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MODELING DRIFTING FISH AGGREGATING DEVICES (FADS) TRAJECTORIES ARRIVING AT ESSENTIAL HABITATS FOR SEA TURTLES IN THE PACIFIC OCEAN

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SUMMARY

Purse seine fishers extensively deploy drifting Fish Aggregating Devices (FADs) to aggregate and catch tropical tuna, with 46,000 to 65,000 FADs deployed in the Pacific Ocean annually, and 16,000–25,000 FADs in the eastern Pacific Ocean (EPO) only. Main concerns related to the loss and abandonment of FADs are i) marine pollution; ii) the potential risk of entanglement of sea turtles and other marine fauna in FAD netting while drifting at sea or when stranded; and iii) the potential to cause ecological damage to vulnerable ecosystems via stranding events, including reefs, beaches, and other essential habitats for sea turtles. To explore and quantify the potential connectivity between FADs and important oceanic or coastal sea turtles habitats in the Pacific Ocean, a series of passive-drift Lagrangian simulation experiments were undertaken based on possible FAD drifting behaviour. Corridors of connectivity between industrial FAD fishing grounds and zones of important habitats for sea turtles were identified. For FADs deployed in the EPO, the main areas of concern appear to be the turtle habitats in the south-eastern Pacific Ocean, corresponding to oceanic leatherback turtle (*Dermochelys coriacea*) migration and feeding grounds. Moderate accumulation of FADs 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, important leatherback turtle foraging habitat, exhibited large numbers of FADs transiting when deployed in the equatorial zones north of the equator, from both the EPO and WCPO. It should be noted that the connectivity patterns detected appear to be somewhat mitigated against by the current deployment distribution of FADs in the EPO. Additional research and analyses should be performed i) to better understand at-sea interactions between FADs and sea turtle populations and potential entanglements; and ii) to quantify the likely changes in connectivity and distribution of FADs within the equatorial fishing grounds and higher latitude sea turtle habitats, under proposed non-entangling and Biodegradable FAD measures or changes in FAD deployment strategies.

RESUMEN

La flota de cerco en el Pacífico Oriental despliega de forma extensiva dispositivos de concentración de peces (DCP), llamados comúnmente plantados, para agregar y capturar atún tropical. Se estima que en el Océano Pacífico se despliegan unos 46,000-65,000 plantados anualmente, 16.000-25.000 solo en el Océano Pacifico Oriental (OPO). Dada la estrategia de pesca con plantados a la deriva, muchos se pierden y se abandonan. Las principales preocupaciones relacionadas con la pérdida y el abandono de los plantados son: i) la contaminación marina, ii) el riesgo de que las tortugas marinas y otra fauna marina se enmalle en las redes de los plantados, cuando están a la deriva en el mar y cuando terminan varados, y iii) el potencial daño ecológico en ecosistemas vulnerables debido a los varamientos, incluido en arrecifes, playas y otros hábitats esenciales para las tortugas marinas. Para explorar y cuantificar la potencial conectividad entre los plantados y los hábitats esenciales, tanto oceánicos como costeros, para las tortugas marinas en el Océano Pacífico, se llevaron a cabo una serie de simulaciones lagrangianas de deriva pasiva, basadas en el comportamiento de deriva de los plantados. Se identificaron corredores de conectividad entre las zonas de pesca con plantados y las zonas de hábitats importantes para las tortugas marinas. En el caso de los plantados desplegados en el OPO, las principales zonas de preocupación parecen ser los hábitats de las tortugas en el sureste del Océano Pacífico, correspondientes a las zonas de migración y alimentación de las tortugas baulas (*Dermochelys coriácea*). También se detectó una acumulación moderada de plantados en los hábitats costeros y oceánicos del ecuador y sitios de anidación alrededor de México, Costa Rica y Panamá. Por último, una amplia zona ecuatorial, al sur de Hawai, importante hábitat de alimentación de la tortuga baula, mostró un gran número de plantados en tránsito cuando se desplegaron en las zonas ecuatoriales al norte del ecuador, tanto desde el OPO como desde el WCPO. Cabe señalar que los patrones de conectividad detectados parecen estar algo mitigados cuando se utilizan zonas concretas reales de despliegue de los plantados en el OPO. Es necesaria más investigación y análisis adicionales para i) poder entender mejor la interacción plantado-tortuga marina en el mar, es decir el riesgo de enmallamiento y para ii) cuantificar los potenciales cambios en la conectividad y distribución de los plantados, dentro de los caladeros ecuatoriales y el hábitat de las tortugas marinas en latitudes más altas, si se implementara el uso de plantados biodegradables o cambios en las estrategias de despliegue de los plantados.

INTRODUCTION

Purse seine fishers extensively deploy drifting Fish Aggregating Devices (FADs) to facilitate their catch of tropical tuna. Recent estimates vary from 46,000 to 65,000 FADs deployed in the Pacific Ocean annually, with 16,000 to 25,000 in the eastern Pacific Ocean (EPO) only (Lopez *et al.*, 2020; Escalle *et al.*, 2021c). Modern FADs are made of a bamboo raft with submerged appendages reaching up to 40–60m in the Pacific Ocean (Escalle *et al.*, 2017; Lopez *et al.*, 2019) and equipped with satellite linked echosounder buoys to locate FADs and get a rough estimate of the amount of tuna aggregated underneath remotely (Lopez et al., 2014). In addition to the concerns regarding the sustainability of tuna stocks, sets on FADs also lead to higher bycatch rates than on free school and dolphin-associated sets for most species, including the catch of sensitive marine megafauna, such as sharks and sea turtles (Dagorn *et al.*, 2013; Bourjea *et al.*, 2014). Ghost fishing of these species while FADs are drifting at-sea may also be occurring and remains mostly unnoticed (Filmalter *et al.*, 2013). Finally, common loss or abandonment of FADs by fishers can lead to marine and coastal pollution and damage to vulnerable ecosystems, including essential habitats for sea turtles and other marine fauna, via stranding events (Balderson and Martin, 2015; Maufroy *et al.*, 2015; Escalle *et al.*, 2019a), with the potential for at-sea interactions between these species and FADs largely unknown.

While fisheries interaction is one of the major threats to sea turtles worldwide, the impact of the active catch of the purse seine fishing gear is considered low (Bourjea *et al.*, 2014; Moreno *et al.*, 2022). In the Pacific Ocean, it has been found that less than 400 and 800 sea turtles were caught annually in the Western and Central Pacific Ocean (WCPO) and Eastern Pacific Ocean (EPO), respectively (Peatman *et al.*, 2018; IATTC, 2021); and mortality is estimated at less than 0.1%. The five species of sea turtles present in the Pacific Ocean (olive ridley *Lepidochelys olivacea*; green turtle *Chelonia mydas*; loggerhead *Caretta caretta*; hawksbill *Eretmochelys imbricata;* and leatherback turtles *Dermochelys coriacea*) are found as bycatch in the fisheries operating in the Pacific Ocean and are considered species of concern internationally. However, in addition to turtles captured as bycatch, FAD use by the purse seine fishery may also impact turtle populations in two other ways. First, turtles may become entangled in the netting still allowed to be used in the EPO for FADs construction (Filmalter *et al.*, 2013; IATTC, 2019). This source of mortality may remain unnoticed, as when FADs are visited, observers are not often able to detect turtles entangled in the submerged appendages unless the FAD is lifted. In addition, FADs are visited a limited number of times in their active lifetime, and may entangle sea turtles once lost or abandoned by fishers. However, up to date, observer data in the EPO show no strong evidence of this happening broadly. In this sense, areas of overlap between FAD aggregations at sea and important migratory routes for sea turtles could highlight potential risk areas. Second, stranded FADs could potentially have impacts on critical nesting habitats for sea turtles. While information on stranding events is difficult to collect, given that satellite buoy data is commonly turned off by the time it reaches coastal areas, in-situ data collection is starting to indicate the magnitude of stranded FADs and the ecosystems impacts they may cause (NOAA, 2019; Escalle *et al.*, 2021a). For example, recent data on real FAD stranding events in Hawaiian Islands contains 112 entries from the main Hawaiian Islands, the Northwestern Hawaiian Islands and Palmyra Atoll (Lynch *et al.*, 2019). The majority of the FADs and GPS trackers (i.e. satellite-linked buoys) reported were from the main Hawaiian Islands. These stranded events show the connectivity of FAD fishing grounds with northern latitudes and the potential impact that lost and abandoned FADs can have on essential habitats for turtles far from their fishing grounds.

This particular project aims at investigating the risks faced by the populations of the Pacific sea turtles from potential oceanic interactions with FADs and FADs stranding in sensitive coastal areas, with a particular focus on leatherback turtles, a species classified as critically endangered on the IUCN red list (Wallace *et al.*, 2013). While highly informative, trajectories from real FADs are currently limited in number and the duration of time-series in the Pacific Ocean (Lopez *et al.*, 2020; Escalle *et al.*, 2021b), particularly in areas outside the main purse seine fishing grounds (10°N to 10°S). To explore and quantify the potential connectivity between FADs and important oceanic or coastal habitats in the Pacific Ocean, a series of passive-drift Lagrangian simulations (Escalle *et al.*, 2019b; Scutt Phillips *et al.*, 2019) were undertaken. Such experiments allow a characterization of the physical oceanography and connectivity in a region, as experienced by passively drifting FADs. The overarching objective of the work is to help inform the management of the FAD fishery in the Pacific, in particular by limiting the adverse effects FADs might cause on sea turtles.

METHODS

Lagrangian simulations were implemented using the Parcels framework (Delandmeter and van Sebille, 2019), with the objectives of determining the probability and percentages of FADs arriving in key sea turtle habitats in time scales comparable to the current use of FADs, including their lifetime at-sea before reaching coastal or specific oceanic areas. Passively drifting Lagrangian particles, representing virtual FADs (vFADs), were released evenly throughout the tropical, equatorial zone (scenario 1 - Figure 1) and FAD deployment hotspot zones (scenario 2 - Figure 2), and forced forwards in time with a FAD-type drift profile, driven by the top 50m current velocities (median FAD 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 on the first of July, to correspond with the beginning of the WCPO FAD-closure period and few weeks before one of the IATTC purse-seine closures, and three separate simulations were undertaken, beginning July 2012 (ENSO neutral year), July 2010 (a moderate La Niña year), and July 2015 (a strong El Niño year).

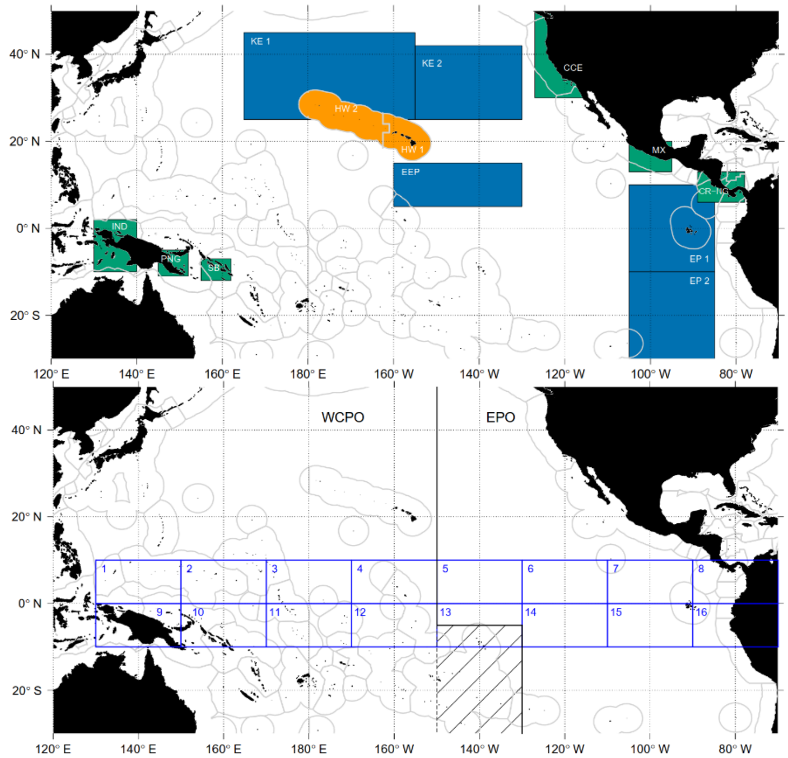

FIGURE 1. Spatial distribution of Equatorial Zones (EZ; bottom) used in the simulations to identify area of release of virtual FADs throughout the equatorial Pacific in the simulations; and of the Turtle Zones (TZ; top) used in the simulations and corresponding to i) important oceanic areas for leatherback turtles (blue); ii) main leatherback nesting grounds (green) and iii) the Hawaiian EEZ. KE = Kuroshio Extension; EEP = equatorial eastern Pacific; CCE = California Current Ecosystem; IND = Indonesia; PNG = Papua New Guinea; SB = Solomon Islands; HW = Hawaii; MX = Mexico; CR-NG = Costa Rica – Nicaragua; and EP = Eastern Pacific. The black line indicates the WCPFC and IATTC convention areas, the black dotted line the overlapping area between both convention areas.

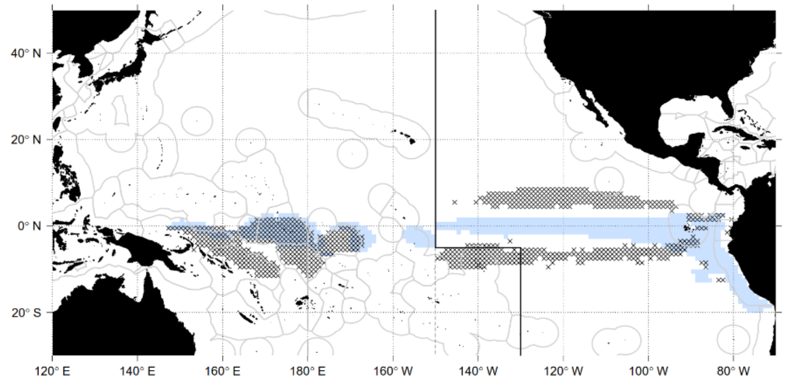

FIGURE 2. Spatial distribution of the 1° cells included in the main FAD deployments areas (blue) and main FAD densities areas (black crosses) defining the FAD Zones (FZ) in the simulations. The black line indicates the WCPFC and IATTC convention areas, the black dotted line the overlapping area between both convention areas.

The spatial extent of the simulations included the whole Pacific Ocean, from 120°E to 90°W and from 50°N to 30°S in order to cover most of both the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC) convention areas and key sea turtles' habitats (Figure 1). Two groups of areas between which to examine connectivity were defined, corresponding to zones of habitat importance in sea turtle life history, and equatorial zones, where FADs are known to drift and be deployed (Figures 1 and 2). Leatherback turtle habitat zones were separated into large, oceanic or key nesting zones (“Turtle Zones” (TZ), Figure 1). For FAD zones, two scenarios were investigated: (1) large broad longitudinally square areas spanning the entire tropical, equatorial zone from 10° south to 10° North (“Equatorial Zones” (EZ); Figure 1); and (2) several identified hotspot areas of FAD deployment and FAD densities from observed and operational buoy data in both the WCPO and EPO (“FAD Zones“ (FZ); Figure 2). In the WCPO high FAD density and deployment hotspots are derived from Escalle *et al.* (2021b), which used the PNA FAD tracking database over the 2016–2020 period and the monthly average number of unique active satellite buoys and the annual average number of deployments per 1°x1°. In the EPO, high FAD density hotspots have been identified using the monthly average number of unique active satellite buoys attached to FADs (IATTC buoy database, information reported to the IATTC under Resolutions C-17-02) detected per 1°x1° cell over the 2018–2020 period (Lopez *et al.*, 2020). FAD deployment hotspots have been identified using the annual average number of deployments per 1°x1° cell over the 2016–2020 period from the IATTC observer database (Lopez *et al.*, 2020). Cells corresponding to values of FAD density and deployments above the 90th quantile were selected for each convention area separately.

The vFAD simulated drift trajectories were then tracked, and metrics of potential connectivity were calculated as a function of transition between FAD operational use zones and turtle habitat zones, and the length during which vFAD particles had drifted. The spatial distribution of vFADs, after various drift durations (i.e., quarterly, up to 30 months), were then compared to key sea turtles oceanic and coastal nesting habitat.

VFAD density maps summarize the spatial distribution and evolution of vFADs across a particular time-period of the experiment. Transition matrices were also used to summarize the connectivity of different zones by tracking the trajectories of individual vFADs over a time-period, quantifying the proportion of vFADs released in one zone arriving in another for each drift-time. The zones used here correspond to the different equatorial fishing ground deployments (EZ or FZ) and large-scale important turtle habitats (TZ). By calculating such proportional movement rates, these matrices can be interpreted as the probability of movement between the two zones, given the assumptions of the physical ocean model.

RESULTS

In general, the simulations suggested strong connectivity between the majority of the large turtle habitat zones and vFADs deployed in the equatorial zone under the uniform deployment of vFADs scenario (scenario 1; Figures 3, 4, S1 and S2). However, when considering only those vFADs seeded in areas of known FAD deployment and high density (scenario 2), the connectivity was lower, compared to when vFADs were deployed through the whole equatorial band (Figures 5, 6 and S3). This was mainly a result of the equatorial zones most consistently responsible for connectivity to turtle habitats lying north of the equator, where in general there was a lower overlap with observed FAD hotspots (Figures 1 and 2). However, these zones showed the potential to drive significant numbers of vFADs (13–50%) north into the eastern equatorial area between 5°N and 15°N known as an important foraging habitat for leatherback turtles, although particles tended to transition through this zone rather than accumulate (Figures 3 to 6).

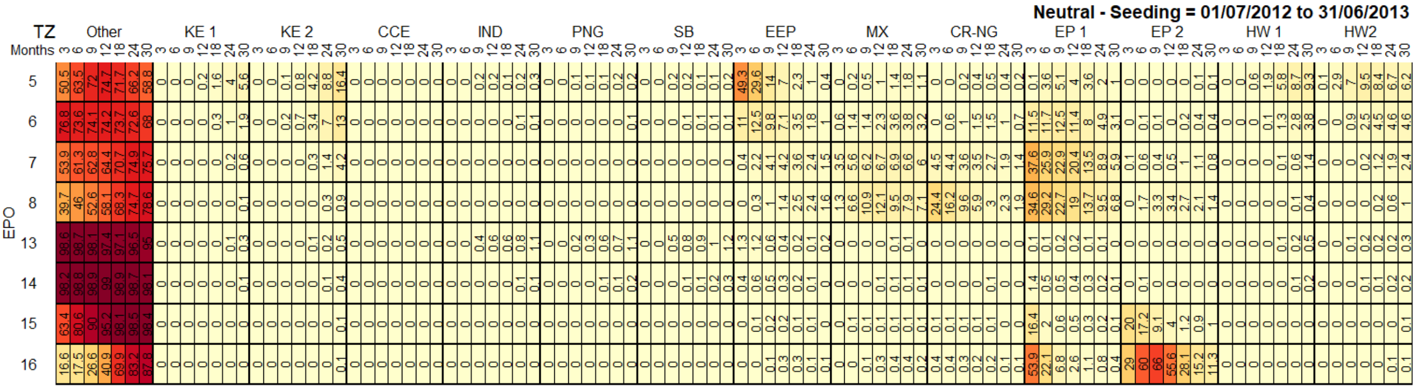

FIGURE 3. Percentage connectivity matrix of virtual particles in the time-forward simulation during an ENSO Neutral period (01/07/2012 to 31/06/2013) by Turtle Zones (TZ) against seeding in EPO Equatorial Zones (EZ) and separated by drift time in periods of 3 months. Cells are coloured proportionally to the simulated particles arriving in each TZ by drift-time.

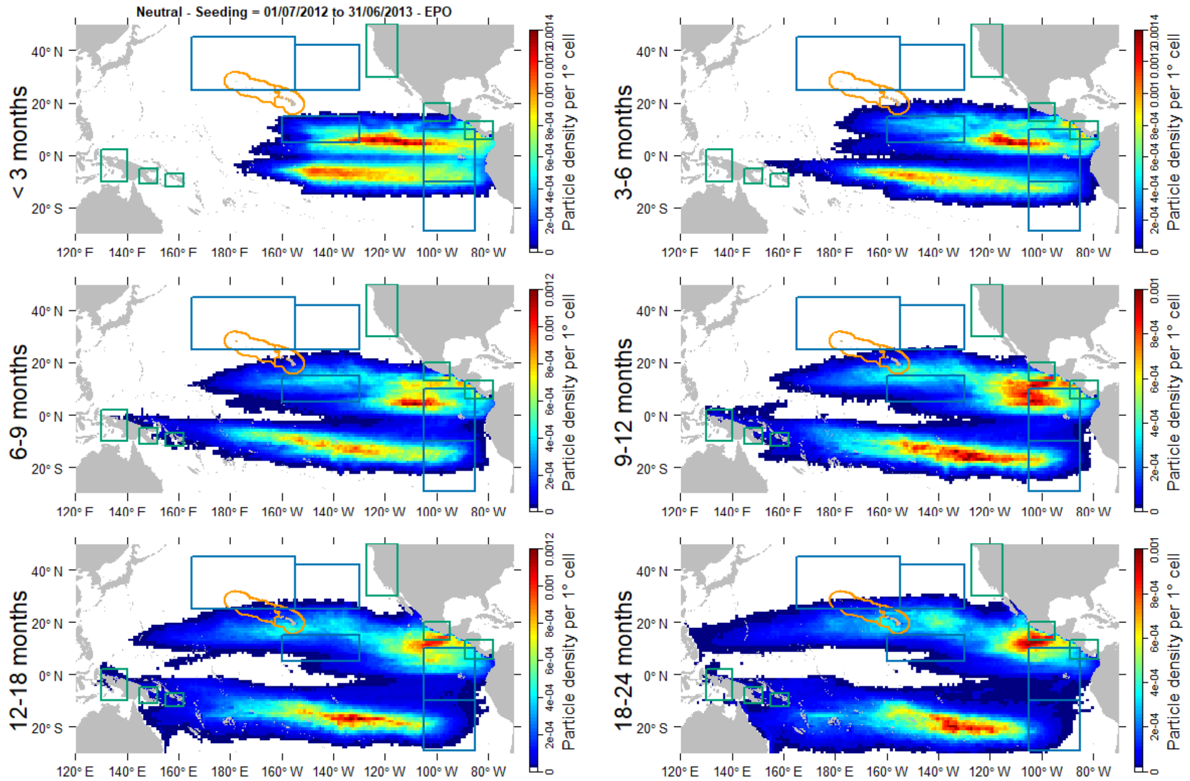

FIGURE 4. Spatial probability density for virtual particles deployed in the whole equatorial region in the EPO (EZs 5–8 and 13–16) during a Neutral period (01/07/2012 to 31/06/2013) during six drifting time bins after deployment.

In the EPO, central and south of the equator, two large zones important to migration and foraging of leatherback turtles, experienced very high levels of connectivity with vFADs originating from the whole equatorial EPO region, both north and south of the equator (up to 66% of all deployed vFADs, depending on the exact equatorial zone and drift-time; Figures 3 and 4). Such connectivity remained present, though reduced, even when just considering zones of observed high FAD deployment (up to 26%; Figures 5 and 6). The majority of vFADs are projected to again transit through this zone into a gyre of accumulation in the south-eastern Pacific Ocean, which only partially overlapped with these turtle habitats zones (Figures 4 and 6). Similarly, the regions offshore of Mexico, and Costa-Rica and Nicaragua, connecting to important nesting zones for the leatherback population, showed the potential for moderate connectivity and accumulation of vFADs deployed near the equator (up to 24%;

Figures 3 and 4), although this was largely reduced when only considering vFADs deployed in FAD hotspots in the EPO (up to 5%; Figures 5 and 6).

Hawksbill and green sea turtle habitats around the Hawaiian Islands appeared connected to the equatorial zone via two pathways. For the main Hawaiian Islands, with higher connectivity to the equatorial region than the northern Islands, vFADs are simulated to arrive in small but consistent numbers from the central EPO zones north of the equator (up to 10%; Figure 3), after at least 3 months of drifting. The magnitude of this connectivity was considerably lower when particles started in observed FAD deployment hotspots (up to 2%). For both the northern and main Hawaiian Islands, there was an additional pathway linked to the Kuroshio current and its eastern extension into a large area of leatherback turtle foraging habitat and migration route, but this was mostly detected for vFADs deployed in the WCPO (Figures S1 and S2). This pathway transported vFADs from northern equatorial zones in the WCPO along the Kuroshio and back out into the northern Pacific over drift-times of at least one year. This resulted in small to moderate proportions of vFADs arriving from these equatorial zones over longer drift-times (up to 12%, for northern Hawaiian Islands vFAD presence after drifting 2.5 years, Figure S1). Once again, the magnitude of this connectivity was considerably reduced when only particles beginning in observed FAD deployment and density hotspots were considered (up to 1.9% from the EPO and 0.7% from the WCPO).

Finally, the small offshore leatherback turtle habitats in Papua New Guinea and the Solomon Islands consistently received and retained vFADs arriving from the southern equatorial regions of the WCPO (Figures S1 and S2). This was also the case, despite the connectivity being reduced, when only considering observed FAD deployment hotspot (Figure 5 and S3). The archipelagic Indonesian leatherback turtle habitat experienced similar high connectivity with vFADs arriving from mostly one region of the WCPO, the south-western area (28%), though vFADs appeared more transiting through this zone. Again, a similar but reduced pattern was seen in connectivity when observed FAD hotspots were used in the WCPO (up to 5%).

Consistent effects of ENSO were difficult to distinguish, due to the variability in ocean circulation over the 2.5 year drift-time. There was, however, a slight increase in connectivity for western Pacific Papua New Guinea and the Solomon Islands turtle habitat zones during La Niña, driven by increased westerly currents carrying vFADs into this archipelagic zone during this period, mainly projected to arrive from the WCPO.

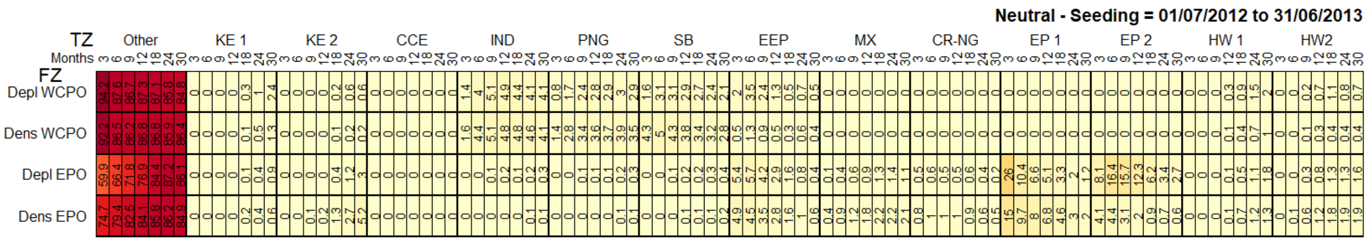

FIGURE 5. Percentage connectivity matrix of virtual particles in the time-forward simulation during an ENSO Neutral period by Turtle Zones (TZ) against seeding in FAD Zones (FZ; Depl = Deployment hotspot; Dens = FAD density hotspot) and separated by drift time in periods of 3 months. Cells are coloured by proportion of simulated particles arriving in each TZ by drift-time.

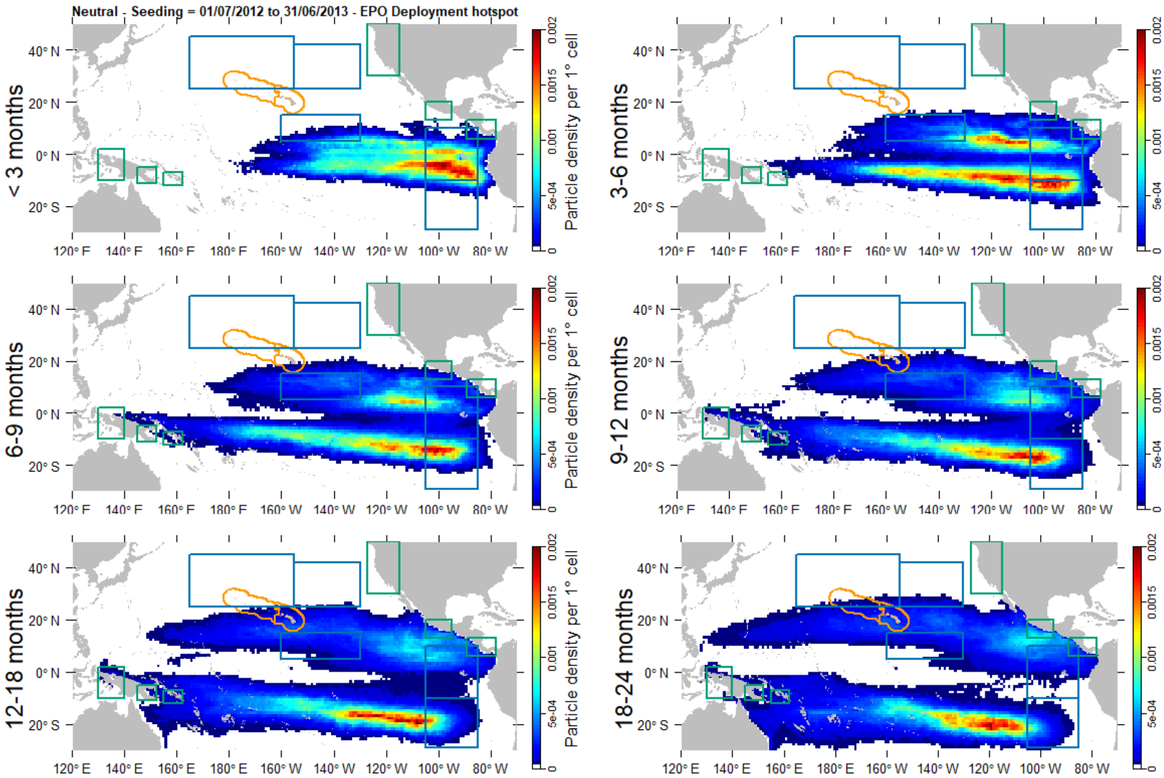

FIGURE 6. Spatial probability density for virtual particles deployed in the EPO FAD deployment hotspots during a Neutral period (01/07/2012 to 31/06/2013) during six drifting time bins after deployment.

Discussion

There is considerable potential connectivity between many important turtle oceanic and coastal habitats with the equatorial Pacific where FADs operate. However, given our information on wherepurse seine fleets deploy FADs, and their observed density hotspots, this potential connectivity appears minimized in most cases.

For FADs deployed in the EPO, the main areas of concern appear to be:

1. The turtle habitats in the south-eastern Pacific Ocean, corresponding to oceanic leatherback turtle migration and feeding grounds (EP1 and EP2), which experience dense aggregation of FADs deployed in the EPO over short to moderate drift-durations (0-18 months). Given the lack of inhabited land mass in this area, aside from the Pitcairn Islands, such a large throughput and potential aggregation of FADs leaving the main purse seine fishing ground may currently exist (although note that there is seasonal FAD fishing around 20°S), as indicated by recent fisheries and FAD buoy density data (Lopez *et al.*, 2020, 2021, 2022a), with little observation in terms of stranding events. This significant connectivity projected between EPO FAD deployment hotspots and the southern EPO turtle habitat zones appears to be driven by the same near-surface currents that the Eastern Pacific leatherback turtles may use to migrate south in this area. Although some recent studies have improved the understanding of the Eastern Pacific leatherback distribution in the region (Hoover *et al.*, 2019; Degenford *et al.*, 2021; Lopez *et al.*, 2022b), telemetry and other fine and large-scale turtle distribution data should be examined to better assess the degree of overlap in these pathways, and whether the southern gyre that appears to potentially entrain many EPO FADs also overlaps with these species feeding grounds. It is possible that the same ocean flow driving FADs into this gyre is responsible for high levels of mixing and associated productivity favorable to leatherback turtles.

2. Secondly, a moderate simulated connectivity and accumulation of vFADs was detected between the equatorial coastal and oceanic habitats/nesting sites around Mexico, Costa Rica, Nicaragua and

Panama, and the neighboring equatorial zones, although this appears to be somewhat mitigated against by the current FAD deployment and density distributions in the EPO.

3. Finally, the large, eastern equatorial area (south of Hawaiʻi) of leatherback turtle foraging habitat, exhibited large numbers of FADs transiting when deployed in the equatorial zones north of the equator, from both the EPO and WCPO. Again, this connectivity was significantly reduced when considering current FAD deployments and densities hotspots.

Clear differentiation in vFAD origin between the main Hawaiian Islands, where the few Critically Endangered Hawksbill Turtles are found, and the northern Hawaiian Islands, including the green turtles main nesting sites was predicted. VFADs arriving in the main Hawaiian Islands appear to have likely origin in the EPO, even after moderate drift times of a year or less. To the contrary, northern Hawaiian islands turtle habitats and the general Kuroshio extension zones have non-negligible connectivity with vFADs deployed in the northern, equatorial zone, though mostly from the WCPO and only after long drift-times of at least two years. Higher vFADs were detected in the Kuroshio extension zones for deployments during El Niño periods. Thus, measures to reduce potential sea turtle impacts from FADs drifting for such long periods, including reduction in subsurface structure or raft netting, should be identified and promoted.

Current operational patterns appear to result in a great density of FADs being deployed south of the equator, which reduces the interaction and connectivity between vFADs and sea turtles. A northern shift in FAD deployment positions could lead to higher vFADs arrival in many important oceanic sea turtles habitat and the Hawaiian EEZ.

Generally, and as expected, higher vFAD connectivity is detected with oceanic and coastal key sea turtle habitats located along the equatorial region, in particular large migration and feeding zones in the southern EPO, the central Pacific habitats south of Hawaii, and nesting sites in the western Pacific Ocean and central America. Changes in the lifespan of FADs, through adoption of new designs, such as Biodegradable FAD designs, could therefore largely reduce the number of FAD reaching non-equatorial zones, but would likely still reach the important near-by habitat and nesting zones.

In the WCPO, a transition towards fully non-entangling and Biodegradable FADs is currently on-going (WCPFC CMM 2021-01), which will therefore help mitigate and reduce the interaction between FADs and sea turtles in oceanic and coastal areas. Although the use of non-entangling and biodegradable FADs is currently encouraged by the IATTC (Res. C-19-01), with some materials and designs specifically prohibited, the same transition towards the adoption of fully non-entangling and Biodegradable FADs is recommended in the EPO to reduce the interaction and potential risks between FADs and sea turtles. The effect on connectivity and density of FADs under proposed fully non-entangling and Biodegradable FAD measures should be further quantified by examining real and simulated trajectories for each type of design.

Overall, vFADs released in the EPO exhibited more dense aggregation after long drift time, with local retention, centered in the southern Pacific Ocean gyre and off the coast of Central America, than those released in the WCPO, which spread throughout the western Pacific Ocean. Much of the high connectivity of vFADs within turtle habitats near the fishing ground appears highly transient in nature, as divergent surface currents near the equator push vFADs away and into higher latitudes. As such zones are close to, or even within, the fishing grounds of purse seiners targeting tropical tunas, it appears that little can be done to prevent their entry into such areas. In these cases, the speed at which FADs transit these zones, and mitigation actions against their potential impacts on sea turtles while in these areas, should be maximized.

CONCLUSION

While our results indicate that FADs 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 FADs, particularly in the open ocean. Potential impacts on coastal areas, for Pacific sea turtle populations 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 FAD use, the extent of actual FAD stranding events, and their ecological impacts, cannot be determined. Working with real FAD 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 will work with fleets operating in the EPO and WCPO to define guidelines to reduce the impact of FADs on sea turtles, by designing best practices to reduce the loss and abandonment of FADs, including improved FAD designs and retrieval protocols for lost or abandoned FADs, among others.

RECOMMENDATIONS

- Given the overlap of FADs with turtles oceanic and coastal habitats, consider no netting materials for FAD construction and eliminate potential entanglement.
- Consider expanding the research and exploration of spatial-management options for FADs, based on the results of the current work; potential connectivity between FADs and sea turtle habitats in the central equatorial Pacific, archipelagic areas of the western warm pool, and the south east Pacific Ocean gyre seems significant for the whole equatorial zone and reduced for known FAD deployment/density hotspots.
- Conduct additional research to beter understand the magnitude and effect of at-sea interactions between active or abandoned FADs and at-risk sea turtle populations.
- Support the continuation of the work, using observed and simulated FAD trajectories, to quantify the connectivity, and potential interaction, of FADs and sea turtle habitats assuming that fully non-entangling, without netting, and biodegradable FADs management measures are implemented.

ACKNOWLEDGMENTS

In the EPO, FAD density and deployment hotspots were identified using the IATTC buoy database (information reported to the IATTC under Resolution C-17-02) and the IATTC observer database. In the WCPO, hotspots of FAD deployments and FAD densities are derived from Escalle *et al.* (2021b), which are based on the Parties to the Nauru Agreement (PNA) FAD tracking database. Passive drift simulations were run on resources and services from the National Computational Infrastructure (NCI), which is supported by the Australian Government. The authors thank Scott Benson, Maxime Lalire, and Irene Kelly for their participation to the Lagrangian simulation preparatory workshops; their expertise and advice helped design the experiment presented in this report. This project received funding under award NA20NMF4540142 from NOAA Fisheries Pacific Islands Regional Office. The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of NOAA.

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SUPPLEMENTARY FIGURES

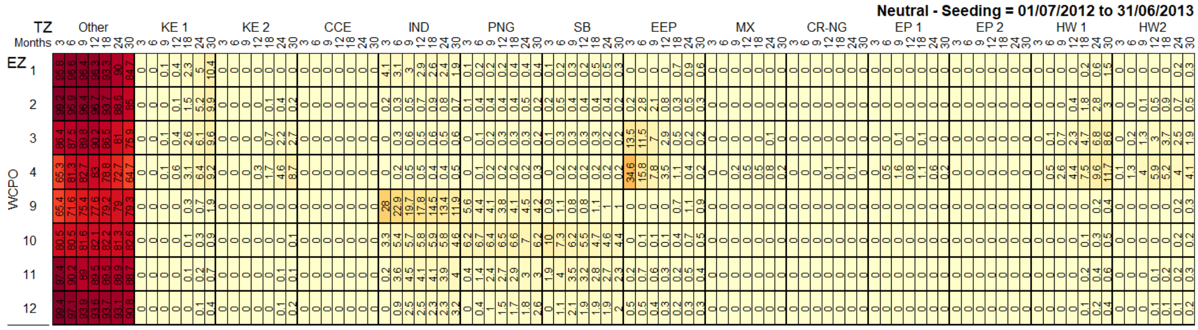

FIGURE S1. Percentage connectivity matrix of virtual particles in the time-forward simulation during an ENSO Neutral period (01/07/2012 to 31/06/2013) by Turtle Zones (TZ) against seeding in WCPO Equatorial Zones (EZ) and separated by drift time in months. Cells are coloured by proportion of simulated particles arriving in each TZ by drift-time.

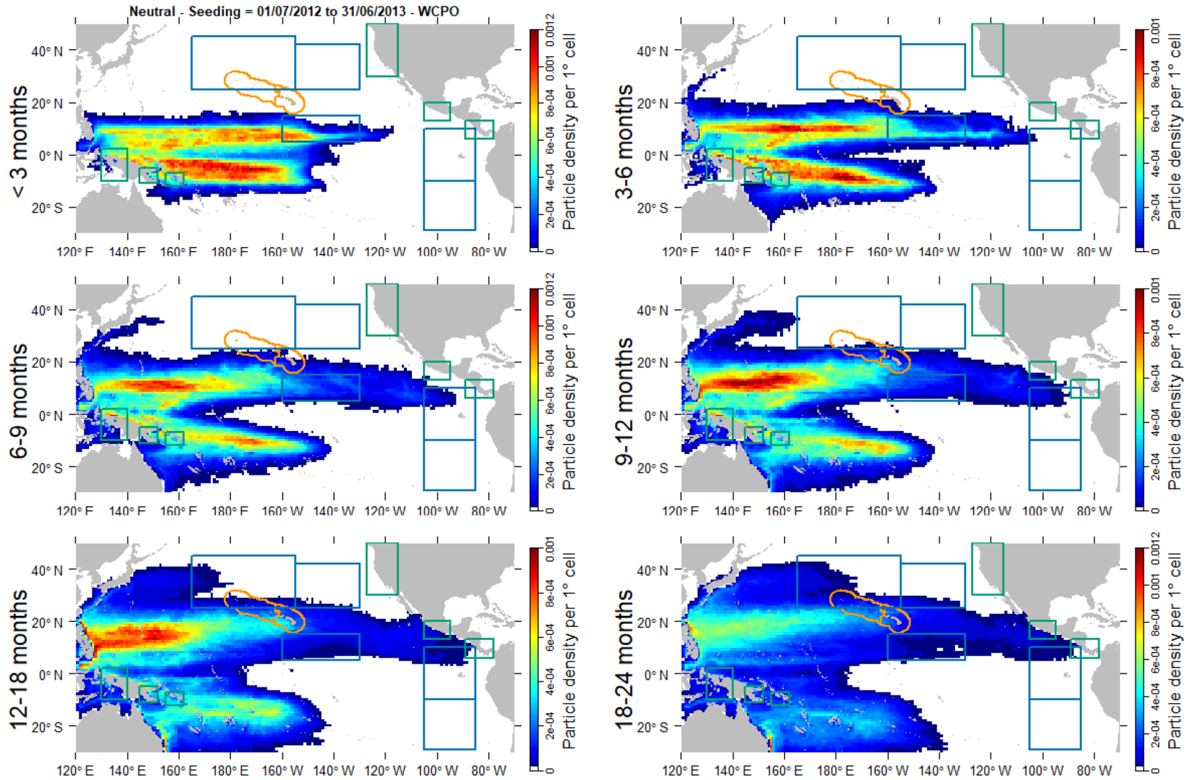

FIGURE S2. Spatial probability density for virtual particles deployed in the whole equatorial region in the WCPO (EZs 1–4 and 9–12) during a Neutral period (01/07/2012 to 31/06/2013) during six drifting time bins after deployment.

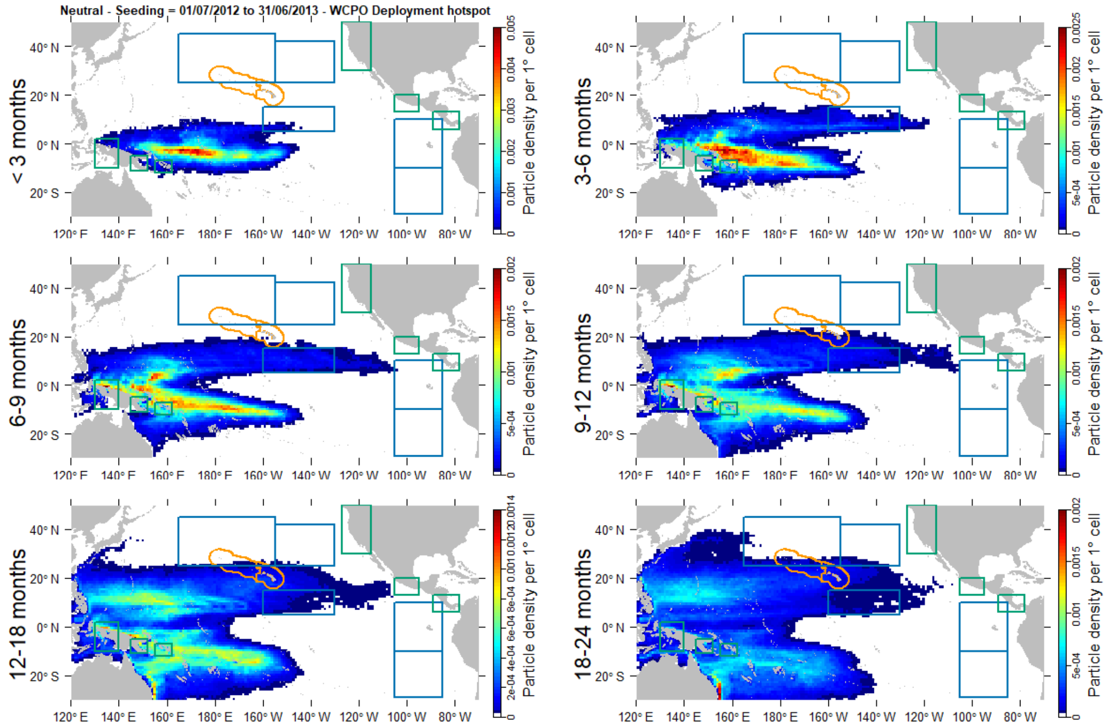

FIGURE S3. Spatial probability density for virtual particles deployed in the WCPO FAD deployment hotspots during a Neutral period (01/07/2012 to 31/06/2013) during six drifting time bins after deployment.