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MODELING DRIFTING FISH AGGREGATING DEVICES (FADS) TRAJECTORIES ARRIVING AT ESSENTIAL OCEANIC AND COASTAL HABITATS FOR LEATHERBACK AND HAWKSBILL TURTLES IN THE PACIFIC OCEAN

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SUMMARY

Purse seine fishers using drifting Fish Aggregating Devices (dFADs) to aggregate and catch tropical tuna, deploy an estimated 46,000 to 65,000 dFADs per year in the Pacific Ocean. Major problems associated with this widespread fishing device are i) the potential entanglement of vulnerable marine fauna in dFAD netting and ii) marine pollution, with potential ecological damage via stranding on coral reefs, beaches, and other essential habitats. To explore and quantify the potential connectivity between dFAD deployment areas and important oceanic or coastal critically endangered leatherback (*Dermochelys coriacea*) and hawksbill (*Eretmochelys imbricata*) sea turtle habitats in the Pacific Ocean, we conducted passive-drift Lagrangian experiments using simulated dFAD drift profiles. Some connectivity between equatorial areas of dFAD deployments and essential sea turtle habitats was identified, although it was reduced when considering only areas where dFADs are currently deployed. Potential at-risk hotspots of dFAD interaction with sea turtle habitats are i) the migration and leatherback feeding habitats in the tropical southeastern Pacific Ocean; ii) leatherback and hawskbill coastal habitats in the western Pacific (Indonesia, Papua New Guinea, and the Solomon Islands); iii) a large equatorial area south of Hawai'i, important for leatherback turtle foraging. Additional research is needed to better understand the entanglements of sea turtles with dFADs at sea and to quantify the likely changes in connectivity and distribution of dFADs under new management measures, such as using alternative dFAD designs that degrade, or changes in deployment strategy.

RESUMEN

Pescadores de cerco empleando plantados o dispositivos concentradores de peces (DCPs) para agregar y capturar atún tropical, siembran según estimas entre 46,000 y 65,000 plantados al año en el Océano Pacífico. Problemas importantes asociados con el uso generalizado de estos plantados son i) el potencial enmalle de fauna marina vulnerable en la red del DCP y ii) polución marina, con potenciales daños ecológicos por varamiento en arrecifes de coral, playas, y otros hábitats esenciales. Para explorar y cuantificar la potencial conectividad entre zonas de plantado de DCPs e importantes hábitats de tortugas marinas en estado de peligro como la tortuga laud (*Dermochelys coriacea*) y la tortuga carey (*Eretmochelys imbricata*) en el Océano Pacifico, realizamos experimentos de deriva pasiva Lagrangiana empleando perfiles de derivas de DCPs simuladas. Alguna conectividad entre zonas ecuatoriales de plantado de DCPs y hábitats esenciales de tortugas marianes fue identificado, aunque esta se reducía cuando solo se tenían en cuenta áreas donde los DCPs son plantados en la actualidad. Potenciales zonas calientes de riesgo de interacción de DCPs con hábitats de tortugas marinas son i) los hábitats de migración y alimentación de la tortuga laud en sudeste tropical del Océano Pacífico; ii) hábitats costeros de la tortuga laud y carey en el Pacífico Occidental (Indonesia, Papua Nueva Guinea, y las Islas Salomon), iii) una amplia zona ecuatorial al sur de Hawaii, importante para la alimentación de la tortuga laud. Investigación adicional es necesaria para comprender mejor los enmalles de tortugas marinas en DCPs y cuantificar las posibilidades de conexión y distribución de DCPs bajo nuevas medidas de regulación, tales como el empleo de diseños alternativos de DCPs que se degradan, o cambios en las estrategias de plantado.

INTRODUCTION

Purse seine fishers extensively deploy drifting Fish Aggregating Devices (dFADs) to aggregate and catch tropical tuna, with 46,000 to 65,000 FADs deployed in the Pacific Ocean annually, and 16,000–25,000 dFADs in the eastern Pacific Ocean (EPO) only, according to the latest estimations. The main concerns related to the loss and abandonment of dFAD structures are i) marine pollution; ii) the potential risk of entanglement of sea turtles and other vulnerable marine fauna in dFAD netting while drifting at sea or when stranded; and iii) the potential impacts on fragile ecosystems via stranding events. Although direct bycatch of sea turtles is relatively low in purse seine fisheries as compared to other gear types (Bourjea *et al.*, 2014; Montero *et al.*, 2016; Swimmer *et al.*, 2020), the proliferation of dFAD use in the fishery is concerning given that the potential dFAD sea turtle entanglement in their netting is unknown. In addition, dFADs stranded in nearshore habitats or along the shoreline could potentially have indirect impacts on critical nesting or coral reef habitats for sea turtles. In this study, we further explore the potential for the dFAD interactions (entanglement and nearshore habitat impacts), focusing on the critically endangered leatherback (*Dermochelys coriacea*) and hawksbill (*Eretmochelys imbricata*).

METHODS

To explore and quantify the potential connectivity between dFAD deployment areas and important oceanic or coastal critically endangered leatherback and hawskbill sea turtle habitats in the Pacific Ocean, we conducted passive-drift Lagrangian experiments using simulated dFAD drift profiles and compared them with known important sea turtle areas (Figure 1).
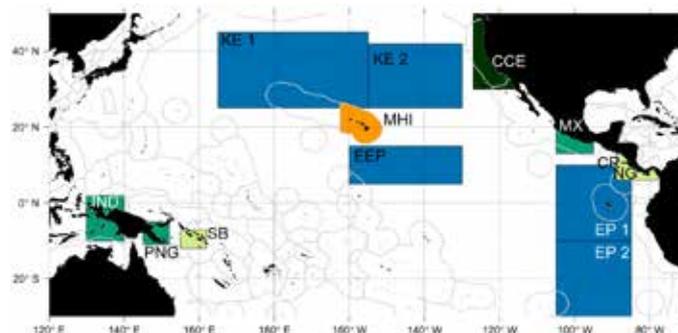
FIGURE 1. Spatial distribution of sea Turtle Zones (TZ) used in the simulations and corresponding to important oceanic areas (blue) for leatherback turtles and coastal areas (green) for leatherback foraging (dark green), leatherback nesting (medium green), hawksbill nesting (orange), and leatherback and hawksbill nesting (light green). KE = Kuroshio Extension; EEP = Equatorial Eastern Pacific; CCE = California Current Ecosystem; IND = Indonesia; PNG = Papua New Guinea; SB = Solomon Islands; MX = Mexico; CR-NG = Costa Rica – Nicaragua; and EP = Eastern Pacific.

Lagrangian simulations were implemented using the Parcels framework (Delandmeter and van Sebille, 2019). Passively drifting Lagrangian particles, representing virtual dFADs (vFADs), were released evenly throughout the tropical, equatorial zone (scenario 1 – Figure 2) and dFAD deployment/ high density hotspot zones (scenario 2 - Figure 2), and forced forwards in time with a dFAD-type drift profile, driven by the top 50m current velocities (median dFAD net depth of 40m in the EPO and 50m in the WCPO (Escalle *et al.*, 2017; Lopez *et al.*, 2020)) from the Bluelink Reanalysis 2020 circulation model (BRAN2020 Chamberlain *et al.*, in review). New particles were seeded weekly during one year and left to drift for up to a further 2.5 years. Particles were seeded beginning July 2012 (ENSO neutral year), July 2010 (a moderate La Niña year), and July 2015 (a strong El Niño year).
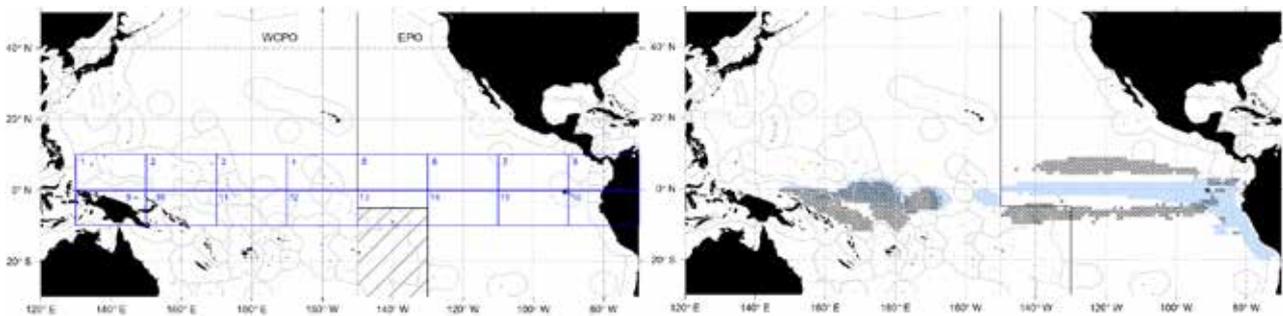

FIGURE 2. Spatial distribution of Equatorial Zones (EZ; left) and dFAD Zones (FZ; rigth) used in the simulation in Scenario 1 and 2, respectively. DFAD zones include main dFAD deployments areas (blue) and main dFAD densities areas (black crosses). The black line indicates the WCPFC and IATTC convention areas, the black dotted line the overlapping area between both convention areas.

Several areas were defined and used in the simulations to study connectivy between dFAD areas of deployment and sea turtles critical habitats. Two types of vFAD deployment zones, were used: i) the entire tropical equatorial zone from 10 °S to 10 °N divided into 16 large boxes of 20° longitude by 10° latitude ("Equatorial Zones" (EZ); Figure 2); and ii) specific hotspot areas where dFAD deployment and high density are known ("dFAD Zones" (FZ); Figure 2). This information was derived from observers and operational buoy data in both the WCPO and EPO (Parties to the Nauru Agreement dFAD tracking database, 2016–2020; IATTC buoy database, 2018–2020 and IATTC observer database, 2016–2020). Cells corresponding to values of density and deployments above the 90th percentile were selected as hotspots for each convention area separately, due to different data types available for each convention area (Figure 2). Second, sea turtle habitat zones ("Turtle Zones" (TZ)) were determined (Figure 1) using maps available within the interactive Ocean Biodiversity Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP) platform; scientific publications and expert opinions (SWOT, 2008; Benson *et al.*, 2011; Bailey *et al.*, 2012; Laúd opo Network, 2020).

RESULTS AND DISCUSSION

Corridors of connectivity between industrial dFAD fishing grounds and zones of important habitats for sea turtles were identified. For dFADs deployed in the EPO, the main areas of concern appear to be the turtle habitats in the south-eastern Pacific Ocean (EP1 and EP2), corresponding to oceanic leatherback turtle migration and feeding grounds (Figures 3 and 4). Moderate accumulation of dFADs was also detected in the equator, coastal and oceanic habitats and nesting sites around Mexico, Costa Rica and Panama. Finally, a large equatorial area, south of Hawai'i, an important leatherback turtle foraging habitat, exhibited large numbers of vFADs transiting when deployed in the equatorial zones north of the equator, from both the EPO and WCPO. In the WCPO, the small coastal sea turtle nesting

habitats in Papua New Guinea (PNG) and the Solomon Islands (SB) consistently received and retained vFADs arriving from the southern equatorial regions of the WCPO (Figure 4). The archipelagic Indonesian (IND) nesting habitat experienced similar high connectivity with vFADs arriving from mostly one region of the WCPO (the southwestern EZ 9), although the relatively low densities in this region suggests that while vFADs reach this region they do not remain there for extended periods. It should be noted that the connectivity patterns detected appear to be somewhat mitigated against by the current deployment distribution of dFADs in the EPO (Scenario 2; Figures 3 and 4). Results for scenario 1 are not shown in the report for simplicity.

Additional research and analyses should be performed i) to better understand at-sea interactions between dFADs and sea turtle populations and potential entanglements; and ii) to quantify the likely changes in connectivity and distribution of dFADs within the equatorial fishing grounds and higher latitude sea turtle habitats, under proposed non-entangling and biodegradable dFAD measures or changes in dFAD deployment strategies.
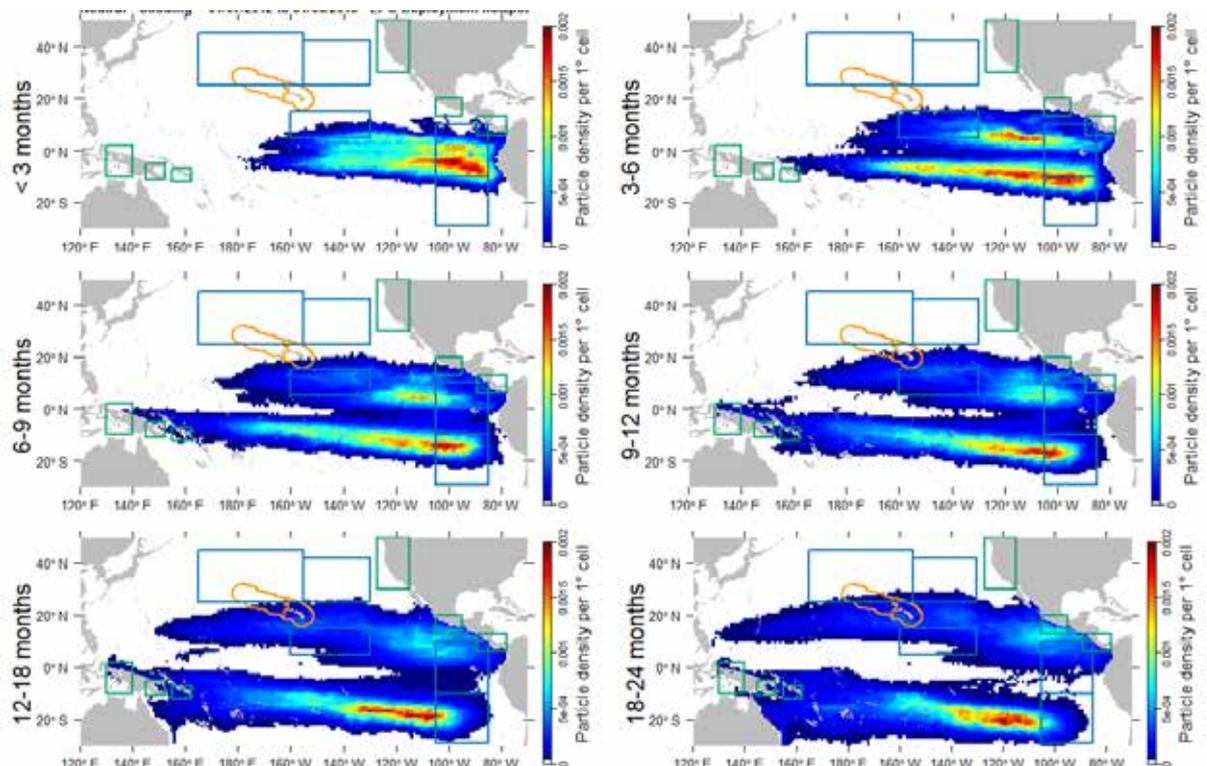

FIGURE 3. Time integrated spatial probability density for virtual particles (vFADs) deployed in Scenario 2 (deployment hotspots only), evenly across dFAD deployment hotspots in the WCPO (left panels; EZs 1–4 and 9–12) and the EPO (right panels; EZs 5–8 and 13–16) during the an ENSO neutralperiod considered combined and over three drifting periods after deployment.

TZ	Other			KE 1			KE 2			CCE			IND			PNG			SB			EEP			MX			CR-NG			EP 1			EP 2			MHI		
Months	3	12	24	3	12	24	3	12	24	3	12	24	3	12	24	3	12	24	3	12	24	3	12	24	3	12	24	3	12	24	3	12	24	3	12	24	3	12	24
FZ Depl WCPO	54	67	65	0	0.1	1.8	0	0	0.5	0	0	0	1.4	4.8	4.4	0.8	3.2	3.4	1.9	3.8	2.7	1.2	0.9	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.6
Dens WCPO	62.3	67	65.8	0	0	0.8	0	0	0.2	0	0	0	1.4	4.9	4.9	1.4	4	4.3	4.6	4.8	3.5	0.2	0.4	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.2
Depl EPO	62.3	67.9	79.3	0	0	0.5	0	0	1.2	0	0	0	0	0.1	0.2	0	0.1	0.2	0	0.2	0.2	4.6	3.6	0.7	0	0.6	0.8	0.4	0.3	0.3	22.6	3.3	1.6	10	23.2	13.5	0	0.7	1.5
Dens EPO	72.6	83.1	86.8	0	0	0.6	0	0	0.3	0	0	2.8	0	0	0	0	0	0.1	0	0	0.1	6.1	4.2	1.1	0.2	1.4	1.7	0.8	1	0.6	16	5.4	2.8	4.3	3.2	1	0	1.4	2.4

FIGURE 4. Percentage connectivity matrix of virtual particles during the three ENSO periods considered combined from Scenario 2, in which vFADs were seeded in known dFAD Zones (FZ; Depl = Deployment hotspot; Dens = dFAD density hotspot shown as rows) arriving in sea Turtle Zones (TZ shown as columns) and separated by drift time in months. Cells are coloured by the proportion of simulated particles arriving in each TZ by drift time. Other indicates any location outside of the specified TZ.

CONCLUSION

While our results indicate that dFADs deployed in equatorial purse seine fishing grounds are overlapping with important sea turtles and coastal habitats, more research is needed to exactly quantify how sea turtles are impacted by dFADs, particularly in the open ocean. Potential impacts on coastal areas, for Pacific sea turtle habitats, but also for other species, in terms of marine pollution, for example, still need to be further assessed as well. While Lagrangian simulations are a useful tool to assess the connectivity between some coastal zones and key areas of dFAD use, the extent of actual dFAD stranding events, and their ecological impacts, cannot be determined. Working with real dFAD trajectories and collecting in-situ additional data to quantify the number and consequences of these events should therefore be encouraged (Escalle *et al.*, 2020). Finally, scientists in this project also worked with fleets operating in the EPO and WCPO to define guidelines to reduce the impact of dFADs on sea turtles, by designing best practices to reduce the loss and abandonment of dFADs, including improved dFAD designs and retrieval protocols for lost or abandoned dFADs, among others.

RECOMMENDATIONS

- Note the results on potential connectivity, which is large for all equatorial zone while is reduced for the dFAD deployment/density hotspots, between known areas of dFAD deployment and sea turtle habitats in the central equatorial Pacific, archipelagic areas of the western warm pool, and the south east Pacific Ocean gyre.

- Given the overlap of dFADs with turtles oceanic and coastal habitats, no netting should be used in FAD construction to eliminate potential entanglement.

- Recognize the need for greater knowledge on at-sea interactions between active or abandoned dFADs and at-risk sea turtle populations.

- Support the continued analysis of observed and simulated dFAD trajectories to quantify the likely changes in connectivity and distribution of dFADs within the equatorial fishing grounds and higher latitude sea turtle habitats under proposed fully non-entangling, without netting, and biodegradable dFAD management measures.

ACKNOWLEDGMENTS

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