Supplementary Information

Fishing Operations

Atlantic bluefin tuna were caught by sport fishing vessels in North Carolina and New England using rod and reel techniques and tagged in all cases on the deck of the fishing vessel[2,3,5,6]. In the Gulf of Mexico, bluefin tuna were captured using U.S. registered pelagic longline vessels that routinely fish for yellowfin tuna. Our fishing efforts in the GOM were conducted solely for the purpose of deploying PAT tags and all sets were made in the US exclusive economic zone from 86.06°W to 94.90°W in longitude and 26.67°N to 28.5°N to in latitude. Circle hooks were baited with squid or sardines and positioned at depths of 100-200 m in 1999 and 40-120 m in 2000-2002. Thermocline depths were determined with a CTD profiler (SBE19 plus SEACAT Profiler, Seabird Electronics). Bluefin were tagged at the side of the vessel using a 2 m aluminum tagging pole, and released by cutting the leader as close to the hook as possible. In some cases, the circle hook was removed prior to release. The tags were attached to titanium darts (59 mm x 13 mm) with 136 kg monofilament line (~15 cm). The dart was dipped in antiseptic and inserted into the dorsal musculature at the base of the second dorsal fin.

Six exploratory sets were made in April 1998, averaging 214 hooks per set, using 182 kg monofilament leaders and Mustad 39960 16/0 J hooks (Supplement Table 1). No bluefin were captured but we had several instances where large fish, presumably bluefin tuna, had broken off. We hypothesized that the monofilament leaders and the hooks, which were both old, might be relatively weak and allowed the fish to break off. In 1999, we tested new 136 and 182 kg monofilament Moi Moi leaders and Mustad 39960 16/0 circle hooks. In 2000, we used 182 kg monofilament leaders and Mustad 39960 16/0 and Eagle Claw 20/0 circle hooks. In 2001, we used 182 kg monofilament line leaders and Mustad 39966DT 16/0 circle hooks. In 2002, we used 182 and 227 kg Moi Moi monofilament line leaders and Mustad 39966DT 16/0 circle hooks. In 1999, we increased the hook numbers, and soak time simultaneously in an effort to capture bluefin tuna. We then encountered mortality on longline sets that exceeded experimental fishing permit quotas and operations ceased. The following years, we worked to optimize hook number and reduced soak times to avoid mortality and improve the live release of giant bluefin (Supplement Table 1). Mortalities of bluefin tuna occurred even when sets were of short durations (2000-2002). We hypothesized that sympathetic stress upon capture in warm waters with relatively low oxygen played a role in rapid mortality. Ventilation for fish caught on the longline may also be restricted. Eighteen mortalities of bluefin tuna were encountered during experimental longline operations in the GOM from 1999-2002 (one mortality was partially eaten by a pilot whale and was not measured; another mortality detached from the hook before it could be brought aboard the vessel). All bluefin tuna mortalities were brought aboard the vessel for biological sampling. In sport fishing operations in North Carolina, bluefin tuna were sampled if a mortality occurred during tagging operations (n=3), or from the commercial winter bluefin tuna fishery (n=21). Two giant bluefin tuna (one male and one female) that were captured during a sport fishing tournament in the Bahamas in June were also sampled. Gonad samples from North Carolina and the Gulf of Mexico were preserved in 10% formalin buffered in 0.1M cacodylate at pH 7.4. Tissues were subsequently embedded in paraffin, sectioned (8-10 um), stained with haematoxylin and eosin, and viewed in an Olympus microscope to determine stage of reproductive development.

Electronic Tags

Both types of electronic tags that were used, implantable archival tags with external sensor stalks and PAT tags, provided comparable types of data (Supplement Fig. 1). The numbers of archival and PAT tag deployments from 1996-2004 are shown in Table 1. In this study, both tag types most often provided one year or less of geolocation data. When track lengths were one year or less, both types of tags produced similar spatial distributions in the North Atlantic (Supplement Fig. 1a and b). Analysis of the position datasets indicates a 75.4% overlap of positional data collected with PAT tags (Supplement Fig. 1a, 7455 geopositions) and archival tags (Supplement Fig. 1b, 3641 geopositions). More bluefin geopositions were located in the GOM with PAT tags than archival tags. This was partly due to the selected targeting of larger fish for this tag type, providing increased coverage in this region with the PAT tag (Fig. 1a; Supplement Fig. 1a and b). All geolocations that were from more than 365 days after release (Supplement Fig. 1c, n = 1595), were derived from archival tag tracks. These tracks (≥365 days), while lower in number, demonstrate trans-Atlantic movements of individuals into the Mediterranean Sea. To date, PAT tagged fish have been recaptured in the Mediterranean Sea but only after the electronic tag has released.

Mixing

The electronic tag data indicate that the two stocks are mixing on the foraging grounds (Fig. 1). Estimating mixing rates from electronic tagging data remains difficult and potentially misleading due to the abrupt end of records associated with tag failure (sensor stalk failure, battery failure) or early release of PATs. Together these abbreviated tracks will bias the data to the western Atlantic (Supplement Fig. 1). The effect of time at liberty on the likelihood of a tagged fish being located in the western management unit was investigated. We estimated the probability of Atlantic bluefin tuna being located in the western management unit (Supplement Table 2) after being tagged in the western Atlantic for the three groups of fish identified in this study. The dataset for each group of fish (west, east or neutral) was divided into 6-month intervals and the geoposition data were bootstrapped (1000 bootstrap samples) to estimate the probability that an individual fish would be located in the western management unit during each period. During the initial 6 months post-tagging, fish identified as western spawners and eastern spawners had a high probability of remaining in the western management unit (West: $0.994 > p > 0.982$, East: $0.933 > p > 0.900$, 95% CI, Supplement Table 2). As time at liberty increases, the probability remains relatively high for western fish but decreases rapidly for eastern fish. Fish identified as eastern spawners, at large for more than 720 days, have a relatively low probability of being in the western management unit ($0.082 > p > 0.050$), in comparison to western spawners. During the initial 6 months post-tagging, tuna smaller than 200 cm CFL also had a high probability of remaining in the western Atlantic management unit ($0.999> p > 0.991$, 95% CI, 1000 bootstrap samples).

Our mixing rate assessments with current electronic tag data have biases associated with sample sizes, tag reporting rates, varying release and recapture rates at different locations, and track durations. As electronic tagging technology improves and more archival tags are deployed around the Atlantic Ocean, longer tracks can be expected to provide more information that will be useful for discerning the mixing rate of the bluefin tuna populations.

Supplement Table 1. Catch per unit effort (CPUE)* and mortality per unit effort (MPUE) during scientific longline cruises in the Gulf of Mexico from 1998 to 2002.

Year	Catch (fish)	Mortality (fish)	Number of sets	Soak time (h)	Hooks per set	Total effort (hook hours)	CPUE**	MPUE**
1998	0	0	6	11.3 ± 8.5	214 ± 122	1.52×10^4	0.00	0.00
1999	12	4	8	9.5 ± 2.4	471 ± 96	3.52×10^4	0.34	0.11
2000	20	4	36	1.8 ± 1.1	203 ± 42	1.33×10^4	1.50	0.30
2001	13	5	29	0.9 ± 0.5	133 ± 13	3.61×10^3	3.60	1.38
2002	14	5	33	1.5 ± 0.4	145 ± 4	7.32×10^3	1.91	0.68

*Catches include tagged fish, mortalities, and escapes. Soak times were calculated as the number of hours between the end of the set and the start of the haul.

** Units are fish per 1000 hook hours.

Supplement Table 2. Probability of Atlantic bluefin tuna being located in the western management unit after being tagged in the western Atlantic.[a]

	Probability of fish being located in the western management unit[b]		
Days at large	Western (36)	Eastern (26)	Neutral (268)
1-180	0.994 – 0.982	0.933 – 0.900	0.996 – 0.984
181-360	0.962 – 0.934	0.606 – 0.542	0.951 – 0.927
361-720	0.887 – 0.844	0.347 – 0.288	0.954 – 0.927
>720	1.000 – 1.000	0.082 – 0.050	0.898 – 0.857

[a] Each fish was identified as a western spawner, eastern spawner or neutral fish, based on the criteria described in the text. Fish were released at 3 locations in the western Atlantic (Fig. 1, arrows).

[b] The probabilities shown are the 95% confidence intervals. The numbers of fish used to make these estimates are shown in parentheses. All geoposition data, inclusive of geolocation estimates based on light and SSTs, release and recapture points were used.

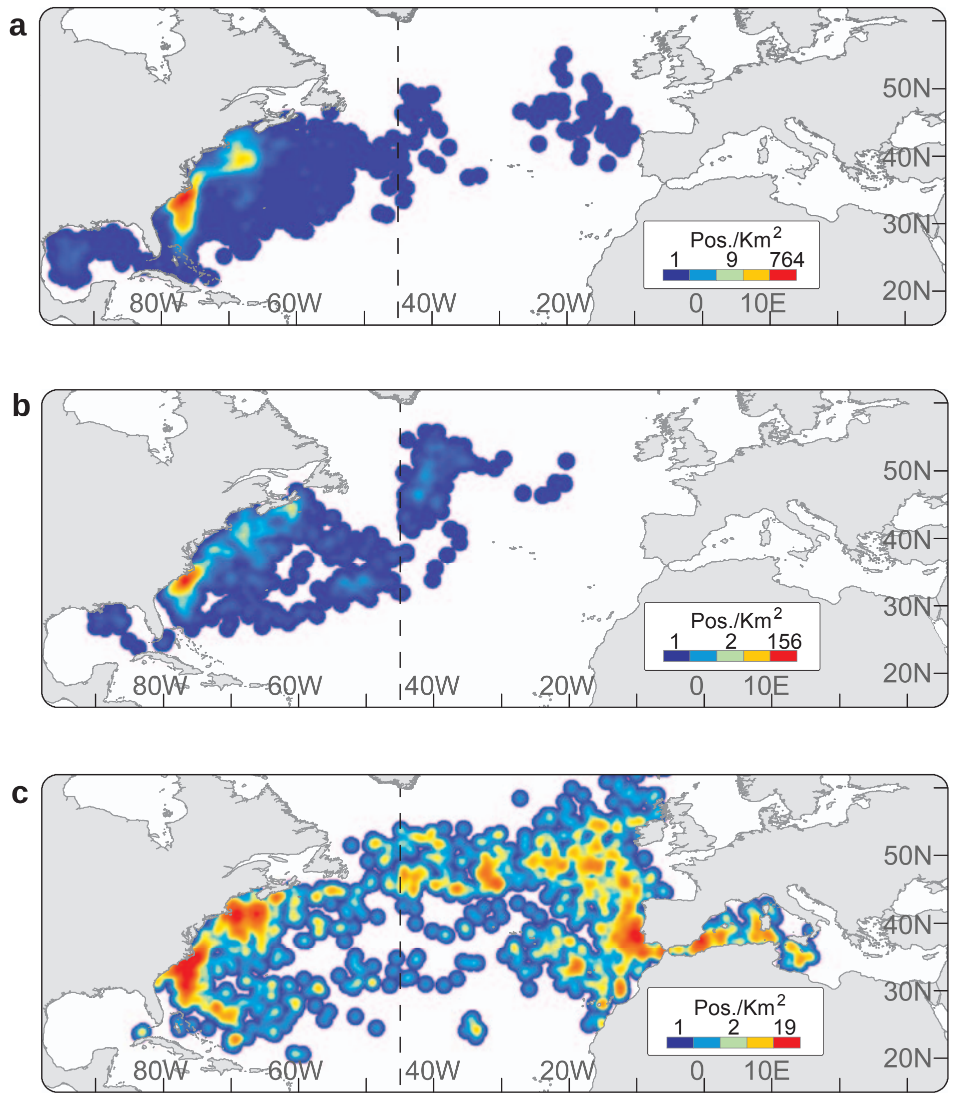
Supplement Figure Legends

Supplement Figure 1. Comparison of geoposition data from two types of electronic tags. Kernel density maps of geoposition data, showing the spatial coverage obtained from archival and PAT tags (1.25° search radius) [29]. **a**, Spatial coverage obtained in the first year post-release using PAT tags (n=244, 212 ± 22 cm CFL). **b**, Spatial coverage of archival tagged fish that recorded data for less than one year (n=27, 199 ± 9 cm CFL). **c**, Spatial coverage of archival tagged fish at large for longer than one year (n=75, 219 ± 15 cm CFL). Long-term tracks are from fish identified as western spawners (n=9); eastern spawners (n=23) and neutral (n= 43). The dashed line in all panels indicates the current ICCAT management boundary.

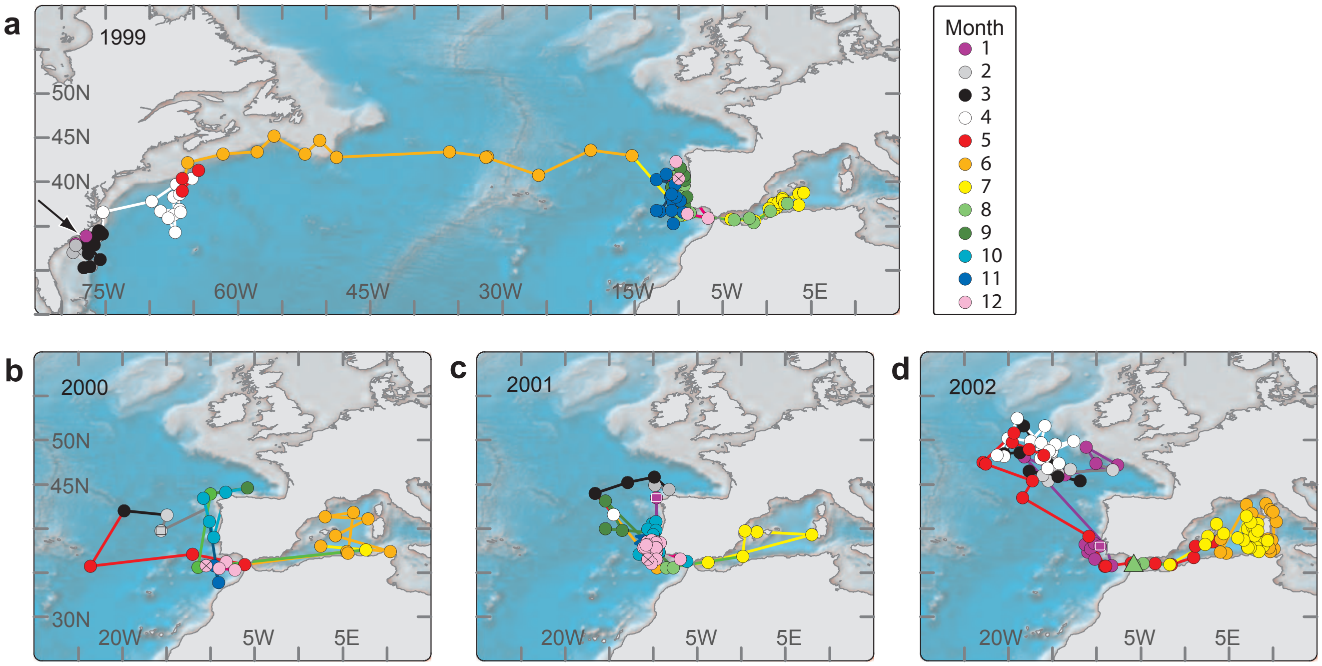
Supplement Figure 2. Movements of an individual Atlantic bluefin tuna (705) that was tagged in the western Atlantic and showed spawning site fidelity to the Mediterranean Sea (222 cm CFL at tagging, 1999-2002). **a**, Archival tag 705 was deployed off North Carolina on the 11 February 1999 (black arrow). In the first year of the track, the fish migrated from the North American shelf waters to the Mediterranean spawning areas. **b-d**, It spent the next three years (2000-2002) in the eastern Atlantic, visiting putative Mediterranean spawning areas in each year and was recaptured in the Straits of Gibraltar on 31 August 2002 (green triangle). Daily latitude estimates were made using SSTs[9], up to when the temperature sensor broke (7 October 2001). Subsequent daily latitude estimates were made using light levels[9]. Geopositions are color coded by month. Start and endpoints for each year are denoted by a square and crosshatched circle, respectively.

Supplement Figure 3. Yellowfin tuna catch per unit effort (CPUE) in the Gulf of Mexico. **a,** Yellowfin tuna CPUE in the Gulf of Mexico, based on the data from the US pelagic longline scientific observer program (1992-2004). **b,** Yellowfin tuna CPUE in the Gulf of Mexico, based on US pelagic longline logbook data (1992-2003). Only 1 x 1° areas with a total effort exceeding 50,000 and 500,000 hook hours are shown for panels a and b, respectively. Areas exceeding this effort without any yellowfin tuna caught are denoted as black crosses.

Supplementary Figure 1

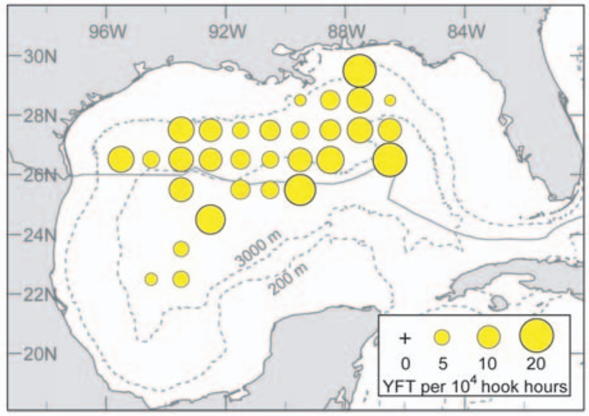


Supplementary Figure 2



Supplementary Figure 3

a



b