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THE SACRAMENTO HARVEST MODEL (*SHM*)

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U. S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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Abstract

Sacramento River fall Chinook (SRFC) salmon contribute heavily to California and Oregon ocean salmon fisheries and support a Sacramento basin recreational river fishery. An overhaul of the SRFC stock assessment methods commenced in 2008, including development of a new ocean abundance index (the Sacramento Index: *SI*) and harvest model (the Sacramento Harvest Model: *SHM*), both of which are currently used for assessment and fishery planning within the annual Pacific Fishery Management Council (PFMC) salmon management process. The *SHM* is an aggregate-age harvest model that, when combined with the forecast *SI*, predicts the SRFC spawner escapement and overall exploitation rate given proposed ocean and river fishery management measures. This memorandum provides comprehensive documentation of the *SHM*, beginning with a description of the basic model structure. Detailed descriptions of the *SHM* ocean and river submodels, and the methods used to estimate their parameters follow. The *SHM* has been a central part of PFMC salmon fishery planning since its initial development and will likely remain an important part of that process until improved coded-wire tag and escapement data sets for this stock mature, potentially enabling an age-structured assessment.

1 Introduction

Sacramento River fall Chinook (SRFC) salmon are the largest contributor to ocean salmon fishery harvest off the coasts of California and Oregon (O’Farrell et al. 2013). Management of salmon fisheries through the Pacific Fishery Management Council (PFMC) aims to meet, in expectation, the annual conservation objectives for all salmon stocks, including SRFC. In the case of SRFC, the conservation objective is a spawning escapement of 122,000–180,000 natural and hatchery adults (\geq age-3). Since the adoption of Amendment 16 to the Pacific Coast Salmon Fishery Management Plan (PFMC 2012), SRFC have been managed according to a harvest “control rule”, depicted in Figure 1, that specifies the maximum allowable overall exploitation rate on SRFC as a function of the Sacramento Index (SI), an index of adult SRFC ocean abundance (O’Farrell et al. 2013). Here, the overall exploitation rate is defined as the sum of SRFC adult ocean and river harvest in retention fisheries plus release mortality in non-retention fisheries divided by the SI . A mathematical model is used to forecast the spawning escapement and exploitation rate as a function of the SI forecast and the proposed set of annual fishery management measures. The model that generates these forecasts for the purposes of PFMC fishery planning is the Sacramento Harvest Model (SHM).

Prior to 2008, SRFC stock abundance had not been a limiting factor to account for in the crafting of annual PFMC management measures, and little attention had been given to the fishery assessment methods used for the stock, and in particular, to the model used to forecast SRFC spawning escapement as a function of proposed management measures. During this time the PFMC forecasted SRFC spawning escapement, E , as

$$E = CVI \times (1 - h_{CVI}) \times \pi, \quad (1)$$

based on forecasts of the three right-hand side quantities. The Central Valley Index (CVI) is an annual index of ocean abundance of all Central Valley Chinook stocks combined, and is defined as the calendar year sum of ocean fishery Chinook harvests south of Point Arena, California, to the California / Mexico border, plus the Central Valley adult Chinook spawning escapement. The CVI harvest rate index (h_{CVI}) is an annual index of the ocean harvest rate on all Central Valley Chinook stocks combined, and is defined as the ocean harvest landed south of Point Arena, California, di-

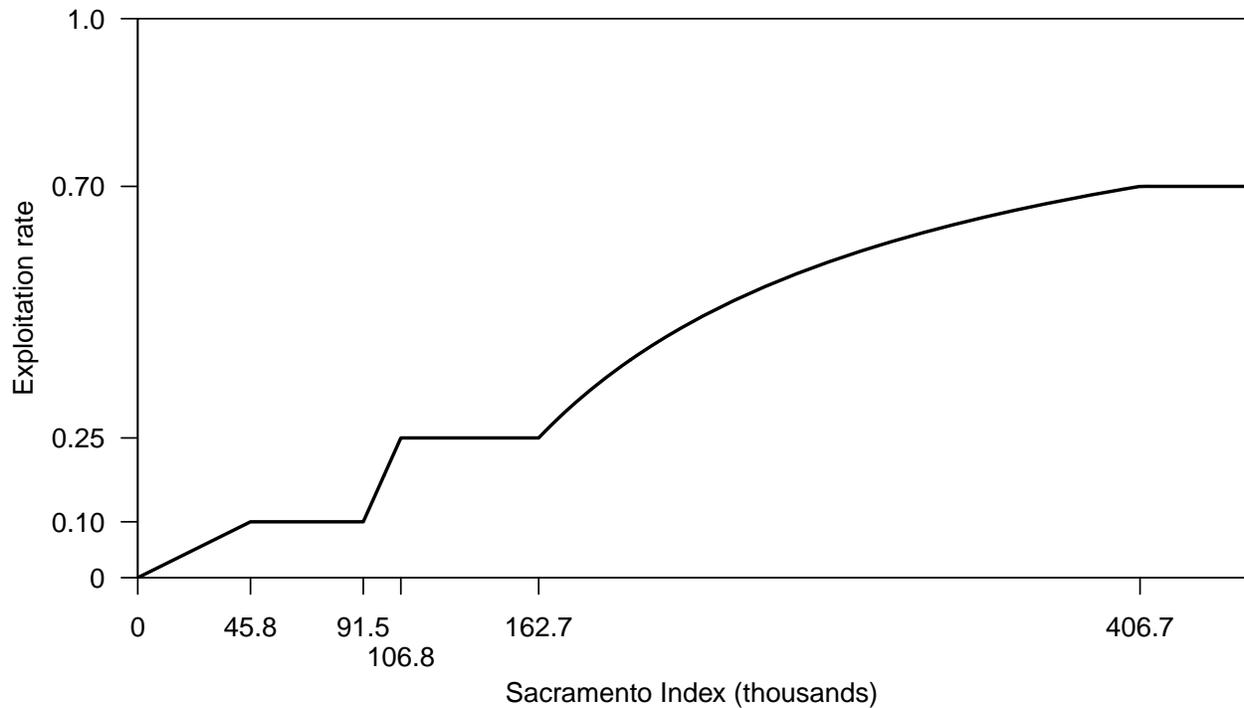


Figure 1. The Sacramento River fall Chinook harvest control rule. Rationale for the reference points that define the rule is provided in PFMC (2012).

vided by the *CVI*. Finally, π is the annual proportion of the Central Valley adult Chinook combined spawning escapement that are SRFC. The model was largely incapable of evaluating the effect of variation in ocean and river fishery management measures.

As crude as this model is, it was sufficient for fishery management purposes until 2008 when there were indications that the SRFC stock had collapsed. The 2007 SRFC escapement was well below the lower end of the goal range, and the age-2 escapements in 2006 and 2007 were the lowest values on record (PFMC 2013b). These back-to-back SRFC brood failures and the over-optimistic 2007 forecast of *E* prompted a thorough review of the data and methods used to forecast *E* prior to the development of fishery management measures for 2008 (PFMC 2008a,b). The review findings included the following recommendations: (1) the *E* model components should all be made SRFC-specific, if possible, (2) SRFC ocean harvest north of Point Arena, California, to Cape Falcon, Oregon, should be included in the model, and (3) SRFC river harvest should be explicitly included in the model.

In response, a major effort was launched to overhaul the SRFC stock and fishery assessment methods in 2008, culminating in the development of the *SHM*, which provides a direct link between fishery impacts on SRFC and ocean and river fishery management control measures. The remainder of this report provides a detailed description of the *SHM* and its components as constructed at the time of publication.

2 Model Description

The SRFC stock and fishery assessment methods used by the PFMC were revised beginning in 2008 as follows. First, historical SRFC coded-wire tag (CWT) recovery data from ocean salmon fisheries were used to develop estimates of SRFC ocean harvest in all area-month-fishing sector strata south of Cape Falcon, Oregon, for all years since 1983 (SRFC harvest north of Cape Falcon was found to be small; O’Farrell et al. 2013). Second, Sacramento River historical angler survey data were used to develop estimates of SRFC river harvest for years in which these surveys were conducted. For years when angler surveys were not conducted, a method was developed to hind-cast river harvest, resulting in an uninterrupted river harvest time series (O’Farrell et al. 2013). Third, the *SI* for year y was derived by summing SRFC adult ocean harvest from September 1 ($y - 1$) through August 31 (y), $H_{o,S}$, SRFC adult river harvest (y), H_r , and SRFC adult spawning escapement (y), E :

$$SI = H_{o,S} + H_r + E, \quad (2)$$

where the notation for equation (2) follows that in O’Farrell et al. (2013). For the remainder of this paper, SRFC adult ocean harvest is denoted as H_o and all other harvest-related quantities are SRFC-specific unless otherwise noted. The fall ($y - 1$) through summer (y) “biological year” accounting of ocean harvest better reflects the period during which ocean fishery mortality directly impacts SRFC spawning escapement (y), given the late summer / early-fall river return timing of the stock. Fourth, a SRFC-specific ocean harvest rate, h_o , was defined as the SRFC harvest divided by the *SI*: $h_o = H_o/SI$. Fifth, a SRFC-specific river harvest rate, h_r , was defined as the SRFC river harvest divided by the SRFC river return, R : $h_r = H_r/R$, where $R = H_r + E$. Finally, a new SRFC

spawning escapement forecast model

$$E = SI \times (1 - i_o) \times (1 - i_r), \quad (3)$$

and exploitation rate forecast model

$$F = i_o + [(1 - i_o) \times i_r], \quad (4)$$

were constructed based on forecasts of the right-hand side quantities, where i_o and i_r are the SRFC ocean and river fishery impact rates, respectively, that depend on the proposed set of ocean and river fishery management measures. For retention fisheries, the impact rate equals the harvest rate. For non-retention fisheries, the impact rate equals the nominal harvest rate multiplied by the release mortality rate. In the absence of ocean and river fisheries, $E = SI$; natural mortality is not explicitly accounted for in either the SI or SHM .

The SHM is a one-year, forward projection model. It is used annually by the PFMC at their March (y) and April (y) meetings to forecast $E(y)$ and $F(y)$ as a function of:

1. The ocean management measures that were enacted for the September 1 ($y - 1$) through April 30 (y) period.
2. A proposed set of ocean management measures for the May 1 (y) through August 31 (y) period.
3. A proposed set of management measures for the river fishery (y).

We now present the SHM model components: the ocean fishery submodel for i_o and h_o , and the river fishery submodel for i_r and h_r . The SI itself is described in a companion paper (O’Farrell et al. 2013).

3 Ocean Submodel

The SHM ocean submodel is stratified by management area a , time period m , and fishing sector x . In general, we use the term “fishery” to refer to a given area-month-sector-specific stratum.

Area: The model coverage is south of Cape Falcon, Oregon, to the California / Mexico border. SRFC fishing impacts are small north of Cape Falcon (O’Farrell et al. 2013). Within this coverage, area is stratified according to the PFMC management areas depicted in Figure 2. The subscript a is used to denote area-specific quantities, with $a \in \{\text{NO, CO, KO, KC, FB, SF, MO}\}$.

Time: The model coverage is September 1 ($y - 1$) through August 31 (y) in accordance with the SRFC “biological year” described above and the definition of the SI . Within this period, time is stratified by month. The subscript m is used to denote month-specific quantities, with $m \in \{\text{Sep, Oct, } \dots, \text{Aug}\}$.

Sector: The model coverage is salmon-directed fisheries, which is stratified into the commercial and recreational sectors. The subscript x is used to denote fishing sector-specific quantities, with $x \in \{\text{Commercial, Recreational}\}$.

At its core, the ocean submodel deducts September 1 ($y - 1$) through August 31 (y) harvest impacts from the SI with the remaining fish constituting the river return, R (y). This simple model of SRFC dynamics is a necessary consequence of the SI definition, which itself is a consequence of the limitations of the data available for SRFC assessment (O’Farrell et al. 2013). For this reason, the SHM is not fully dynamic in the sense that the modeled abundance available for ocean harvest later in the season is independent of the magnitude and extent of the harvest that preceded it. As a result,

$$i_{o,a,m,x} = I_{o,a,m,x}/SI, \quad i_o = \sum_{a,m,x} i_{o,a,m,x}, \quad (5)$$

and

$$h_{o,a,m,x} = H_{o,a,m,x}/SI, \quad h_o = \sum_{a,m,x} h_{o,a,m,x}. \quad (6)$$

Sections 3.1 and 3.2 describe the ocean submodel in greater detail. Section 3.3 describes the estimation of ocean submodel parameters. All model quantities at this level are fishery-specific, however, to simplify the presentation, we omit the fishery-specific subscripts a, m, x . For the definition of all notation used in this paper, refer to Table 1.

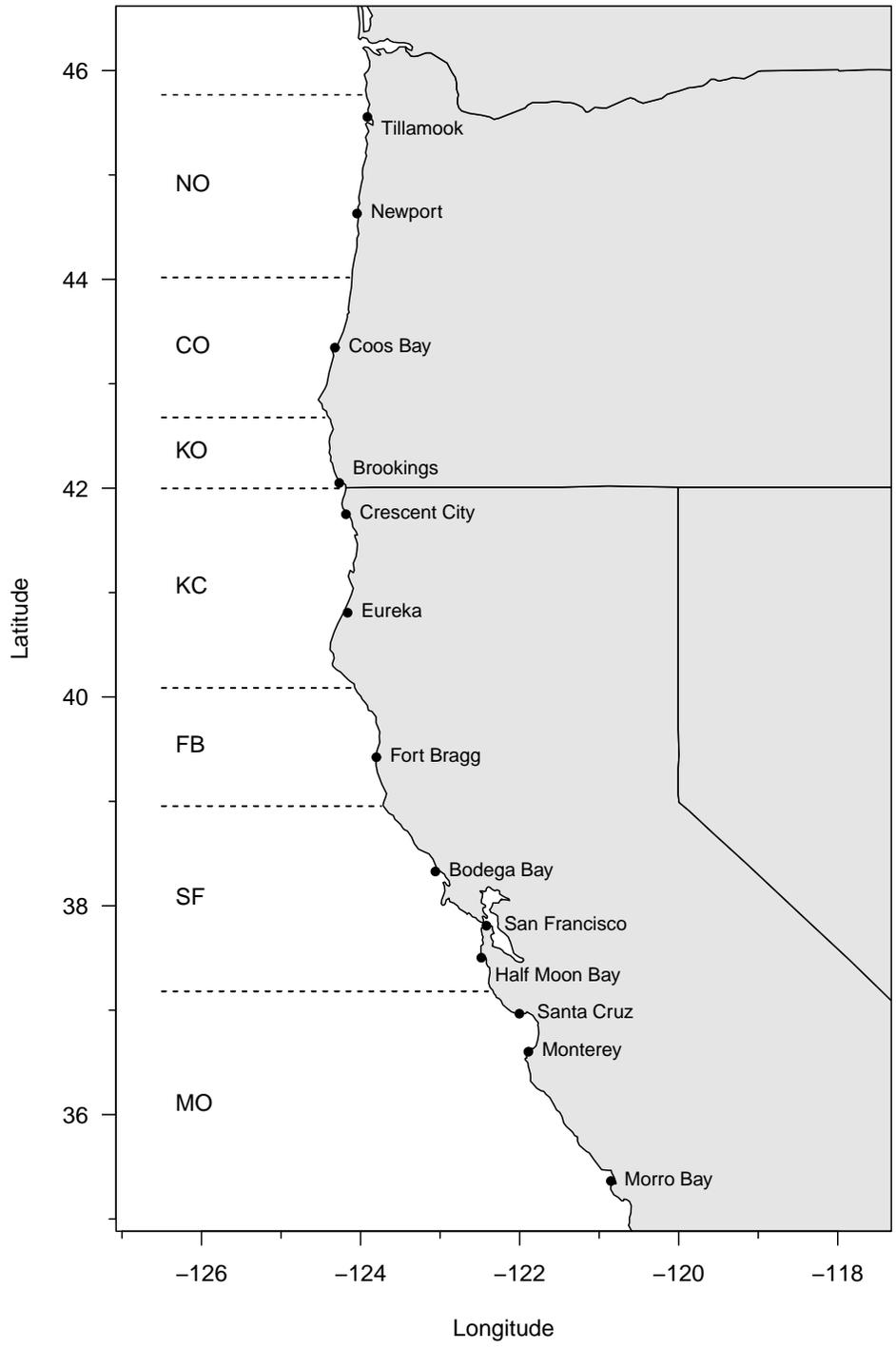


Figure 2. Map of PFMC salmon management areas and major ports south of Cape Falcon, Oregon.

Table 1. Definition of notation used in this paper (exclusive of Appendix A). For definition of the management areas NO, CO, KO, KC, FB, SF, MO, see Figure 2 and O’Farrell et al. (2013, Table 2).

<i>Symbol</i>	<i>Definition</i>
\sim	Scaled quantity
*	Forecast quantity
A	Ocean abundance
a	Management area (NO, CO, KO, KC, FB, SF, MO)
β	Average ratio
C	Number of released fish in a non-retention fishery
CVI	Central Valley Index
CWT	Coded-wire tag
D	Number of days open
d	Days-open fishery
E	Escapement
F	Exploitation rate
f	Fishing effort
g	Stock unit (S, K, V, N, T)
H	Harvest
h	Harvest rate
I	Impacts
i	Impact rate
K	Klamath River fall Chinook
k	Retention (keep) fishery
m	Month (Sep, Oct, . . . , Aug)
N	Non-Central Valley hatchery-origin Chinook other than Klamath River fall run
n	Non-retention (catch-and-release) fishery
o	Ocean
$PFMC$	Pacific Fishery Management Council
p	Proportion of harvest that is SRFC
π	Proportion of Central Valley Chinook escapement that is SRFC
Q	Quota
q	Quota fishery
R	River return
r	River
ρ	Proportion caught by mooching
S	Sacramento River fall Chinook
s	Release mortality rate
SHM	Sacramento Harvest Model
SI	Sacramento Index
$SRFC$	Sacramento River fall Chinook
T	Total Chinook
V	Central Valley hatchery-origin Chinook other than SRFC
x	Sector (Commercial, Recreational)
y	Year of forecast

3.1 i_o, h_o : September 1 ($y - 1$) through December 31 ($y - 1$) period

The *SHM* is used annually for assessment and management in March (y) and April (y). The fisheries during the September 1 ($y - 1$) through December 31 ($y - 1$) period have already occurred by this time, and the monitoring data for those fisheries is available for the March (y) and April (y) assessment. A variety of methods are used to estimate I_o and H_o for this period depending on the nature of the fishery, and the corresponding i_o and h_o are then derived from equations (5) and (6), respectively.

The first distinction made in the estimation methods has to do with whether the fishery was retention or non-retention for Chinook salmon. For retention fisheries, H_o is estimated based on SRFC CWT recoveries as described in O’Farrell et al. (2013), and $I_o = H_o$. Mortality associated with release of SRFC smaller than the minimum size limit in retention fisheries is not accounted for in the *SHM*.

Non-retention Chinook fisheries are atypical, but do sometimes occur. Examples include non-retention genetic stock identification studies and Oregon coho-only fisheries. In such cases, $H_o = 0$, and

$$I_o = C \times p \times s, \quad (7)$$

where C is the number of released Chinook that equaled or exceeded the customary minimum size limit for that fishery, p is the proportion of these fish that are SRFC, and s is the release mortality rate. The value C may be known (e.g., research studies with a known number of fish sampled) or estimated (e.g., on-board observer data or angler interview data). In cases where data for C do not exist, I_o is predicted using the methods described in Section 3.2, noting that $I_o = SI \times i_o$. The value p may be estimated (e.g., genetic stock identification data), or predicted (e.g., average historical p for that fishery adjusted for current year forecasts of stock complex component abundances (Section 3.3.3)). The value s is assumed to be a known fixed value for commercial and recreational fisheries, with the exception of recreational fisheries in the SF and MO areas, where s depends on the prevalence of mooching versus trolling (Section 3.3.4).

If for a given area-month-sector, the fishery was retention for a portion of the month, and non-retention for a different portion of the month (non-overlapping time periods), the respective

quantities are determined as described above and then summed for the month.

3.2 i_o, h_o : January 1 (y) through August 31 (y) period

While some of the fisheries during this period have occurred prior to use of the *SHM* in March (y) and April (y), the associated monitoring data is typically unavailable for this purpose. A variety of methods are thus used to forecast the fishery-specific i_o and h_o for this period depending on the nature of the fishery, and the corresponding I_o and H_o are then derived implicitly using equations (5) and (6), respectively.

Ocean salmon fisheries south of Cape Falcon, Oregon are regulated either by the number of “days open” or by “quota” (catch ceiling) within an area-month-sector fishery stratum. Both types of regulation may be retention or non-retention although, as mentioned above, Chinook non-retention fisheries have occurred relatively infrequently in this region. The *SHM* ocean submodel allows for all four of these regulations within an area-month-sector fishery stratum, as long as they are non-overlapping within this time period.

The harvest rate for a days-open fishery, h_o^d , is forecast as

$$h_o^d = \beta^{hf} \times \beta^{fD} \times D^k, \quad (8)$$

where β^{hf} is the average harvest rate per unit of effort, β^{fD} is the average effort per day open, and D^k is the number of days open in a retention fishery. For a quota fishery, the harvest rate, h_o^q , is forecast as

$$h_o^q = (Q^k \times p) / SI, \quad (9)$$

where Q^k is the quota (number of Chinook) in a retention fishery, and p is the proportion of Chinook harvest that is SRFC. The harvest rate forecast for the entire area, month, and sector is $h_o = h_o^d + h_o^q$.

The impact rate for the fishery is equal to the retention harvest rate plus the mortality rate in non-retention (n) fisheries. Thus,

$$i_o = h_o + [(h_o^{d,n} + h_o^{q,n}) \times s], \quad (10)$$

where $h_o^{d,n}$ and $h_o^{q,n}$ are determined from equations (8) and (9), respectively, with D^n and Q^n substituted for D^k and Q^k , respectively.

Month, area, and sector specific impact rates are then summed over all fisheries to determine the overall i_o term in equation (3), as described in equation (5).

Thus, the i_o and h_o are a function of the (1) forecast SI , (2) estimated parameters β^{fD} , β^{hf} , p , s , and (3) management control variables D^k , D^n , Q^k , Q^n . The SI forecast and estimated model parameters are updated annually just prior to the development of PFMC management measures, while the management control variables depend on the set of management measures under consideration. The method used to forecast the SI is described annually in the PFMC Preseason I report (e.g., PFMC 2013a). The next section describes the methods that are used annually to estimate the parameters β^{hf} , β^{fD} , p , and s .

3.3 Parameter estimation

3.3.1 β^{fD} : average effort per day open

Portions of this section borrow heavily from Mohr (2006b).

For days open fisheries, the average effort per day open, β^{fD} , is estimated separately for each area-month-sector from the historical time series of fishing effort f and number of days open to fishing D . These data are displayed in Figures 3 and 4 for the commercial and recreational sectors, respectively, where each point within a panel represents the data from an individual year. The ratio estimator (Appendix A),

$$\beta^{fD} = \frac{\text{average}\{f\}}{\text{average}\{D\}}, \quad (11)$$

where the averages are taken over the historical data, is used to estimate β^{fD} because it is the slope of the best fitting (in a least-squares sense) zero-intercept line through these data under the assumption that the residual error in f is additive, with mean zero and variance proportional to D , which appears to be appropriate for these data.

The fitted lines with slopes equal to the estimated β^{fD} are shown in Figures 3 and 4. Note that fishing effort is defined for the commercial sector in vessel day units while for the recreational

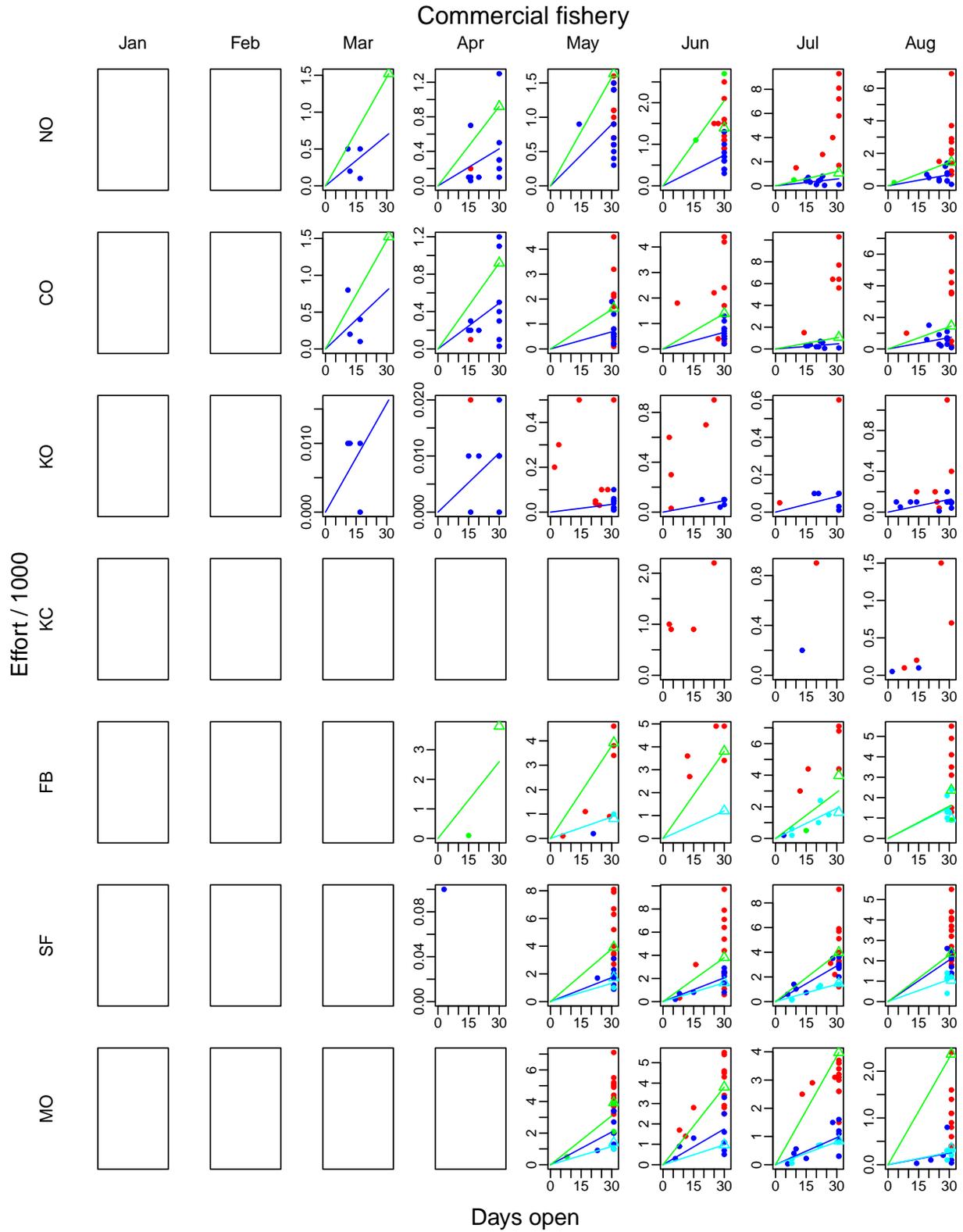


Figure 3. Commercial sector fishing effort plotted as a function of days open to fishing by management area and month. Effort is in vessel day units. See text for description of symbols, lines, and color coding.

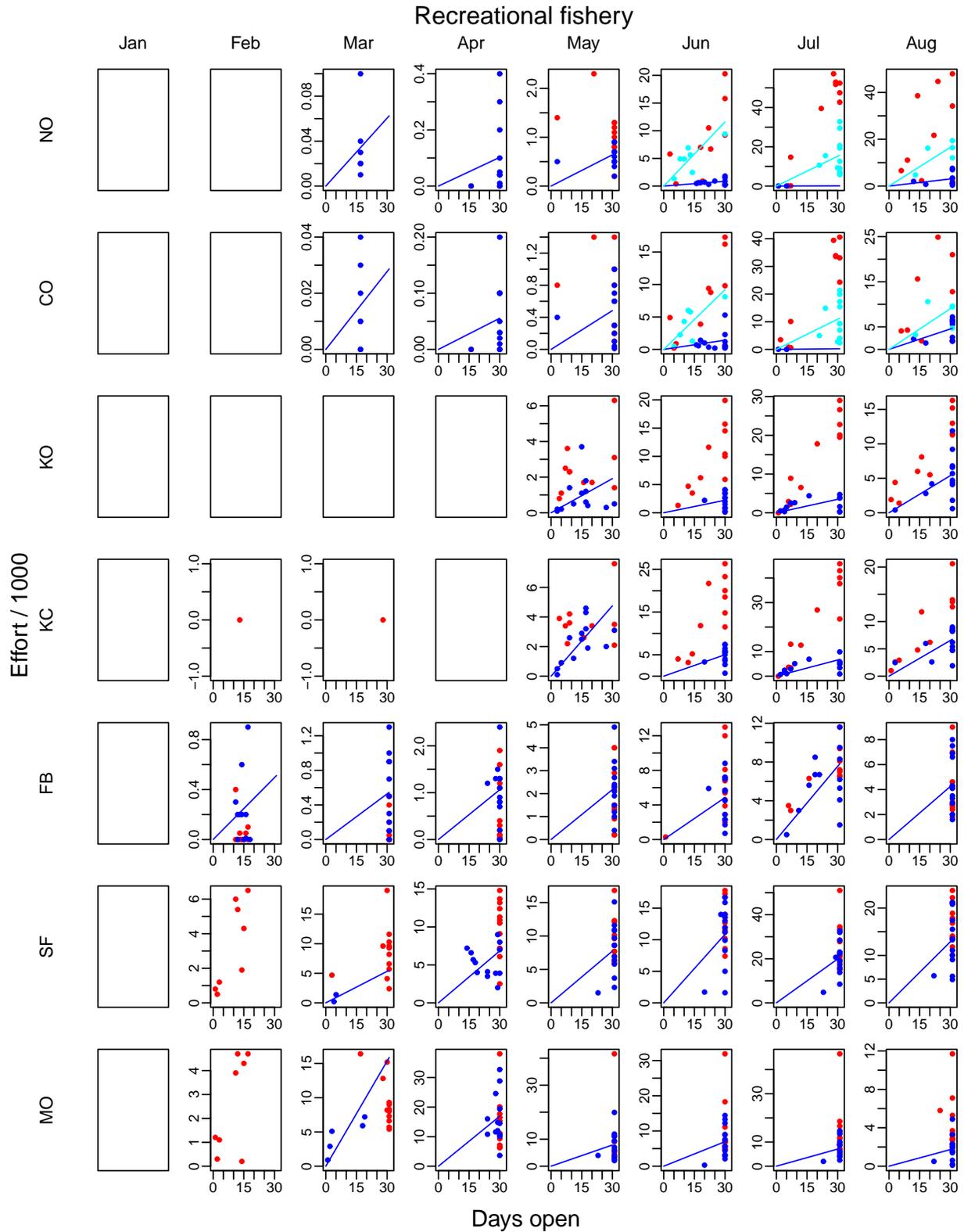


Figure 4. Recreational sector fishing effort plotted as a function of days open to fishing by management area and month. Effort is in angler day units. See text for description of symbols, lines, and color coding.

sector it is in angler day units, so that the estimated β^{fD} (line slopes) are not directly comparable across the two sectors. Color coding of the data and lines corresponds to alternative subsets and treatments of the data considered for the purpose of improving the applicability of the β^{fD} estimates. A description of these subsets and treatments follows. We also note that these same estimates of the average fishing effort per day open are used not only for the *SHM*, but for other west coast salmon harvest models as well (Mohr 2006a; O’Farrell et al. 2012).

Effort data: limited to 1998–forward

Commercial fishing capacity south of Cape Falcon, Oregon, as indexed by the number of boats making landings, has declined since the early 1980s (PFMC 2013b, Tables D-12 and D-13), and the recreational sector has been increasingly restricted since the early 1990s. For these reasons, effort data from 1991–forward had been used to estimate β^{fD} for use in harvest models through management year 2011. After management year 2011, an analysis of recent trends in effort per day and the performance of effort predictions concluded that including effort data from the early 1990s in the estimation of β^{fD} led to frequent over-prediction of effort, and that the early 1990s data no longer represented the current state of the fishing fleets (M.R. O’Farrell, *unpublished data*). As a result, beginning with management year 2012, data prior to 1998, denoted by red circles, were excluded from the estimation of β^{fD} for both the commercial and recreational sectors.

Commercial sector: accounting for effort transfer

The commercial sector is characterized by increased mobility relative to the recreational sector, resulting in the transfer of fishing effort across management area boundaries. As a result, the closure of certain management areas would not result in an expected loss of total effort in many cases because much of the effort would be redistributed to nearby, open management areas. To account for such effort transfers, fishery “types” have been defined to classify the effort data according to the configuration of open and closed fisheries under which it occurred.

Type 0 fisheries are denoted by dark blue dots and lines in Figure 3. For the NO and CO areas, Type 0 corresponds to data collected when both management areas were open simultaneously. For the KO and KC areas, Type 0 fisheries are the default, and all data used for effort estimation

purposes is designated as Type 0. For the FB, SF, and MO area, Type 0 corresponds to data collected when FB is closed but SF and MO are open simultaneously. This fishery configuration for the three southernmost management areas has occurred frequently as FB has experienced more closures than management areas further to the south.

Type 1 fisheries are defined only for the FB, SF, and MO areas, and are denoted by the light blue dots, triangles, and lines. Type 1 fisheries correspond to data (dots) collected when these three management areas were open simultaneously. Upon initial identification and implementation of Type 1 fisheries, Mohr (2006b) noted that little or no contemporary effort data were available for FB owing to frequent closures. As a result, it was assumed that if FB, SF, and MO were to be open simultaneously, effort in FB would originate entirely from the SF and MO areas, and that total effort would be distributed among FB, SF, and MO in the same proportions as estimated for years 1986–1991. During the 1986-1991 period, the three management areas were open simultaneously and the data from these years was used to infer the future spatial distribution of effort under this commercial fishery configuration. The result of distributing the pool of SF and MO effort to FB, SF, and MO is represented by the light blue triangles. Since the first implementation of this approach in 2002, there have been several Type 1 fisheries that have contributed data to the magnitude and distribution of effort across FB, SF, and MO. The assumed data point denoted by the light blue triangle continues to be treated as a “real” data point for purposes of estimating β^{fD} , noting that as data has accumulated, the influence of this assumed datum has diminished (Mohr 2006b).

Type 2 fisheries are defined for the NO and CO areas in Oregon and the FB, SF, and MO areas in California. For NO and CO, a Type 2 fishery results when only one of the two areas is open, and it is assumed that the total effort expected when both areas are open simultaneously will fully transfer into the single open area. For the FB, SF, and MO areas, Type 2 fisheries also result when only one of these management areas is open and the other two are closed. It is assumed that the effort pool in the SF and MO areas (mentioned in the description of Type 1 fisheries) will fully shift to the single open area. Type 2 fisheries are denoted by green dots, lines, and triangles, where the triangles again represent an assumed data point based on the expected effort transfer.

Recreational sector: accounting for coho fishing opportunity

The recreational sector is characterized by reduced mobility relative to the commercial sector, resulting in little transfer of fishing effort across management area boundaries. Hence, an accounting for effort shifts resulting from patterns of closed and open areas, as described for the commercial sector, does not occur for the recreational sector. Fishery types for the recreational sector instead pertain to Chinook-only fisheries, and in NO and CO, fisheries where coho salmon (*Oncorhynchus kisutch*) retention is also allowed.

Type 0 fisheries are denoted by dark blue dots and lines in Figure 4. This is the default fishery type for recreational Chinook fisheries.

Type 1 fisheries are defined only for the NO and CO areas in months June–August, and are denoted by the light blue dots and lines. It has been noted for these management areas that when coho retention is allowed, the effort per day open can be substantially higher relative to Chinook-only fisheries. As a result, Type 1 fisheries result for the aforementioned management areas and months when coho fishing opportunity exists. Coho fishing opportunity may also occur in the KO management area, but this has not affected the effort response as in the more northern Oregon management areas. Coho retention is prohibited in California.

3.3.2 β^{hf} : average harvest rate per unit effort

The average harvest rate per unit effort, β^{hf} , is estimated separately for each area-month-sector from the historical time series of SRFC harvest rates h_o and fishing effort f . The harvest rates themselves were determined using equation (6), where the time series of H_o and SI were estimated as described in O’Farrell et al. (2013). The h_o and f data are displayed in Figures 5 and 6 for the commercial and recreational sectors, respectively, where each point within a panel represents the data from an individual year. The ratio estimator (Appendix A),

$$\beta^{hf} = \frac{\text{average}\{h_o\}}{\text{average}\{f\}}, \quad (12)$$

where the averages are taken over the period 1983–forward, is used to estimate β^{hf} because it is the slope of the best fitting (in a least-squares sense) zero-intercept line through these data under

the assumption that the residual error in h_o is additive, with mean zero and variance proportional to f , which appears to be appropriate for these data.

The fitted lines with slopes equal to the estimated β^{hf} are shown in Figures 5 and 6. Note that the within-sector panels have the same axes scales, and thus the estimated β^{hf} (lines slopes) within a sector are directly comparable across the areas and months in these figures.

Harvest rates per unit effort are a function of the SRFC spatial distribution and catchability. Estimated β^{hf} tend to be highest in the FB, SF, and MO management areas for both the commercial and recreational sectors. For the recreational sector, estimates of β^{hf} are much lower in Oregon management areas relative to California. As a result, a single unit of fishing effort, for both sectors, in the southern management areas results in higher expected SRFC harvest and impact rates.

3.3.3 p : SRFC stock proportion

Forecasts of the SRFC stock proportion in the harvest p , stratified by area, month, and sector, are needed for predicting SRFC harvest and impacts in quota and non-retention fisheries. While these types of fisheries are relatively rare in ocean fisheries south of Cape Falcon, and have not historically accounted for the bulk of SRFC impacts, forecasts of p are nevertheless made for all strata.

Estimates of historical harvest have been made for two stocks (S : SRFC, and K : Klamath River fall Chinook) and two stock groups (V : Central Valley hatchery-origin Chinook stocks other than SRFC, and N : non-Central Valley hatchery-origin Chinook stocks other than Klamath River fall run) for all area-month-sectors from 1983–forward (for details regarding these stock units and the estimation of their harvest see O’Farrell et al. 2013). In combination, these stock units ($g = S, K, V, N$) account for the large majority of ocean Chinook harvest south of Cape Falcon, Oregon, and it is assumed in the estimation of these harvests that they constitute the entire harvest.

For a particular stratum and year p is a function of the spatial distribution and catchability of SRFC, but also the relative abundance of the other stock units contributing to the total harvest. Recognizing this, p is forecast separately for each area-month-sector from the historical stock

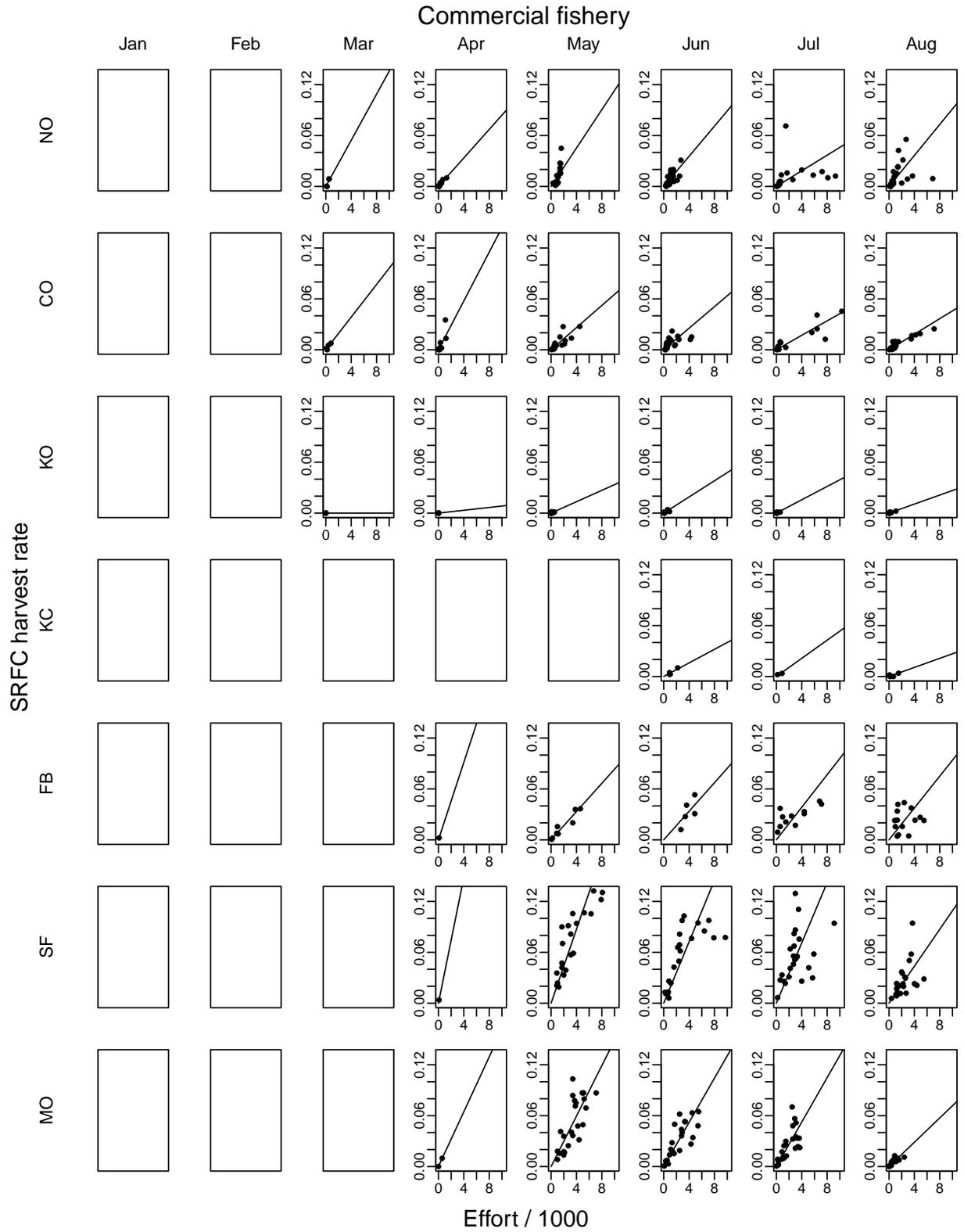


Figure 5. Commercial sector SRFC harvest rates plotted as a function of fishing effort by management area and month. Effort estimates are in units of vessel days. Line slope is estimated average harvest rate per unit of effort.

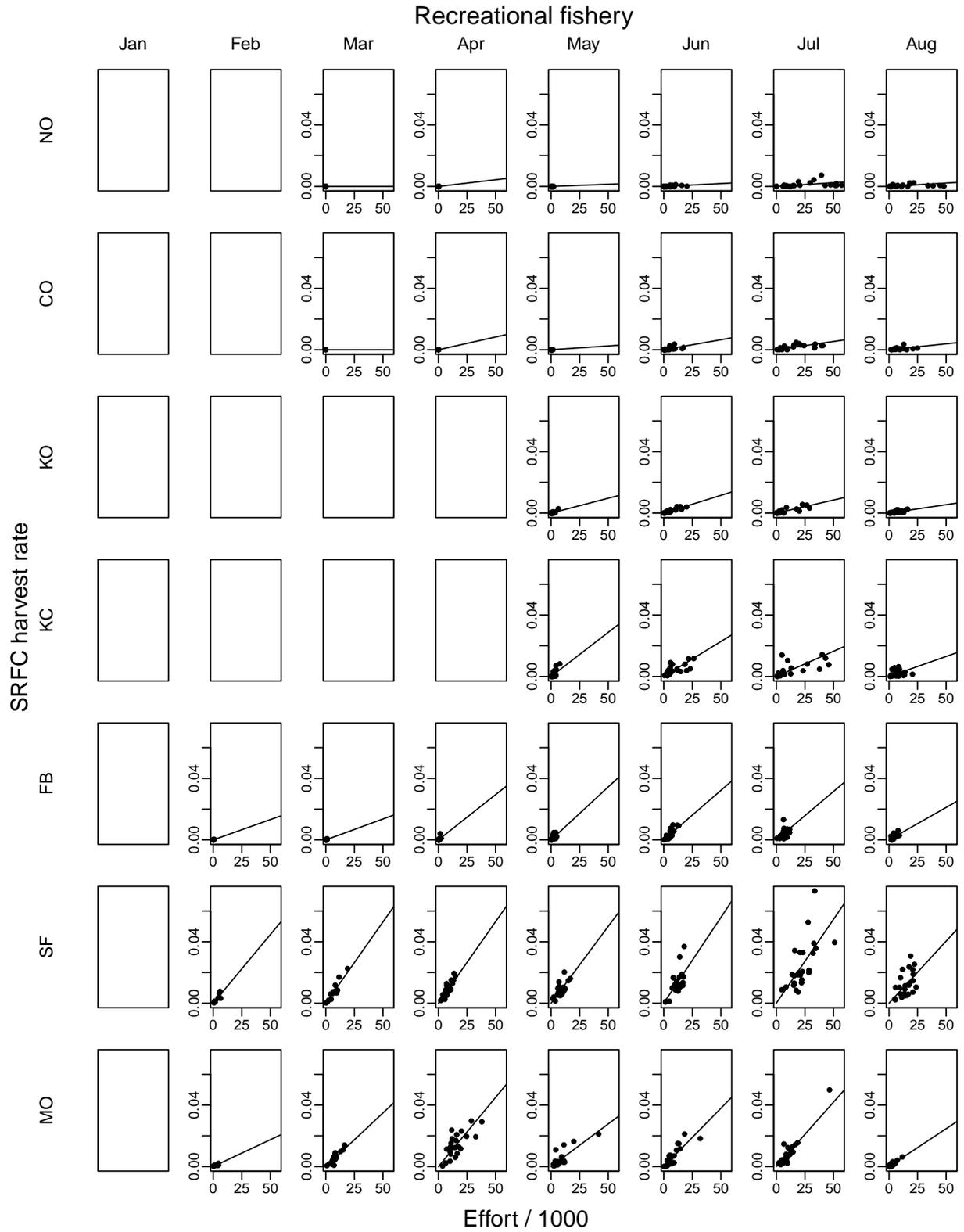


Figure 6. Recreational sector SRFC harvest rates plotted as a function of fishing effort by management area and month. Effort estimates are in units of angler days. Line slope is estimated average harvest rate per unit of effort.

proportion estimates as

$$p = \text{average}\{\tilde{p}\}, \quad (13)$$

where the average is taken over the period 1983–forward, and \tilde{p} is a given year’s proportion of SRFC in the harvest adjusted for each stock unit’s current year ocean abundance forecast, A_g^* , relative to its estimated ocean abundance at the time, A_g :

$$\tilde{p} = \frac{H_{o,S}(A_S^*/A_S)}{\sum_g H_{o,g}(A_g^*/A_g)}, \quad (14)$$

where $H_{o,g}$ is the harvest of stock unit g , and the sum is over $g = S, K, V, N$. A_S^* is the forecast SI and A_K^* is the aggregate-age ocean abundance forecast for Klamath River fall Chinook. The A_S^* and A_K^* forecasts and the time series of $\{A_S\}$ and $\{A_K\}$ estimates are provided in PFMC (2013a). Forecasts of A_V^* and A_N^* and the time series of $\{A_V\}$ and $\{A_N\}$ estimates are produced and maintained by the California Department of Fish and Wildlife, Ocean Salmon Project, as part of the annual stock assessment process.

3.3.4 s : release mortality rate

Estimates of the release mortality rate, s , are needed for forecasting impacts in non-retention fisheries. When the method of fishing is trolling, the release mortality rate is assumed equal to 0.26 and 0.14 for the commercial and recreational sectors, respectively, as recommended by the PFMC Salmon Technical Team (STT 2000) based on their review of west coast salmon hook and release mortality studies.

Recreational fisheries in the SF and MO management areas have, to varying degrees over time, also employed a method of fishing known as “mooching” in lieu of trolling. Mooching in this region typically consists of drifting a bait rigged with either a single or double hook. The prevalence of gut hooking has been shown to be higher for mooching than trolling, which leads to increased release mortality under this method of fishing. Grover et al. (2002) estimated a release mortality rate of 0.422 when the method of fishing is mooching with barbless circle hooks (the mooching gear requirement currently in place). Therefore, for the recreational sector in the SF and MO areas, the release mortality rate for a particular area-month is a weighted average of the mooching and

trolling release mortality rates, the weights being equal to the proportion of the harvest caught by the respective method.

Thus,

$$s = \begin{cases} 0.26, & x = \text{Commercial}, \\ 0.14, & x = \text{Recreational}, \quad a \neq \{\text{SF}, \text{MO}\}, \\ (\rho \times 0.422) + ((1 - \rho) \times 0.14), & x = \text{Recreational}, \quad a = \{\text{SF}, \text{MO}\}, \end{cases} \quad (15)$$

where ρ is forecast as the most recent 5-year average proportion of the area-month recreational harvest caught by mooching.

4 River Submodel

Following completion of the August ocean fisheries, the SRFC river return, R , is forecast as

$$R = SI \times (1 - i_o), \quad (16)$$

and the river harvest submodel is then used to forecast the river fishery impact rate, i_r , based on the type of proposed river fishery. The two types of river fishery that have been employed in the Sacramento basin are an “unconstrained” fishery and a quota fishery; a non-retention fishery has not been used to date.

The most common type of fishery in the basin is referred to as “unconstrained”, which is characterized by the Sacramento River and its major tributaries being open to Chinook retention during the bulk of the SRFC migration and spawning period. However, such a fishery is not completely unconstrained because regulations specify daily bag and possession limits, closures to many minor tributary streams, and closures to select reaches of rivers otherwise open to Chinook retention. For the unconstrained fishery, O’Farrell et al. (2013) estimated an average historical harvest rate of 0.14, and the *SHM* thus assumes for this type of river fishery that

$$i_r = h_r = 0.14. \quad (17)$$

Quota fisheries have been employed only when the *SI* forecast was low and river fishery impacts needed to be reduced below unconstrained fishery levels. Under quota fisheries, the *SHM* assumes that

$$i_r = h_r = Q_r^k/R, \quad (18)$$

where Q_r^k is the river retention fishery quota size in numbers of fish.

5 Discussion

The development of the *SHM*, in conjunction with the *SI*, represented a marked improvement over the previous SRFC assessment procedure. In contrast with the *CVI*-based harvest model, the *SHM* (1) stratified ocean harvest by management area, month, and sector for the region south of Cape Falcon, Oregon and (2) accounted for Sacramento basin recreational river fisheries. These capabilities now allow the PFMC to use area-month-sector closures and quotas to more directly control ocean harvest of SRFC. Alternative river fishery configurations can also be accounted for in the forecasts of *E* and *F*. Neither of these management controls were available prior to the development of the *SI* and *SHM*.

While the *SHM* represented a significant advance over the previous harvest model, there are limitations to models with the *SHM*'s structure. The historical SRFC CWT and spawner escapement data did not allow for an age-structured assessment in the form of cohort reconstructions which precludes age-specific abundance, harvest, and escapement forecasts. One example of a limitation resulting from an aggregate-age assessment is that it does not allow for the estimation and forecasting of impacts associated with hook and release mortality for fish smaller than the minimum size limit in retention fisheries. The inability of the *SHM* to account for this form of release mortality does not allow the i_o forecast to be sensitive to changes in minimum size limits, a management tool frequently used by the PFMC to achieve conservation objectives for other salmon stocks.

The lack of age-specific accounting in the *SI* and *SHM* can lead to *E* and *F* forecast errors in other ways as well. For example, there may be age-specific patterns in SRFC harvest rates per

unit effort that, when undetected, could result in poor impact rate forecast performance. With the age-structured Klamath River fall Chinook assessment, for example, there are notable differences between the age-3 and age-4 contact rates per unit effort in the commercial sector, and in some areas and months in the recreational sector. This age structure effect is readily accounted for in the Klamath Ocean Harvest Model yet the ability to identify and respond to those differences does not exist for the *SHM*. In addition, there are likely large differences in age-specific maturation rates for SRFC that are not recognized in the *SI* and *SHM*. An aggregate-age index of abundance will be composed of different relative contributions of the age-3 and age-4 cohorts as a result of variable year class strength. The fraction of the total index that will mature in that year will vary from year to year inasmuch as the underlying age structure and the age-specific maturation rates differ. Such processes likely have effects on forecast performance, though the magnitude of those effects are not known.

The use of the *SI* and *SHM* is likely to be an interim assessment for SRFC, bridging the gap to an age-structured approach. Beginning in 2006 a “constant-fractional marking” program (Buttars 2012) was implemented. The goal of the program is to mark (adipose fin clip) and tag (CWT) 25% of SRFC hatchery production. Increased effort is also being made to improve escapement monitoring and recover CWTs in natural spawning areas (Bergman et al. 2012). The California Department of Fish and Wildlife has developed a scale aging program capable of estimating age-specific run size (Grover and Kormos 2008). If these programs are appropriately and consistently implemented, a time series of data sufficient for cohort reconstructions will eventually exist for SRFC, and this will allow for a fully age-structured assessment similar to that for Klamath River fall Chinook.

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Appendix A Ratio Estimation

The choice of which estimator to use when estimating the average harvest rate per unit of effort, β^{hf} , or average effort per day open, β^{fD} , depends on the nature of the relationship between the numerator (Y) and denominator (X) variables of the respective ratio (β). For each area-month-sector stratum, we assume that the following zero-intercept, linear (ratio) model adequately characterizes

the relationship between the Y and X variables:

$$Y = \beta X + \varepsilon, \quad \mu_\varepsilon = 0, \quad \sigma_\varepsilon^2 = aX^b, \quad (\text{A-1})$$

where for $\beta = \beta^{hf}$, $Y = h_o$ and $X = f$, and for $\beta = \beta^{fD}$, $Y = f$ and $X = D$. Under this model, the expected value of Y increases linearly from the origin with X , and the slope of this line, β , is the average (expected value) of Y per unit X . The residual error in Y about this linear relationship, ε , has a mean value of 0 and a variance that is proportional to X^b , where b is a specified constant. Figure A-1 illustrates these model features for the most commonly specified variance functions: constant variance ($b = 0$), variance proportional to X ($b = 1$), and variance proportional to X^2 ($b = 2$).

This variance function should be taken into account when estimating β from a particular set of data, $\{X_j, Y_j\}$, and one technique for doing this is to use the method of weighted least squares, where each observation is weighted inversely proportional to its residual variance in the sum of squared-errors function:

$$SS(\hat{\beta}) = \sum_j w_j (Y_j - \hat{Y}_j)^2 = \sum_j \frac{(Y_j - \hat{\beta} X_j)^2}{X_j^b} = \sum_j Y_j^2 X_j^{-b} - 2\hat{\beta} \sum_j Y_j X_j^{1-b} + \hat{\beta}^2 \sum_j X_j^{2-b}. \quad (\text{A-2})$$

The value of $\hat{\beta}$ that minimizes $SS(\hat{\beta})$ is the weighted least squares estimator of β , and it can be found by setting the derivative of $SS(\hat{\beta})$ with respect to $\hat{\beta}$,

$$\frac{dSS(\hat{\beta})}{d\hat{\beta}} = -2 \sum_j Y_j X_j^{1-b} + 2\hat{\beta} \sum_j X_j^{2-b}, \quad (\text{A-3})$$

to zero and solving for $\hat{\beta}$, giving

$$\hat{\beta} = \frac{\sum_j Y_j X_j^{1-b}}{\sum_j X_j^{2-b}}. \quad (\text{A-4})$$

For the specific values $b = 0, 1, 2$, this results in the following estimators for β :

$$\hat{\beta} = \begin{cases} \frac{\sum_j Y_j X_j}{\sum_j X_j^2}, & b = 0 : \text{ordinary (unweighted) least-squares estimator} \\ \frac{\sum_j Y_j/n}{\sum_j X_j/n}, & b = 1 : \text{“ratio of means” (ratio estimator)} \\ \frac{\sum_j Y_j/X_j}{n}, & b = 2 : \text{“mean of ratios”}, \end{cases} \quad (\text{A-5})$$

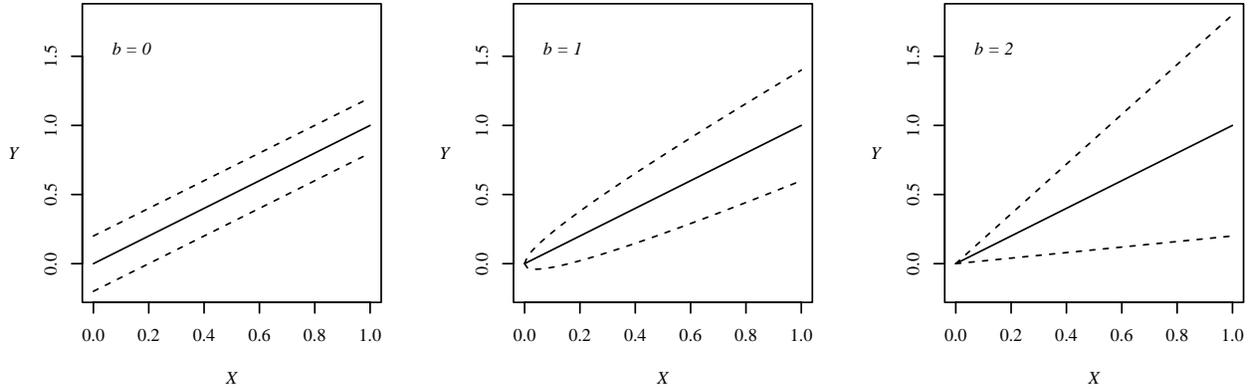


Figure A-1. Illustration of the ratio model defined by equation (A-1) for specified values $b = 0, 1, 2$, respectively. Solid line is the expected value of Y ; dashed lines are the expected value \pm two standard deviations. To highlight the effect of b in the model, the slope of the expected value line is equal ($\beta = 1$) in all panels, as is the residual variance at $X = 0.25$ ($\sigma_{\varepsilon}^2 = 0.01$).

where n is the number of $\{X_j, Y_j\}$ data points.

Based on the data patterns exhibited in the area-month-sector specific panels of Figures 3, 4, 5, and 6, we conclude that the ratio model with $b = 1$ provides the most apt description of these data, and that β is therefore most appropriately estimated using the ratio estimator.

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