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Modelling drifting Fish Aggregating Devices (FADs) trajectories arriving at essential habitats for sea turtles in the Pacific Ocean

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Executive Summary

Purse seine fishers extensively deploy drifting Fish Aggregating Devices (dFADs) to aggregate and catch tropical tunas, with 46,000 to 65,000 dFADs deployed in the Pacific Ocean annually, and 30,000 to 40,000 in the Western and Central Pacific Ocean (WCPO) alone. Main concerns related to the loss and abandonment of dFADs are i) marine pollution; ii) the potential risk of entanglement of sea turtles and other marine fauna in dFAD 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 dFADs and important oceanic or coastal sea turtle habitats in the Pacific Ocean, a series of passive-drift Lagrangian simulation experiments were undertaken based on possible dFAD drifting behaviour. 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, corresponding to oceanic leatherback turtle (*Dermochelys coriacea*) migration and feeding grounds. 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, important leatherback turtle foraging habitat, exhibited large numbers of dFADs 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 dFADs in the EPO. 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.

We invite WCPFC-SC18 to:

- Note the Pacific-wide project to define best practice guidelines and conservation recommendations to reduce the impact of FAD structure on sea turtle populations and habitats in the Pacific Ocean.
- Ensure effective implementation on the prohibition of using mesh net material in the construction of dFADs, as per para 17 of CMM 2021-01, to reduce potential for entanglement given the overlap of dFADs with turtles' oceanic and coastal habitats.
- Note the results on potential connectivity between 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. This connectivity is high when considering all equatorial purse seine fishing grounds for FAD deployment, but reduced for known dFAD deployment/density hotspots.
- Recognize the need for greater knowledge on at-sea interactions between active or abandoned dFADs and at-risk sea turtle populations, including improved understanding for potential for mortality.
- 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, including under various management scenarios such as fully non-entangling, without netting, and biodegradable dFAD management measures.

1. Introduction

Purse seine fishers extensively deploy drifting Fish Aggregating Devices (dFADs) to facilitate their catch of tropical tunas. Recent estimates vary from 46,000 to 65,000 dFADs deployed in the Pacific Ocean annually, with 30,000 to 40,000 in the Western and Central Pacific Ocean (WCPO) alone (Escalle et al., 2021b; Lopez et al., 2020). Modern dFADs are made of a bamboo raft with submerged appendages reaching up to 40–60 m in the Pacific Ocean (Escalle et al., 2017; Lopez et al., 2019) and equipped with satellite linked echosounder buoys to locate dFADs 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 dFADs 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 (Bourjea et al., 2014; Dagorn et al., 2013). Ghost fishing of these species while dFADs are drifting at-sea may also be occurring and remains mostly unnoticed (Filmalter et al., 2013). Finally, common loss or abandonment of dFADs 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; L. Escalle et al., 2019; Maufroy et al., 2015), with the potential for at-sea interactions between these species and dFADs 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 WCPO and Eastern Pacific Ocean (EPO), respectively (IATTC, 2021; Peatman et al., 2018); 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, dFAD 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 WCPO and EPO for dFADs construction (Filmalter et al., 2013; IATTC, 2019). This source of mortality may remain unnoticed, as when dFADs are visited, observers are not often able to detect turtles entangled in the submerged appendages unless the dFAD is lifted. In addition, dFADs are visited a limited number of times in their active lifetime, and may entangle sea turtles once lost or abandoned by fishers. To date, however, observer data in the EPO show no strong evidence of this happening broadly. In this sense, areas of overlap between dFAD aggregations at sea and important migratory routes for sea turtles could highlight potential risk areas. Second, stranded dFADs 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 dFADs and the ecosystems impacts they may cause (Escalle et al., 2021a; NOAA, 2019). For example, recent data on real dFAD 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 dFADs and GPS trackers (i.e. satellite-linked buoys) reported were from the main Hawaiian Islands. These stranded events show the connectivity of dFAD fishing grounds with northern latitudes and the potential impact that lost and abandoned dFADs can have on essential habitats for turtles far from their fishing grounds.

2. Project Objectives

The present project aims to simultaneously form the basis for cooperation of key stakeholders across the Pacific Ocean (fishers, ship-owners and scientists) to minimize the impacts caused by lost and abandoned FADs on sea turtles, while also defining future guidelines to reduce the impact of dFAD structures on sea turtles´ populations and habitat. The project expects to achieve this overarching objective through the following four specific objectives:

1. **State of knowledge**: This objective will review the known and unknowns of dFAD structure impact on marine turtles' habitat and populations. It will identify the information gaps to estimate entanglements and lost and abandoned dFADs numbers, as well as their impact on sea turtles and their habitats. The review will gather information from scientific experts on sea turtles, dFAD ghost fishing, marine debris, dFAD fishing strategy, as well as from tuna RFMOs. The expected outcome will be the definition of recommendations in terms of research and data collection needs to inform science-based dFAD management to reduce the impact of lost and abandoned FADs on sea turtle populations and habitat.
2. **Modelling FAD trajectories:** this objective will simulate virtual FAD trajectories arriving at essential habitats for turtles with special focus on leatherback turtle and Hawaiian Islands. Due to the lack of real dFAD trajectories till the end of dFADs´ lifetime, this task will model dFAD trajectories to address (i) the identification of patterns (eg. in deployment areas, FAD design, oceanographic conditions) linked to the more frequent arrival of lost dFADs in essential habitats for leatherback turtles and the Hawaiian EEZ and (ii) identification of potential ghost fishing hotspots related to dFAD density and leatherback inter-nesting areas in open ocean. Lagrangian simulation will be used to examine spatial and temporal patterns of overlap, and possible risk of interaction, between dFAD drifts and turtle habitats both in open ocean and coastal habitats (Escalle et al., 2019; Scutt Phillips et al., 2019). Preliminary results are presented by Escalle et al. (2022) in the 11th Meeting of the Working Group on Bycatch.
3. **Evaluating options to reduce dFAD impact and definition of best practices guidelines**: Based on previous work and discussions with key purse seine fleets in expert workshops, best practices to reduce the impact of dFAD structures in sea-turtles as well as best practices at-sea to avoid dFAD loss, dFAD recovery from land and at sea will be discussed and agreed. The definition of effective guidelines to reduce the impact of lost and abandoned dFADs will require a clear understanding of the logistical and economic challenges that fleets need to face to adopt a given best practice.
4. **Outreach to fishers, scientists and managers** will be done by disseminating the outcome of this project to (i) tuna purse-seine fishers in the Pacific region, (ii) to the tuna RFMOs to influence the adoption of conservation measures, (iii) to the scientific community, through presentations at symposia, and finally(iv) to the general public.

The present paper focus on Objective 2, the modelling of dFADs trajectories arriving at essential habitats for sea turtles in the Pacific Ocean. In particular, we aimed at investigating the risks faced by the populations of the Pacific sea turtles from potential oceanic interactions with dFADs and dFADs 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 dFADs are currently limited in number and the duration of time-series in the Pacific Ocean (Escalle et al., 2021c; Lopez et al., 2020), particularly in areas outside the main purse seine fishing grounds (10°N to 10°S). To explore and quantify the potential connectivity between dFADs and important oceanic or coastal habitats in the Pacific Ocean, a series of passive-drift Lagrangian simulations (Lauriane Escalle et al., 2019; 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 dFADs. The overarching objective of the work is to help inform the management of the dFAD fishery in the Pacific, in particular by limiting the adverse effects dFADs might cause on sea turtles.

3. Methods

Lagrangian simulations were implemented using the Parcels framework (Delandmeter and van Sebille, 2019), with the objectives of determining the probability and percentages of dFADs arriving in key sea turtle habitats in time scales comparable to the current use of dFADs, including their lifetime at-sea before reaching coastal or specific oceanic areas. Passively drifting Lagrangian particles, representing virtual dFADs (vFADs), were released evenly throughout the tropical, equatorial zone (scenario 1 - Figure 1) and dFAD deployment and density hotspot zones (scenario 2 - Figure 2), and forced forwards in time with a dFAD-type drift profile, driven by the top 50 m current velocities (median dFAD net depth of 40 m in the EPO and 50 m in the WCPO (Escalle et al., 2017; Lopez et al., 2020)) from the Bluelink Reanalysis 2020 circulation model (BRAN 2020, Chamberlain et al., n.d.). 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 dFAD-closure period and few weeks before one of the EPO 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).

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 dFADs 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 dFAD 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 dFAD deployment and dFAD densities from observed and operational buoy data in both the WCPO and EPO ("dFAD Zones" (FZ); Figure 2). In the WCPO high dFAD density and deployment hotspots are derived from Escalle *et al.* (2021b), which used the PNA dFAD 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 dFAD density hotspots have been identified using the monthly average number of unique active satellite buoys attached to dFADs (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). DFAD 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 density and deployments above the 90th quantile were selected for each convention area separately.

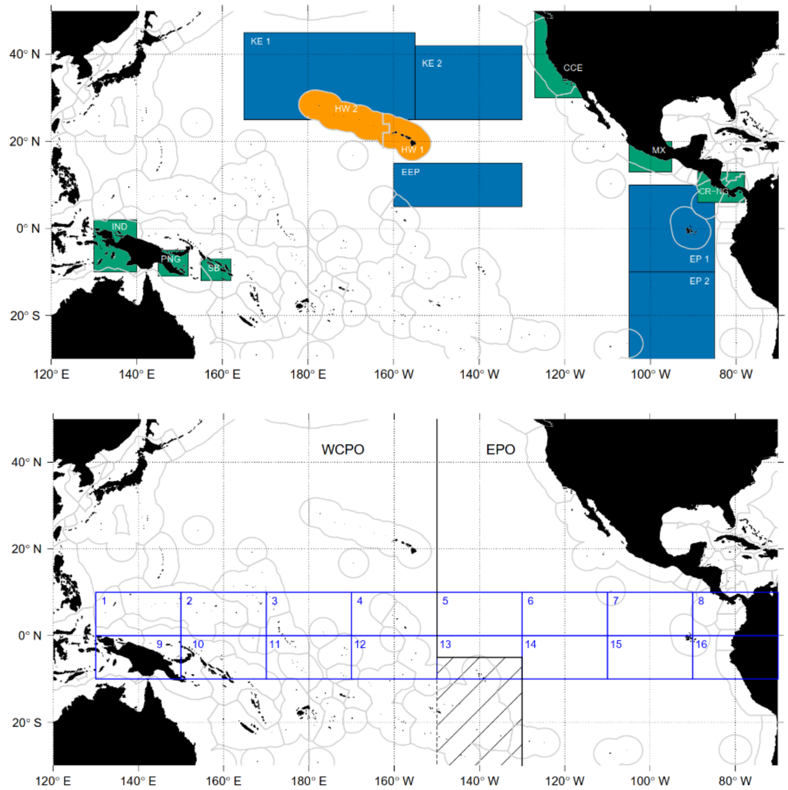

Figure 1. Spatial distribution of Equatorial Zones (EZ; bottom) used in the simulations to identify area of release of virtual dFADs throughout the equatorial Pacific in the simulations; and of the Turtle Zones (TZ; top) used in the simulations and corresponding to i) important oceanic areas for leatherback 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.

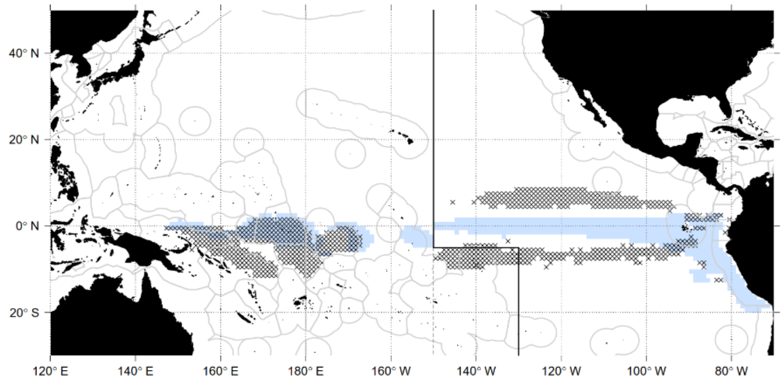

Figure 2. Spatial distribution of the 1° cells included in the main dFAD deployments areas (blue) and main dFAD densities areas (black crosses) defining the dFAD Zones (FZ) in the simulations. The black line indicates the WCPFC and IATTC convention areas, the black dotted line indicates the overlapping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

The vFAD simulated drift trajectories were then tracked, and metrics of potential connectivity were calculated as a function of transition between dFAD 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.

4. 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 dFAD 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 dFAD 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, 4, S1 and S2).

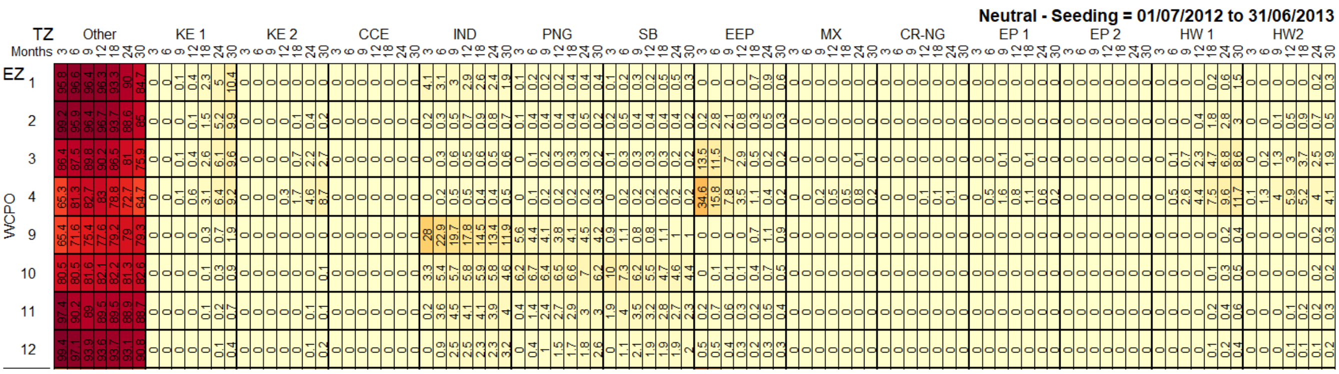

Figure 3. Percentage connectivity matrix of virtual particles in the time-forward simulation during an ENSO Neutral period (01/07/2012 to 31/06/2013) by Turtle Zones (TZ) against seeding in WCPO Equatorial Zones (EZ) and separated by drift time in months. Cells are coloured by proportion of simulated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

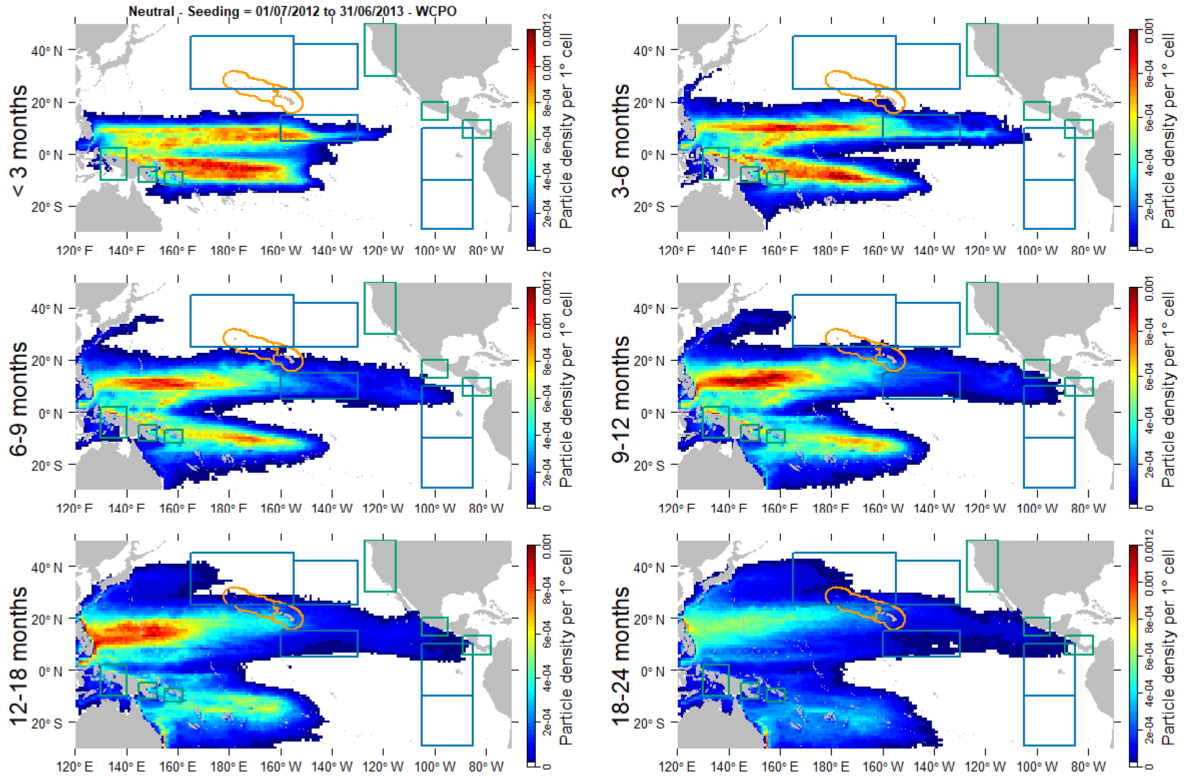

Figure 4. Spatial probability density for virtual particles deployed in the whole equatorial region in the WCPO (EZs 1–4 and 9–12) during a Neutral period (01/07/2012 to 31/06/2013) during six drifting time bins after deployment.

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 (up to 6% and 10%, Figures 3 and 4). This was also the case, despite the connectivity being reduced (up to 5%), when only considering observed dFAD deployment hotspot (Figure 5 and 6). 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 (Figures 3 and 4). Again, a similar but reduced pattern was seen in connectivity when observed dFAD hotspots were used in the WCPO (up to 5% after nine months of drift).

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 S1), after at least three months of drifting. The magnitude of this connectivity was considerably lower when particles started in observed dFAD 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 3 and 4). 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 3). Once again, the magnitude of this connectivity was considerably reduced when only particles beginning in observed dFAD deployment and density hotspots were considered (up to 1.9% from the EPO and 0.7% from the WCPO, Figures 5 and 6).

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 S1 and S2). Such connectivity remained present, though reduced, even when just considering zones of observed high dFAD deployment (up to 26%; Figures 5 and S3). 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 S2 and S3). 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 S1 and S2), although this was largely reduced when only considering vFADs deployed in dFAD hotspots in the EPO (up to 5%; Figures 5 and S3).

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.

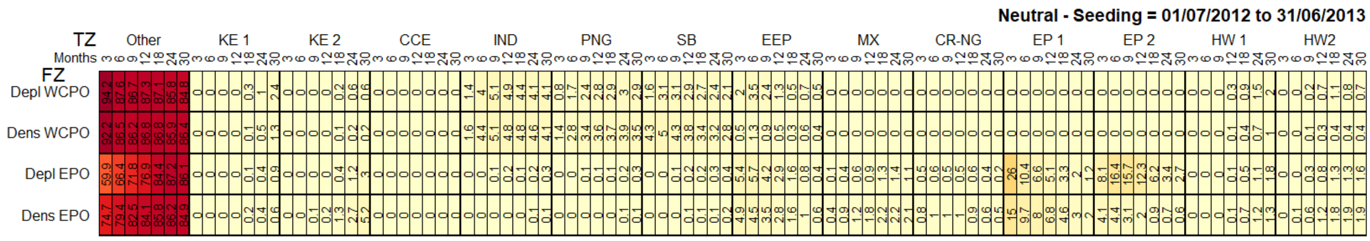

Figure 5. Percentage connectivity matrix of virtual particles in the time-forward simulation during an ENSO Neutral period by Turtle Zones (TZ) against seeding in dFAD Zones (FZ; Depl = Deployment hotspot; Dens = dFAD density hotspot) and separated by drift time in periods of three months. Cells are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

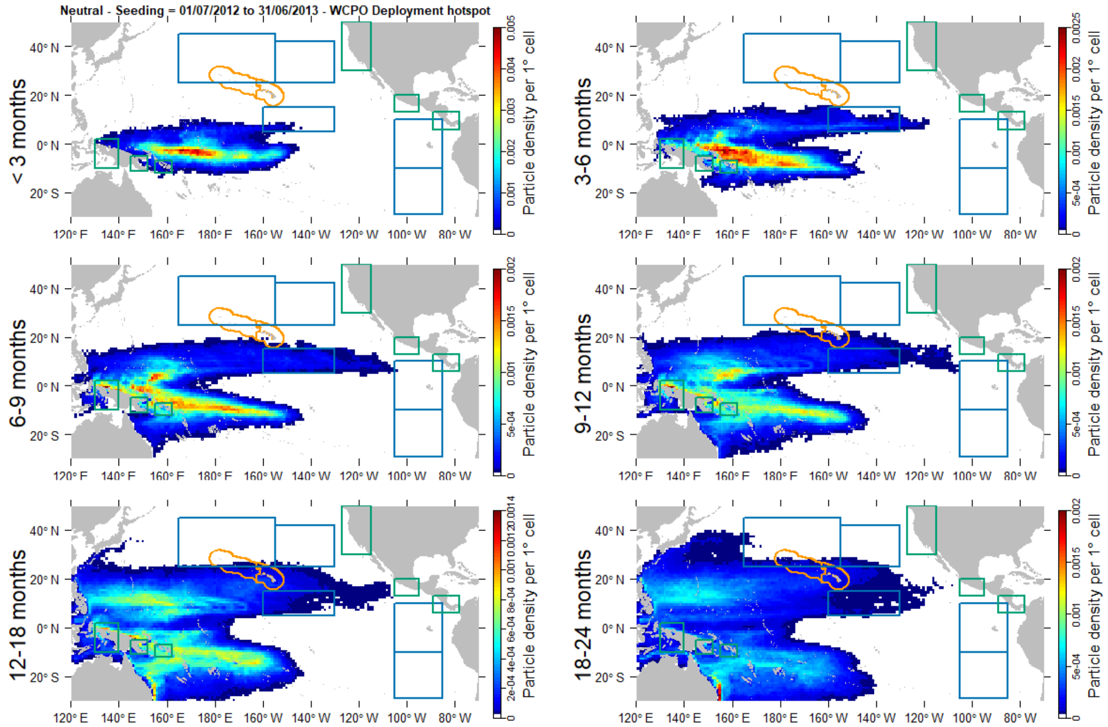

Figure 6. Spatial probability density for virtual particles deployed in the WCPO dFAD deployment hotspots during a Neutral period (01/07/2012 to 31/06/2013) during six drifting time bins after deployment.

5. Discussion

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

For dFADs deployed in the WCPO, it appears that the main areas of concern are:

1. The small leatherback turtle habitats, offshore the nesting sites of Papua New Guinea and the Solomon Islands consistently received and retained vFADs arriving from the southern equatorial regions of the WCPO, which remained being the case when only considering observed dFAD deployment hotspot, although the potential connectivity is reduced.

2. The archipelagic Indonesian leatherback turtle habitat experienced similar high connectivity to the southern equatorial regions of the WCPO, though vFADs appeared more transitive through this zone and arriving after moderate drift times. Again, a similar but reduced connectivity pattern was observed when observed dFAD deployment and FAD density hotspots in the WCPO were used.

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

4. The northern Hawaiian Islands turtle habitats, where the main nesting sites of green turtles are found, 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 dFADs drifting for such long periods, including reduction in subsurface structure or raft netting, should be identified and promoted. A different pattern in vFAD origin was predicted for the main Hawaiian Islands, where the few Critically Endangered Hawksbill Turtles are found. VFADs arriving in the main Hawaiian Islands appear to have likely originated in the EPO, even after moderate drift times of a year or less.

In the EPO, a strong connectivity was noted between the turtle habitats in the south-eastern Pacific Ocean, corresponding to oceanic leatherback turtle migration and feeding grounds (EP1 and EP2), and vFADs deployed in the EPO over short to moderate drift-durations (0-18 months). 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 neighbouring equatorial zones, although this appears to be somewhat mitigated against by the current dFAD deployment and density distributions in the EPOCurrent operational patterns appear to result in a great density of dFADs being deployed south of the equator, which reduces the interaction and connectivity between vFADs and sea turtles. A northern shift in dFAD 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 Hawaiʻi, and nesting sites in the western Pacific Ocean and central America. Changes in the lifespan of dFADs, through adoption of new designs, such as biodegradable dFAD designs, could therefore largely reduce the number of dFAD 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 dFADs is currently on-going (WCPFC CMM 2021-01), which will therefore help mitigate and reduce the interaction between dFADs and sea turtles in oceanic and coastal areas. Although the use of non-entangling and biodegradable dFADs 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 dFADs is recommended in the EPO to reduce the interaction and potential risks between dFADs and sea turtles. The effect on connectivity and density of dFADs under proposed fully non-entangling and biodegradable dFAD measures should be further quantified by examining real and simulated trajectories for each type of design.

Overall, vFADs released in the WCPO spread throughout the western Pacific Ocean, while those 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. 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. Due to such zones being 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 dFADs transit these zones, and mitigation actions against their potential impacts on sea turtles while in these areas, should be maximized.

6. Conclusion

While our results indicate that dFADs deployed in equatorial purse seine fishing grounds overlap with important sea turtles and coastal habitats, although the potential interaction is reduced when observed FAD deployment and FAD density hotspots are used in the analysis, more research is needed to more accurately quantify how sea turtles are impacted by dFADs, 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 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 will work 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.

We invite WCPFC-SC18 to:

- Note the Pacific-wide project to define best practice guidelines and conservation recommendations to reduce the impact of FAD structure on sea turtle populations and habitats in the Pacific Ocean.
- Ensure effective implementation on the prohibition of using mesh net material in the construction of dFADs, as per para 17 of CMM 2021-01, to reduce potential for entanglement given the overlap of dFADs with turtles' oceanic and coastal habitats.
- Note the results on potential connectivity between areas of dFAD deployment and sea turtle habitats in the central equatorial Pacific, archipelagic areas of the western warm pool, and the southeast Pacific Ocean gyre. This connectivity is high when considering all equatorial purse seine fishing grounds for FAD deployment, but reduced for known dFAD deployment/density hotspots.
- Recognize the need for greater knowledge on at-sea interactions between active or abandoned dFADs and at-risk sea turtle populations, including improved understanding for potential for mortality.
- 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, including under various management scenarios such as fully non-entangling, without netting, and biodegradable dFAD management measures.

Acknowledgments

In the EPO, dFAD 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 dFAD deployments and dFAD 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

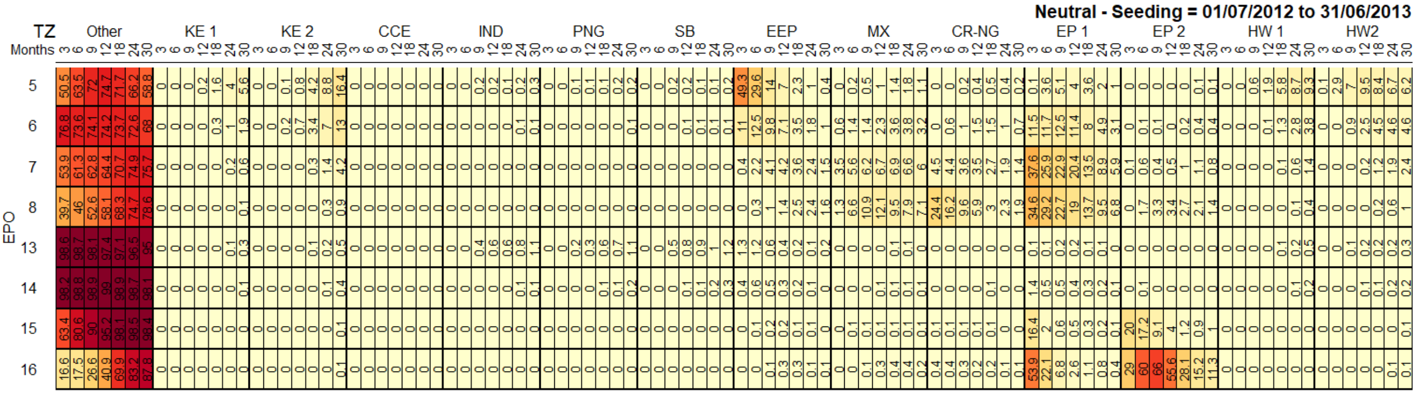

Figure S1. Percentage connectivity matrix of virtual particles in the time-forward simulation during an ENSO Neutral period (01/07/2012 to 31/06/2013) by Turtle Zones (TZ) against seeding in EPO Equatorial Zones (EZ) and separated by drift time in periods of three months. Cells are coloured proportionally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

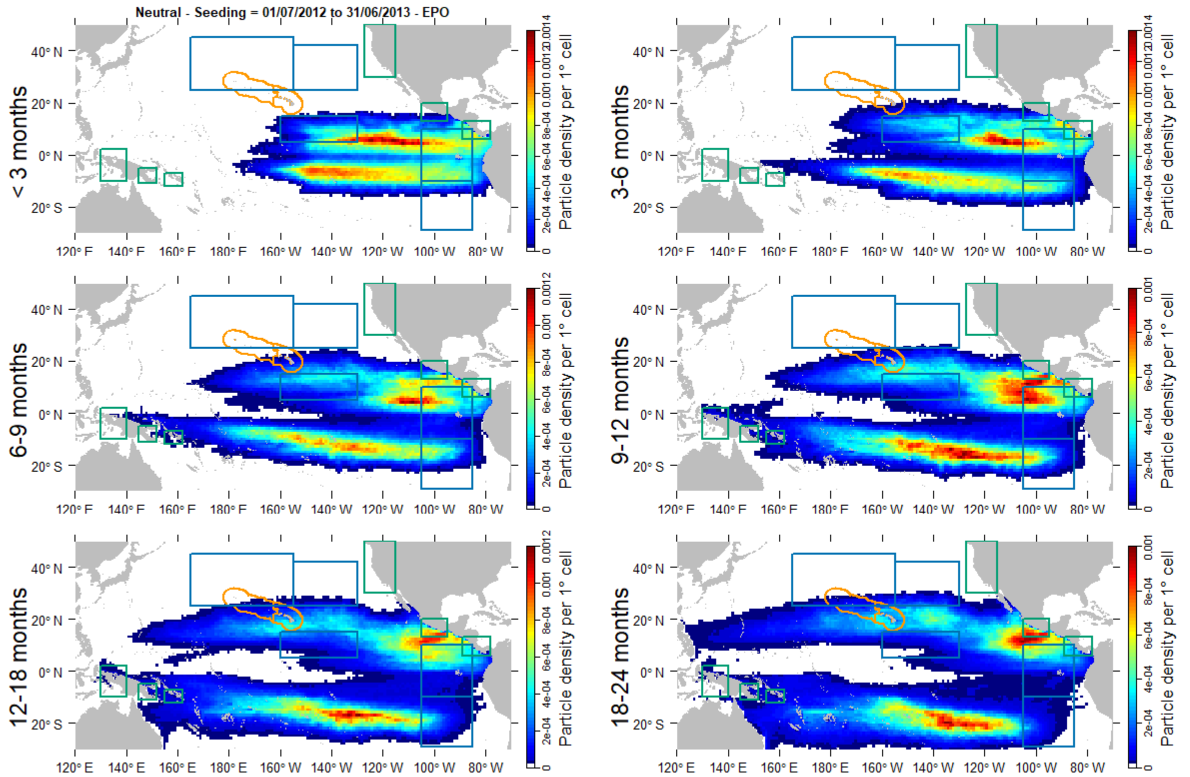

Figure S2. Spatial probability density for virtual particles deployed in the whole equatorial region in the EPO (EZs 5–8 and 13–16) during a Neutral period (01/07/2012 to 31/06/2013) during six drifting time bins after deployment.

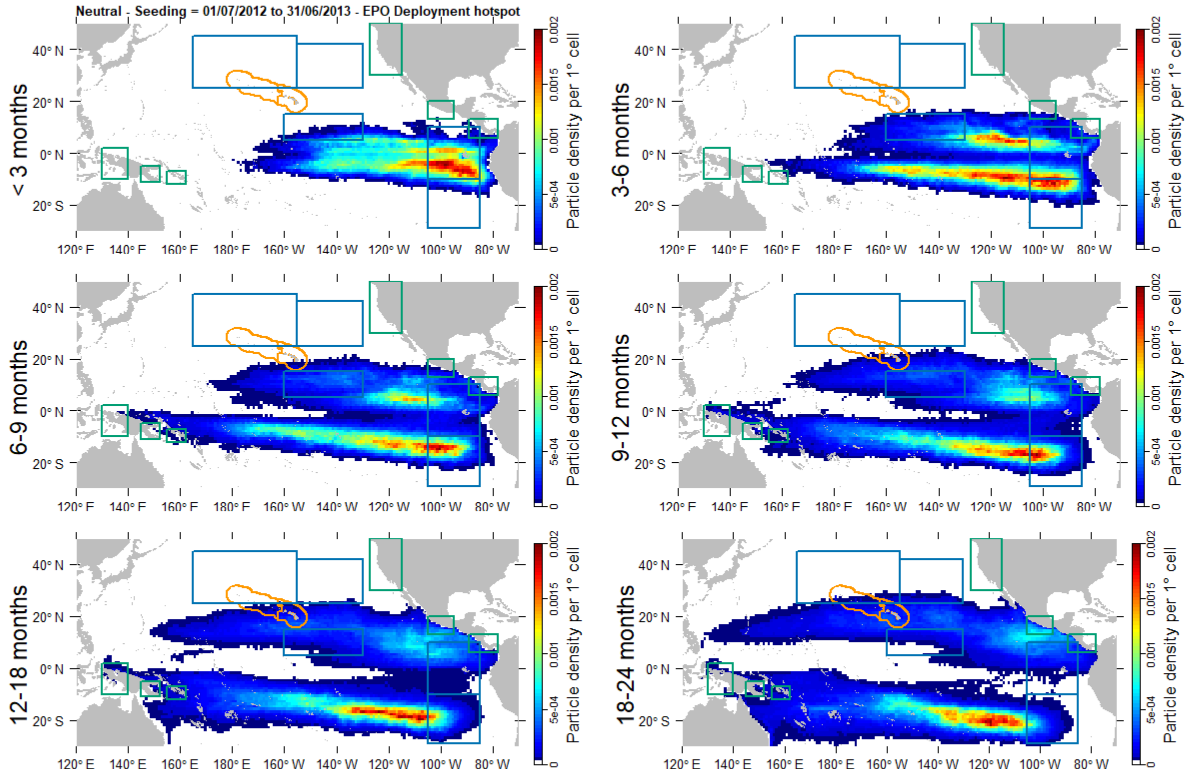

Figure S3. Spatial probability density for virtual particles deployed in the EPO dFAD deployment hotspots during a Neutral period (01/07/2012 to 31/06/2013) during six drifting time bins after deployment.