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SEVENTEEN YEARS AND $3 MILLION DOLLARS LATER: PERFORMANCE OF PSAT TAGS DEPLOYED ON ATLANTIC BLUEFIN AND BIGEYE TUNA

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SUMMARY

In the 1990s, development of the PSAT tag was a major milestone for investigations of Atlantic bluefin tuna. Although early studies tested the technology and described general migration patterns, fisheries scientists now seek analytical approaches to use the spatial and temporal information returned by PSATs in stock assessments. Nonetheless, PSATs remain expensive, have multiple sources of error, and poorly resolved data. The evolving dynamics of hardware and international tagging programs also confound interpretation, delaying progress towards integration of population-level data. There are few PSAT datasets where tagging was performed by the same individuals, using consistent methods, over a long period. From 1997-2013, we deployed PSAT tags on 568 bluefin tuna (Thunnus thynnus) and 21 Atlantic bigeye (Thunnus obesus). We present details of the tags' highly variable performance records, and given realized costs of PSATs, advocate for innovations including 1) robust experimental design of tag release, 2) open source software, 3) reduction in size and cost, 4) innovation in capability, 5) integrated data repositories. Major advances in tracking technologies will require multi-disciplinary expertise as well as adequate funding.

RÉSUMÉ

Dans les années 90, le développement de la marque PSAT a constitué un jalon important en matière de recherche sur le thon rouge de l'Atlantique. Même si les premières études testaient la technologie et décrivaient les schémas migratoires généraux, les scientifiques halieutiques cherchent actuellement des approches analytiques permettant d'utiliser les informations spatio-temporelles fournies par les PSAT dans les évaluations de stocks. Néanmoins, les PSAT sont encore onéreuses, ont de multiples sources d'erreur et des données de faible résolution. Les dynamiques en constante évolution du matériel et les programmes internationaux de marquage compliquent également l'interprétation, retardent les progrès en vue de l'intégration des données au niveau de la population. Quelques jeux de données de PSAT contiennent des données de marquage des mêmes spécimens, utilisant des méthodes cohérentes, pendant une longue période. Entre 1997 et 2013, nous avons apposé des marques PSAT sur 568 thons rouges (Thunnus thynnus) *et 21 thons obèses* (Thunnus obesus). *Nous présentons les détails du rendement très variable des marques et, compte tenu des coûts des PSAT, nous préconisons des innovations incluant 1) une conception expérimentale solide de marquage, 2) un logiciel en open source, 3) une réduction de la taille et des coûts, 4) l'innovation de la capacité et 5) des plateformes de données intégrées. Des progrès importants en matière de technologie de suivi nécessiteront une expertise multidisciplinaire et un financement adapté.*

RESUMEN

En los 90, el desarrollo de las marcas PSAT fue un gran hito para las investigaciones sobre atún rojo del Atlántico. Aunque los primeros estudios probaron la tecnología y describieron unos patrones de migración generales, los científicos pesqueros buscan ahora enfoques analíticos para usar la información espacial y temporal proporcionada por las PSAT en las evaluaciones de stock. No obstante, las PSAT siguen siendo caras, tienen muchas fuentes de error y datos mal resueltos. La dinámica evolutiva del hardware y los programas internacionales de marcado también confunden la interpretación, retrasando el progreso hacia la integración de los datos a nivel de la población. Hay pocos conjuntos de datos PSAT en los que el marcado se haya realizado por los mismos individuos, usando métodos coherentes y

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durante un largo periodo. Entre 1997-2013 colocamos marcas PSAT en 568 atunes rojos (Thunnus thynnus) *y 21 patudos (*Thunnus obesus). *Se presentan detalles de los registros de rendimiento de las marcas, muy variables, y teniendo en cuenta los costes de las PSAT, abogamos por innovaciones que incluyan: 1) diseño experimental robusto de la colocación de la marca, 2) software de código abierto, 3) reducción de tamaño y coste, 4) innovación de las capacidades y 5) repositorios de datos integrados. Para lograr mayores avances en las tecnologías de seguimiento se requerirá experiencia multidisciplinar, así como una financiación adecuada.*

KEYWORDS

Bluefin tuna, Bigeye tuna, Data collections,
Migrations, Popup satellite archival tags, Tagging

1. Introduction

Until recent electronic tagging studies were successfully completed almost all information for Atlantic bluefin tuna (ABFT) relied on fishery-dependent catch data, biological sampling from the US recreational fishery, and conventional tagging programs (Fromentin and Powers 2005). Since 1997, Large Pelagics Research Center (LPRC) scientists have deployed pop-up satellite archival tags (PSATs) on ABFT, recovering high resolution information on dispersal, depth patterns, temperature and daily locations for maximum missions of 12 months. We identified habitat utilization and biophysical characteristics of adult and juvenile ABFT, and their vertical and horizontal distribution and dispersal rates (e.g., Galuardi and Lutcavage 2012; Galuardi *et al.* 2010; Royer *et al.*, 2009;Sibert *et al.* 2006; Wilson *et al.* 2005).

There is no doubt that the fishery-independent PSAT tag opened the doors to a new era of effective and creative data acquisition for large pelagic, highly migratory species. However, the advances in understanding heralded by the new fisheries research tool did not occur without nearly two decades of frustration and complaints related to their high cost and myriad sources of disappointment and failures in deployments. In fact, while commenting on the poor data performance of early PSATs at the Lake Arrowhead Tuna Conference, an eminent US tuna assessment scientist wryly noted that researchers seemed to be "throwing laptops over the side!".

LPRC scientists were among the first to use and develop deployment approaches for cooperative PSAT tagging from the US commercial bluefin fishery, and routinely served as inadvertent "beta testers" for tag manufacturers, sharing our insights with colleagues, as well as tag manufacturers, when asked for feedback. Since 1997, at about $4,000 USD each, the financial investment in tags alone for our ABFT PSAT tagging program, not including other US programs by other investigators, was about $2.3M USD, primarily from competitive federal grants. Since LPRC has a unique PSAT dataset where tagging was performed by the same individuals, using essentially the same materials and methods, on different sizes of fish over a long time period, we can comment on PSAT tag performance on Atlantic tunas, and make recommendations based on our findings and field experiences.

2. Evolution of a tuna tagging program

Between 1997 and 2013, we deployed a total of 568 and 21 PSATs on bluefin *(Thunnus thynnus)* and bigeye tuna *(Thunnus obesus)*, respectively. These included five specific models (**Table 1**) from three tag manufacturers (MWT: Microwave Telemetry, Inc., Columbia MD; WC: Wildlife Computers, Redmond WA; DS: Desert Star Systems, Marina CA), with the majority of tags supplied by MWT (n = 563). We learned during initial years of deployments that most of the tags released prematurely, with only a minor portion remaining attached for a one-year mission. Based on first principles, we urged manufacturers to reduce the size of the tag body, which would reduce drag, and should result in a higher percentage of longer attachments. A transition to the smaller size MWT X-tag occurred in 2007 for the perceived benefits of reduced footprint on the tagged fish. In recent years we used WC and DS tags to diversify the hardware portfolio, and spread the potential risks of non-reporting associated with a single manufacturer.

Consistency in tag programming and setup was maintained throughout the study period. Most PSATs were programmed to be released after 10 to 12 months in hopes of capturing annual migrations, and potential spawning areas for western ABFT, which Mather and others had suggested were broader than recognized. We used custom built tethers, usually assembled by the same individual, with a single-point attachment throughout most of our tagging campaigns (Lutcavage *et al.* 1999), except for minor changes in tether materials. In 2007 we tested a holding loop anchored via a secondary attachment but discontinued its use after finding no increase in attachment duration for juvenile ABFT tagged on deck (Galuardi and Lutcavage 2012). Biomedical nylon darts served as anchors, with the exception of 2001-2003, when we tested sharp, flat metal anchors (Wilson *et al.* 2005) used by other tuna taggers.

3. Overall performance

Over 89% of WC Mk-10s, WC MiniPATs and DS SeaTag-MODs communicated with Argos satellites upon pop off (**Table 1**). In this paper, we will not address the issue of data transmission and quality, but it is worth noting that only 3 out of 8 reported DS SeaTag-MODs transmitted some usable data. For MWT, overall reporting rate was between 57% (X-tag) and 80% (PTT-100) on ABFT and 38% (X-tag) on bigeye tuna. Only MWT tags remained attached up to, or over, one year (maximum, 562 days, an X-tag that did not release from a bigeye tuna, recovered still attached to the fish), but this might be an artifact of the smaller number of WC (n = 17) and DS (n = 9) tags used.

4. Temporal differences in non-reporting

We further considered the issue of non-reporting with our long time series for MWT PTT-100s and X-tags. As PSAT technology and our field applications and testing expanded between 1997 and 2003, non-reporting PTT-100s represented a smaller proportion of tags deployed, from 50% in 1998 to 10% in 2002, and remained small (usually < 20%) during 2004-2009 (**Figure 1**). Over this time little changed in our tag set up or deployment methods. The application of PTT-100's ended in 2009 with the transition to the smaller X-tags. In 2009 we obtained the first and only 0% non-reporting, with all 14 PTT 100's transmitting data. The majority of reporting PTT-100s were early releases, usually within the first 6 months of deployment (not shown here), although from 15-24% of tags each year remained attached for the full mission, with an average of about 17% (**Table 1**).

Time series of MWT X-tags presented a contrasting trend (**Figure 2**). Proportion of non-reporting showed a marked increase when compared to PTT-100s, ranging between 31% and 74%, with the later years (2010, 2011) at about 45% non-reporting. In comparison with previous years/batches, an exceptionally high reporting rate (93%) was observed for 2013 deployments. Notably, the majority of reporting X-tags were on time, i.e., full term releases. In contrast, releases from early years with PTT-100s were distributed quite evenly over the first 11 months of the 1 year mission (not shown here). It's possible that the smaller tag (first principles, lower drag, etc.) and our honed techniques (from the test-retest cycle) had achieved better attachment and retention by the tuna, but our success in refining tag attachment had subjected tags to the elements and hardware failures during the additional months at sea.

5. Potential causes of tag failure

Having a long running program has allowed us to conduct a longitudinal self-evaluation of tagging and PSAT performance. Specific to Atlantic tunas, this experience offers different insights than those available from the valuable meta-analysis of tagging results conducted by Musyl *et al.* (2011). We reduced the influence of confounding factors such as differences in individual researcher/ team practices and preferences. Here we provide (**Fig. 3**) a pruned and updated fault tree of Musyl *et al.* (2011) and offer our valuation of risk from each factor using a linguistic scale used in engineering, as recently applied to animal tagging studies (Bidder *et al.* 2014). We eliminated a number of failure modes (see gray boxes; **Figure 3**) and reduced the plausible causes of failure based on expertise as well as objective evidence (e.g., recovered, non-reporting tags). In the following flowchart, causes are reviewed in the order of increasing risk:

5.1 Predation, social or nuptial bites – Very low risk

The evidence is convincing from multiple studies and species that tags attached to bluefin and bigeye tuna that experience predation "bites", if indeed this occurs, will still work and report (e.g., Béguer-Pon *et al.* 2012; Lacroix 2014). Since predation on tuna tags has not been observed behaviorally, and we have not observed evidence of predation on any tag (except for tiny bite marks from reef fish on antennas and floats from PSATs recovered in the tropics, from sea turtles), this is unlikely in bluefin and bigeye tuna. Despite the lack of evidence, predation of X-tags by other bluefin tuna was offered by the manufacturer as their explanation for the low reporting rate (**Figure 2**) of 2011 MWT X-tags (Dr. Lance Jordan, Microwave Telemetry, Inc., personal communication). Two of the 22 non reporting X-tags were eventually recovered still attached to fish.

5.2 Pin breaks on nose cone – Fairly low risk

Our tagging results support the finding that a weak nose cone is a possible (and likely) source of early reporting in some tag models, but offers low risk of non-reporting. The WC nosecone pin was designed to break at certain applied stress in order to reduce animal entanglement (Melinda Braun Holland, Wildlife Computers, Inc., personal communication). We suspect that it accounts for some of the premature WC tag releases on bluefin tuna because MWT tags, fitted with same tether and anchor assemblies, had higher proportions of tags meeting full year attachments (**Table 1**). We also confirmed through tag recovery that the DS SeaTag-MOD nosecone sheared, resulting in the lowest attachment duration (13-33 days) of any tag model. The manufacturer suggested that the model that we purchased and deployed on adult ABFT experienced breakage due to high acceleration forces (Marco Flagg, Desert Star Systems LLC, personal communication), and has since reinforced the tag. Unfortunately, in this case, the investigators, as early adopters, assumed the role of beta testers, and paid for lessons learnt by manufacturers.

5.3 Firmware errors – Medium risk

In 2008 the X-tags deployed on ABFT and bigeye tuna returned notably low reporting rates (**Figure 2**), which we could not attribute to user error, as initially suggested by the manufacturer, or from extrinsic factors. In 2009, following extended discussions the manufacturer eventually confirmed that there had been a firmware programming error, and offered replacement inventory for deployment in 2010. We also determined from returned data that a WC firmware exiting procedure had a bug, and did not delete testing messages. Because of that error the tags used some Argos bandwidth to transmit “junk” data, reducing the amount of useful data. The few transmitted data that we received from DS tags indicated that a combination of float design and their Argos transmission protocol may have been contributing factors. From our experiences it is clear that firmware problems, not usually discovered until the next year’s reporting record is confirmed, can undermine tagging campaigns.

5.4 Drag from movement/ tissue healing - high risk

Based on veterinary understanding of tissue healing and implantation of external devices in fishes and other marine animals (see Braun and Holland 2003) and our observations of recaptured, tagged tunas, we expect that tags shed within a few weeks of tagging do so because of inadequate healing, inflammatory responses, and/or inadequate anchor placement in the pterygiophores. Best practices and adequate fish and tag equipment handling are important for good results, and require extensive experience and understanding of correct protocols for tagging with PSATs. As is the case for conventional tags, best results seem to be achieved when the number of taggers is kept very low, and methods remain consistent.

5.5 Pressure housing fails - Very high risk

From at least two non-reporting X-tags that were recovered still attached to bluefin or bigeye tuna, we have observed clear indications of leakage and sea water infiltration. Likely consequences of water damaged electronics are that tags will not release and transmit data, not even a status message, or in more extreme cases, may not record data. It is the general case that for tags that don’t communicate at all, it is extremely difficult to determine failure modes. It is even more unlikely to recover all non-reporting tags still attached to tunas, and therefore, hard to assign accountability. In the case of the deep and repetitive diving species such as bluefin and bigeye, we attributed the low reporting rates on repetitive stress on the X-tag housing (Lam *et al.* 2014), as suggested by Musyl *et al.* (2011).

6. True cost of tagging and future strategies

Despite advances in ocean exploration tools such as AUVs, sonars, UAVs (i.e., drones) and other technological developments, there is still a great need for innovation in fish tracking and sensing technology. Our seventeen years of experience with popup satellite tags has revealed the need to have smaller, smarter and less expensive tags to deploy on migratory, open ocean species. Although marine animal tag manufacturers continually innovate tag hardware, software, and data processing algorithms for existing technology, tags have not evolved at the rate of advances in engineering, IT, and biomedical fields, despite a clear and compelling need. With downsized federal science budgets, funds to purchase satellite tags have become harder to secure. Users rarely have the capability to build tags or devices that suit their specific research objectives, and manufacturers may lack financial support or incentives to depart radically from proven, existing tag models. The basic PSAT technology has not changed very much since first or second generation tags of the late 1990's, nor have their cost, at about $4-5K. Since then, advances in performance have been modest and incremental, and our record shows that they did not always benefit the end user. In many instances, new batches of PSATs had undetermined failures, with financial and research costs of the lengthy tag test/retest cycles (e.g., 12 months) were often borne by customers, functioning as unsuspecting "beta testers". When tags worked well (e.g., high data reporting rates, e.g., 80-90%), technological details were not often shared with the user or user community because the tag market remained small, and dominated by the competitive manufacturers selling to a relatively small market. When tag batches failed, reporting rates could be as low as 17% of tags returning useful data, and some manufacturers did not provide warranties or replacements of non-reporting tags unless the tags were recovered from the animals. The total purchase cost of our PSAT tags was about $2.3 M, but hidden costs of charters, Argos fees, personnel (e.g., **Table 2**), not including tangible costs of failed research programs, provides an actual program cost exceeding $3M.

It is our recommendation that going forward, RFMO's should consider how to make tagging programs more successful and affordable so that they deliver information needed to improve stock assessments. Considerations should include, at a minimum, 1) robust experimental design of tag release, 2) transparent, open source software, 3) reductions in size and cost, innovation in capability, and 4) integrated tag data repositories. Major advances in tracking technologies will require shared, multi-disciplinary expertise as well as adequate funding for support of innovation by manufacturers and tag developers, but the information to be gained is central to understanding population dynamics of tunas.

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Table 1. Summary of tag performance on bluefin and bigeye tuna.

Manufacturer	Model*	Target duration (month)	Tags deployed	Tags reported (full term)	Attachment duration (days)
		Median			*Median (range)*
Microwave Telemetry	PTT-100	10	348	276 (58)	123 (1-366)
	X-tag	12	194	111 (51)	237 (4-721)
	X-tag (bigeye)	12	21	8 (0)	107 (6-562)
Wildlife Computers	Mk-10	12	10	9 (0)	78 (48-150)
	MiniPAT	12	7	7 (0)	76 (25-149)
Desert Star Systems	SeaTag-MOD	12	9	8 (0)[#]	19 (13-33)

* On bluefin tuna other than indicated.
[#] Only 3 out of 8 tags transmitted some usable data.

Table 2. The true cost of deploying a PSAT.

Budget item	Estimated cost in USD
1. Tag hardware	4,000 (typical, range: 1000-4000)
2. Argos fees	300-600 (may be higher depending on required data services)
3. 1-day of vessel time and fuel (averaged per tag)	800
4. 1-day of labor (2 field personnel, 8 hour workday)	1,000
Total	**6,100 – 6,400**

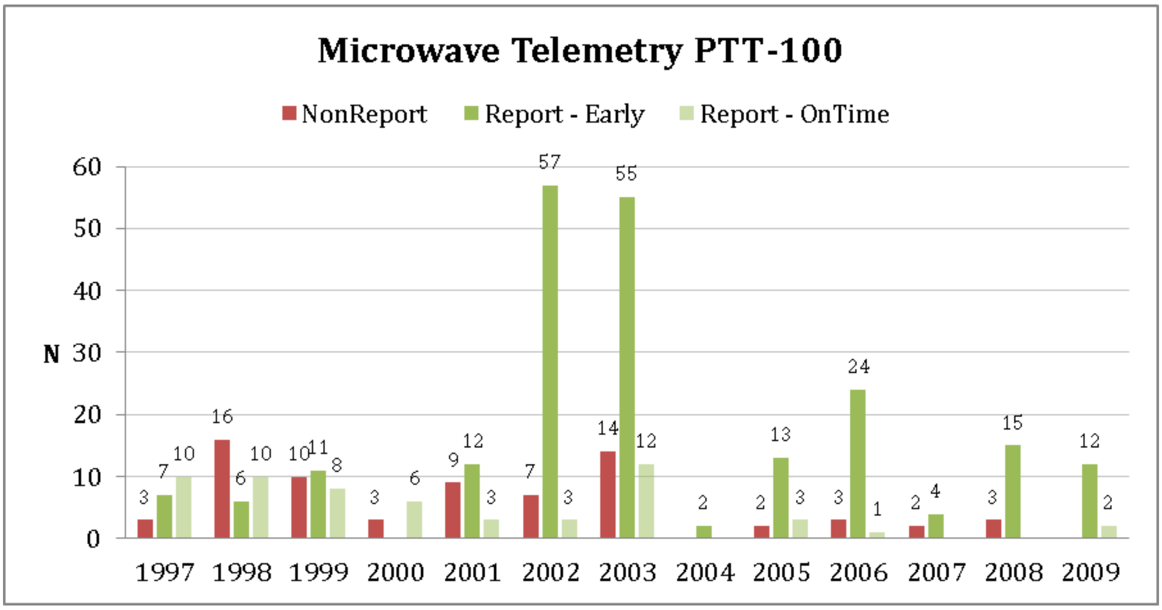

Figure 1. Reporting performance of Microwave Telemetry PTT-100 on bluefin tuna from 1997-2009.

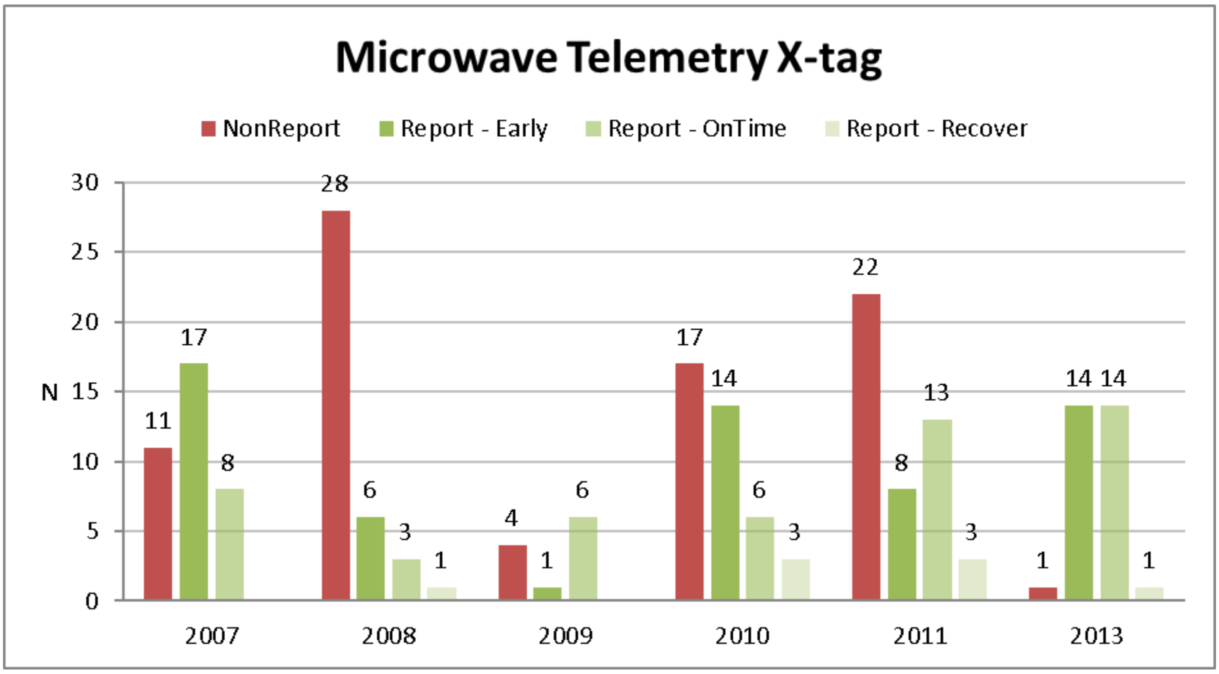

Figure 2. Reporting performance of Microwave Telemetry X-tag on bluefin tuna from 2007-2013.

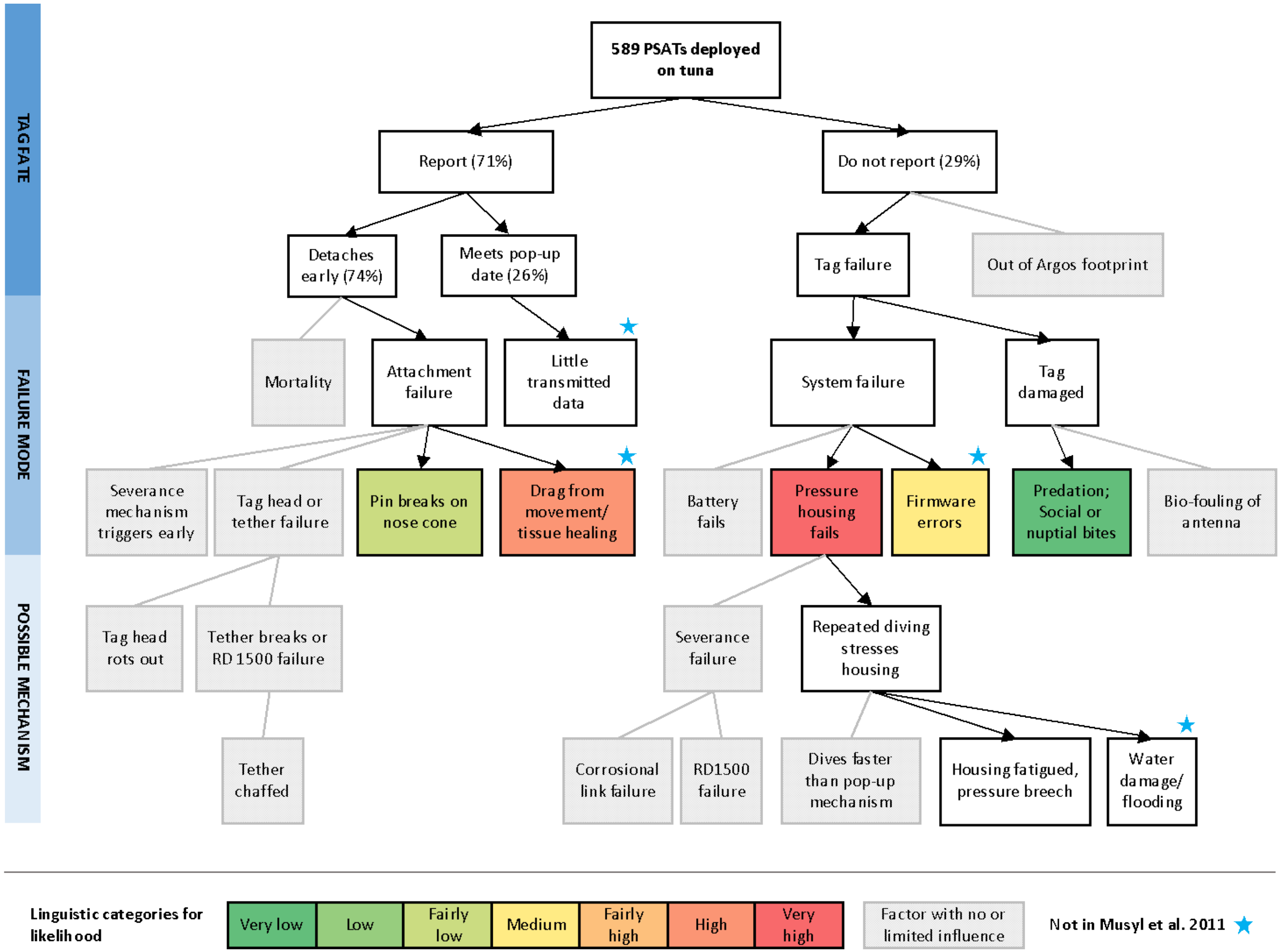

Figure 3. Fault tree summarizing failure modes of PSATs deployed on tuna, adapted from Musyl *et al.* 2011. Grayed out boxes represent failure modes in the original paper that were not applicable or of limited influence. Stars denote failure modes not included in the original paper. Failure modes are assigned a likelihood based on expert opinions (Bidder *et al.* 2014).