Marine Policy 96 (2018) 278–284

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Understanding causes of gear loss provides a sound basis for fisheries management

Kelsey Richardson[a,*], Riki Gunn[b], Chris Wilcox[c], Britta Denise Hardesty[c]

[a] University of Tasmania, Commonwealth Scientific and Industrial Research Organisation, Oceans and Atmosphere (CSIRO), A: 3-4 Castray Esplanade, Hobart, TAS 7000, Australia
[b] GhostNets Australia, A: PO Box 619, Ravenshoe, QLD 4888, Australia
[c] Commonwealth Scientific and Industrial Research Organisation, Oceans and Atmosphere (CSIRO), A: Oceans and Atmosphere, CSIRO, Hobart, Tasmania, Australia

ARTICLE INFO

Keywords:
Abandoned, lost or otherwise discarded fishing gear (ALDFG)
Arafura Sea
Fisheries management
Ghost nets
Illegal, unreported or unregulated fishing (IUU)
Marine debris

ABSTRACT

Derelict fishing nets comprise a significant amount of the marine debris in the world's oceans and on its shorelines. These 'ghost nets' result in economic losses for the fishing industry, pose hazards to navigation at sea, and can entangle marine and terrestrial wildlife. Ghost nets are an acute problem along Australia's northern coastline, with most nets originating from Southeast Asian fishing vessels outside Australia's Exclusive Economic Zone (EEZ). To understand the causes of gear loss and identify tractable solutions to this transboundary problem, Australian and Indonesian fishers (N = 54) were asked why, when and in what circumstances and conditions they are likely to lose gear. Fishers identified snagging of nets (78%) and gear conflicts (19%) as the main causes of gear loss. These interviews informed the development of a fault tree, as a tool to identify the chain of events that result in gear loss or abandonment. The fault tree analysis provides recommendations for interventions and improvements in regional fisheries management to reduce fishing gear loss ultimately resulting from overcrowding, overcapacity and illegal, unreported and unregulated Fishing (IUU).

1. Introduction

Abandoned, lost or otherwise discarded fishing gear (ALDFG) comprises a significant amount of global marine plastic pollution, with an estimated 640,000 t of fishing gear lost to the marine environment each year [1]. This ALDFG is widely recognised to result from a number of environmental, spatial, operational, economic, and enforcement pressures. These pressures may include poor weather, overcrowding, gear conflicts, improper gear storage, lack of shore-side collection facilities for end of life gear, high costs of gear disposal and vandalism or theft [1–3]. One of the significant challenges with this gear is its potential to continue to fish, as well as entangle and ensnare other marine wildlife as nets remain in the ocean and travel with ocean currents. These derelict nets are commonly referred to as 'ghost nets' for this continued ability to ensnare unintended 'catch' [4–6]. Most modern fishing nets are made of plastic materials. This not only results in increased durability for fishing, but also means that when these nets become derelict fishing gear they are persistent and long lasting in the marine environment, further exacerbating potential impacts [1].

Derelict nets are especially problematic in northern Australia's Gulf of Carpentaria ('the Gulf'), where thousands of nets have been recorded along the region's remote coastlines. Up to 3 t of derelict nets have been reported per kilometre of coastline in a given year, which is among the highest levels recorded globally [7–9]. Ghost nets have been documented to entangle invertebrates, crabs, fish, sharks, rays, sawfish, turtles, crocodiles and dugongs (Fig. 1, a and c) [9–11]. Other impacts from ghost nets include damage to fragile benthic habitats, hazards to navigation and high costs of removing nets, particularly in remote locations (Fig. 1, a–f) [1,7,12].

More than 85% of nets found in the Gulf are presumed to originate from fishing vessels operating outside of Australia's Exclusive Economic Zone (EEZ), most likely in Indonesian waters of the neighbouring Arafura Sea [13]. Net fisheries operating in the Arafura Sea use mostly trawl and gillnets, and some purse seine nets to target prawns, sharks and finfish including snappers, mackerel, and tuna [12,14,15]. When nets from these fisheries are lost or discarded in the Arafura Sea they can be transported by currents and north-western monsoon winds to the Gulf (Fig. 1, g) [10,11].

A range of stakeholders in the Gulf including the Australian government, Indigenous communities, non-profit organisations and researchers have been working since the 1990s to collect data about these nets and remove them. For example, since 2004 the non-profit

* Corresponding author.
E-mail addresses: Kelsey.richardson@csiro.au (K. Richardson), riki.ghostnets@northerngulf.com.au (R. Gunn), Chris.Wilcox@csiro.au (C. Wilcox), Denise.Hardesty@csiro.au (B.D. Hardesty).

https://doi.org/10.1016/j.marpol.2018.02.021
Received 28 October 2017; Received in revised form 16 February 2018; Accepted 21 February 2018
Available online 02 March 2018

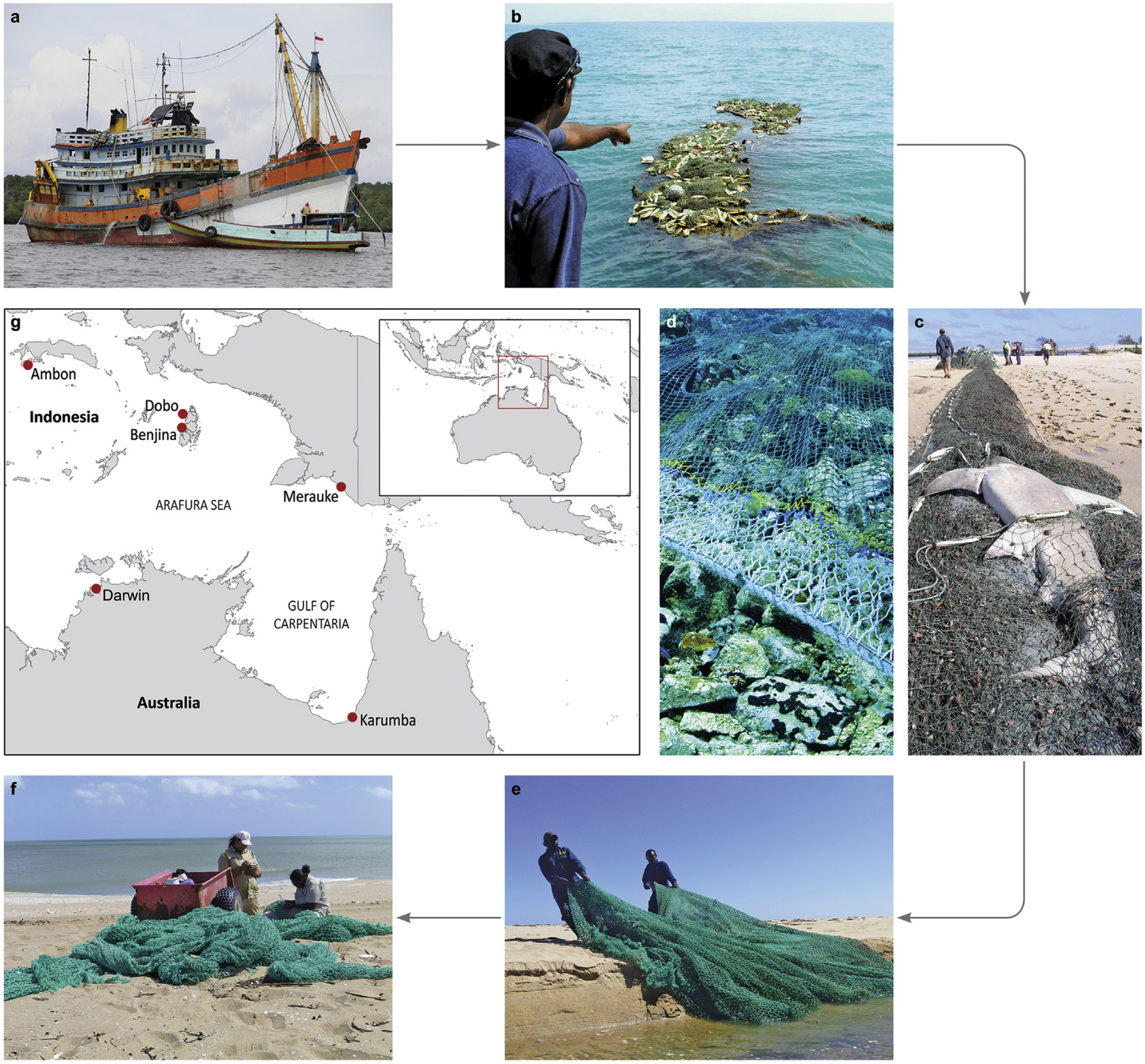

Fig. 1. Ghost nets in the Arafura Sea can be transported by currents and winds to the Gulf of Carpentaria. Moving clockwise from top left, fishing nets can be lost from vessels (a) where they can act as hazards to navigation (b), and result in impacts to wildlife (c) and benthic habitats (d). These nets can either sink (d) or wash ashore along the Gulf where they are removed (e) with data collected (f). Map includes the ports where fisher interviews were conducted (g) (Australia: Darwin and Karumba; Indonesia: Ambon, Benjina, Dobo and Merauke).

organisation Ghost Nets Australia (GNA) and its partners have removed more than 14,000 ghost nets along the Gulf's more than 3500 km of coastline, extending from the Torres Strait in the Northeast to the Arafura Sea in the Northwest (Fig. 1, e and f) [16]. The work of these stakeholders has been invaluable in informing and mitigating the impacts of the ghost net issue. However, long-term, sustainable solutions require an understanding of the causes and underlying drivers of net loss that can inform solutions designed to reduce gear loss at its source.

This paper identifies the chain of events that lead to fishing net loss. To identify these events, structured interviews were carried out with Australian and Indonesian fishers who are active in trawl, gill net and purse seine fisheries in the region. The overall goal was to develop a tool that could be used to identify strategic management responses and reduce future gear loss. This paper addresses four main questions: 1) what are the primary causes of gear loss; 2) what are the chains of events that ultimately result in gear loss; 3) what, if any, ongoing and past initiatives have been undertaken to address these causes of gear loss; and 4) what additional interventions and measures could be undertaken to further reduce gear loss.

2. Methods

2.1. Interviews

Interviews were undertaken with 54 Australian and Indonesian fishers from two ports in Australia and four ports in Indonesia that use trawl, gill and purse seine nets as their primary gear types (see locations of ports where interviews took place in Fig. 1, g). An oceanic drift model was used to trace the paths of ghost nets found along the shores of the Gulf of Carpentaria northwest to their likely origins of loss or discard in the Indonesian jurisdiction of the Arafura Sea [10]. Previous analyses showed that the bulk of nets recovered along the Gulf's shorelines are likely from Southeast Asia, including largely Indonesian origins [17,18]. Hence, interviews focused on Indonesian and Australian fishers. An investigation into the profiles of Australian and Indonesian fisheries operating in the Arafura Sea-Gulf region was additionally used to determine locations and fisheries for interviews, which is further summarised in Section 2.3.

Interview questions aimed to identify the causes for gear repair/

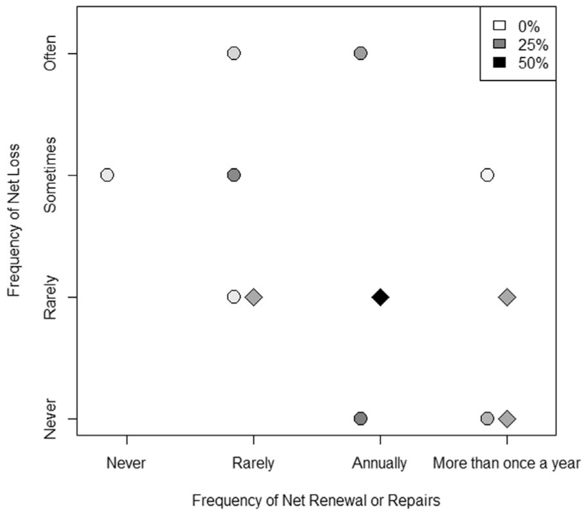

Fig. 2. Frequency of net loss by frequency of net repairs/replacements. ◆ = Australian fishers • = Indonesian fishers.

replacement and loss (Appendix A). Interviews with the Australian fishers were conducted individually, whereas interviews with Indonesian fishers were conducted in small groups at a series of workshops. A summary of responses was presented to participants at a fourth and final workshop in Indonesia. At this workshop, fishers and other attendees used the summarised results to focus discussions around the underlying chains of events that ultimately result in gear loss. Finally, participants identified potential solutions to minimise and manage gear loss.

2.2. The relationship between gear loss and gear maintenance

Following interviews, responses were compiled about the frequency of net loss and frequency of net repair/replacement. Spearman rank correlations were used to determine whether there was a relationship between the frequency of net loss and frequency of net repair/replacement, under the hypothesis that there is a negative relationship between net loss and regular net maintenance.

2.3. The relationship between gear loss and fishing effort

To answer whether there was a relationship between fishing effort and gear loss, data about the number and types of ghost nets removed from the Gulf from 2004 to 2009 were used as a proxy for gear loss and compared against the numbers of active vessels in the region that fished using similar gear [18]. A Pearson's correlation was used to test whether there was a significant relationship between gear loss and fishing effort.

Specific information was unavailable about the numbers of active vessels in the region from different net fisheries. Hence, these numbers were estimated from best available information about net fisheries in the region using multiple sources [15,21–31]. The data used included net type, locations where the nets are used, target species, and the number of active fishing vessels or number of licenses allocated for each fishery. Numbers of licenses were used as a proxy for active vessels for Australian fisheries in the region. The number of licenses allocated for each fishery within Australia's jurisdiction were determined almost entirely from information at the time of the study from the Queensland Government's Department of Agriculture and Fisheries and the Northern Territory Seafood Council, in addition to the interviews with Australian fishers [22,23,27]. The number of active fishing vessels for each fishery within Indonesia's jurisdiction were determined from the four workshops, information provided by Indonesia's Ministry of Maritime Affairs and Fisheries (MMAF), and relevant information from literature related to the study area [15,21,24,26,28–31].

2.4. Fault tree development

Group discussions from interviews with Australian and Indonesian fishers informed the development of a 'fault tree' that summarises the chains of events that ultimately result in gear loss or abandonment at sea. Fault tree analysis is traditionally used as a risk analysis tool for engineering and industrial systems, although it has also been applied to ecological systems [19,20]. Fault trees employ a top-down methodology to graphically represent the occurrence of all parallel and sequential events that result in some end event of interest [19,20]. This study modifies the traditional fault tree methodology to communicate the wide range of causes of fishing gear loss identified in the interviews with fishers, and show how these events influence one another to result in derelict fishing gear.

Common fault tree terminology was used, and 'Derelict fishing gear' was identified as the tree's 'top-event', which is defined as the 'primary undesired event of interest' [20]. Moving top-down, the interviews with fishers and stakeholders at the fourth Indonesian workshop informed identification of the 'intermediate events' which both ultimately result in the top-event and are 'caused by more primary level events described below' [20]. In this way, the 'tree' was developed in a downward direction, growing various levels of 'branches' as all parallel and sequential events were identified. Each branch of the tree ended in some 'basic initiating event' which were also identified by fishers and workshop participants, and which indicate that the causal flow 'does not need to be developed further' [20].

3. Results

3.1. Interviews with fishers

When fishers were asked about the frequency of net repair/replacement, most Australian fishers reported repairing/replacing their nets at a minimum of annually, with fewer Australian fishers reporting they undertook net repairs a few times a year. Australian fishers also reported that they rarely to never lost nets (Fig. 2). Results of the Spearman correlation indicated that there was no significant association between the frequency of net repair/replacement and net loss for Australian fishers ($r_s(4) = -0.57$, $p = 0.242$).

In contrast, Indonesian fishers reported repairing or replacing their nets much less frequently than did Australian fishers. They also reported more frequent net loss (Fig. 2). This was especially the case for Indonesian gill net fishers, most of whom reported rarely replacing nets (74%), with the majority of their nets lost sometimes (41%) or often (35%).

Results of the Spearman correlation indicated that there was a significant negative association between frequency of Indonesian net repair/replacement and net loss ($r_s(46) = -0.45$, $p = 0.001$). Results of the Spearman correlation for all fishers combined indicated a significant negative association between frequency of net repair/replacement and net loss ($r_s(52) = -0.50$, $p < 0.001$).

Australian fishers reported replacing nets more often because they were worn out (67%) compared to damaged (33%). Conversely, more Indonesian fishers replaced nets because of net damage (67%) compared to net wear (27%) or net loss (6%).

All fishers across all fisheries reported taking damaged nets to port frequently to fix the damaged nets. However, one third of Indonesian trawl fishers and 12% of Indonesian gillnet fishers reported that if net damage was too severe and repairs were not possible, they discard unusable nets overboard. Almost half (48%) of Indonesian trawl fishers reported that if the net damage is too great to repair, they use the good parts of the net as patch material for future repairs. In contrast, Australian fishers did not report discarding nets overboard, nor did Australian fishers report using net materials for repairs.

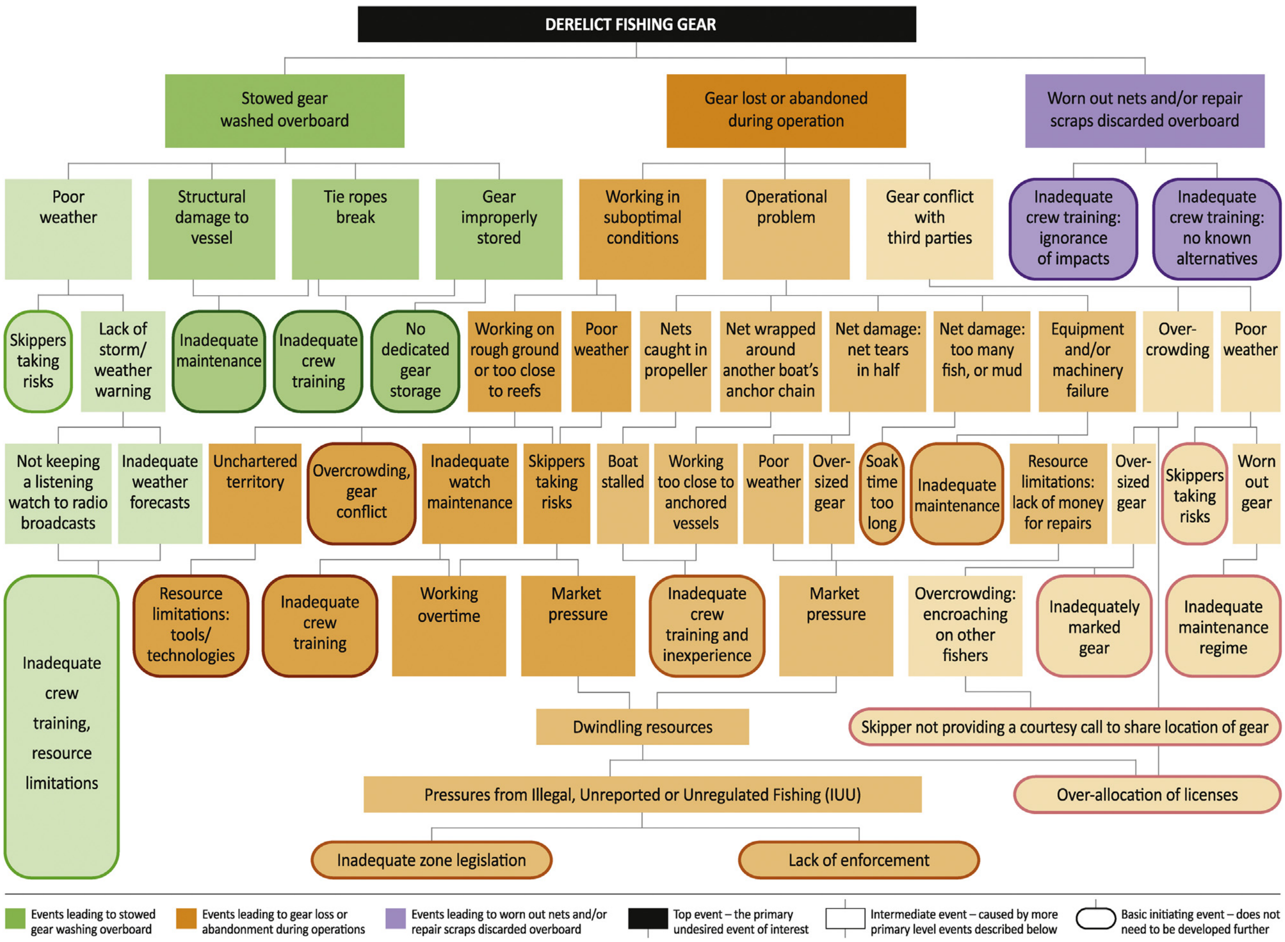

Fig. 3. Fault tree identifying the causes of derelict fishing gear from trawl, gillnet and purse seine vessels. Fault tree symbols and descriptions modified from Acosta and Forrest [20]. Colours are designed to help the reader differentiate between different tree 'branches' to better follow the overall causal flow. Shades of green denote events that ultimately result in stowed gear washed overboard, shades of orange denote events that ultimately result in gear lost or abandoned during operations, and purple denotes events that result in worn out nets and/or repair scraps discarded overboard. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Interviews from all fishers across all gear types revealed that gear loss occurred mostly as a result of snagging on an obstruction (78%), followed by gear conflicts with third parties (19%), and poor weather conditions (2%). All Australian trawl, gillnet and purse seine fishers and all Indonesian trawl fishers reported 'snagging on an obstruction' as the only cause of net loss. In contrast, while 'snagging on an obstruction' was a common cause of net loss for Indonesia's gillnet (41%) and purse seine fishers (79%), these fishers also cited gear conflict with trawl vessels as another common cause for gear loss (47% and 21%, respectively). Losing gear because of storms and bad weather was reported by 12% of Indonesian gillnet fishers.

Following identification of the primary causes of net loss, the fault tree reveals the chain of events that ultimately lead to fishing gear loss (Fig. 3). The primary causes of gear loss (snagging on an obstruction, gear conflict and poor weather) are included in the upper 'branches' of the tree, starting on the third branch down from the top event (Derelict Fishing Gear). Snagging on an obstruction was identified by fishers to result from 'working in suboptimal conditions' and 'working on rough ground or too close to reefs'. This primary cause was not specified in the tree, however, as fishers felt other events better described causes of gear loss (Fig. 3). Some of the most common causes for net loss identified by fishers included poor weather conditions; poor equipment and/or vessel maintenance; inadequate crew education and training; overcrowding and skippers taking risks (Fig. 3). As intermediate events were further identified in the fault tree, other events identified as contributing to eventual gear loss included inadequate to no gear marking or identification; lack of access to or training in tools and technologies such as navigation equipment and weather forecasts; and market pressures (Fig. 3).

Respondents ultimately identified the over-allocation of licenses, inadequate zone legislation and lack of enforcement as the 'basic initiating events' of gear loss in the region (Fig. 3). Respondents further emphasized the combination of pressures from IUU (which result from the initiating events inadequate zone legislation and lack of enforcement) and over-allocation of licenses as the two key underlying drivers behind the chain of events that result in derelict fishing gear (Fig. 3). According to participants, both pressures from IUU and the legal over-allocation of licenses result in dwindling fisheries resources and reduced catches. This, in turn, increases market pressures on fishers to increase their own effort to produce the same amount of catch. Moving up the fault tree, these market pressures can drive fishers to work overtime and skippers to take risks by fishing in suboptimal conditions. Suboptimal conditions can include working in poor weather conditions or snagging nets on an obstruction while working on rough ground or too close to reefs, both of which can result in net loss (Fig. 3). The over-allocation of legal fishing licenses was also recognised by fishers to result in overcrowding, increased competition and gear conflicts, which result in gear loss or discard (Fig. 3).

3.2. The relationship between gear loss and fishing effort

The investigation into the active net fisheries in the Arafura Sea-Gulf of Carpentaria region revealed a conservative estimate of 973 net fishing vessels operating across 17 fishing sectors in the Arafura Sea-

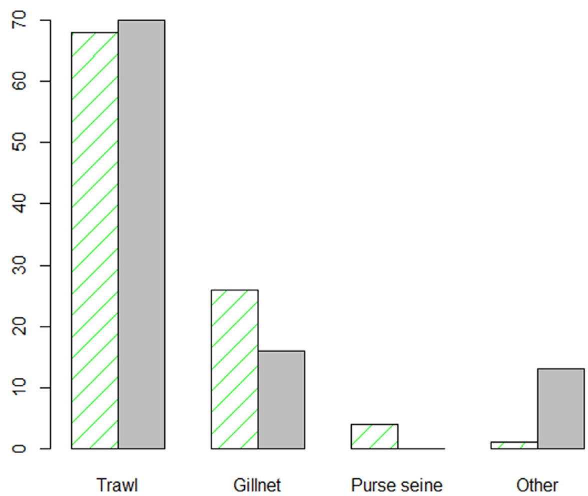

Fig. 4. Percentages of Active Vessels and Ghost Nets by Fishing Sector. Legend: Green, hashed bars indicate active vessels; grey, solid bars indicate ghost nets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Gulf region, as of 2013 (comprised of 198 Australian licenses and 775 active Indonesian vessels) (Appendix B). Trawl vessels comprised the greatest number of active vessels in the region (68%), followed by vessels that use gill nets (26%), purse seine nets (4%) and a mixture of 'other' nets (2%) (Appendix B).

A comparison between the percentage of vessels that operate different types of net gear in the Arafura Sea-Gulf region and GNA's ghost net retrieval data revealed a correlation between the high percentage of active trawl (68%) and gill net (26%) fishing vessels and the percentage of ghost nets attributed to these vessels (70% and 17%, respectively) [18], (Fig. 4). Using ghost net retrieval data from the region as a proxy for gear loss there, a significant positive association between fishing effort and gear loss ($r(2) = 0.96$, $p = 0.044$) was detected [18].

4. Discussion

To effectively address the full chain of events that result in fishing gear loss, there is a critical need to reduce the key underlying drivers of gear loss. Using a fault tree developed by fishers and on-ground managers from multiple jurisdictions, it is clear that both the over-allocation of legal fishing licenses and IUU fishing initiate a chain of events that ultimately results in derelict fishing gear (Fig. 3). The over-allocation of licenses to vessels operating legally and the presence of vessels operating illegally (IUU fishing) can result in increased levels of fishing effort. The relationship observed between ghost nets and fishing effort clearly shows that gear loss is proportional to fishing effort. Hence, a logical step might be to suggest strategies to limit fishing effort, given that this directly result in fewer net losses. However, the estimated number of active net fishing vessels in the region is conservative, as it does not include small-scale commercial and artisanal vessels, vessels that operate across multiple fisheries, or the presence of illegal fishing vessels, given limited to no available data for these sectors.

Fisher interviews and the fault tree additionally revealed that too much fishing effort, from illegal or legal fishing concentrated in a given location can result in overcrowding. Overcrowding can often drive vessels to fish riskier grounds that they would not otherwise fish, risking damage to or loss of gear via snagging on an obstruction (as noted by 78% of interviewees). Overcrowding can also result in gear conflict between vessels, particularly between trawl and gillnet vessels, which was the second most common reason reported for gear loss (19%). This most commonly occurs when trawl vessels run over static gill nets in the course of their operations, resulting in damage to the gillnets and loss of net pieces to the surrounding marine environment (Fig. 3).

The significant increase in numbers of industrial and foreign fishing vessels (FFVs) in Indonesia over the last few decades further exacerbates pressures from the over-allocation of licenses. As noted, such over-allocation results in high levels of fishing effort, overcrowding and gear conflict [13]. Historical catch reconstructions showed an almost threefold increase in the number of fishing vessels from 1997 to 2007 in the Arafura-Timor Sea part of Indonesia's EEZ [13,32]. Between 1980 and 2015, the Arafura Sea was also the only area of Indonesia where trawl fishing was allowed, following a ban in 1980 on the practice elsewhere [28,29]. This resulted in a greater concentration of both Indonesian and foreign trawl vessels concentrating their effort in this shared sea [15,33]. In 2015 however, Indonesia enacted the Ministerial Degree of the Ministry of Marine Affairs and Fisheries No. 2/PERMEN-KP/2015 on the Prohibition of the Usage of Trawl and Seine Nets in Indonesia Fishery Management Area, which will ban all trawl fishing countrywide beginning in 2018, including in the Arafura Sea [34,35]. This ban is expected to follow the current transition period, which is designed to allow fishers time to change their nets and associated gear types to more sustainable ones in the interim [36]. Given the correlation between fishing effort and gear loss, and the identification of gear conflict between trawl and gillnet vessels as an important event that leads to gear loss, this ban could significantly reduce the number of lost trawl nets in the region.

4.1. Effectiveness of national, bilateral and regional efforts

On a national level, in addition to the ghost net removal and associated data collection, Australia has been active across its fishing and security sectors in working to reduce the amounts of derelict fishing nets in the Arafura Sea-Gulf region, and to combat IUU nationally and regionally. Australia's Northern Prawn Fishery (NPF), for example, has shown leadership by incorporating fisheries management measures that have successfully led to reductions in derelict fishing gear. The NPF is Australia's largest prawn fishery, and uses trawl gear to target prawns [37]. In the 1990s a significant amount of ghost gear could be traced back to Australian trawl vessels in the Gulf. For example, surveys in Groote Eylandt in 1997 traced 34% of ghost nets back to Australian trawl fisheries [38]. In response to fisheries management challenges, including large amounts of derelict gear, the NPF implemented a series of spatial and temporal fisheries closures, restrictions on certain gear types, requirements for vessel monitoring systems, improvements in waste management practices including education among fishing vessel crews, and, most significantly, a seven-fold reduction in the overall NPF fleet [39–42]. Following these reforms, a decrease in ghost nets was observed across the Gulf. For instance, follow up surveys on Groote Eylandt in 2002 traced less than 7% of the ghost gear back to Australian trawl vessels [42].

The Australian Border Force, Australian Defence Force and the Australian Fisheries Management Authority (AFMA) have also shown national collaborative leadership across sectors in their work to recover ghost nets at sea and return entangled animals, such as endangered Hawksbill sea turtles, to the marine environment [43,44]. In 2016 these three agencies worked together to intercept at sea and coordinate the removal of 7 ghost nets weighing almost 30 combined tonnes from the Arafura and Timor Seas and the Torres Strait [43]. AFMA additionally works with local Indigenous communities to repurpose some of the ghost gear into educational art pieces [43]. Upstream, Australia works to combat IUU fishing, a key event that leads to gear loss identified in the fault tree (Fig. 3), through its ambitious National Plan of Action to Prevent, Deter and Eliminate IUU-Fishing (NPOA-IUU) [45].

Particularly since 2015, Indonesia has also shown leadership in taking steps to combat IUU fishing in its EEZ. The country has been extremely effective in addressing a key driver of fishing gear loss. Measures by Indonesia to combat IUU fishing include developing a National Plan of Action to Prevent, Deter and Eliminate IUU Fishing

(NPOA-IUU); the establishment of a task force to prevent and deter IUU fishing; a moratorium on ‘ex-foreign fishing vessels’ (fishing vessels built abroad); a ban on transhipment; a ban on seine nets and trawl nets; compliance audits on more than a thousand foreign fishing vessels; the publicly advertised sinking of hundreds of illegal fishing vessels; and the strengthening of enforcement measures including improvements in cross-agency coordination [34,35,46]. Indonesia also developed a “roadmap to improve governance in fisheries business” that further outlines improvements in vessel registration systems, port state controls, fisheries license governance, surveillance systems, and regional and international collaborations [46].

Understanding the transboundary nature of this complex issue, Australia and Indonesia are working together to address IUU fishing. In 2001, both countries started the Working Group on Marine Affairs and Fisheries, which operates under the bilateral 1992 Fisheries Cooperation Agreement and meets annually to collaborate on regional environmental and fisheries issues in the Arafura Timor Seas [47]. The key focus of the Working Group is to deter and eliminate IUU fishing in the region, with agreement by members to also enhance regional fisheries management, training and development, and cooperation for environmental issues [47]. In 2015, both countries further committed to joint efforts to combat IUU through a joint communique of cooperation on IUU. Furthermore, the countries entered the bilateral Civil Maritime Enforcement and Security Partnership, which provides a framework for engagement and improvements in information sharing, operational cooperation and capacity development in training, planning and communications [48,49].

With large numbers of foreign fishing vessels from neighbouring Southeast Asian countries actively fishing (and losing gear) in the Arafura Sea, efforts to address the underlying causes of gear loss in the region will need to adopt a regional focus. In 2007, 11 countries[1] came together to create the Regional Plan of Action to Promote Responsible Fishing Practices including Combating Illegal, Unreported and Unregulated Fishing in the Region (RPOA-IUU) [50]. The RPOA-IUU works to enhance and strengthen regional fisheries management in Southeast Asia, provide sustainable fisheries and environmental resources, supports responsible fishing practices, and manages fishing capacity and combats IUU [50]. The RPOA-IUU also includes a subregional group focused on monitoring, control and surveillance specifically for the Arafura-Timor Seas (ATS) [50]. Despite the impressive aims and organisation of the RPOA-IUU, a recent study highlighted the need for greater engagement by the RPOA-IUU with the commercial fisheries sector [51]. The same study noted the opportunity for capacity building efforts to be undertaken by the private sector given a relatively well-established and organised national and sub-national set of commercial fisheries associations [51]. Overall, the RPOA-IUU is a good example of and foundation for regional collaboration that addresses the underlying drivers of gear loss identified in the fault tree (Fig. 3).

4.2. Additional efforts to improve fisheries management and minimise gear loss

In addition to IUU fishing, it is important to consider socioeconomic and development issues around food security, poverty and population growth as drivers of gear loss into the marine environment [13]. Overall, fishers in the Indonesian workshops related human and technological capacity shortcomings to the low profitability of the fisheries in the region, which in turn is driven by overcapacity and the resulting overfishing. When vessels are not making significant financial returns, it is difficult to maintain high-functioning, well-trained crew and quality ship systems.

There is a strong negative relationship between net repair/replacement and net loss. This suggests that regular gear maintenance will result in less net damage and loss. Snagging on an obstruction, for example, was identified as the most common cause of net loss. This relationship suggests that better maintained nets are less likely to fail and be lost when they encounter an obstruction compared to poorly maintained, worn out nets, because of being stronger and more resilient to damage. This is demonstrated in responses by fishers in Australia and Indonesia. Most Australian fishers reported repairing or replacing their nets proactively (e.g. in response to net wear (67%)). In contrast, Indonesian fishers reported repairing/replacing nets retroactively (e.g. in response to net damage (67%)). This could be driven by economics: there is more fishing competition in Indonesia where more vessels operate than in the highly regulated prawn fishery in northern Australia. Hence, financial costs and repair time may be driving different responses between fishers in the two countries. This contrast suggests an opportunity for interventions to support investment in programs and incentives that promote gear maintenance in low socioeconomic and developing fisheries, and help offset potentially prohibitive costs associated with regular gear maintenance.

Fishers and on-ground managers in the region also used events identified in the fault tree to inform workshop discussions around recommendations for improvements in fisheries management to reduce the likelihood of gear loss. These recommendations included requirements for vessel maintenance including regular vessel inspections, and requirements for and improvements in fishing gear marking. Fishers further emphasized the importance of education, awareness raising and capacity building among fishing vessel crews regarding best practices for proper gear management and disposal, with all materials and outreach provided in the local language on the vessels such as Bahasa or Thai. Education, awareness raising and capacity building measures also include supporting training in and access to tools and technologies that can help to minimise the risk of gear loss, such as on-board navigation equipment and weather forecasts for fishing vessels, operators and crewmembers. All of these measures require an engaged fisheries management authority with dedicated human and financial resources to oversee and carry out such initiatives.

5. Conclusions

Interviews with Australian and Indonesian fishers from the Arafura Sea-Gulf region revealed that causes of fishing gear loss ultimately arise from fisheries management challenges. While fishers identified the primary causes of net loss to be snagging on an obstruction (78%) and gear conflicts (19%), the fault tree analysis revealed that all of these causes result from chains of underlying events. The fault tree analysis revealed that the over-allocation of fishing licenses and IUU fishing pressures lead to overcrowding, overcapacity, increased competition and risk-taking behaviours by skippers and crews. This results in fishing net damage, discard and loss. Effective, long term, sustainable solutions to the ghost net issue need to address the full chain of events that lead to gear loss. Improvements in national and regional fisheries management that focus on strategic reductions in overall fishing effort, improvements in spatial management measures, continued efforts to combat IUU fishing, and regular gear and vessel maintenance designed to prevent net loss at source will all reduce gear loss. Furthermore, capacity-building measures for crews that include education and awareness raising and improved access to on-board tools and technologies that can minimise gear loss will see further reductions in derelict fishing gear. These recommendations apply both specifically to the Arafura Sea-Gulf region examined in this study, and to other regions facing similar fisheries management challenges and gear loss. The reduction of derelict fishing gear requires cross-collaboration between stakeholders. Key stakeholders will undoubtedly include non-profit organisations and local communities working to mitigate the fate and impacts of nets; collaboration between government agencies to intercept and recover nets at sea; and national and regional fisheries

[1] Australia, Brunei Darussalam, Cambodia, Indonesia, Malaysia, Papua New Guinea, Philippines, Singapore, Thailand, Timor-Leste and Vietnam [50].

management authorities working together to reduce the loss of nets at the source.

Conflicts of interest

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2018.02.021.

References

[1] G. Macfadyen, T. Huntington, R. Cappell, Abandoned, lost or otherwise discarded fishing gear. UNEP Regional Seas Reports and Studies No. 185; FAO Fisheries and Aquaculture Technical Paper, No. 523. Rome, UNEP/FAO, 2009.
[2] J. Brown, G. Macfadyen, T. Huntington, J. Magnus, J. Tumilty, Ghost Fishing by Lost Fishing Gear. Final Report to DG Fisheries and Maritime Affairs of the European Commission. Fish/2004/20. Institute for European Environmental Policy / Poseidon Aquatic Resource Management Ltd joint report, 2005.
[3] M.N. Santos, H. Saldanha, M.B. Gaspar, C.C. Monteiro, Causes and rates of net loss off the Algarve (southern Portugal), Fish. Res. 64 (2) (2003) 115–118.
[4] M. Stelfox, J. Hudgins, M. Sweet, A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs, Mar. Pollut. Bull. 111 (1) (2016) 6–17.
[5] D.W. Laist, T. Wray, Marine debris entanglement and ghost fishing: a cryptic and significant type of bycatch. Solving Bycatch: Considerations for Today and Tomorrow, University of Alaska, 1995.
[6] T. Matsuoka, T. Nakashima, N. Nagasawa, A review of ghost fishing: scientific approaches to evaluation and solutions, Fish. Sci. 71 (4) (2005) 691–702.
[7] J.R. Butler, R. Gunn, H.L. Berry, G.A. Wagey, B.D. Hardesty, C. Wilcox, A value chain analysis of ghost nets in the Arafura Sea: identifying trans-boundary stakeholders, intervention points and livelihood trade-offs, J. Environ. Manag. 123 (2013) 14–25.
[8] D. White, Marine Debris in Northern Territory Waters). WWF Australia, WWF-Australia, Sydney, 2006.
[9] C. Wilcox, G. Heathcote, J. Goldberg, R. Gunn, D. Peel, B.D. Hardesty, Understanding the sources and effects of abandoned, lost, and discarded fishing gear on marine turtles in northern Australia, Conserv. Biol. 29 (1) (2014) 198–206.
[10] C. Wilcox, B.D. Hardesty, R. Sharples, D.A. Griffin, T.J. Lawson, R. Gunn, Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia, Conserv. Lett. 6 (4) (2012) 247–254.
[11] R. Gunn, B.D. Hardesty, J. Butler, Tackling 'ghost nets': local solutions to a global issue in northern Australia, Ecol. Manag. Restor. 11 (2) (2010) 88–98.
[12] I. Kiessling, Finding Solutions: Derelict Fishing Gear and other Marine Debris in Northern Australia, Report prepared for the National Oceans Office by the Key Centre for Tropical Wildlife Management, Charles Darwin University, Darwin, 2003.
[13] K.S. Edyvane, S.S. Penny, Trends in derelict fishing nets and fishing activity in northern Australia: implications for trans-boundary fisheries management in the shared Arafura and Timor Seas, Fish. Res. 188 (2017) 23–37.
[14] N. Stacey, S. Nurhakim, D. Nugroho, H. Soselisa, B. Resosudarmo, O. Kalis, J. Monteiro, J. Prescott, J. Martin, J. Karim, Socio-economic profile of the Arafura and Timor Seas. Report of the Transboundary Diagnostic Component of the Arafura Timor Seas Ecosystem Action Program. Jakarta, 2011.
[15] N. Af-idati, S.G. Lee, Management measures of shrimp trawling fishery in Arafura Sea, Indonesia: a challenge, J. Coast. Dev. 12 (2) (2011) 56–63.
[16] GhostNets Australia. Who We Are. (Accessed 1 June 2017) from 〈http://www.ghostnets.com.au/about/who-we-are/〉.
[17] J. Goldberg, G. Heathcote, R. Gunn, S. Morrison, Summary Report 2010-2012, GhostNets Australia, Cairns, 2013.
[18] G. Heathcote, R. Gunn, J. Goldberg, L. Hamblin, S. Morrison, Summary Report 2004-2009, GhostNets Australia, Darwin, 2011.
[19] K.R. Hayes, Identifying hazards in complex ecological systems. Part 1: fault-tree analysis for biological invasions, Biol. Invasions 4 (3) (2002) 235–249.
[20] H. Acosta, B.M. Forrest, The spread of marine non-indigenous species via recreational boating: a conceptual model for risk assessment based on fault tree analysis, Ecol. Model. 220 (13–14) (2009) 1586–1598.
[21] Pak. Isworo, November). Fisheries statistician for Indonesia's Ministry of Maritime Affairs and Fisheries (MMAF). Who is Fishing in ATS? Lecture presented at the Merauke Workshop on Fisheries Gear, Merauke, Indonesia, 2012.
[22] The State of Queensland (Department of Agriculture and Fisheries) Queensland Government, (2010–2017). Department of Agriculture and Fisheries. (Accessed 15 August 2012) from 〈https://www.daf.qld.gov.au/〉, 2012.
[23] Northern Territory Seafood Council. Northern Territory Seafood Council. (Accessed 15 August 2012) from 〈www.ntsc.com.au〉.
[24] Budy P. Resosudarmo, Lydia Napitupulu, David Campbell, Illegal fishing in the Arafura Sea, in: Budy P. Resosudarmo, Frank Jotza (Eds.), Working with Nature against Poverty: Development, Resources and the Environment in Eastern Indonesia, Institute of Southeast Asian Studies, Singapore, 2009, pp. 178–200.
[25] Riki Gunn, Dobo Ghostnets Workshop 2 May 2013. Dobo, Aru Islands, Indonesia, 2013.
[26] G.R. Morgan, D.J. Staples, The History of Industrial Marine Fisheries in Southeast Asia, RAP PUBLICATION 2006/12 Food and Agriculture Organization of the United Nations Regional Office for Asia and the Pacific, Bangkok, 2006, p. 2006.
[27] Biagio Spinella, November), Skipper and owner of Northern Territory (NT) fishing vessel in NT Offshore Net and Line fishery. Personal interview with R. Gunn, 2011.
[28] W. Sokimi, S. Beverly, Small-scale Fishing Techniques using Light: a Manual for Fishermen Noumea, Secretariat of the Pacific Community, New Caledonia, 2010, p. ix (54 p).
[29] C. Bailey, A. Dwiponggo, F. Marahudin, Indonesian Marine Capture Fisheries ICLARM Studies & Review 10, 196p International Centre for Living Aquatic Resources Management, Manila, Philippines; Directorate General of Freshwater and Marine Fisheries Research Institute, Ministry of Agriculture Jakarta Indonesia ISBN 971-1022-30-3, 1987.
[30] G.A. Wagey, S. Nurhakim, V.P.H. Nikijuluw, T.J. Badrudin Pitcher, A study of Illegal, Unreported and Unregulated Fishing in the Arafura Sea, Indonesia Research Centre for Capture Fisheries, Agency for Marine and Fisheries Research Ministry of Marine Affairs and Fisheries, Jakarta Indonesia 2009, 2009.
[31] G.K. Yearsley, P.R. Last, R.D. Ward, Australian Seafood Handbook: An Identification Guide to Imported Species, CSIRO Marine Research and Fisheries Research and Development Corporation, Australia, 2003, p. 2003 (ISBN 1 876996 31 5).
[32] V. Budimartono, M. Badrudin, E. Divovich, D. Pauly. A reconstruction of marine fisheries catches of Indonesia, with emphasis on Central and Eastern Indonesia, 1950–2010. Pp. 2–26 in D. Pauly, V. Budimartono (eds.) Marine Fisheries Catches of Western, Central and Eastern Indonesia, 1950–2010. Fisheries Centre Working Paper #2015-61, 2015.
[33] R. Gillett, Global study of shrimp fisheries. Food and Agriculture Organization of the United Nations Rome, 2008 FAO Fisheries Technical Paper 475, 2008.
[34] WWF, 27 February). Blowing up the bad guys: Will Indonesia's new fisheries laws deliver? (Accessed 2 October 2017) from 〈http://wwf.panda.org/?240152/Blowing-up-the-bad-guys-〉.
[35] International Organization for Migration (IOM), Report on Human Trafficking, Forced Labour and Fisheries Crime in the Indonesian Fishing Industry. (Accessed 24 October 2017) from 〈https://www.iom.int/sites/default/files/country/docs/indonesia/Human-Trafficking-Forced-Labour-and-Fisheries-Crime-in-the-Indonesian-Fishing-Industry-IOM.pdf〉, 2016.
[36] The Jakarta Post, 3 May). Jokowi tells minister to extend use of fishing trawlers. (Accessed 3 October 2017) from 〈http://www.thejakartapost.com/news/2017/05/03/jokowi-tells-minister-to-extend-use-of-fishing-trawlers.html〉.
[37] NPF Industry Ltd. The Northern Prawn Fishery Industry Sustainability, Innovation, Excellence. (Accessed 22 January 2017) from 〈http://npfindustry.com.au/〉.
[38] S. Sloan, B. Wallner, R. Mounsey, Fishing Debris around Groote Eylandt in the Western Gulf of Carpentaria. A Report on the fishing gear debris project 1998 for the Northern Prawn Fishery Management Advisory Committee (NORMAC), 1998.
[39] AFMA, (ed & rev), Northern Prawn Fishery Operational Information Booklet 2014, Australian Fisheries Management Authority. Canberra, Australia. Published by the Australian Fisheries Management Authority (AFMA), 2014.
[40] DPIE, New Direction for Commonwealth Fisheries management in the 1990s: a Government Policy Statement 1989, Australian Government Publishing Service Canberra, 1989 (ISBN 0 644 J 1268 9).
[41] P.C. Pownall, Australia's Northern Prawn Fishery the first 25 years NPF25, Cleveland Australia CSIRO Publication, 1994 (ISBN: 0 646 172581).
[42] D. White, Marine Debris in Northern Territory Waters 2002. WWF Report, WWF Australia, Sydney, 2003.
[43] Australian Fisheries Management Authority, 5 November). Ghost net removal saves marine life. (Accessed 1 June 2017) from 〈http://www.afma.gov.au/ghost-net-removal-saves-marine-wildlife/〉.
[44] Australian Fisheries Management Authority, 22 May). Who ya gonna call. (Accessed 1 June 2017) from 〈http://www.afma.gov.au/ya-gonna-call/〉.
[45] Department of Agriculture, Australia's Second National Plan of Action to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing. CC BY3.0, 2014.
[46] M.A. Santosa, 11 November). Strategy on the Prevention and Eradication of IUU Fishing and Post-Moratorium Policies. (Accessed 1 June 2017) from 〈http://fisheriestransparency.org/wp-content/uploads/2015/11/Presentation_Combating_IUUF_Efforts_in_Indonesia_20151109.pdf〉.
[47] Commonwealth of Australia, June 7). Indonesia – Australia Fisheries Cooperation. (Accessed 1 June 2017) from 〈http://www.agriculture.gov.au/fisheries/international/cooperation/indonesia〉.
[48] Commonwealth of Australia, 7 October). Indonesia-Australia strengthen partnership to combat illegal fishing. (Accessed 1 June 2017) from 〈http://minister.agriculture.gov.au/joyce/pages/media-releases/indo-aus-partnership-to-combat-illegal-fishing.aspx〉.
[49] Australian Government Department of Immigration and Border Protection, October 1). Australia and Indonesia agree to new civil maritime security partnership. (Accessed 1 June 2017) from 〈http://newsroom.border.gov.au/releases/australia-and-indonesia-agree-to-new-civil-maritime-security-partnership〉.
[50] RPOA-IUU. RPOA-IUU. (Accessed 1 June 2017) from 〈http://www.rpoaiuu.org/〉.
[51] R. Pomeroy, J. Parks, K. Courtney, N. Mattich, Improving marine fisheries management in Southeast Asia: results of a regional fisheries stakeholder analysis, Mar. Policy 65 (2016) 20–29.