PRELIMINARY RESULTS ANALYSES OF WEIGHT GAIN OF BLUEFIN TUNA (*THUNNUS THYNNUS*) IN FARMS FROM THE FARM HARVEST DATABASE 2015 -2020

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SUMMARY

Fattening of bluefin has become one of the main operations and destination of the catches of eastern bluefin in the Mediterranean Sea. Since 2008 a regional observer program (ROP-BFT) collects size and weight measures of harvested bluefin. Data from 2015-2020 harvest operations were reviewed to estimate the weight gain of eastern bluefin in farming operations. It was also estimated the potential growth associated with farming as function of days-at-farm, size at catch, and farm. Preliminary results from in situ tagging experiments and from size-mode progression analysis data from stereoscopic camera experiments indicated an increase in length growth of the farmed with respect to the wild ones for medium and large E-BFT fish. A preliminary analysis and results estimating a farm-growth model equation are presented. This study addressed part of the 2018 ICCAT Commission request on the maximum expected growth of farmed E-BFT.

RÉSUMÉ

L'engraissement du thon rouge est devenu l'une des principales opérations et destination des captures de thon rouge de l'Est en mer Méditerranée. Depuis 2008, un programme d'observateurs régionaux (ROP-BFT) collecte les mesures de taille et de poids des thons rouges mis à mort. Les données des opérations de mise à mort de 2015-2020 ont été examinées afin d'estimer la prise de poids du thon rouge de l'Est dans les opérations d'élevage. On a également estimé la croissance potentielle associée à l'engraissement en fonction des jours passés à la ferme, de la taille à la capture et de la ferme. Les résultats préliminaires des expériences de marquage in situ et des données d'analyse de la progression du mode de taille provenant des expériences des caméras stéréoscopiques indiquaient une augmentation de la croissance en taille des poissons d'élevage par rapport aux poissons sauvages pour les thons rouges de l'Est de taille moyenne et grande. Une analyse préliminaire et les résultats de l'estimation d'une équation du modèle ferme-croissance sont présentés. Cette étude a répondu à une partie de la demande de la Commission de l'ICCAT de 2018 sur la croissance maximale attendue du thon rouge de l'Est d'élevage.

RESUMEN

El engorde de atún rojo se ha convertido en una de las principales operaciones y destino de las capturas de atún rojo del este en el Mediterráneo. Desde 2008, un programa regional de observadores (ROP-BFT) recopila mediciones de talla y peso del atún rojo sacrificado. Se examinaron los datos de las operaciones de sacrificio de 2015-2020 para estimar la ganancia de peso del atún rojo oriental en las operaciones de cría. También se estimó el crecimiento potencial asociado con la cría como una función de días en la graja, talla de captura y granja. Los resultados preliminares de los experimentos de marcado in situ y de los datos de progresión del modo de talla de los experimentos con cámaras estereoscópicas indicaban un aumento en el crecimiento de la talla de los peces de granja respecto a los salvajes para los atunes rojo del este medianos y grandes. Se presentan un análisis preliminar y los resultados que estiman una ecuación del modelo granja-crecimiento. Este estudio abordaba parte de la solicitud de la Comisión de ICCAT de 2018 sobre el crecimiento máximo previsto del atún rojo del este de granja.

KEYWORDS

Bluefin tuna, Thunnus thynnus, farm, growth, size distribution

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1. Introduction

Fattening of bluefin is one of the main operations and objectives for the catches of eastern bluefin in the Mediterranean Sea and East Atlantic during the last decades. Based on catches from purse-seine vessels about 75% of the annual catch of eastern bluefin are destined to farms. Farms hold the fish from few months to over 2 years, depending on the size and other factors including market conditions.

Bluefin for farming operations is almost all caught with purse-seine vessels that transfer the live fish to holding pens, which are slowly towed and finally transfer to sea-cages in the farms. A relatively small portion of caged fish is caught from BFT traps which are transferred to holding cages for fattening. Because of the nature of the fishing operations, it is difficult to obtain estimates of the catch in both numbers, weight, and size/age distribution of the wild fish caught. However, since the full implementation of stereo-camera systems in 2015, more reliable estimates of the number of fish and their size distribution have been available.

As with most aquaculture operations, farming of bluefin enhances the growth compared to wild populations, but whether this growth is only on weight (e.g. condition index) and or both size and weight (intrinsic growth rate) is still being investigated. Early research studies with small bluefin tuna in the Adriatic Sea have confirmed and reported increases in growth rates of both size and weight for farmed Eastern Atlantic bluefin (Katavic et al, 2010). While, for medium and large bluefin fish kept in farms for less than 2 years reported only increases in weight (Gordoa 2010 Deguara et al. 2011), with size increments similar to wild fish. However, recent experimental studies using *in-situ* tagging experiments, and analysis of size-mode progression (MPA) from periodic monitoring of size distribution within cages with stereoscopic cameras, are suggesting increases of the Eastern BFT intrinsic growth compare to the wild fish (SCRS/2021/145, SCRS/2021/150). Similarly, in farming operations with Pacific BFT (*Thunnus orientalis*) they have also reported increases in intrinsic growth rates, both in length and weight, when compared to wild populations (Masuma et al, 2008, Vergara-Solana 2019).

There are however large variations in size/weight gains among BFT farms in the Atlantic and the Mediterranean Sea, likely in response to differences in husbandry and environmental conditions. If it is assumed that intrinsic growth rates of bluefin tuna are not affected by farming, then it is possible to estimate the size at catch if the size at harvest and the time in the farm are known. Previous studies have presented estimates of catch at size from harvesting size data provided by the farms and CPCs to ICCAT since 2008 (Ortiz 2017, Ortiz et al 2014). The present study updated estimates of potential growth for farmed E-BFT as function of the initial size at caging and the time in the farm, using results from the MPA experiments. This study is part of the SCRS response to the 2018 ICCAT Commission request on the maximum expected growth rates for farmed E-BFT (Rec. 20-07, para 8).

2. Data

The size and weight of sacrificed bluefin tuna from farms started to be reported in June 2008, following the Rec 08/05. In 2014 a database was created identifying each harvesting operation (per day when available) by registered farm and auxiliary data such as date of catch, or the bluefin catch document number where the details of the catching operations are recorded. Harvest operations at farms require the presence of a scientific observer from the ICCAT Regional Observer Program (ROP-BFT) currently operated by MRAG/COFREPECHE Consortium, which collects and enters the data into a database and provided it to the ICCAT Secretariat. For 2015-2021 there were 10,005 harvest operations (e.g. per flag, farm, cage, and date of harvesting) monitored in 29 farms from eight CPCs EU-Croatia (6 farms), EU-Spain (5 farms), EU-Malta (6 farms), EU-Italy (1 farm), Morocco (1 farm), Tunisia (3 farms) and Turkey (7 farms). The reports for 2021 are partial and were not included in this analysis. Of the 9,938 harvest operations monitored between 2015 and 2020, size and weight measures were collected with over 155 thousand fish measured and weighted, with a total harvested weight monitored of 31,933 t (**Table 1**, **Fig 1**).

At harvest size measurements are reported as straight (SFL, 49%) or curved (CFL, 58%) fork length, with 8584 fish where both measures were recorded. This data subset was used to estimate an at-harvest conversion factor for CFL measures using a robust linear function, to convert all size measures to standard SFL (cm) units (**Fig 2**). Size conversions by farm were explored but no statistical differences were found compared to the combined data. The weight of harvested fish is mainly reported as whole round whole weight (RWT kg, 96%), with few reports of gutted head off (3.5%), or gilled and gutted (0.3%) (**Fig 3**). For this analysis, only RWT observations were used. 90% of the harvest operations have their corresponding bluefin catch documentation record (about 1,355 BCDs) and by linking with the BCD database it was possible to obtain the date of the caging and or date of catch if missing caging information. In few instances (98 records out of 14,044) the date of harvest was before the date of catch/caging, these records were excluded. Days at farm was calculated for each observation. Harvesting included fish caught as early as 2012 however, most of the fish are harvested during the 1st or 2nd year after being caught (**Fig 4**). **Figure 5** shows the size distribution (SFL) of the harvested bluefin by the flag of the farms 2015 - 2020.

Methods

If it is assumed that farmed bluefin tuna maintain their intrinsic growth rates of size at age, as done in prior analyses (Ortiz et al. 2014), then size at catch can be simply estimated using the invert of the growth equation (Cort et al, 1991) for eastern bluefin tuna and discounting the days-at-farm. So, as a first approach in this study, once the estimated size at catch was estimated, then the expected weight at catch was calculated using the current monthly conversion factors for weight-at-size (Rodriguez-Marin et al. 2015) or the length-weight relationship for monitoring weight at catch from stereo-camera measures (Deguara *et al*., 2017).

An initial analysis was done comparing the overall weight at size for harvest versus wild bluefin tuna. Data of weight at size of wild fish was made available from the study of Rodriguez-Marin et al. (2015). **Figure 6** shows the overall gain in weight vs days at farm, with an increasing trend as fish, are held for longer times in the farms. However, it is noticeable the large variability in weight and even in the initial week(s) of caging, some reductions in weight due likely to the stress induced by the catch and transfer of fish from the wild until they restore feeding behavior in the farms. Because of this large variability in weight at size it was decided to use quantile regression analysis to compare if the weight at size differs between wild and farmed fish. **Figure 7** shows the comparison of the predicted quantile regression weight at size for the wild vs farmed bluefin tuna with corresponding 95% percentile bounds (shaded areas).

For eastern Atlantic bluefin tuna is has been demonstrated that growth rates in farms for smaller fish (e.g. < 100 cm SFL) is higher than for wild fish (Katavic et al 2010), therefore the estimation of weight gain in farms was restricted to fish over 100 cm SFL. However, recent studies of farmed Pacific bluefin tuna and ongoing trials with Atlantic bluefin farmed fish, suggest an increase of intrinsic growth rates also for medium and large-size fish. Unfortunately, there is not sufficient data to directly estimate a growth model for farmed Atlantic bluefin. Preliminary results from the mode-size progression analysis (MPA) by fish size category carried out recently by GBYP (**Table 2**) indicate larger increases of size per month of farmed fish compared to the current growth model of wild fish (Cort et al, 1991). It must be taken into account that these monthly growth rates, due to the short duration of the trials, correspond only to the warmer months were the growth rated are expected to be higher. Therefore, it was decided to use the MPA estimates from experiments that monitored the caged fish for the whole year. If we can assume that farming increases mainly the metabolic rates of growth (e.g. K parameter of the von Bertalanffy growth model), as food intake and supply is greater and energy consumption associated for example with migration or food searching is lower, while the overall maximum size does not change as this is likely more a genetic trade associated with age (e.g. L_{inf}), then we can estimate a K-modification factor that when applied to the growth model of wild fish increases the growth rates. Based on this, it was used the current SCRS E-BFT growth model (Cort et al, 1991) parameters and minimize the sum of squares between the MPA observed increases and the predicted average monthly increases in size by class groups. With this approach, it was estimated a K-modification factor of 1.30. **Figure 9** shows the estimated farm growth model for bluefin tuna using this preliminary approach.

With the estimated farm growth model it was recalculated the gain in weight as function of days at farm and the initial size at caging using the harvesting data. Briefly, the size at catch was estimated using the inverse of the farm growth model and discounting the days at farm. Then, weight gain in the farm was modeled as function of the time spent in farm, the initial size at caging, and other factors that may account for the differences among farms that are likely associated with local husbandry, biotic and environmental conditions. The initial model was specified as

$$\ln(Wgt\ at\ harvest) = \beta_0 + \beta_1 * days\ farm + \beta_2 * size\ catch + \beta_{3i} * farm_i + \cdots + \varepsilon$$

Other factors evaluated in the model, included the month at harvest, the month at caging, flag of farm, year of catch, and area (west, central, and east Mediterranean) of the farm. The objective was to identify the major factors that can explain variance in weight at harvest. Because the weight at size relationship is non-linear, models were fitted to the natural logarithm of weight at harvest. A table of AIC, BIC, and factor effect was estimated for models adding one factor at a time (**Table 3**).

As the request from the Commission, ask for the expected maximum growth of farmed bluefin tuna, this was interpreted as a value with a relatively low probability of exceeding this “expected maximum”. Hence it was decided to estimate the 95% upper confidence interval of predicted observation from the model as the maximum gain where it will be expected that only 5 out of 100 times, will be observed a value above it. Initially, the gain of weight was translated to percent weight gain rather than using absolute weight units. As such the model was modified as:

$$\frac{(wgt\ hrv - \widehat{wgt\ cag})}{\widehat{wgt\ \ cag}} = \beta_0 + \beta_1 * days\ farm + \beta_2 * size\ catch + \beta_{3i} * farm_i + \cdots + \varepsilon$$

Where $wgt\ hrv$ is the weight at harvest time, $\widehat{wgt\ \ cag}$ is the expected weight of the fish at caging, estimated using the current weight at size conversion factors (by month) for Mediterranean bluefin tuna (Ref), and ε is the error $N(0, \sigma)$. Both days-at-farm and size-at-catch were considered continuous variables, while other factors evaluated were considered fixed factors, $i = 1, \ldots farms$.

Quality control of the input data indicated some errors in the data collection, using a quantile density contours, observations above 95% density bound were consider outliers and excluded (**Figure 10**).

Results and conclusions

Between 2015 – 2020, the days-at-farm ranged from 1 to 2973 (8+ years) but with a median of 165 days (**Figure 4**), most of the fish are held for less than 1 year and almost all are harvested before the end of 2nd year. Only the small fish of the Croatian farms are kept in farms for longer times. For other farms, it appears that farms split, in general, the holding of bluefin into two time periods; one group is harvest at 6-12 months, while the others are held for almost 24 months. The Spanish farms show a rather distinct pattern, with more continuous harvesting of fish all year around.

Figure 10 shows a scatter plot of weight at size for harvest bluefin. In size harvested fish ranged from 56 to 449 (SFL cm) with a bimodal distribution of size, one peak at 150 SFL cm, and the second at 230 SFL cm, nothing that small fish (< 100 SFL) were excluded from modeling weight expected at harvest. Similarly, the weights of harvested bluefin show a bimodal distribution with a first mode at about 65 kg and a second mode at 245 kg. But weights ranged from 14 to 697 RWT kg. The scatter plot also shows the large variability of weight at size, with a mean coefficient of variance of 18%. At smaller sizes (< 100 SFL cm) the variance of weight at size is much larger. Comparing the weight at harvest versus the weight of wild fish of similar size (**Figure 7**) shows clearly that farmed bluefin attain larger weights. **Figure 6** shows the trends of this weight gain vs days-at-farm, and as expected there is a positive correlation although there is substantial variability in the data. The smoother trend in **Figure 6** suggests that in 6 months at farm, roughly the fish increase 30% in mass compared to wild fish and that by 2 years it will double their gain weight. Notice however that there are cases where fish weighted at harvest less than wild counterparts. The back-calculated size distribution at catch of farmed bluefin tuna is shown in **Figure 8**.

The model fit of expected weight at harvest (ln-wgt) associated all factors evaluated are show in **Table 4** and **Figure 10**. The full model accounts for about 94% of the variability and each factor included was statistically significant in the model, as indicated by the effect Test F-ratio and the AIC/BIC. However, the leverage plots (**Figure 10**) and the LogWorth values clearly indicate that the main explanatory factors are the size at cage and the days at farm. Although the area, month of harvest, year and month of catch are statistically significant, their influence in the predictions are minor, and for the purpose to produce a table of expected weight at harvest, it was decided to use only size at catch and days at farm, including the farm ID as random factor, that will likely incorporate some of the area, and local biotic and husbandry effects and being able to estimate for each month and average year the expected gain in weight.

Table 5 summarizes the fit of the GLMM to weight at harvest as function of days at farm and size at caging, and including farms ID as random factor. This model was used to predict the expected weight at harvest for bluefin of ages 4 to 25 at catch (> 100 cm SFL) and for the corresponding days at farm of 1 to 12 months. **Table 6** shows the updated expected weight in a similar format as the one provided in 2009 by the SCRS under the hypothesis of increase of intrinsic growth rates (e.g. length) in farming conditions. In this table the values are the mean predicted weight at harvest and the values between parenthesis in each cell correspond to the estimated 95% upper confidence interval of the prediction, that can be interpreted as the maximum expected growth value. **Table 7** shows the updated expected gain in percent weight compared to the initial weight at caging of bluefin tuna, values in parenthesis represent the upper 95% CI.

The 2009 SCRS estimations of expected weight at harvest were based on five research studies publications (Katavic et al 2009, Gordoa 2010, Deguara et al 2010, Deguara et al 2011, Tzoumas et al 2010), that reported percent of weight increase by time at farm, the matrix table was constructed by interpolating these percentages. Since then much more information is available including the size and weight at harvest, details of the catch and caging operations from the BCD databases (eBCD), and ongoing research experiments on farms with individual fish and close monitoring of size frequency in cages using stereoscopic cameras. Preliminary results indicate a mean gain weight higher compared to the 2009 matrix and comparable with the results from ongoing individual tagging studies.

The expected mean gain in weight is larger if the intrinsic growth in the farms is greater compared to wild fish, about twice more for 6 months caging of a 200 SFL fish. However, there is not yet sufficient data to directly estimate growth in farms, and the approach used in this study is preliminary. Further analysis will continue, to estimate growth of bluefin tuna in the first months after caging, and after a year at farm. Models that accommodate the non-linear growth pattern should be further investigated to have a more robust prediction models.

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Table 1. Summary of harvest bluefin tuna from monitored farming operations 2015 – 2020 as reported by the ROP-BFT program.

Year	CPC	N Harvest Oper	N fish measure	Wgt kg harvest
2015	EU-HRV	97	3,253	247,576
	EU-ITA	1	1	88
	EU-MLT	264	6,071	1,270,994
	EU-SPA	561	8,035	1,991,045
	MAR	19	543	170,297
	TUN	12	259	56,539
	TUR	127	1,865	365,175
2016	EU-HRV	154	9,383	621,313
	EU-MLT	642	9,292	2,186,651
	EU-SPA	641	10,199	2,368,049
	MAR	25	195	58,793
	TUN	8	141	36,456
	TUR	315	2,816	603,814
2017	EU-HRV	81	4,598	349,002
	EU-MLT	529	8,483	1,739,546
	EU-POR	27	418	76,973
	EU-SPA	804	15,453	4,269,744
	MAR	50	754	233,629
	TUR	670	5,930	981,960
2018	EU-HRV	28	-	-
	MAR	102	-	-
	EU-MLT	292	30	5,283
	EU-SPA	213	95	25,729
	TUR	496	1,282	124,916
2019	EU-HRV	250	4,573	271,226
	EU-MLT	521	6,667	1,516,336
	EU-POR	52	703	89,049
	EU-SPA	699	8,372	1,866,868
	MAR	127	1,892	540,118
	TUN	74	1,783	358,605
	TUR	620	3,721	531,421
2020	EU-HRV	150	7,232	460,781
	EU-MLT	442	8,009	2,643,212
	EU-POR	16	1,229	201,949
	EU-SPA	439	12,769	3,659,020
	MAR	145	2,740	875,872
	TUN	142	4,887	937,560
	TUR	103	1,497	197,553
Total		**9,938**	**155,170**	**31,933,142**

Table2.Average growth rates (size cm increment per month) for Atlantic bluefin tuna from wild fish (Cort et al, 1991) and preliminary results from consecutive monitoring of size distributions of caged fish with stereoscopic cameras and using modal progression analysis (MPA) for all experiments and for experiments that covered 12 months (SCRS/2021/145). Estimates are provided by size class groups.

Average growth rate:
size (cm) per month for Atlantic bluefin tuna

Fish size class (SFL cm)	Wild fish (Cort et al 1991)	MPA Sterocam study ALL	MPA 12 month studies
Small (< 100)	1.97	2.69	3.05
Medium (100 - 180)	1.37	4.63	2.21
Large (> 180)	0.49	2.81	1.83

Table3. Summary AIC, BIC of the GLM model on the weight at harvest (ln) as function of size at caging, days at farm, month of harvest, year of catch, month of catch, and the geographical area of the farm.

Model	*Nobs*	*N param*	*AIC*	*BIC*
Size caging + Days farm	126673	2	-103237	-103198
Size caging + Days farm + Month harv	126673	14	-105550	-105404
Size caging + Days farm + Month harv + Year catch	126673	22	-107822	-107597
Size caging + Days farm + Month harv + Year catch + Month catch	126673	28	-110501	-110219
Size caging + Days farm + Month harv + Year catch + Month catch + Area	126673	30	-112269	-111967

Table 4. Summary of the GLM model fit of weight at harvest of farmed bluefin tuna as function of days at farm, size at caging, month of harvest, area, year of catch, and month of catch.

Response ln_wgt

Effect Summary

Source	FDR LogWorth	FDR PValue
Psize_catch	63091.89	0.00000
Days_farm	7097.321	0.00000
MonthHarv	530.919	0.00000
YearCatch	517.245	0.00000
MonthCatch	500.810	0.00000
Area	384.657	0.00000

Summary of Fit

RSquare	0.942312
RSquare Adj	0.942299
Root Mean Square Error	0.155329
Mean of Response	5.104164
Observations (or Sum Wgts)	126673

AICc	BIC
-112269	-111967

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Days_farm	1	1	899.420	37278.48	<.0001*
Psize_catch	1	1	27243.608	1129173	<.0001*
MonthHarv	11	11	60.980	229.7673	<.0001*
Area	2	2	43.039	891.9295	<.0001*
YearCatch	8	8	58.992	305.6343	<.0001*
MonthCatch	6	6	56.823	392.5232	<.0001*

Table 5. Summary of the GLMM model fit of percent weight gain at harvest of farmed bluefin tuna as function of days at farm, size at caging, and farm ID as random factor.

Whole Model

Effect Summary

Source	LogWorth	PValue
Rel_SzCag	38830.75	0.00000
Rel_Monthfarm	2882.324	0.00000

Summary of Fit

RSquare	0.864877
RSquare Adj	0.864874
Root Mean Square Error	31.25622
Mean of Response	231.4592
Observations (or Sum Wgts)	97950

AICc	BIC
952434.2	952481.7

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	-265.4871	2.085856	32.11	-127.3	<.0001*
Rel_Monthfarm	75.39122	0.631914	95031	119.31	<.0001*
Rel_SzCag	836.43169	1.168246	97515	715.97	<.0001*

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
FarmICCAT_ID	0.1043078	101.90361	29.184171	44.703684	159.10353	0.0005*	9.446
Residual		976.95125	4.4151951	968.35505	985.66296		90.554
Total		1078.8549	29.51406	1023.2672	1139.1213		100.000

-2 LogLikelihood = 952424.24534

Note: Total is the sum of the positive variance components.

Total including negative estimates = 1078.8549

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Rel_Monthfarm	1	1	95031	14233.96	<.0001*
Rel_SzCag	1	1	97515	512616.6	<.0001*

Table 6. Updated matrix table of the expected mean weight at harvest of farmed bluefin tuna as function of size at caging (rows) and time in farms (columns, months after caging). The values in parenthesis correspond to the estimated 95% confidence interval.

		Predicted wgt (kg) at harvest BFT farmed								
Start Age	**Size SFL cm**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	**53**									
2	**77**									
3	**98**									
4	**118**	57 (121)	60 (124)	63 (127)	66 (131)	69 (133)	72 (137)	75 (140)	79 (143)	82 (146)
5	**136**	104 (168)	107 (171)	110 (175)	113 (178)	116 (181)	120 (184)	123 (187)	126 (190)	129 (193)
6	**152**	146 (210)	149 (213)	152 (217)	155 (220)	158 (223)	162 (226)	165 (229)	168 (232)	171 (235)
7	**167**	185 (250)	188 (253)	192 (256)	195 (259)	198 (262)	201 (265)	204 (268)	207 (272)	210 (275)
8	**180**	219 (284)	222 (287)	226 (290)	229 (293)	232 (296)	235 (299)	238 (302)	241 (306)	244 (309)
9	**193**	253 (318)	257 (321)	260 (324)	263 (327)	266 (330)	269 (333)	272 (337)	275 (340)	278 (343)
10	**204**	282 (347)	285 (350)	289 (353)	292 (356)	295 (359)	298 (362)	301 (365)	304 (369)	307 (372)
11	**214**	309 (373)	312 (376)	315 (379)	318 (382)	321 (385)	324 (389)	327 (392)	330 (395)	334 (398)
12	**223**	332 (397)	335 (400)	338 (403)	342 (406)	345 (409)	348 (412)	351 (415)	354 (418)	357 (421)
13	**232**	356 (420)	359 (423)	362 (426)	365 (430)	368 (432)	371 (436)	374 (439)	378 (442)	381 (445)
14	**240**	377 (441)	380 (444)	383 (447)	386 (451)	389 (453)	392 (457)	395 (460)	399 (463)	402 (466)
15	**247**	395 (459)	398 (463)	401 (466)	405 (469)	408 (472)	411 (475)	414 (478)	417 (481)	420 (484)
16	**253**	411 (475)	414 (478)	417 (481)	420 (485)	423 (488)	426 (491)	430 (494)	433 (497)	436 (500)
17	**259**	427 (491)	430 (494)	433 (497)	436 (500)	439 (503)	442 (506)	445 (510)	448 (513)	452 (516)
18	**264**	440 (504)	443 (507)	446 (510)	449 (513)	452 (516)	455 (520)	458 (523)	462 (526)	465 (529)
19	**269**	453 (517)	456 (520)	459 (523)	462 (527)	465 (529)	468 (533)	472 (536)	475 (539)	478 (542)
20	**273**	463 (528)	466 (531)	470 (534)	473 (537)	476 (540)	479 (543)	482 (546)	485 (549)	488 (552)
21	**278**	476 (541)	480 (544)	483 (547)	486 (550)	489 (553)	492 (556)	495 (559)	498 (562)	501 (566)
22	**281**	484 (548)	487 (552)	491 (555)	494 (558)	497 (561)	500 (564)	503 (567)	506 (570)	509 (573)
23	**285**	495 (559)	498 (562)	501 (565)	504 (568)	507 (571)	510 (575)	513 (578)	517 (581)	520 (584)
24	**288**	503 (567)	506 (570)	509 (573)	512 (576)	515 (579)	518 (582)	521 (585)	525 (589)	528 (592)
25	**290**	508 (572)	511 (575)	514 (578)	517 (582)	520 (584)	524 (588)	527 (591)	530 (594)	533 (597)

Table 7. Updated matrix table of the expected mean percent weight gain of farmed bluefin tuna as function of size at caging (rows) and time in farms (columns, months after caging). The values in parenthesis correspond to the estimated 95% confidence interval.

		Expected percent wgt (kg) increase at harvest BFT farmed								
Start Age	**Size SFL cm**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	**53**									
2	**77**									
3	**98**									
4	**118**	87% (299%)	97% (309%)	108% (320%)	118% (331%)	128% (340%)	138% (351%)	149% (361%)	159% (371%)	169% (382%)
5	**136**	127% (267%)	134% (274%)	141% (281%)	148% (288%)	154% (294%)	161% (301%)	168% (308%)	175% (315%)	181% (322%)
6	**152**	130% (232%)	135% (237%)	140% (242%)	145% (247%)	150% (252%)	155% (257%)	160% (262%)	165% (267%)	170% (272%)
7	**167**	123% (200%)	126% (204%)	130% (207%)	134% (211%)	137% (215%)	141% (219%)	145% (222%)	149% (226%)	153% (230%)
8	**180**	112% (174%)	115% (177%)	118% (180%)	121% (183%)	124% (186%)	127% (189%)	130% (192%)	133% (195%)	136% (198%)
9	**193**	100% (151%)	102% (153%)	105% (156%)	107% (158%)	110% (160%)	112% (163%)	115% (165%)	117% (168%)	120% (170%)
10	**204**	90% (133%)	92% (135%)	94% (137%)	96% (139%)	98% (141%)	100% (143%)	102% (145%)	104% (147%)	106% (149%)
11	**214**	80% (118%)	82% (120%)	84% (121%)	86% (123%)	87% (125%)	89% (127%)	91% (129%)	93% (131%)	95% (132%)
12	**223**	72% (105%)	74% (107%)	75% (109%)	77% (110%)	79% (112%)	80% (114%)	82% (115%)	83% (117%)	85% (118%)
13	**232**	64% (94%)	66% (95%)	67% (97%)	69% (98%)	70% (100%)	72% (101%)	73% (103%)	74% (104%)	76% (106%)
14	**240**	58% (85%)	59% (86%)	60% (87%)	62% (89%)	63% (90%)	64% (91%)	65% (92%)	67% (94%)	68% (95%)
15	**247**	52% (77%)	53% (78%)	55% (79%)	56% (80%)	57% (82%)	58% (83%)	59% (84%)	61% (85%)	62% (86%)
16	**253**	47% (71%)	49% (72%)	50% (73%)	51% (74%)	52% (75%)	53% (76%)	54% (77%)	55% (78%)	56% (80%)
17	**259**	43% (65%)	44% (66%)	45% (67%)	46% (68%)	47% (69%)	48% (70%)	49% (71%)	50% (72%)	51% (73%)
18	**264**	39% (60%)	40% (61%)	41% (62%)	42% (63%)	43% (64%)	44% (65%)	45% (66%)	46% (67%)	47% (68%)
19	**269**	36% (55%)	37% (56%)	38% (57%)	39% (58%)	40% (59%)	41% (60%)	42% (61%)	43% (62%)	44% (63%)
20	**273**	33% (52%)	34% (53%)	35% (54%)	36% (55%)	37% (55%)	38% (56%)	39% (57%)	40% (58%)	40% (59%)
21	**278**	30% (48%)	31% (48%)	32% (49%)	33% (50%)	33% (51%)	34% (52%)	35% (53%)	36% (54%)	37% (54%)
22	**281**	28% (45%)	29% (46%)	30% (47%)	31% (48%)	31% (48%)	32% (49%)	33% (50%)	34% (51%)	35% (52%)
23	**285**	26% (42%)	26% (43%)	27% (44%)	28% (44%)	29% (45%)	30% (46%)	30% (47%)	31% (47%)	32% (48%)
24	**288**	24% (40%)	25% (40%)	25% (41%)	26% (42%)	27% (43%)	28% (43%)	28% (44%)	29% (45%)	30% (46%)
25	**290**	23% (38%)	23% (39%)	24% (40%)	25% (40%)	26% (41%)	26% (42%)	27% (43%)	28% (43%)	29% (44%)

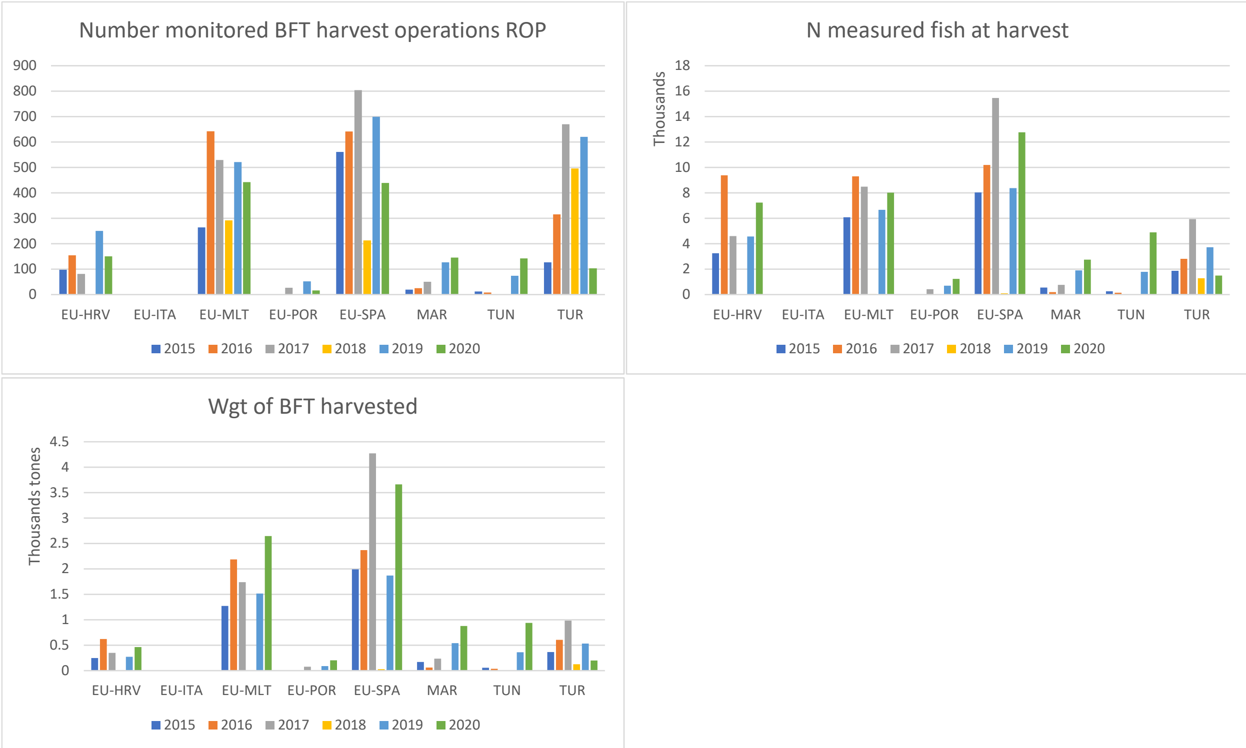
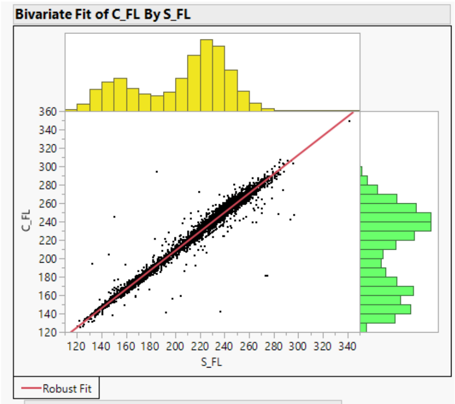


Figure 1. Summary of ROP monitored harvest operations for bluefin tuna 2015 – 2020 by CPC.



Summary Statistics

	Value	Lower 95%	Upper 95%	Signif. Prob
Correlation	0.991084	0.990701	0.991452	<.0001*
Covariance	1185.899			
Count	8584			

Variable	Mean	Std Dev
S_FL	204.1873	37.46321
C_FL	206.4937	44.30921

Robust Fit

Sigma	ChiSquare	PValue	LogWorth
2.90005	1188825	<.0001*	258153

Parameter	Robust Estimate	Std Error
Intercept	1.88591	0.19611
S_FL	1.04046	0.00095

Figure 2. Scatter plot of straight fork length (cm) vs. curved fork length (cm) measures of harvested bluefin tuna 2015-2020 and estimated conversion factor.

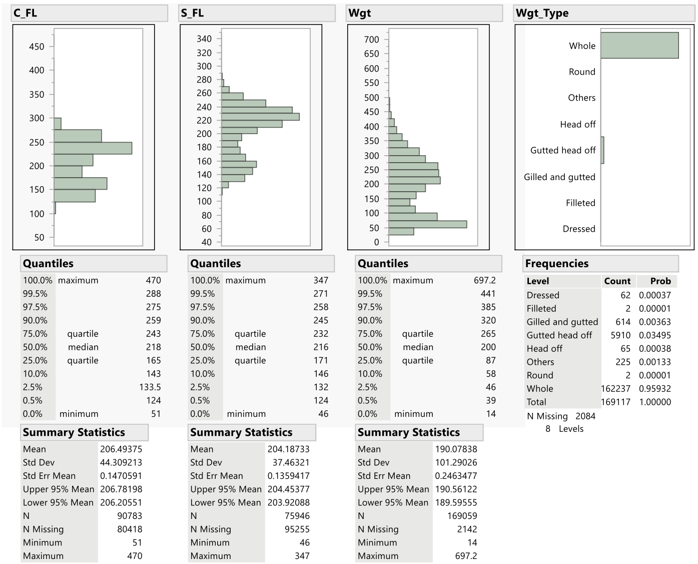


Figure 3. Harvested BFT size by type and weight and weight type measurement distributions from the ROP database 2015-2021.

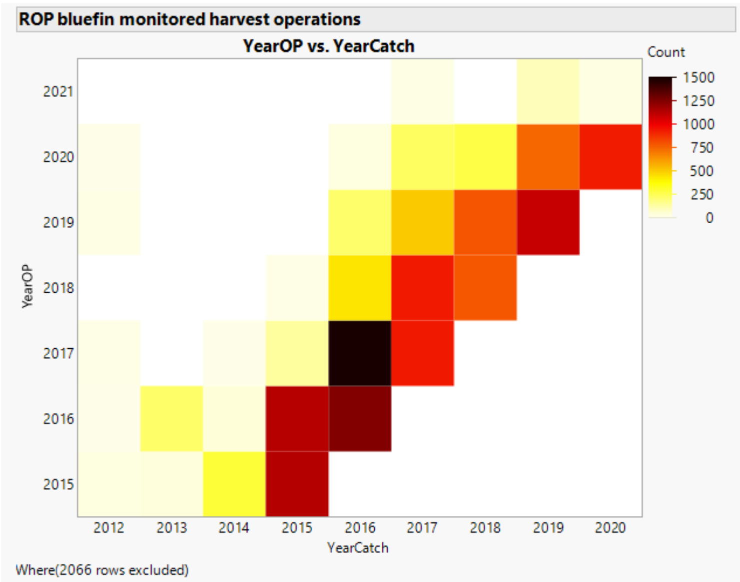


Figure 4. Heatmap of the year of catch and the year of the harvest operation (*y-axis*) from the ROP BFT monitored harvesting operations.

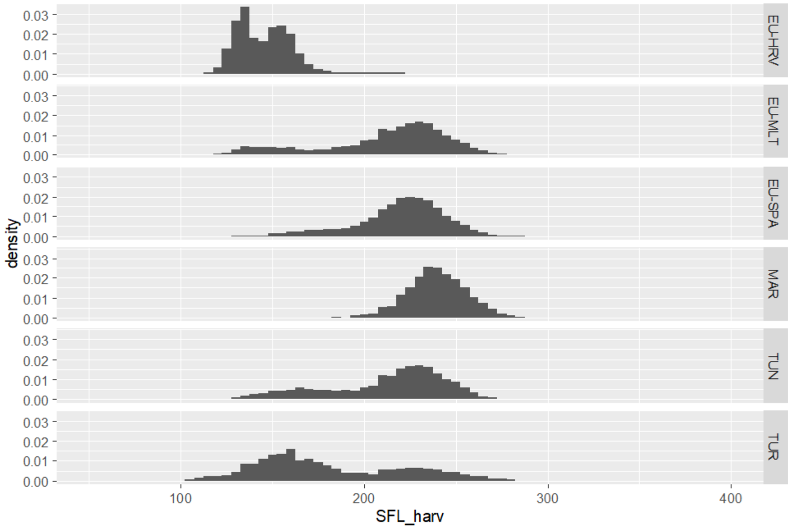


Figure 5. Distribution of size at harvest (SFL) by Flag of farms for the 2015 – 2020 period.

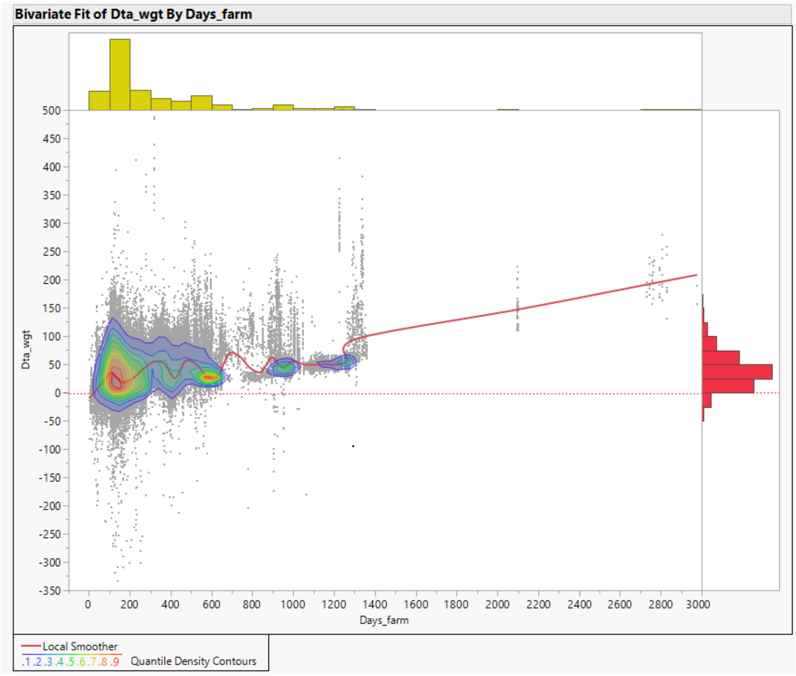


Figure 6. Scatter plot of weight gain (kg) vs. days-at-farm for harvested bluefin tuna (dots) 2015-2020 and marginal distributions. Red solid line shows the local smoother function to visualize trends, and the contour's correspond to the 10th quantiles density to illustrate the distribution of samples.

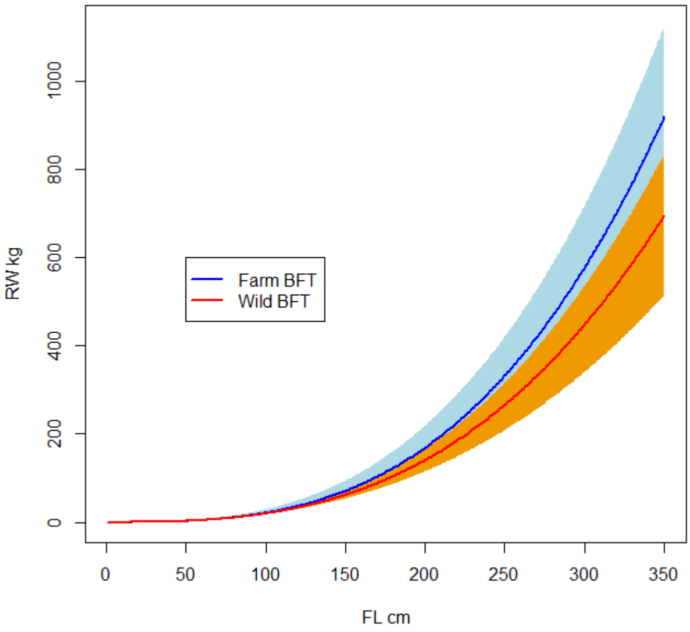


Figure 7. Estimated median weight at size (solid lines) and expected confidence bounds (95% percentiles, shade areas) for farmed vs wild bluefin tuna as estimated by quantile regression.

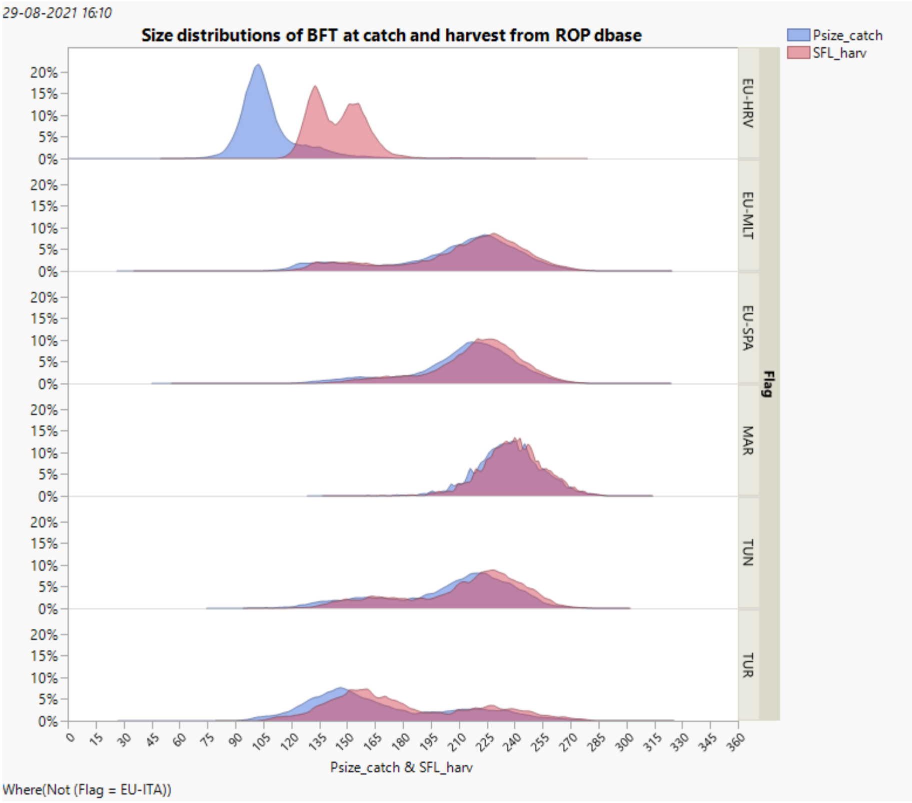


Figure 8. Estimated size-at-catch (blue) and measure size-at-harvest distributions of farmed BFT harvested by flag of farm2015 – 2021. Estimate size-at-catch assumes the same growth rate as wild fish (Cort et al 1991).

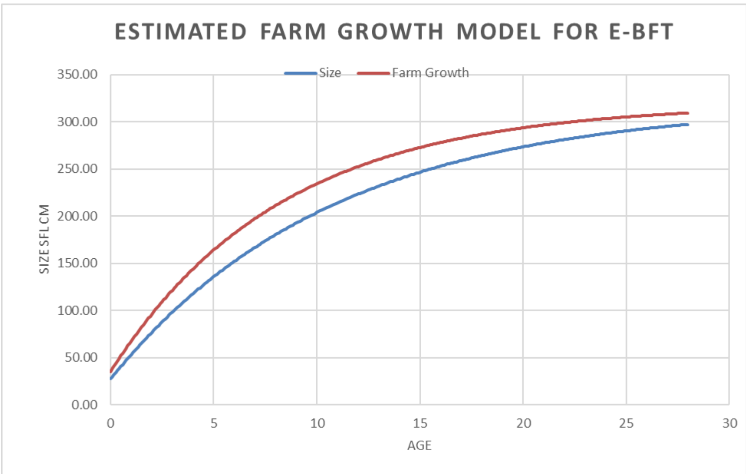


Figure 9. Estimated intrinsic growth model for farmed BFT based on the modification of the wild von Bertalanffy growth model (Cort et al, 1991) adjusted to the average increase in length from the MPA studies as reported in SCRS/2021/145.

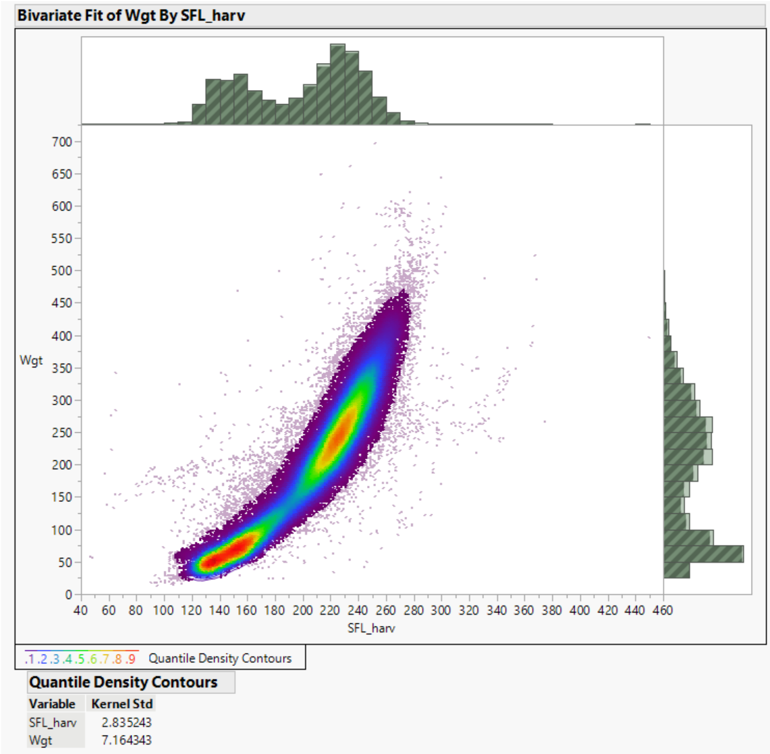


Figure 10. Scatter plot of observed weight (RWT kg) and size (SFL cm) of harvested bluefin tuna 2015 – 2020. Shade colors show the bivariate quantile density contours, values above the 95% quantile were considered outliers, marginal histograms show in light color the proportion of outliers by bin size or weight.

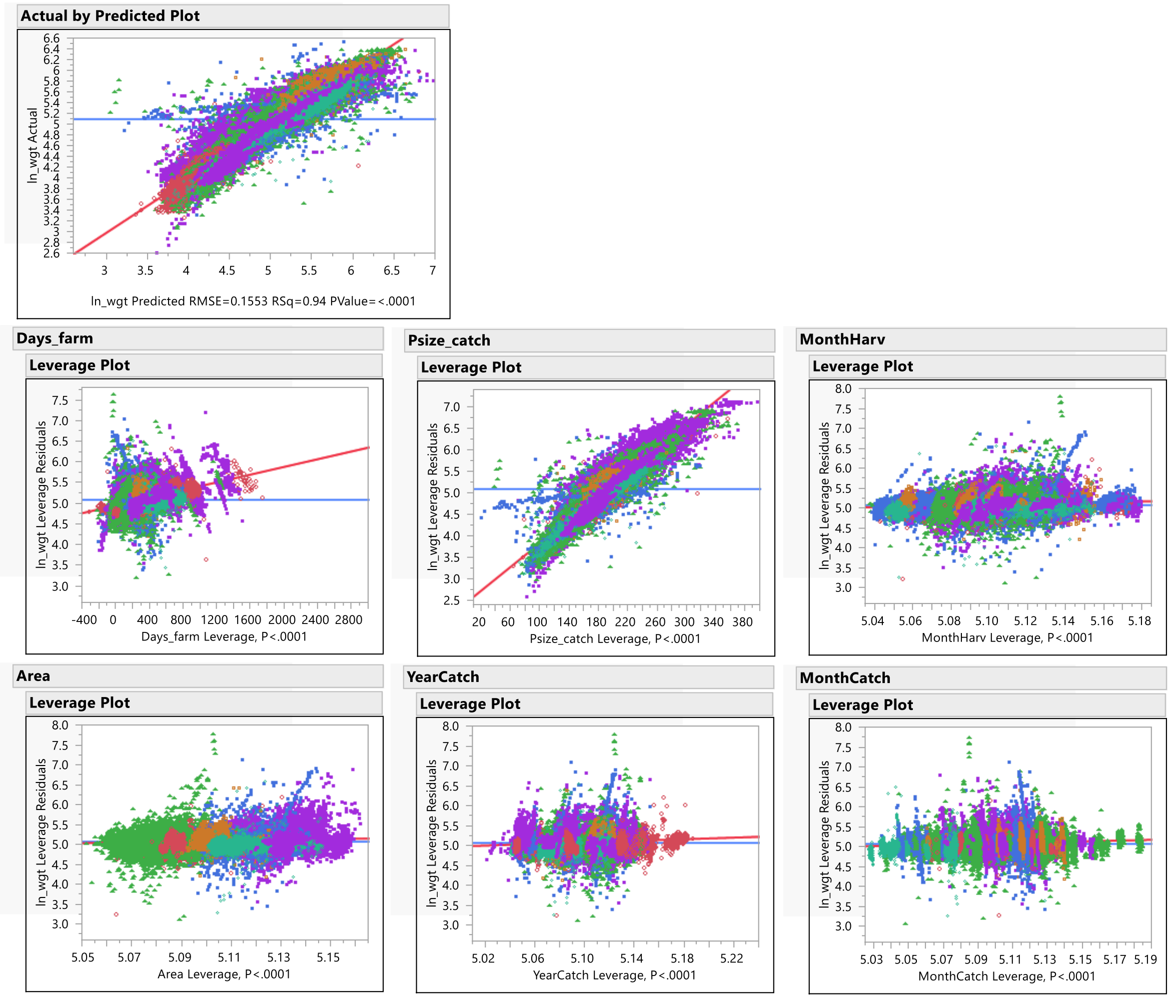


Figure 11. Fitted results from the GLM model on ln_weight at harvest (ln_wgt) predicted vs observed (top row). Other plots show the leverage plots for the factors in the model; days at farm, size at caging, month of harvest (middle row), area, year of catch, and month of caging (bottom row). Observations are color coded by Flag of farm.