-publicized tagging effort in Iceland in which fishers receive 1000 ISK (ca. US$15) reward for returning each tag and are requested to hand in otoliths for age determination and to submit information on recapture date, place, latitude and longitude, depth, gear, name of boat, length of fish, sex, and maturity stage. A reward of 4000 ISK is given for an electronic tag. For double-tagged fish, a reward was given only for a returned tag and not for a missing tag. An advertisement with detailed description and photographs of both types of tag and the reward for each tag is published every year in the Icelandic Fishermen's Almanac, which is distributed free to all Icelandic fishing vessels. Posters advertising the tagging programme and pre-addressed tag-return envelopes are also sent regularly to all major fishing ports and fish-processing plants in Iceland.

Data analysis

For commercial boats (non-chartered), the number of anchor tags not reported (X) was calculated from

$$\frac{R_{EO}}{R_{TO}+X}=\frac{R_{EM}}{R_{TM}},\quad \text{i.e. } X=\frac{R_{EO}\times R_{TM}}{R_{EM}}-R_{TO}, \tag{1}$$

where R_{EO} is the number of electronic tags reported by commercial boats, R_{EM} the number of electronic tags reported by boats chartered by the Marine Research Institute (MRI), R_{TO} the total number of tags reported by commercial boats, and R_{TM} the total number of tags reported by chartered boats (including fish with electronic tags). In these calculations, it is assumed that all electronic tags (high-reward tags) detected by fishers were reported and that the detection rate was the same for all boats. Moreover, it is assumed that the chartered boats reported all the tags detected.

The reporting rate (RR) of anchor tags by commercial boats could therefore be calculated from

$$\mathrm{RR}=\frac{R_{TO}}{R_{TO}+X}. \tag{2}$$

Some 20% of the double-tagged fish were reported by fish processors. This suggests that the rate of tag detection of double-tagged fish at sea (D_D) was ~0.8, assuming 100% reporting by both fishers and fish processors (high-reward tags) and that all double-tags that enter fish-processing plants are detected (two tags, good light conditions, fish handled by several people).

The number of single-tagged fish not detected by chartered boats (Y) was calculated from

$$\frac{R_{EM}/0.8}{R_{TM}+Y}=\frac{T_{ET}}{T_{TT}},\quad \text{i.e. } Y=\frac{T_{TT}}{T_{ET}}\times\frac{R_{EM}}{0.8}-R_{TM}, \tag{3}$$

where T_{ET} is the total number of fish tagged with electronic tags and T_{TT} the total number of fish tagged (including fish with electronic tags). In these calculations, it is assumed that all tags detected by charter boats, both electronic and anchor, were reported (reporting rate = 1.0).

The rate of tag detection of single-tagged fish at sea (D_S) could therefore be estimated from

$$D_S=\frac{R_{TM}}{R_{TM}+Y}. \tag{4}$$

Both single- and double-tagged fish were tagged simultaneously, and estimates of the rates of tag reporting and detection were based on the proportions of double-tagged fish separately for chartered boats and other boats [Equations (1) and (3)]. Therefore, it was unnecessary to make assumptions about the availability of tagged fish to chartered boats vs. other boats. However, it was necessary to assume that natural mortality and migratory behaviour was the same for single- and double-tagged fish.

The recaptures inside (R_i) and outside (R_o) Arnarfjördur were compared to estimate migration. The percentage of fish recaptured outside Arnarfjördur (R_o%) provides an indication of emigration from the fjord:

$$R_o\% = 100\times\frac{R_o}{R_i+R_o}. \tag{5}$$

Note that R_o% is affected by the relative fishing effort inside and outside the fjord. Although migration, fishing effort, and natural mortality affect the recapture rates, it is assumed that these factors affect both single- and double-tagged fish equally and do not influence the calculations of Equations (1)–(4).

The rate of tag loss could be estimated because almost all cod tagged with electronic tags were also tagged with an anchor tag (93 of 95 fish), and an accurate record of each tag returned was kept. No correction for tag loss using the rates of tag detection and reporting was attempted. Conventional 2×2 χ^2 tests were used to compare the recapture ratios statistically.

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Results

Recapture rates

Recapture rates were about double for cod tagged with an electronic tag plus an anchor tag as for cod tagged only with one anchor tag. The 2-year cumulative recaptures were 46.6 vs. 20.0% for TRAWL-2005 (Figure 2a, $\chi^2 = 24.8$, $p < 0.001$, d.f. = 1) and 62.2 vs. 29.2% for HERD-2006 (Figure 2b, $\chi^2 = 16.0$, $p < 0.001$, d.f. = 1) for double- vs. single-tagged cod, respectively. If tags reported without a recapture month are included, the percentages are 48.3 vs. 20.7 and 67.6 vs. 31.0, respectively.

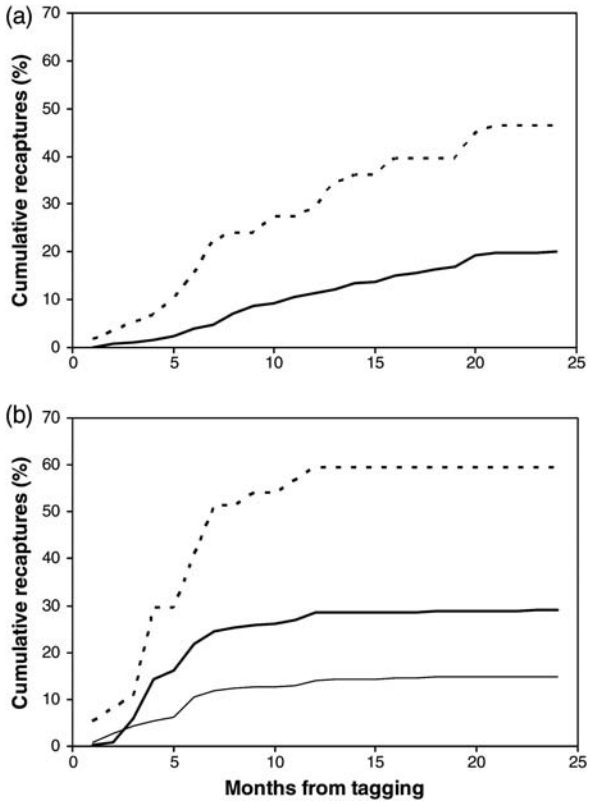

Figure 2. Cumulative recaptures of tagged cod for (a) TRAWL-2005, and (b) HERD-2006 and TRAWL-2006, showing single-tagged fish with anchor tags (solid lines) and double-tagged fish with electronic and anchor tags (dotted lines). TRAWL-2006 data indicated with a thin solid line.

For TRAWL-2005, the mean lengths at tagging were 59 and 52 cm for electronic- and anchor-tagged cod, respectively, and for HERD-2006, the mean length at tagging was 62 and 59 cm for the same tag type. However, there was no difference in the mean length at tagging for the recaptured fish compared with all tagged fish (Table 2).

For TRAWL-2005, HERD-2006, and TRAWL-2006, the fraction of anchor-tagged fish <40 cm was 16.4 (559 of 3409), 1.5 (24 of 1604), and 2.1% (19 of 897), respectively. The recapture rates for the two smallest length classes were less than for the balance of the tagged fish (Table 3). If all single-tagged fish <40 cm are omitted from the analysis, the 2-year cumulative recaptures were 23.9, 29.5, and 15.0% for TRAWL-2005, HERD-2006, and TRAWL-2006, respectively. This correction did not change the significance of the differences in recapture rates between double- and single-tagged fish (TRAWL-2005, $\chi^2 = 16.5$, $p < 0.001$; HERD-2006, $\chi^2 = 15.7$, $p < 0.001$).

Cod <40 cm tended to be resident in Arnarfjördur during the first 12 months from tagging, and emigration from the fjord was low too for 40–69 cm cod compared with larger fish (Table 3).

Tagging-related mortality

There was no immediate capture-related mortality observed for cod captured with a liftnet (HERD-2006), but some for cod caught with a shrimp trawl (TRAWL-2005 and TRAWL-2006), increasing with catch size. Tagging-related mortality was only studied for cod tagged with electronic tags in HERD-2006 and kept in sea cages for 48 h. In all, 3 fish of 36 died in the cages (8.3%).

Tag loss

A total of 5 of 53 recaptured double-tagged fish (9.4%) lost an anchor tag, and 5 of 53 double-tagged fish lost an electronic tag (Table 4). Calculated for recaptures reported within 12 months of tagging, tag loss was 10% (4 of 40) for both tag types.

Rates of tag reporting and detection

Overall, ~80% of the tags for single- and double-tagged fish were returned by fishers and ~20% by workers in fish-processing plants

Table 2. Details of the cod tagged in Arnarfjördur and at their subsequent recapture (status as at 31 October 2008).

	Electronic tags		Anchor tags	
Details	**Tagged fish**	**Recaptured fish**	**Tagged fish**	**Recaptured fish**
TRAWL-2005 (June 2005 outside herds)				
Number of fish	58	28	3 409	758
Mean length (cm)	59.2	59.3	52.0	52.4
s.d. of length (cm)	7.2	7.7	11.4	10.2
Median of length (cm)	59	58.5	54	54
Minimum length (cm)	44	44	20	25
Maximum length (cm)	76	76	86	82
HERD-2006 (July 2006 within herds)				
Number of fish	37	25	1 604	494
Mean length (cm)	61.5	61.6	58.9	58.5
s.d. of length (cm)	7.5	6.3	10.2	9.4
Median of length (cm)	61	61	59	59
Minimum length (cm)	46	52	33	37
Maximum length (cm)	79	79	96	88

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Table 3. Size-dependent recapture of all cod tagged in Arnarfjördur in 2005 and 2006.

LG (cm)	*T*	*R*	*R*%	R_i	R_o	R_o%	Lt	Lr
TRAWL-2005 (1st 12-month period from tagging, June 2005–May 2006)								
20–29	163	5	3.1	5	0	0.0	28.0	36.8
30–39	396	38	9.6	38	0	0.0	36.2	45.3
40–49	643	94	14.6	81	11	12.0	44.2	51.8
50–59	1 318	151	11.4	98	45	31.5	55.5	58.6
60–69	809	97	12.0	60	33	35.5	63.6	66.8
70–79	133	19	14.3	5	14	73.7	72.5	76.6
80+	5	1	20.0	0	1	–	82.0	88.0
Total	3 467	405	11.7	287	104	26.6	53.4	57.9
TRAWL-2005 (2nd 12-month period from tagging, June 2006–May 2007)								
20–29	163	8	4.9	4	3	42.8	27.9	50.4
30–39	396	31	7.8	22	5	18.5	35.4	54.2
40–49	643	74	11.5	53	13	19.7	44.8	59.4
50–59	1 318	121	9.2	84	25	22.9	54.8	63.9
60–69	809	61	7.5	37	17	31.5	62.7	71.1
70–79	133	8	6.0	2	4	66.7	71.0	84.0
80+	5	0	–	–	–	–	–	–
Total	3 467	303	8.7	202	67	24.9	51.7	63.0
HERD-2006 (1st 12-month period from tagging, August 2006–July 2007)								
20–29	0	–	–	–	–	–	–	–
30–39	24	4	16.7	4	0	0.0	38.0	48.5
40–49	296	84	28.4	58	23	28.4	45.6	56.6
50–59	548	163	29.7	113	47	29.4	55.1	64.0
60–69	533	175	32.8	121	51	29.6	63.8	72.5
70–79	192	45	23.4	23	21	47.7	73.7	80.0
80+	48	7	14.6	3	3	50.0	83.0	88.5
Total	1 641	478	29.1	322	145	31.0	58.7	67.5
TRAWL-2006 (1st 12-month period from tagging, August 2006–July 2007)								
20–29	1	0	–	–	–	–	–	–
30–39	18	0	0.0	–	–	–	–	–
40–49	103	7	6.8	7	0	0.0	43.9	49.9
50–59	422	58	13.7	46	11	19.3	55.5	58.3
60–69	307	54	17.6	37	15	28.8	63.9	66.1
70–79	40	7	17.5	3	4	57.1	72.6	75.0
80+	6	0	0.0	–	–	–	–	–
Total	897	126	8.7	93	30	24.4	59.4	62.0

Number of tagged fish (*T*), number and percentage of recaptured fish (*R*), number of recaptured fish inside (R_i) and outside (R_o) Arnarfjördur, percentage of recaptured fish outside Arnarfjördur, mean tagging length of recaptured fish (Lt), and mean recapture length (Lr) by length group (LG).

Table 4. Tag loss of double-tagged cod for TRAWL-2005 and HERD-2006 (status as at 31 October 2008).

Tag and recapture detail	TRAWL-2005	HERD-2006	Total
Number of double-tagged fish	56[a]	37	93
Recaptures of double-tagged fish	28	25	53
Recaptures of anchor tags	25	23	48
Recaptures of electronic tags	26	22	48
Loss of anchor tags (%)	10.7	8.0	9.4
Loss of electronic tags (%)	7.1	12.0	9.4

[a]By mistake, 2 of the 58 fish tagged with electronic tags were not tagged with anchor tags (these two fish were not recaptured).

(Table 5). Most of the tags found at sea were returned by relatively few fishers from a number of boats fishing in Arnarfjördur, mainly with Danish seines and longlines. Most of the tags found in processing plants came from five fishing ports. For both TRAWL-2005 and HERD-2006 (Table 5), the relative recaptures of double-tagged fish by both fishers and fish processors were approximately twice as high as would be expected assuming equal reporting and detection rates of double- and single-tagged fish.

Table 5. Number of recaptures of all tagged and double-tagged fish by fishers and fish processors (status as at 31 October 2008) and the percentage of double-tagged fish.

Tag and recapture detail	Number tagged	Double-tagged	% double-tagged
TRAWL-2005			
Total tagged	3 467	56	1.6
Total recaptures	786	28	3.6
Chartered boat recaptures	148	5	3.4
Other boat recaptures	480	19	4.0
Recaptures by fishers	628	24	3.8
Recaptures by fish processors	158	4	2.5
Recaptures by fishers (%)	80	86	–
Recaptures by fish processors (%)	20	14	–
HERD-2006			
Total tagged	1 641	37	2.2
Total recaptures	519	25	4.8
Chartered boat recaptures	229	8	3.5
Other boat recaptures	170	11	6.5
Recaptures by fishers	399	19	4.8
Recaptures by fish processors	120	6	5.0
Recaptures by fishers (%)	77	76	–
Recaptures by fish processors (%)	23	24	–

For the boats chartered by MRI, the number of electronic tags reported amounted to 3.4 and 3.5% of the tags returned in TRAWL-2005 and HERD-2006 (Table 5), respectively. For other boats, electronic tags amounted to 4.0 and 6.5% of the returned tags for TRAWL-2005 and HERD-2006, respectively. Using Equations (1) and (2), the reporting rate of anchor tags by commercial fishers was estimated as roughly 0.85 for TRAWL-2005 and 0.54 for HERD-2006 (and 0.74 for pooled data).

For HERD-2006, only one tag from the experimental liftnet fishery in the period 19 October–23 November 2006 was reported by a fish processor compared with 190 tags returned by MV "Höfrungur", suggesting a high detection rate on board. However, during the experimental Danish seine fishery by "Höfrungur" in the period 11 December 2006–31 January 2007, 25 anchor tags were found at sea and 18 in fish-processing plants, suggesting a low detection rate on board the vessel.

Some of the double-tagged fish were not detected by fishers. For TRAWL-2005, 14% of the tags from double-tagged fish were returned by fish processors, and for HERD-2006, the value was 24%, an average of 19% (Table 5). These results suggest that the rate of tag detection at sea was ~0.8 for double-tagged fish, assuming that all double-tagged cod entering the fish-processing plants were detected and reported.

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For TRAWL-2005 and HERD-2006, the crew of MV "Höfrungur" returned ~19 and 41% of the total recaptures, respectively. It can be assumed that, in these cases, all tags detected were returned, both anchor and electronic (100% reporting rate). For TRAWL-2005, 1.6% of all cod recaptured were double-tagged, compared with 3.4% of those returned by the crew of "Höfrungur" (Table 5). For HERD-2006, 2.2% of all cod recaptured were double-tagged, compared with 3.5% of those returned by the crew of "Höfrungur" (Table 5), demonstrating that the crew had overlooked a significant number of single-tagged fish. The rate of tag detection of single-tagged fish at sea was estimated from Equations (3) and (4) at ~0.38 for TRAWL-2005 and ~0.52 for HERD-2006 (and 0.45 for pooled data).

Discussion

Recapture rates were about twice as high for cod double-tagged with an electronic tag than for fish tagged with just a single anchor tag. This is in spite of the potential mortality caused by surgically implanting electronic tags into the abdominal cavity of the fish. Potentially, several factors may have caused these differences, including tagging-related mortality, tag loss, and the rates of tag reporting and detection. The setup of the study made it possible to estimate these parameters, although these estimates are not precise owing to the relatively few fish double-tagged.

Tagging-related mortality

For HERD-2006, ~68% of the double-tagged fish were retrieved within 2 years, which is among the highest rates of recapture reported for Atlantic cod (Robichaud and Rose, 2004). In this case, most of the post-tagging mortality may have been accounted for, because the majority of the fish (35 of 37) were kept in recovery cages for 2 d before being released. For TRAWL-2005, some 48% of the fish with electronic tags were retrieved within 2 years. Those fish probably suffered some tagging-related mortality owing to the more stressful method of capture and lack of adaptive treatment following tagging (Hislop and Hemmings, 1971; Tytler and Blaxter, 1973). The low recapture rate during the first 2 years for TRAWL-2006 (15%) may also be attributable to a high level of tagging-related mortality caused by thermal shock (Brattey and Cadigan, 2004). For TRAWL-2006, tagging was performed in late July 2006 when surface temperatures (12°C) were much higher than bottom temperatures (3°C). On the other hand, for TRAWL-2005, surface temperatures (6–8°C) at tagging in early June 2005 were only 4–6°C higher than bottom temperatures (2°C; Björnsson *et al.*, in press). Stomach fullness was also noticeably greater in late July 2006 than in early June 2005, probably causing the fish a greater physiological stress during tagging.

It can be assumed that large cod were the main predators of smaller cod in Arnarfjördur during tagging. Cod can consume other cod up to 50% of their own length (Bogstad *et al.*, 1994). The high risk of cannibalism for juvenile cod released in the presence of older cod was demonstrated in an earlier study where tagged cod 20–35 cm long were released in Stödvarfjördur, East Iceland. Three of eight 54–67 cm cod captured on a handline during release had consumed a total of five tagged cod 22–32 cm long (BB, unpublished data). Assuming some plausible rate of natural mortality while growing to fishable size, the relatively low recapture rates of small cod (20–29 cm) suggest that there may have been some cannibalism before the small cod had recovered fully from the tagging trauma. However, for fish tagged in the herds, the risk of predation or cannibalism following release was probably negligible because 98% of the fish were ≥40 cm long.

It is likely that most post-tagging mortality of the double-tagged cod placed in the recovery cages had already taken place during the 2-d recovery period. The percentage of total mortality of handlined cod kept in submersible enclosures for 9 d was 95.3% during the first day and 96.5% during the first 2 d (Pálsson *et al.*, 2003). The mortality of adult cod captured by otter trawl and kept for 5 d in tanks on board a research vessel was 8.5 and 10.3–11.8% for adult cod captured with handlines, otter trawls, and cod traps and kept in submersible enclosures for 5–10 d (Brattey and Cadigan, 2004). In a 54-d laboratory study, just 2% of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) that had been surgically implanted with radio transmitters died (Adams *et al.*, 1998). In our study, the electronic tags were only some 1% of body weight compared with 4% in the study by Adams *et al.* (1998).

Tag loss

Tag loss within 12 months of tagging was estimated at ~10%, the same percentage found for coastal cod in Norway (Otterå *et al.*, 1998), but tag loss of 22% was found for cod in coastal Newfoundland (Cadigan and Brattey, 2006). A significant difference has been found in the tag-shedding rate for cod depending on whether the tag was attached at the anterior or the posterior edge of the first dorsal fin (Cadigan and Brattey, 2006). Tag loss will also to some extent depend on the skill of the person carrying out the tagging. In the current study, all the cod, both single- and double-tagged, were tagged by a single experienced worker. For all double-tagged cod recaptured, 9% of the electronic tags were not returned. Shedding of these tags cannot be ruled out and tags may also have been overlooked during catching and gutting. Perhaps the plastic tubing was pulled into the abdominal cavity or broke off, and in some cases, the electronic tag may have been accidentally lost after retrieval, as happened once in the case of the crew of MV "Höfrungur". Cadigan and Brattey (2006) estimated that some 5% of high-reward cod tags were accidentally lost by fishers.

In most cases, double-tagging will reduce total tag loss to acceptable levels. By assuming an annual tag loss of 10%, the probability that both tags of a double-tagged fish are lost in 1 year of tagging is just 1%. The probability increases to 4% if 20% tag loss per year is assumed.

Rates of tag reporting and detection

The average reporting rate for the commercial fleet was estimated as ~74% for single-tagged fish, within the range of 58–100% reported for Newfoundland cod (Cadigan and Brattey, 2006). Factors that may influence reporting rates include lack of information about the tagging programme, lack of initiative, protest against a research institute advising a reduction in catch quotas, total number of tags found, and the level of reward for each tag (Pollock *et al.*, 2001; Cadigan and Brattey, 2006).

A lower reporting rate of anchor tags than of electronic tags may partly explain the different returns for the two types of tag, because the reward was 5× higher for the cod tagged electronically (when both tags were returned, ~US$60 for the electronic tag and ~US$15 for the anchor tag). The finder may also treat the electronic tag with greater respect and show more interest in it than in the anchor tag. The reporting rate may have been influenced by the fact that ~70% of the recaptured fish were caught in Arnarfjördur (Björnsson *et al.*, 2010) by relatively few boats,

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most of them returning large numbers of anchor tags, and hence receiving notable additional income from the rewards.

The average rate of tag detection by fishers at sea was estimated at ~45% for single-tagged and ~80% for double-tagged cod. The average rate of tag detection for fishers and fish processors pooled was estimated at ~54% for single-tagged fish. There are many factors other than number of tags per fish that may influence the detection rate, such as type, size, and colour of the tag, tag location in the fish, number of tagged fish in the catch, conditions on board, movement of the ship, weather, time of year, time of day, and size of the catch (Jakobsson, 1970; Cadigan and Brattey, 2006).

The most likely explanation for much lower returns of anchor relative to electronic tags is that the fish with electronic tags were double-tagged. The anchor tags tend to lie along the back of the fish and may be hidden when the fish are lying on their left side or back. For a double-tagged cod with one anchor tag at the dorsal fin and one electronic tag with coloured tubing protruding from the belly, one tag can be detected from all angles whether the fish is lying on the left or the right side or on the back or belly. Once the first tag is detected it is almost certain that the second tag will be detected too. Greater length and diameter of the colour tubing of the electronic tags relative to the anchor tags may also have contributed to greater detectability of the double-tagged cod.

In the catches of the experimental liftnet fishery by MV "Höfrungur" in October and November 2006, <1% of the recaptured cod were found by fish processors, probably because the catches were modest (1.2 t of cod per day) and the conditions on board favourable. In contrast, in the Danish seine fishery carried out by MV "Höfrungur" from December 2006 to January 2007, many tagged fish were missed by the crew and returned by fish processors. Lower rates of tag detection by the crew may have been caused by the large catches (6.6 t of cod and haddock per day) and because fishing took place during the two darkest months of the year at high latitude (65°45′N). Further, the cod were only bled and iced, not gutted, resulting in minimal handling on board. During bleeding, the head of the fish is normally held by the left hand, exposing the tubing of an electronic tag protruding from the belly, whereas the anchor tag attached dorsally on the left side of the fish may be less visible. This standard means of handling the catch may have resulted in a better rate of tag detection for double- than for single-tagged fish.

Barrowman and Myers (1996) suggested that double tags may be more visible than single. However, Cadigan and Brattey (2006) explained higher returns of double-tagged fish mainly by higher rates of reporting, although a lesser probability of total tag loss can be implied from their study. In their study, double-tagged cod were tagged with two anchor tags inserted at the base of the first dorsal fin ~3 cm apart on the same side of the fish. That form of tagging may increase the detection rate only slightly compared with when one tag is located dorsally and another ventrally, as done here.

The advantage of double- over single-tagging with respect to recapture rates at sea by fishers can be illustrated in the following calculations based on the above estimates of tag loss and tag detection and reporting (disregarding tagging-related mortality and natural mortality). For 100 single-tagged cod recaptured, tags from just 30 cod will be returned by fishers ($100 \times 0.9 \times 0.45 \times 0.74$), whereas for 100 double-tagged cod, tags from 71 cod will be returned, i.e. 6 cod with only one tag ($100 \times 2 \times 0.1 \times 0.9 \times 0.45 \times 0.74$) and 65 cod with both tags ($100 \times 0.9 \times 0.9 \times 0.80 \times 1.00$). Accordingly, recapture rates can be doubled by double-tagging the cod. The estimate is of similar magnitude to the recapture rate observed for HERD-2006, where tagging-related mortality was low and natural mortality probably low too. Similarly in coastal Newfoundland, the odds of reporting a double-tagged cod were almost double those of single-tagged cod (Cadigan and Brattey, 2006).

Proposed tagging method

In most mark–recapture studies, each day of tagging is expensive, especially when large ocean-going vessels are used. The additional time required to double-tag fish is minimal and the additional cost of tags relatively little. It is important to pay for both tags returned for each fish to ensure accurate bookkeeping of lost tags. Relative to the number of fish recaptured and the information provided, it may hence be more cost-effective to double tag than to single tag each fish. This is particularly important when the access to viable fish is limited and the time at sea constrained.

Based on the study here, it is proposed that future tagging studies adopt a strategy of double-tagging every fish to increase the rate of tag detection by fishers significantly, as well as to provide a reliable estimate of tag loss. Tags should be placed on each side of the fish, one dorsally and one ventrally. For many species of fish it may be possible to attach the two tags at the base of the first dorsal and anal fins. For larger fish, anchor tags with longer and thicker colour tubing might be selected to enhance the detectability of double-tagged fish. Higher rates and more reliable tag returns will facilitate the use of tagging experiments to estimate mortality rates independently from statistical catch-at-age models and the survey indices commonly used in fish stock assessments.

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