STOCK MIXING RATES OF BLUEFIN TUNA FROM CANADIAN LANDINGS: 1975-2015

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SUMMARY

Stock origin of Bluefin tuna caught in the western Atlantic fisheries from 1975 to 2015 was estimated using a randomForest classifier fit to stable isotope ratios of carbon and oxygen. Trends in stock origin and the probability of a particular origin indicate increasingly larger numbers of eastern migrants sourced from the most recent cohorts. Consequently, the younger and smaller fish in the catch are more likely to be of eastern origin. Trends were consistent across regions (Gulf of St. Lawrence, coastal Newfoundland and Atlantic coast of Nova Scotia) but more pronounced in the Gulf of St. Lawrence.

RÉSUMÉ

L'origine du stock de thon rouge capturé dans les pêcheries de l'Atlantique Ouest entre 1975 et 2013 a été estimée à l'aide d'un classificateur randomForest ajusté à des ratios d'isotopes stables de carbone et d'oxygène. Les tendances dans l'origine des stocks et la probabilité d'une certaine origine indiquent un nombre toujours plus grand de migrants de l'Est provenant des cohortes les plus récentes. Par conséquent, les poissons plus petits et plus jeunes dans les prises sont plus susceptibles d'être d'origine orientale. Les tendances ont été cohérentes dans toutes les régions (golfe du Saint-Laurent, côtes de Terre-Neuve, et côte atlantique de la Nouvelle-Écosse) mais plus prononcées dans le golfe du Saint-Laurent.

RESUMEN

Se estimó el origen del stock del atún rojo capturado en las pesquerías del Atlántico occidental desde 1975 hasta 2015, utilizando un clasificador de bosque aleatorio ajustado a ratios de isotopos estables de carbono y oxígeno. Las tendencias en el origen del stock y en la probabilidad de un origen en particular indican un número mayor creciente de migradores orientales procedentes de las cohortes recientes. Por consiguiente, los peces más jóvenes y más pequeños en la captura son los que tienen más probabilidad de ser de origen oriental. Las tendencias fueron similares en las diferentes regiones (golfo de San Lorenzo, costa de Terranova y costa Atlántica de Nueva Escocia), pero más pronunciadas en el golfo de San Lorenzo.

KEYWORDS

*RandomForest, bluefin tuna,
natal origin, stable isotope ratios, annual trends*

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1. Introduction

To date, science recognizes the presence of two spawning grounds for Atlantic Bluefin tuna; the Gulf of Mexico and the Mediterranean Sea. However, very recent evidence from Richardson *et al.* (2016) suggests that at least one additional site may occur on the Slope Sea. The degree to which additional spawning areas affect the traditional view that Bluefin tuna from the western management zone are hatched in the Gulf of Mexico while the eastern fish are hatched in the Mediterranean Sea is not known. The mixing rates presented here assume a two spawning ground model and build on the work presented in Hanke *et al.* (2016). Two additional years of biological sampling of the Canadian landings has occurred and shed some light on the factors that affect mixing as well as reveal interesting trends.

2. Methods

2.1. Data Source

Two data sources were required for this analysis. The first is the baseline data on which the classification models were fit and the second is the samples for which the stock or natal origin is predicted.

The samples were collected from fish harvested off the New England coast and north as far as Newfoundland (NL) (**Table 1**, **Figure 1**). The USA samples were collected in the late 1970's but the majority of samples were collected recently (2010-2015) from the Gulf of St. Lawrence (GSL), Atlantic coast of Nova Scotia (NS) and Newfoundland.

The baseline data were made available by Rooker *et al.* (2014) and can be accessed at www.int-res.com/articles/suppl/m504p265_supp.xls.

2.2. Biological Sampling

The details of the USA catch from New England and Virginia dating back to the late 1970s are not known. We assume that these samples were collected by the same methods as the more modern samples described below.

Bluefin tuna heads labeled with a unique commercial tag number were stockpiled by fishermen and co-ops, and then sampled by a field technician. Sampling consisted of extracting sagittal otoliths from Atlantic Bluefin tuna heads and taking snout length measurements (Busawon *et al.* 2013).

The commercial tag number was linked to commercial databases to obtain catch (e.g. location) and size information. In some cases, the curved fork length of the fish was not reported in commercial databases or the label with the commercial tag number was lost. In these instances, we used monthly length-weight conversion (ICCAT 2006) and snout length conversion (Secor *et al.* 2014) to calculate curved fork length.

2.3. Natal origin

A single otolith (right or left) from each sample was embedded in resin and a 2.0 mm thick section was cut from the centre containing the juvenile portion of the otolith. A template from measured juvenile otolith sections was used to identify the first annulus, which increased the consistency of the cut location (Rooker *et al.* 2008). Carbonate material was milled from the identified region using a New Wave Micromill©. Samples were analyzed for $\delta^{18}O$ and $\delta^{13}C$ (±0.1‰ and ±0.6‰ respectively for $\delta^{18}O$ and $\delta^{13}C$) at the University of Arizona Environmental Isotope Laboratory. For more detail on the otolith processing methodology see Schloesser *et al.* (2010) and Secor *et al.* (2013).

Otolith δ18O and δ13C from historical samples collected in New England, Virginia, Caraquet and Miscou (1975-1977) were corrected for the Suess Effect prior to analysis (Schloesser *et al.* 2009). Powdered otolith extracted from the otolith core was analyzed to determine the isotropic differences of ^{13}C and ^{18}O from their isotropic standards. The calculation is:

$$\delta^{A}X_{STD} = \frac{^{A}R_{Sample}}{^{A}R_{STD}} - 1$$

Here δ expresses the abundance of isotope A of element X in a sample relative to the abundance of that same isotope in the isotopic standard (McKinney *et al.* 1950).

2.4. Data analysis

Classification of the samples to a stock was accomplished using a randomForest (Liaw and Wiener 2002) classifier.

2.4.1. RandomForest models

A randomForest model was trained on the base observations of $\delta^{13}C$ and $\delta^{18}O$ with no attempt to expand the basis. Each classifier was based on 500 trees with one variable tried at each split. Given that the base observation probabilities favoured the East, equal sample sizes were specified to reduce the emphasis of this class during training and, through class weighting factors, more priority was given to $\delta^{18}O$ in the fitting. Tuning was performed to determine the optimum threshold value for assigning each sample's class probability to a class. Resampling was not explicitly conducted because training on a subset of the data and testing on the remainder is intrinsic to the randomForest algorithm. This makes randomForest resistant to over fitting.

3. Results

3.1 randomForest Analysis

The reader may refer to Hanke *et al.* 2016 for a comparison of the random Forest and both LDA and QDA classifiers. The randomForest model that was fit by Hanke *et al.* (2016), which accounted for unequal sample size, was also used here.

Origin

Each sample had a class probability which determined the plausibility of belonging to the eastern or western stock. Through a tuning process it was determined that the cutoff or threshold applied to the predicted class probabilities yielded optimal sensitivity and specificity at 0.474 rather than at the default of 0.5. The predicted origin of the samples yielded mixing rates by region (**Table 2**, **Figure 2**) that increased annually since 2010, particularly in the Gulf of St. Lawrence (GSL) and Newfoundland (NL). Nova Scotia also experienced a recent increase in the proportion of eastern migrants.

Size

The relationship between the probability of belonging to the eastern stock and fish size (curved fork length) is shown in **Figure 3.** For both NS and GSL, the probability of eastern origin decreases with increasing fish size. The remaining regions did not have samples across the full range of fish sizes. They do, however, represent samples taken from more northern (NL) and southern (USA) regions which cater to only larger (north) or smaller (south) fish.

Age

Direct ages were estimated for all Bluefin tuna that received a stock assignment and class probability except the USA samples. Ages ranged from 7 to 24 for both the nS and GSL regions. NL had no fish younger than 11. As in the case for size, the probability of eastern origin declined with increasing age (**Figure 4**). This relationship was more evident in the NL and GSL samples than for the NS samples. The NS fish younger than 16 had a marginally higher probability than those older than 16. These trends are also evident in the proportion of eastern fish by age and region.

Cohort

Another perspective on the mixing is afforded by assigning each Bluefin tuna to its year class (**Figure 5**). Because there are six years of data, similarly aged fish caught in different years would come from different cohorts. The oldest cohort dates back to 1977 and the most recent is from 2008. In both NL and the GSL, the more recent cohorts contain a large fraction of eastern migrants. Because there are a smaller number of NL samples, the trend is less continuous. The signal for NS is variable; however, cohorts with a high proportion of eastern migrants occur periodically (1992, 1998, 2005 and 2008).

Figure 6 provides an alternate view of the same data, albeit for the probability of western origin. The linear trends in all regions with sufficient data is for western fish to dominate the older ages and older cohorts.

Sample stable isotope ratios relative to baseline samples

Figure 7 provides the confidence ellipses for both the eastern and western Bluefin stock baseline samples with an inner ellipse containing 68% of the observations and an outer ellipse containing 95% of the observations. The samples obtained from the fishery largely fall within the eastern and western ellipses for $\delta^{18}O$ but a large fraction lies outside these ellipses for $\delta^{13}C$. The larger $\delta^{13}C$ values are associated with the oldest cohorts. A linear model relating $\delta^{13}C$ to the year of hatch of the fish (cohort) had a slope of $-3.04x10^{-2}$ and an intercept of 52.6.

A close examination of the baseline data used in developing the randomForest classifier reveals inter site variability within population, and inter annual variability within site for both $\delta^{18}O$ and $\delta^{13}C$ (**Figure 8**). The variability is larger for $\delta^{13}C$ than it is for $\delta^{18}O$ and results in poor separation between populations on the basis of this metric. The change in $\delta^{13}C$ over years within a site is faster than what is described in Schloesser (2009) and is bidirectional. The Bay of Biscay, for example, shows declines in $\delta^{13}C$ of approximately 0.13 to 0.3 units per year compared to 0.0256 (Schloesser 2009) and 0.0304 from the samples.

4. Discussion

A review of all the mixing information obtained from Bluefin tuna caught in the Canadian EEZ from 2010 to 2015 show trends related to age, size and year of hatch of the fish. Notably, recent cohorts have the largest proportion of eastern fish. The increasing trend is clear in the GSL where we have a lot of data and the fishing is concentrated in a relatively smaller area. Catches off coastal Newfoundland, where Bluefin have been arriving in increasingly larger numbers since 2010, also show this increasing trend, though there is less data. The Atlantic coast of Nova Scotia is the largest of the areas and also provided the most variable, though similar, relationship between the year of hatch and the proportion of eastern fish.

The catch data indicates that the GSL fishery has been capturing an increasingly larger number of small tuna since the early 2000s (SCRS/2017/020) and the stock origin results suggest that the smaller or younger tuna were more likely of eastern origin. In the Atlantic fishery, where the average weight of tuna has been increasing over the same period and approaching that of the GSL, small size is also associated with a higher probability of eastern origin. Given that recent cohorts have a larger proportion of eastern fish and that large fish tend not to be of eastern origin suggests either that only young eastern fish are foraging in the Canadian EEZ or that there has been a recent influx of eastern fish into Canadian waters that continues to increase annually and may persist into the future provided the drivers continue to exist. The recent arrival of large number of Bluefin tuna in coastal Newfoundland and the steady shift in the size composition of the catch in the GSL seem to favour the later. Continued monitoring of the catch should show a larger fraction of older fish of eastern origin if this is the case.

This review of the mixing data did not consider the seasonality of the sampling and the part that this may play in the interpretation of the trends provided. The differences between regions are partially a function of the difference in the timing in the fishing and are dictated by the arrival, residency and departure times of the fish. An examination of the seasonal variation in mixing within regions will be considered in future analyses.

The existence of stable isotope values outside the confidence ellipses of both the eastern and western baseline data has been used to infer that Bluefin tuna are spawning in regions outside the two known spawning grounds. However, these outliers are only with respect to $\delta^{13}C$ which was shown to undergo significant inter annual variation within sample location in the baseline data. Some effort needs to be dedicated to understanding the potential sources of the variability in the baseline stable isotope data as well as providing explanations for the existence of the outliers. Given that there are very few outliers related to $\delta^{18}O$ and that $\delta^{13}C$ has very little discriminatory power in the model, to the extent that one can omit it without affecting the estimated mixing rates or increasing the classification error, resolving the issue with $\delta^{13}C$ will not affect mixing rates unless a more clear separation between eastern and western baseline samples can be achieved.

Lastly, no attempt has been made to provide a model that relates stock origin or probability of a particular origin to features of the sample data like year of hatch, age, location date and size of the fish. For such a model to be useful, it needs to be coordinated/integrated with an overall scheme for estimating mixing rates across the domain of the western Atlantic Bluefin stock. This scheme will include assessing the value or contribution of all stock assignment methods (stable isotope, genetic or shape analyses) in estimating mixing rates.

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Table 1. Number of otoliths milled by region and year. GSL=Gulf of St. Lawrence, NB=New Brunswick, NL=Newfoundland, NS=Nova Scotia

	Years								
Area	***1975***	***1976***	***1977***	***2010***	***2011***	***2012***	***2013***	***2014***	***2015***	***Sum***
GSL	5	0	5	1	187	187	251	163	174	973
NB	0	0	0	0	0	0	0	4	0	4
NL	0	0	0	8	0	0	25	22	7	62
NS	0	0	0	70	119	106	62	110	161	628
USA	0	6	20	0	0	0	0	0	0	26
Sum	5	6	25	79	306	293	338	299	342	1693

Table 2. Regional estimates of the proportion of samples predicted by the base model to be of eastern origin. The fit was based on a randomForest classifier with equal sample sizes per class and heavier class weights on δ18O. The threshold for classification was {0.53, 0.47}.

Region	**1975**	**1976**	**1977**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
GSL	0	.	0	0	0.07	0.08	0.10	0.26	0.28
NL	.	.	.	0	.	.	0.04	0.41	0.86
NS	.	.	.	0.14	0.22	0.14	0.06	0.22	0.37
NB	.	.	.	.	.	.	.	0	.
USA	.	0	0.35	.	.	.	.	.	.

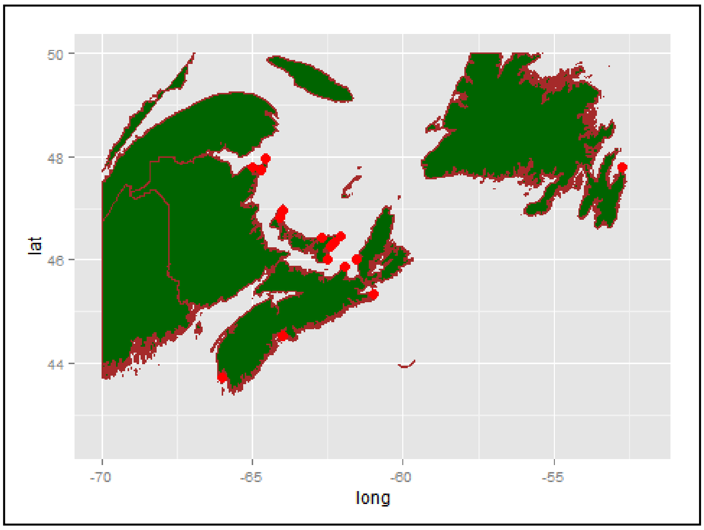

Figure 1. Atlantic Provinces of Canada with main Bluefin tuna head sampling locations for the period 1975 to 2015. USA sites are not shown.

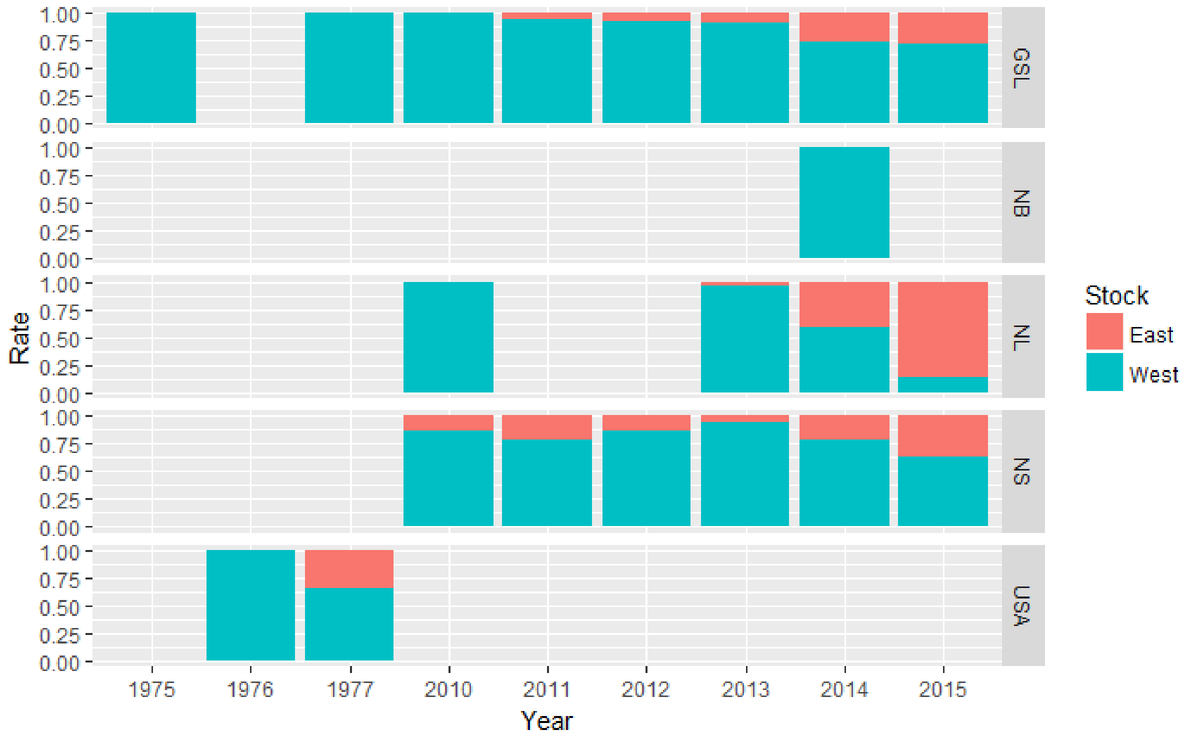

Figure 2. Estimated proportion of landings by region and year predicted by the base model to be of eastern origin. The fit was based on a randomForest classifier with equal sample sizes per class and heavier class weights on δ18O. The threshold for classification was {0.53, 0.47}.

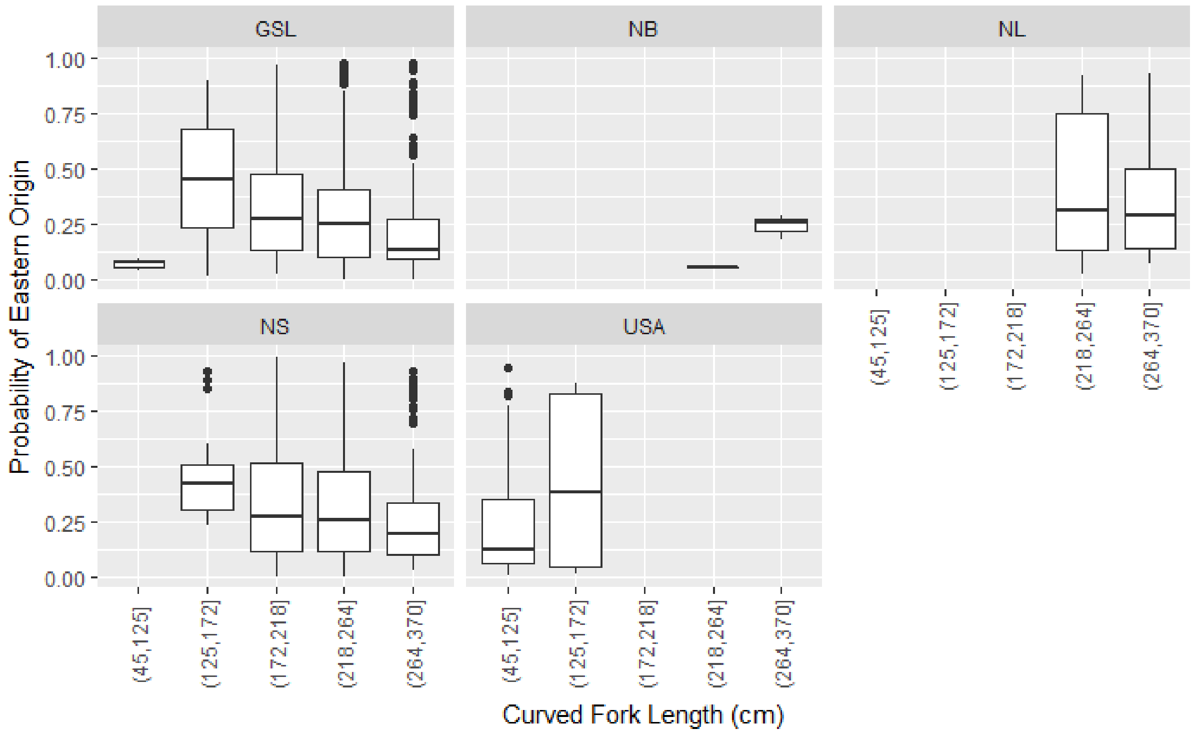

Figure 3. Regional trends in the relationship between the predicted class probability and Bluefin tuna curved fork length.

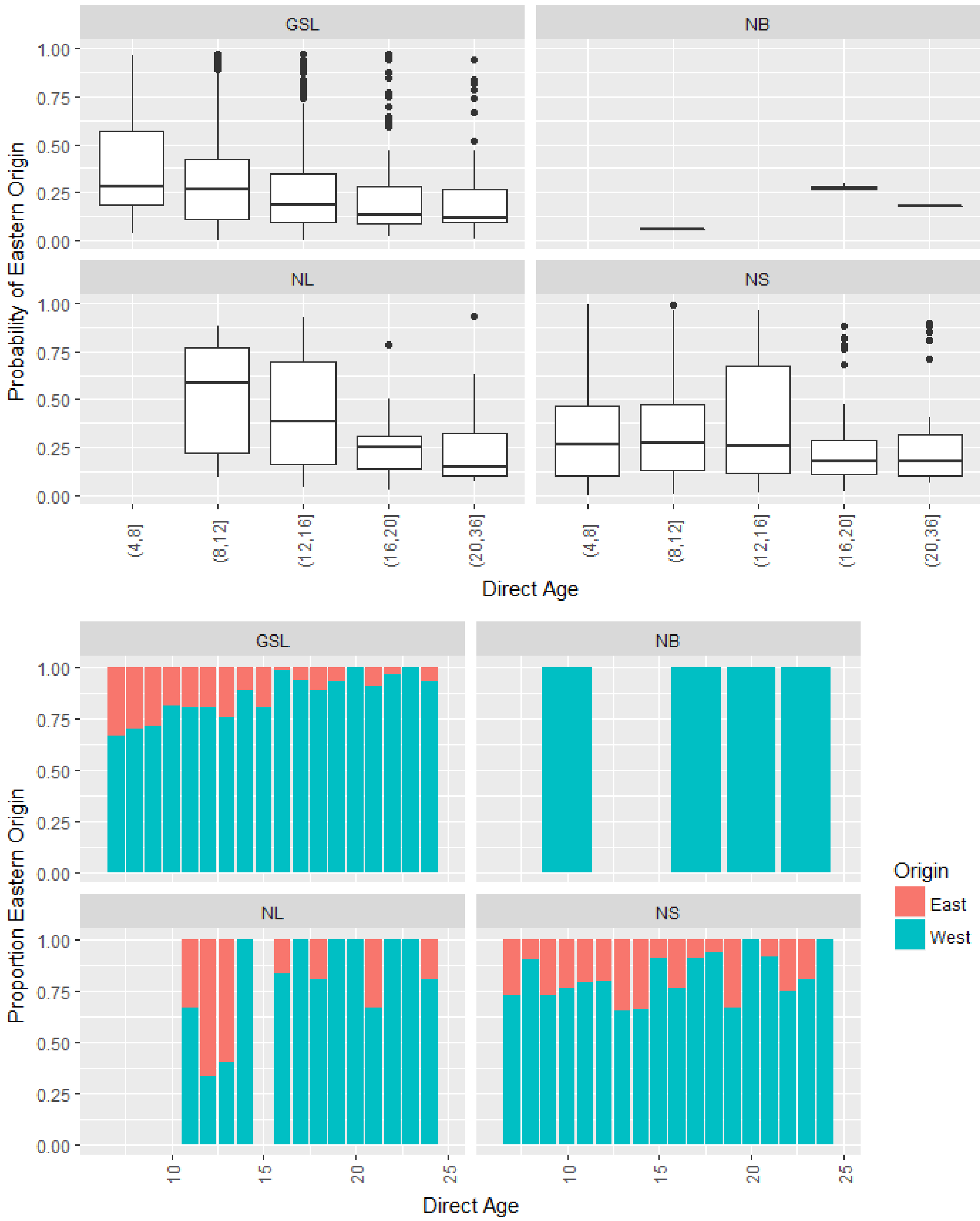

Figure 4. Probability of eastern origin (top) and stock origin composition (bottom) for similar aged Bluefin tuna landed in regions within the Canadian EEZ. Samples were collected in calendar years 2010 to 2015.

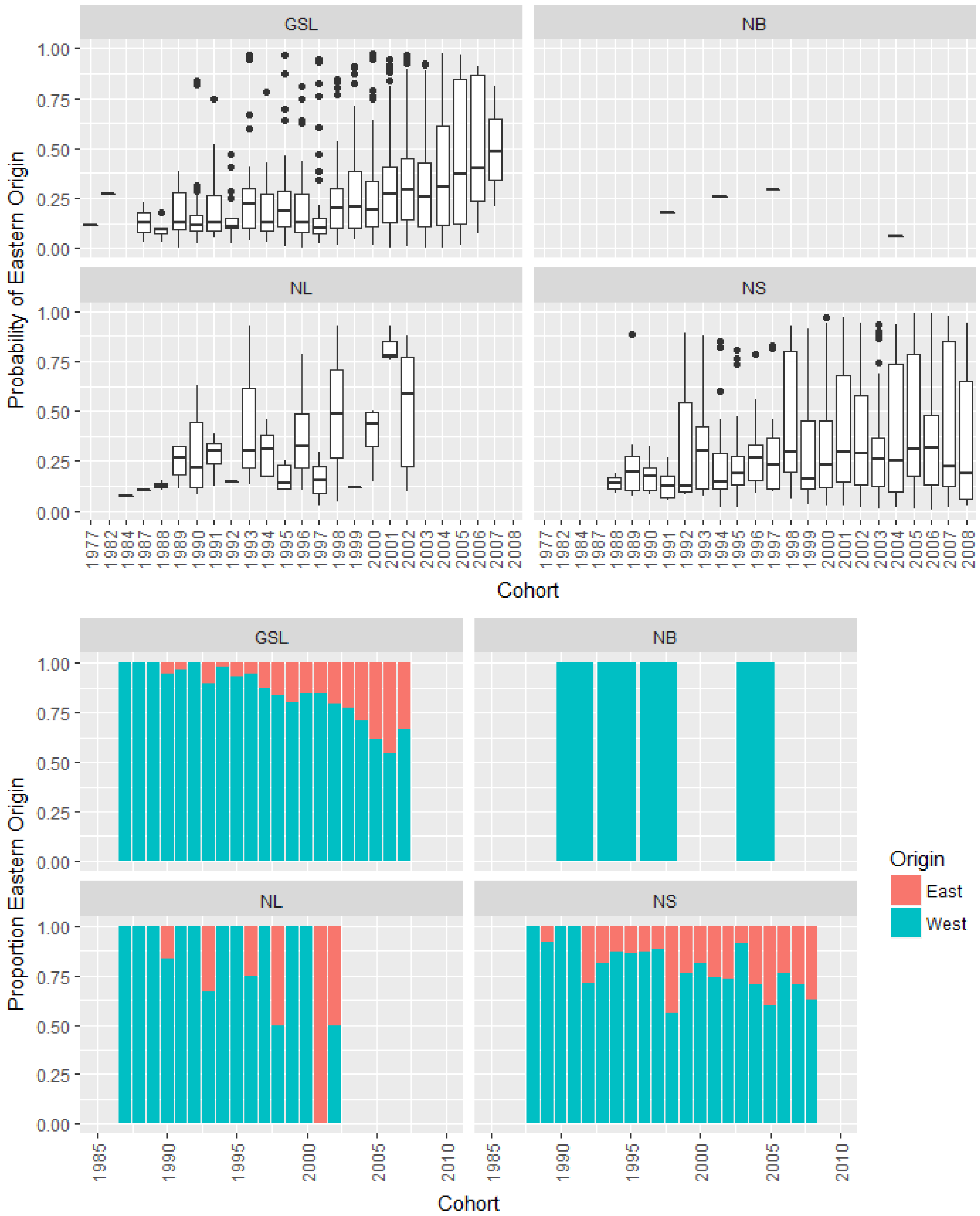

Figure 5. Probability of eastern origin (top) and stock origin composition (bottom) for cohorts of Bluefin tuna landed in regions within the Canadian EEZ. Samples were collected in calendar years 2010 to 2015.

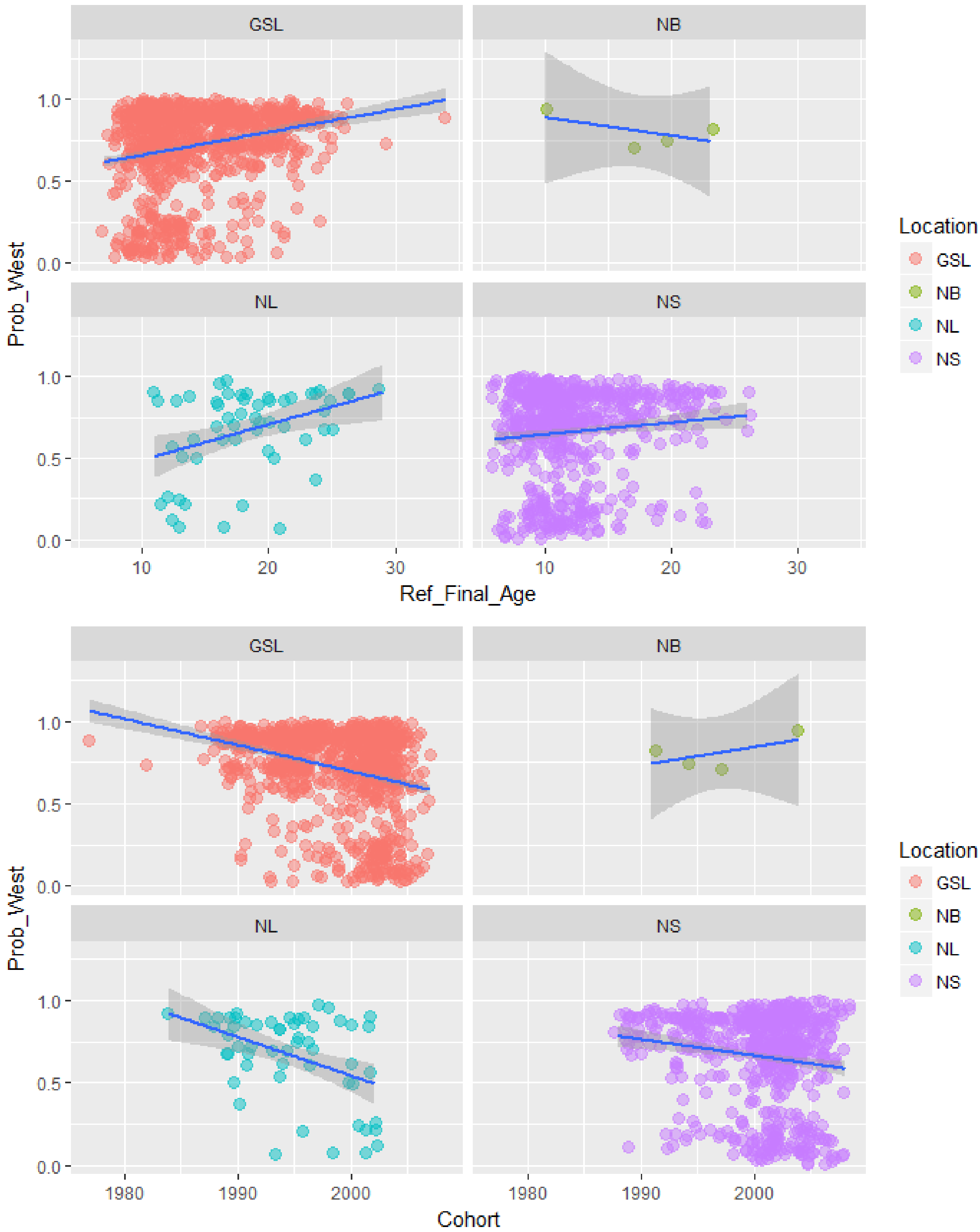

Figure 6. Regional trends in the probability of Western origin by direct age (top) and cohort (bottom).

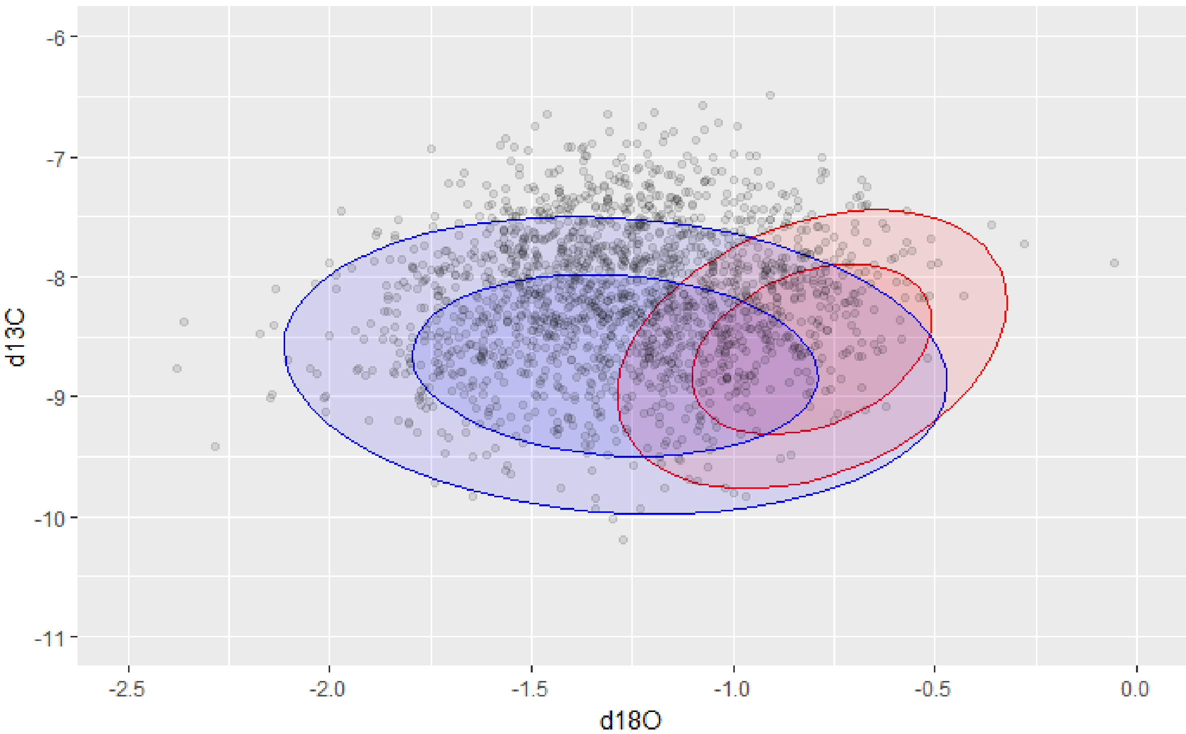

Figure 7. The relationship between the base observations and the sample stable isotope observations. 95% and 68% confidence ellipses for eastern and western base observations are red and blue, respectively, while the sample observations are the black points.

Figure 8. Spatial and inter annual variability of δ13C (top) and δ18O (bottom) from the baseline data (Rooker *et al.* (2014); www.int-res.com/articles/suppl/m504p265_supp.xls).