Fisheries and Oceans Science
Pêches et Océans Sciences

C S A S
Canadian Stock Assessment Secretariat

S C É S
Secrétariat canadien pour l'évaluation des stocks

Research Document 2000/155

Document de recherche 2000/155

Estimating stock biomass from tow-by-tow data for Pacific Groundfish

J.T. Schnute and R. Haigh

Fisheries and Oceans Canada
Science Branch
Pacific Biological Station
Nanaimo, B.C. V9R 5K6

ISSN 1480-4883
Ottawa, 2000

Abstract

This paper describes an analytical technique for estimating groundfish biomass from swept area density measurements. Conceptually, the idea is simple. Tows give estimates of biomass density. Bathymetry, locations of fish capture, and other sources of information give estimates of habitat area. Multiplying the density by the area gives an estimated biomass, which might be interpreted as an absolute measure or a relative index. We present a rigorous description of the method, along with a bootstrap technique for assessing uncertainty. Illustrations from Pacific groundfish commercial fisheries and research surveys demonstrate various limitations and advantages to this approach. Our analyses highlight issues of scientific importance, such as the need to obtain better habitat definitions. Comparisons between surveys and commercial fisheries provide some insight into the underlying processes. Despite their limitations, biomass estimation methods play an important role in groundfish stock assessment. Patterns in the analysis of a particular data set may reflect a variety of factors, such as biomass trends, response by fishermen to regulation, and measurement error.

Résumé

Ce document décrit une technique analytique permettant d'estimer la biomasse des poissons de fond à partir des mesures de la densité des surfaces balayées. En théorie, l'idée est simple. Les traits fournissent des estimations de la densité de la biomasse. La bathymétrie, les endroits de capture des poissons, ainsi que d'autres sources d'information servent à estimer la surface de l'habitat. Une estimation de la biomasse s'obtient en multipliant la densité par la surface, et peut être interprétée en tant que mesure absolue ou comme un indice relatif. Nous faisons un exposé rigoureux de la méthode, et aussi d'une technique «bootstra » permettant d'évaluer l'incertitude. Les illustrations provenant des pêches commerciales du poisson de fond du Pacifique et des relevés de recherche démontrent que cette démarche comporte des restrictions et des avantages divers. Nos analyses mettent l'accent sur des problèmes d'importance scientifique, tels que la nécessité d'obtenir de meilleures définitions de l'habitat. Les comparaisons entre les relevés et les pêches commerciales donnent un certain aperçu des processus sous-jacents. Les méthodes d'estimation de la biomasse jouent un rôle important dans l'évaluation des stocks de poisson de fond, en dépit de leurs contraintes. Les tendances dans l'analyse d'un ensemble de données particulier peuvent refléter divers facteurs, tels que les tendances de la biomasse, la réaction des pêcheurs à la réglementation et l'erreur de mesure.

Table of Contents

List of Tables

List of Figures

Estimating stock biomass from tow-by-tow data for Pacific Groundfish

1. Introduction

Pacific groundfish management relies on data obtained from tows in the commercial fishery and research surveys. Conceptually, a single tow along the sea floor gives an estimate of biomass density for each species caught:

$$(1.1) \qquad \text{density} = \frac{\text{biomass captured}}{\text{area swept by the net}} \,.$$

If the area of available fish habitat is also known, then total stock biomass can also be estimated as:

$$(1.2) \qquad \text{biomass} = \text{density} \times \text{habitat area} \,.$$

Theoretically, many tows produce many density estimates (1.1) that result in a distribution of biomass estimates (1.2). A central statistic of this distribution, such as the mean, might be adopted as a biomass estimate or a relative biomass index.

These simplistic calculations gloss over many difficulties. For example, the concept of density sampling in (1.1) requires a relatively even distribution of fish throughout the habitat. Schooling might produce highly variable estimates in which tows produce frequent low catches interspersed with occasional high catches. The habitat area in (1.2) might be poorly defined, and different habitats might support different densities of fish. Stratified sampling could potentially deal with the problem of uneven fish distributions, but criteria would be needed to select appropriate strata. Furthermore, because fisheries take place over long time periods, strata definitions would have to account for both spatial and temporal density changes.

Schnute et al. (1999b) illustrated a stratified biomass analysis for various species of Pacific slope rockfish, based on data from the commercial fishery. Their design used two stratification levels: depth ranges and square grid blocks within each depth range. In addition to biomass estimates, they obtained estimates of fishery impact on the sea floor by accumulating the area towed within each block. Tows may occur on the same portion of sea floor already impacted by earlier tows. Thus, due to repeated impact on the same locations, the total area swept by all tows can greatly exceed the impacted area.

In this paper, we examine a somewhat simpler analysis, stratified only by depth. For Pacific groundfish fisheries, the relationship between species abundance and depth has been established in many studies, including the two most recent slope rockfish assessments (Schnute et al. 1999a, 1999b). For simplicity, our strata divide time into quarter years (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec) and the ocean floor into depth ranges within four groundfish management areas (3CD, 5AB, 5CD, 5E). We do not consider our results definitive, but rather illustrative of the possible analyses. This “default” analysis at least offers a base line from which to consider any proposed alternative. Furthermore, although basically quite simple, our notation describes a well-defined analysis, complete with a bootstrap method for assessing variance.

We illustrate our methods by applying them to both commercial and research data. We recognize, of course, that commercial tow data differ in many respects from survey data. In particular:

1. Although surveys seek random samples, commercial fishermen may either target or avoid the species of interest.
2. Surveys seek to represent each spatial stratum, whereas commercial tows focus on particular locations of interest to the fishermen.
3. Surveys take place during relatively short time periods, and commercial tows occur throughout the fishing year.
4. A survey usually obtains several dozen tows, whereas the commercial fishery may include thousands.

Because larger sample sizes theoretically reduce uncertainty, item 4 offers at least one reason to compare survey estimates with similar estimates from the fishery. In the comparisons here, we use the same spatial depth strata for both cases. To deal with item 3, we use quarterly time intervals (described above) in the fishery. Results from commercial data provide a starting point for designing a survey conducted by members of the industry.

The available "habitat area" in (1.2) obviously plays a key role in the final estimate of biomass. Where are the fish? Where can they survive and find sufficient food? One extreme view might be that the fish occur only where fishermen catch them. This seems unlikely in the Pacific groundfish fishery, where a rocky sea floor sometimes provides good fish habitat but makes bottom trawling impossible. At the other extreme, fish might occur with a similar density throughout the depth range in which fishermen find them, including areas that cannot be fished. This is probably too optimistic, because the habitat often varies within a depth stratum. For example, both mud bottom and rocky reefs may occur along a depth contour and offer distinct habitats of different suitability to a particular species. Habitat definition remains an important research question along the Pacific coast, and a properly constructed database could have great value for stock assessments.

Lacking a suitable habitat database, we consider the two extremes mentioned above, in which fish occur (A) only where fishermen find them and (B) throughout the available area within a depth stratum. To estimate the areas associated with these extremes, we link coastal bathymetric information with tow location data from bottom trawls in the groundfish fishery. Our analyses stratify density estimates (1.1) by depth, but use square grid blocks to compute the habitat areas in (1.2). Thus, in the calculation of areas only, we use a raster method based on grid blocks similar to those discussed by Schnute et al. (1999b). Given other data, however, the method could easily accommodate more precise estimates of available area than the extremes discussed here.

Informed quota recommendations depend fundamentally on the available biomass of fish, expressed in (1.2) as the product of density and area. Intuitively, the density represents crowding of individuals, where an increased density leaves less space available for each animal. Our inquiries produce a set of interrelated estimates:

- the space available to each fish,
- biomass density,
- available area, and
- total biomass.

Like cattle, fish require a certain amount of space on average to support their existence. A cattle herd or a fish school may roam across an extensive range, but on average this reduces to an area available for each animal. The productive potential of each square kilometer obviously depends on the quality of habitat, and this can vary with climatic conditions. How much ranch land is needed to support a cow? How much sea bottom does a female rock sole need to survive? Is reproductive success density-dependent? Fishermen, like cattle ranchers, benefit from good use of the available range. Populations and habitat conditions may change over time, but the available range remains fixed by the earth's geography. We give our analysis an intuitive focus by investigating its implications on the space available to each fish.

This methods paper has potential implications for assessments of various Pacific groundfish species. We include analyses germane to flatfish species (Fargo et al. 2000) and longspine thornyheads (Starr and Haigh 2000). Our results also give preliminary information useful in the design of surveys for slope rockfish (Starr and Schwarz 2000). In a future paper (Schnute et al 2001), we relate the swept area method (1.1)–(1.2) to classical sampling theory and examine alternative models, such as the compound binomial-gamma distribution proposed by Steffánsson (1996).

2. Data Sources

This study and potential future studies depend on data from four groundfish databases:

[D1]. 'GFCatch' contains commercial catch data prior to 1996. In particular, from 1991–1995, vessel master logs provide information on individual tows.

[D2]. 'PacHarvest' archives catch data from 1996 to the third quarter (Jul–Sep) of 2000, including detailed tow information compiled by on-board observers. Detailed vessel master logs capture data from trips without observers.

[D3]. 'GFBio' primarily contains sample data collected from commercial fisheries and research surveys. It also holds detailed information from individual research tows.

[D4]. A bathymetric database (Schnute et al. 1999b, section 3.6) records an estimated bottom depth for each $1\text{km}\times 1\text{km}$ block within a large rectangle on the BC coast. (Blocks on land have depth 0.) This database now appears as a table in [D2].

Suppose that a particular species is chosen for biomass estimation. Table 1 lists the data for a single tow available from one of the databases [D1]–[D3]. More precisely, this level of detail is available for many tows in [D1] since 1994 and most tows in [D2]–[D3]. Spatial and temporal coordinates (t, x, y, d) are all computed from averages of available data, such as the start and end coordinates of a tow. Theoretically, the spatial coordinates (x, y) determine the bottom depth d and management area M. In case of missing data in [D1]–[D3], the bathymetric database [D4] makes it possible to estimate (d, M) from (x, y).

3. Methods

As indicated in (1.1), a single tow gives an estimate of biomass density. Suppose that a vessel tows a net of width *w* at speed *v*. If the tow lasts for the duration *E*, then the net moves a distance *vE* and sweeps an area *vwE*. Furthermore, if this tow captures a biomass *C* of the given species, then the observed biomass density is

$$d = \frac{C}{vwE} = \frac{1}{vw}U ,$$

where $U = C / E$ is the catch per unit effort (CPUE).

More generally, consider a set of *m* tows, chosen by some criterion. Then each tow $i \ (i = 1, \ldots, m)$ gives a sample measurement of fish density

$$d_i = \frac{1}{vw}U_i , \tag{3.1}$$

where we assume a constant vessel speed *v* and net width *w* among tows. In particular, $d_i = 0$ if tow *i* fails to catch the designated species $(C_i = 0)$. Suppose that a selected management area *M* is divided into *n* depth strata

$$S_j = \{ d \mid D_{j-1} < d \le D_j \} , \tag{3.2}$$

specified by given depths $0 = D_0 < D_1 < D_2 < \cdots < D_n$. Let $m(\cdots)$ denote the mean of a set of numbers. Then a mean estimate of the biomass density in depth stratum S_j is

$$\Delta_j = m \ (\{ d_i \mid d_i \in S_j \} \ ) . \tag{3.3}$$

The bathymetric database [D4] enables us to calculate the total area A_j of each depth stratum *j*. Alternatively, based on a rectangular grid of the coast, tow locations can be used to identify grid blocks in which a particular species has been captured. Summing areas of these blocks within stratum *j* typically gives a habitat area less than the total available area. From suitably defined areas A_j, the logic of (1.2) leads to the biomass estimate

$$B = \sum_{j=1}^{n} A_j \Delta_j \tag{3.4}$$

for the entire selected management area *M*. The data used to estimate biomass must include all tows, even those with no catch of the given species $(d_i = 0)$.

Bootstrap methods can be used to assess uncertainty in the estimate (3.4). The idea is conceptually simple, but computationally lengthy. Each stratum $j\ (j = 1,\ldots,n)$ has a corresponding set of m_j tows indexed in the set

$$T_j = \{\, i \mid d_i \in S_j \} \quad . \tag{3.5}$$

Every tow belongs to exactly one stratum, so the total number of tows is $m = \sum_{j=1}^{n} m_j$. One bootstrap involves sampling the set T_j with replacement for each *j*, while preserving the number m_j of tows in each stratum. The resulting collection of tows (some repeated from the original data, others omitted) gives a new data set for the calculations (3.1)-(3.4). Each bootstrap gives a new estimate B_k from (3.4), where the index *k* enumerates the individual bootstraps. For convenience, denote the original estimate as B_0. Characteristics of the distribution $\{B_k\}_{k \geq 0}$, such as the standard deviation, give measures of uncertainty in the estimator (3.4). We implement this procedure using the bootstrap function in S-Plus (MathSoft 1999), where the stratum *j* acts as a grouping variable. Efron and Tibshirani (1993) also describe a "bias corrected and accelerated" method of improving the confidence intervals obtained directly from the empirical distribution, and S-Plus provides additional support for this analysis. Smith (1997) reviews these concepts and various refinements in the context of trawl survey data.

To summarize the analysis, suppose that a biomass *B* of fish with average weight *W* occupies a total area *A*. Then the number of fish is B/W and the average area available to each fish is

$$l^2 = \frac{AW}{B} = \frac{W}{\Delta}, \tag{3.6}$$

where

$$\Delta = \frac{B}{A} \tag{3.7}$$

is the mean fish density. We have written (3.6) so that l is the side of a square representing the area available to one fish. In other words, if fish are arranged in a uniform square grid, l denotes the distance between neighbouring fish along grid lines. We refer to l as the estimated *inter-fish distance*.

4. Results

We examine data for six groundfish species:

- Pacific ocean perch (*Sebastes alutus*),
- rougheye rockfish (*Sebastes aleutianus*),
- shortspine thornyheads (*Sebastolobus alascanus*),
- longspine thornyheads (*Sebastolobus altivelis*),
- rock sole (*Lepidopsetta spp*), and
- English sole (*Parophrys vetulus*),

The first four of these are slope rockfish associated with a broad depth range along marine slopes descending from the continental shelf. The last two species belong to the flatfish group common to shallower mud and sand habitats. We stratify the data spatially by four combined management regions (3CD, 5AB, 5CD, and 5E). Our information comes from two sources:

- commercial trawls during the years 1994–2000, and
- research surveys in Hecate Strait (area 5CD), conducted approximately every two years from 1984 to 2000.

We use data only from trawls along the ocean floor, as summarized in Table 2. Ideally, the databases would give the vessel speed v and net width w for each tow. This information has not, however, been included in the historical records, and we use the estimated values shown in Table 3.

In the commercial fishery, we select all tow records that include the fields t, M, d, and E shown in Table 1. Within each tow, the catch C is identified by species, so that $C = 0$ if no catch is recorded for a given species. In 1994–1995, the data come from vessel master logs (GFCatch database). Subsequent data (1996-2000) come chiefly from observer logs during a period of complete coverage by onboard observers (PacHarvest database). Prior to 1994, data with the necessary detail are spotty or unavailable. Data for the year 2000 are complete only to the end of the third quarter (Jul–Sep).

Research survey data automatically conform to the specifications in Table 1. Our analysis uses an *ad hoc* database compiled in Microsoft Access from annual spreadsheets, although the data will soon be available in GFBio.

We begin by defining depth strata (3.2) appropriate for the six species considered here. As shown in Table 4, we use depth intervals of 200 m for slope rockfish and 40 m for flatfish. The table lists the total bathymetric area A available coastwide within each stratum. We also examine the area in which a particular species has been captured and use a superscript asterisk to distinguish this area A^* from the total area A. Explicitly, we compute A^* from all commercial tows (1996–2000) recorded in the PacHarvest database, where observer logs give the coordinates (x, y) of each tow. We associate each tow with a corresponding $1\,\text{km} \times 1\,\text{km}$ block and record that block as available habitat for each species captured there. The observed area A^* within a stratum can only increase in time as the fishery identifies more blocks available to the species. From this point of view, the fishery acts as a search mechanism to identify habitat for each species. Table 4 shows total coastwide areas A and A^* for each depth stratum. These come from the similar areas computed for each management region (Fig. 1a-1c).

Table 5a illustrates the calculation (3.3)-(3.4) of shortspine thornyhead biomass from the 1,058 commercial tows that occurred in area 3CD during the 3rd quarter of 1998. Only 751 of these tows caught a measurable biomass of the species, but the mean density estimates Δ_j use all tows available in depth stratum S_j. For $j = 1,\ldots, 8$, notice that the biomass estimates B_j and B_j^* depend on a common density estimate Δ_j but different estimated areas A_j and A_j^*, where

$$(4.1) \qquad \Delta_j = \frac{B_j}{A_j} = \frac{B_j^*}{A_j^*}.$$

From the 8 stratified biomass estimates, the sum (3.4) gives two possible estimates of shortspine thornyhead biomass in area 3CD during the 3rd quarter of 1998:

B = 1157 t, based on a sea surface projection of available sea floor area;

B^* = 440 t, based on the area in which shortspines have been captured.

The ratio $B / B^* = 2.63$ reflects the expansion factor from known fishing locations to the entire bathymetry.

Table 5a shows that shortspine thornyheads are not evenly distributed among the depth strata. We consider three possible measures of mean density Δ for the entire management area 3CD:

$$(4.2a) \qquad \Delta = \frac{1}{8}\sum_{j=1}^{8}\Delta_j,$$

$$(4.2b) \qquad \Delta = \frac{B}{A} = \frac{\sum_j A_j\Delta_j}{\sum_j A_j}, \text{ and}$$

$$(4.2c) \qquad \Delta = \frac{B^*}{A^*} = \frac{\sum_j A_j^*\Delta_j}{\sum_j A_j^*}.$$

The simple mean (4.2a) potentially gives too much weight to strata with small area (or too little weight to strata with large area). Similarly, the weighted average (4.2b) might give inappropriate weight to strata not occupied by the fish. This leaves (4.2c), which assigns weights in proportion to areas where fish have actually been observed. We adopt (4.2c) as our definition of mean density. Furthermore, we define the area

(4.3) $$A' = \frac{B}{B^*} A^* = \frac{B}{\Delta},$$

associated with the biomass *B* that gives the same density (4.2c):

(4.4) $$\Delta = \frac{B^*}{A^*} = \frac{B}{A'}.$$

Comparing (4.4) with (4.1) shows that the density Δ for the entire population has properties similar to the density Δ_j within each stratum *j*. The ratio

(4.5) $$r = \frac{B}{B^*} = \frac{A'}{A^*}$$

gives an expansion factor from known fishing locations to the entire bathymetry.

Table 5b summarizes population statistics from the calculations in Table 5a. The total ocean floor in management region 3CD down to 1600 m has area $A = 28{,}033\ \text{km}^2$. Shortspine thornyheads have been captured in an observed area $A^* = 3{,}428\ \text{km}^2$. The biomass estimate $B^* = 440$ t, cited above, gives the mean density $\Delta = 128\ \text{kg/km}^2$ from (4.2c). This same density is achieved if the second biomass estimate $B = 1157$ t is distributed across the area $A' = 9{,}005\ \text{km}^2$ computed from (4.3). Obviously, shortspine thornyheads cannot use the entire available sea floor area A, and the adjusted area A' provides an estimate consistent with observed densities in the various depth strata. The ratios A'/A^* and B/B^* both give the expansion factor $r = 2.63$. Furthermore, by the logic of (3.6)-(3.7), each fish has an average available area l^2, where $l = 44$ m.

The example in Table 5 pertains to one species in one management region during one quarter. Figure 2 extends this analysis to quarterly estimates B for all 6 species in all four management regions from the 1st quarter of 1994 to the 3rd quarter of 2000. Furthermore, each estimate has an associated bootstrap distribution, portrayed here by boxplots. Table 6 summarizes these results for the four-year period 1996-1999, where we also incorporate quarterly estimates B^*. Figure 3 shows that the estimates B and B^* tend to differ by a scale factor. A straight line in each panel connects the origin to the centroid of the data, and the slope b of this line agrees with the corresponding expansion factor r in Table 6.

We conduct similar analyses for the two flatfish species, based on research survey data from Hecate Strait (part of management region 5CD). These calculations use the same depth stratified areas A_h and A_h^* as in previous examples from the commercial fishery; however, stratified density estimates Δ_j in (3.3) come entirely from research tows. For comparison with results from the commercial fishery, we use only the catch of ‘adult’ soles, defined as animals with length at least 30 cm. Figure 4 shows biomass estimates B and boxplots of bootstrapped distributions derived from May/June surveys conducted approximately every two years. Figure 5 illustrates a pattern similar to that obtained from commercial data. Survey estimates B and B^* generally differ by a scale factor, which can be estimated as the slope b of a line from the origin to the centroid of the data. Figure 6 compares survey estimates in a given year with corresponding estimates from the commercial fishery in the 2nd quarter of the same year.

5. Discussion

This paper describes a systematic approach to biomass estimation, based on data from individual groundfish tows. We have focussed on a rigorous description of the method and straightforward examples of its application. The basic idea is not complicated. Tows give estimates of biomass density. Bathymetry, locations of fish capture, and possible other data give estimates of habitat area. Multiplying the estimated density by the estimated area gives an estimated biomass.

Our worked examples suggest many limitations to this approach. Although we make no attempt to cover them all here, we can highlight a few obvious issues.

1. Many tows fail to capture a given species, while others capture a large quantity. Such highly variable density distributions make it difficult to obtain a reasonable average. Schnute et al. (2001) examine this issue quantitatively using a compound binomial-gamma distribution.
2. Measurement of habitat area similarly has a high variance. In this study, known locations of fish species are typically small compared to the available bottom. This often results in large factors r between potential biomass estimates (Table 6).
3. Our estimates of known species habitat use a $1\,\text{km} \times 1\,\text{km}$ grid. Although smaller or larger blocks might be justified, the analysis remains somewhat robust to the choice. Over a long time period (here 1996-2000), tows tend to identify all adjacent blocks within a patch of habitat relevant to the species. Walters and Bonfil (1999) assume that the known habitat extends somewhat beyond that identified by the fishery.
4. We have used the estimates of vessel speed v and net width w listed in Table 3. Other choices would alter our density and biomass estimates by a factor inversely proportional to the product vw. Ideally, these data should be available for each tow i, so that equation (3.1) would be replaced by $d_i = U_i / (v_i w_i)$.
5. Quarterly biomass estimates from commercial tows reflect fishing activity as well as fluctuations in the population. For example, the fishery experienced major regulatory changes during the period 1995-1997. In Fig. 2, changes in fishing practices could easily mask any real biomass fluctuations. In fact, populations of long-lived groundfish could not vary as rapidly as indicated in Fig. 2. Observed seasonal variation must stem primarily from fishing patterns, not biomass changes.
6. Some quarterly biomass estimates in Fig. 2 have noticeably higher variability than others. Poorly defined values probably reflect low effort levels and poor coverage of depth strata during the time period. At another extreme (e.g., area 5E in Figs. 2d–2f), low fishing rates may produce only one tow per stratum, so that only one bootstrap sample is possible. In this

case, the bootstrap distribution has a zero variance. No method can produce a meaningful variance estimate from a sample of size one, and the bootstrap technique does not apply unless multiple samples occur in each stratum. We include figures with zero variance only for completeness.

7. Standard techniques for bias corrected and accelerated confidence intervals (Efron and Tibshirani 1993; MathSoft 1999) make little difference for most examples presented here. Therefore, we confine our results to boxplots portraying conventional bootstrap distributions.
8. Some apparent biomass increases (e.g., longspine thornyhead in recent quarters, Fig. 2d) might result from a fishery expanding into new areas with a concomitant increase in CPUE.
9. Flatfish biomass estimates from the commercial fishery agree roughly with estimates from research surveys (Fig. 6). Furthermore, fishery estimates tend to have smaller variance, probably due to the larger number of observations.
10. Rock sole biomass estimates from the fishery tend to be higher than corresponding survey estimates. The opposite is true for English sole, particularly in 1998 and 2000. Commercial fishermen state that they fish these two species differently: targeting rock sole and avoiding English sole.
11. We have chosen somewhat arbitrary strata for space, depth, and time. Other options might be more appropriate, depending on the species.
12. We have used the mean $m(\cdots)$ as a measure of central tendency in (3.3). Other options might include a median or trimmed mean. As discussed further by Schnute et al. (2001), various parametric distributions might also be used, including the compound binomial-lognormal (Pennington 1983, 1986; Smith 1988, 1990), Poisson (Swartzman et al. 1992), and compound binomial-gamma (Steffánsson 1996). Furthermore, models have been designed to account for spatial effects, vessel characteristics, and other factors (Pennington 1986; Sullivan 1991; Kulka et al. 1996; Steffánsson 1996).
13. Our methods focus on spatial distribution along the ocean floor. They would not apply to mid-water species, such as redstripe rockfish.
14. We have constructed estimates with units of absolute biomass, although they may at best offer relative indices. Typically, a time series of index values would become part of the input data for a population dynamics model that generates absolute biomass estimates. An index expressed in biomass units allows easy comparison between model input and output. Does the model generate historical biomass estimates much higher or lower than those in the index? If so, the modeler must think beyond the model framework to explain the difference. For example, he might treat with skepticism a catch-age model in which the current estimated biomass differs by a factor of 1000 from recent survey estimates.
15. The estimated inter-fish distance l could possibly be linked to ecological, habitat, and bioenergetic models.

In this report, we apply a simple biomass estimation technique to data available from the Pacific groundfish trawl fishery. We recognize that patterns in the data may result from various factors, such as available biomass, response by fishermen to regulation, interactions between fish and trawl gear, spatial distributions of fish and fishermen, and assumptions about appropriate fish habitat. Schnute et al. (2001) extend the methods introduced here and present additional graphical tools for investigating patterns in groundfish trawl data.

Acknowledgements

Jeff Fargo and Rob Kronlund assisted us with the compilation and interpretation of data from the Hecate Strait surveys. Greg Workman provided a database from the 2000 tanner crab survey.

References

Efron, B., and R. J. Tibshirani. 1993. An introduction to the bootstrap. Chapman & Hall, New York, NY.

Fargo, J., A. R. Kronlund, J. T. Schnute, and R. Haigh. 2000. Stock assessment of rock sole and English sole in Hecate Strait for 2000/2001. Can. Stock Assess. Sec. Res. Doc. 2000/166, 83 p.

Kulka, D. W., A. T. Pinhorn, R. G. Halliday, D. Pitcher, and D. Stansbury. 1996. Accounting for changes in spatial distribution of groundfish when estimating abundance from commercial fishing data. Fish. Res. 28: 321-342.

MathSoft. 1999. S-Plus 2000 guide to statistics, Vol. 2. MathSoft, Inc., Seattle, WA.

Pennington, M. 1983. Efficient estimators of abundance, for fish and plankton surveys. Biometrics 39: 281-286.

Pennington, M. 1986. Some statistical techniques for estimating abundance indices from trawl surveys. Fish. Bull. 84: 519-525.

Schnute, J. T., N. Olsen, and R. Haigh. 1999a. Slope rockfish assessment for the west coast of Canada in 1998. Can. Stock Assess. Sec. Res. Doc. 99/16, 79 p.

Schnute, J. T., N. Olsen, and R. Haigh. 1999b. Slope rockfish assessment for the west coast of Canada in 1999. Can. Stock Assess. Sec. Res. Doc. 99/184, 104 p.

Schnute, J.T., R. Haigh, A.R. Kronlund, and J. Fargo. 2001. Patterns in biomass estimates from groundfish trawl data. Can. J. Fish. Aquat. Sci. In review.

Smith, S. J. 1988. Evaluating the efficiency of the Δ-distribution mean estimator. Biometrics 44: 485-493.

Smith, S. J. 1990. Use of statistical models for the estimation of abundance from groundfish trawl survey data. Can. J. Fish. Aquat. Sci. 47: 894-903.

Smith, S. J. 1997. Bootstrap confidence limits for groundfish trawl survey estimates of mean abundance. Can. J. Fish. Aquat. 54: 616-630.

Starr, P. J. and R. Haigh. 2000. Assessment of the Canadian longspine thornyhead (*Sebastolobus altivelis*) for 2000. Can. Stock Assess. Sec. Res. Doc. 2000/154, 66 p.

Starr, P. J. and C. Schwarz. 2000. Feasibility of a bottom trawl survey for three slope groundfish species in Canadian waters. Can. Stock Assess. Sec. Res. Doc. 2000/156, 42 p.

Steffánsson, G. 1996. Analysis of groundfish survey abundance data: combining the GLM and delta approaches. ICES J. Mar. Sci. 53: 577-588.

Sullivan, P. J. 1991. Stock abundance estimation using depth-dependent trends and spatially correlated variation. Can. J. Fish. Aquat. Sci. 48: 1691-1703.

Swartzman, G., C. Huang, and S. Kaluzny. 1992. Spatial analysis of Bering Sea groundfish survey data using generalized additive models. Can. J. Fish. Aquat. Sci. 49: 1366-1378.

Walters, C. J. and R. Bonfil. 1999. Multispecies spatial assessment models for the British Columbia groundfish trawl fishery. Can. J. Fish. Aquat. Sci. 56: 601–628.

TABLES

Table 1. Data from a single tow in databases [D1]–[D3], given a particular species.

Quantity	Description	Units
t	date	yr (including fraction)
x	longitude	° (decimal degrees)
y	latitude	° (decimal degrees)
M	major management area	label: 3CD, 5AB, etc.
d	depth	m
E	effort (tow duration)	h
C	catch biomass of the given species	kg
U	CPUE (C/E)	kg/h

Table 2. Annual number of bottom tows available from the commercial fishery (coastwide) and the Hecate Strait survey (area 5CD). Data for the year 2000 are complete only to the end of September.

Source	Year	Tows
Commercial:	1994	25,998
	1995	26,760
	1996	19,655
	1997	15,921
	1998	16,749
	1999	16,886
	2000	14,785
Survey:	1984	146
	1987	90
	1989	94
	1991	99
	1993	92
	1995	102
	1996	101
	1998	86
	2000	106

Table 3. Net widths *w* and vessel speeds *v* used in the analyses presented here. Species codes PP, RE, ST, LT, RK, and ES indicate Pacific ocean perch, rougheye rockfish, shortspine thornyheads, longspine thornyheads, rock sole, and English sole.

Data Source	Species	w (m)	v (nm/h)	v (km/hr)
Commercial tows	ST, LT	43	2.1	3.89
Commercial tows	PP, RE, RK, ES	43	2.9	5.37
Research surveys	RK, ES	24	3.0	5.56

Table 4. Depth strata definitions for slope rockfish (Pacific ocean perch, rougheye rockfish, shortspine and longspine thornyheads) and soles (rock sole, English sole). The table shows the maximum depth D_j for each stratum index *j*, where strata for the slope rockfish and sole species span depth ranges of 200 m and 40 m, respectively. The final columns list the total area A coastwide available within each stratum, as well as the coastwide areas A^* in which particular species have been captured. Species codes PP, RE, ST, LT, RK, and ES indicate Pacific ocean perch, rougheye rockfish, shortspine thornyheads, longspine thornyheads, rock sole, and English sole.

Species	Index j	Depth D_j (m)	Area A (km^2)	A^* PP	A^* RE	A^* ST	A^* LT	A^* RK	A^* ES
Slope rockfish:	1	200	75,055	3,042	468	1,640	117		
	2	400	22,293	3,881	1,927	3,472	564		
	3	600	4,186	603	811	1,145	622		
	4	800	3,047	103	179	827	758		
	5	1,000	3,020	21	43	751	731		
	6	1,200	3,644	10	16	317	309		
	7	1,400	3,649	4	6	70	67		
	8	1,600	3,736	2	3	14	12		
Sole:	1	40	13,773					603	387
	2	80	19,495					1,513	1,156
	3	120	15,282					1,292	1,574
	4	160	15,834					511	1,608
	5	200	10,671					181	954
	6	240	6,878					64	346

Table 5a. Sample calculation of shortspine thornyhead (ST) biomass in area 3CD during the 3rd quarter of 1998. For each depth stratum index *j* from Table 4, columns list the total number of commercial tows and the number that caught a measurable ST biomass. The CPUE from all tows gives a mean density Δ_j from (3.3). Total bathymetric areas A_j and fished areas A_j^* give corresponding biomass estimates $B_j = A_j\Delta_j$ and $B_j^* = A_j^*\Delta_j$. Summing these gives the total biomass estimate (3.4).

Index j	Tows	Tows (ST)	Δ_j (kg/m^2)	A_j (km^2)	A_j^* (km^2)	B_j (t)	B_j^* (t)
1	302	16	5.1	16,732	404	84.8	2.0
2	30	16	62.1	1,633	686	101.5	42.6
3	18	17	138.9	1,280	612	177.8	85.0
4	131	131	269.9	1,406	651	379.5	175.7
5	412	408	134.7	1,429	685	192.5	92.3
6	165	163	137.1	1,612	312	220.9	42.8
7	0	0	0.0	1,925	64	0.0	0.0
8	0	0	0.0	2,016	14	0.0	0.0
Total:	1,058	751		28,033	3,428	1157.0	440.4

Table 5b. Summary statistics for the shortspine thornyhead population in area 3CD during the 3rd quarter of 1998, based on the calculation in Table 5a.

Quantity	Value	Units
A	28,033	km^2
A'	9,005	km^2
A^*	3,428	km^2
B	1157	t
B^*	440	t
Δ	128	kg/km^2
r	2.63	
W	250	g
l	44	m

Table 6. Estimated habitat area and biomass for each species and management region M in this study. Species codes PP, RE, ST, LT, RK, and ES indicate Pacific ocean perch, rougheye rockfish, shortspine thornyheads, longspine thornyheads, rock sole, and English sole. The total area A associated with each region and species comes from the depth strata defined in Table 4. Each area A^* reflects commercial fishing locations (1996-2000) that captured the given species. Based on Equations (3.3)-(3.4), biomass values B and B^* represent the average of quarterly estimates (1996–1999) obtained from calculations similar to the one illustrated in Table 5. The mean density estimate $\Delta = B^* / A^*$ implies a corresponding area $A' = B / \Delta$ associated with the biomass B. A mean weight W for each species, obtained from the sample data in Fig. 7, allows the inter-fish distance l to be estimated from (3.6). The ratio $r = A' / A^* = B / B^*$ represents an expansion factor from known fishing locations to the entire bathymetry.

Species	M	A (km²)	A' (km²)	A^* (km²)	B (1000 t)	B^* (1000 t)	Δ (kg/km²)	W (kg)	l (m)	r
PP	3CD	28,033	5,472	1,606	3.30	0.97	602.5	0.89	38	3.41
PP	5AB	24,814	14,508	2,755	17.32	3.29	1,194.0	0.89	27	5.27
PP	5CD	52,698	20,296	2,662	65.47	8.59	3,225.7	0.89	17	7.62
PP	5E	13,085	8,157	643	23.22	1.83	2,846.6	0.89	18	12.69
RE	3CD	28,033	4,162	1,145	0.54	0.15	130.9	1.60	111	3.63
RE	5AB	24,814	8,941	681	0.74	0.06	83.2	1.60	139	13.13
RE	5CD	52,698	14,653	884	2.18	0.13	148.5	1.60	104	16.58
RE	5E	13,085	6,667	743	8.26	0.92	1,239.0	1.60	36	8.97
ST	3CD	28,033	9,461	3,428	1.26	0.46	133.4	0.25	43	2.76
ST	5AB	24,814	11,308	1,626	0.78	0.11	68.7	0.25	60	6.95
ST	5CD	52,698	21,676	2,269	2.69	0.28	124.0	0.25	44	9.55
ST	5E	13,085	5,234	913	0.93	0.16	177.7	0.25	37	5.73
LT	3CD	28,033	8,868	2,421	2.39	0.65	269.7	0.14	23	3.66
LT	5AB	24,814	2,638	211	0.05	0.00	19.2	0.14	86	12.50
LT	5CD	52,698	10,415	223	0.07	0.00	6.3	0.14	150	46.70
LT	5E	13,085	4,787	325	0.12	0.01	24.9	0.14	75	14.73
RK	3CD	17,102	10,901	588	0.81	0.04	74.3	0.50	82	18.54
RK	5AB	19,517	14,002	1,516	3.73	0.40	266.1	0.50	43	9.24
RK	5CD	41,770	29,484	2,056	14.69	1.02	498.2	0.50	32	14.34
RK	5E	3,544	2,703	4	0.03	0.00	10.4	0.50	219	675.87
ES	3CD	17,102	17,592	1,440	1.02	0.08	58.1	0.30	72	12.22
ES	5AB	19,517	16,115	2,018	0.85	0.11	53.0	0.30	75	7.99
ES	5CD	41,770	30,402	2,555	12.74	1.07	419.2	0.30	27	11.90
ES	5E	3,544	9,189	12	0.40	0.00	44.0	0.30	82	765.73

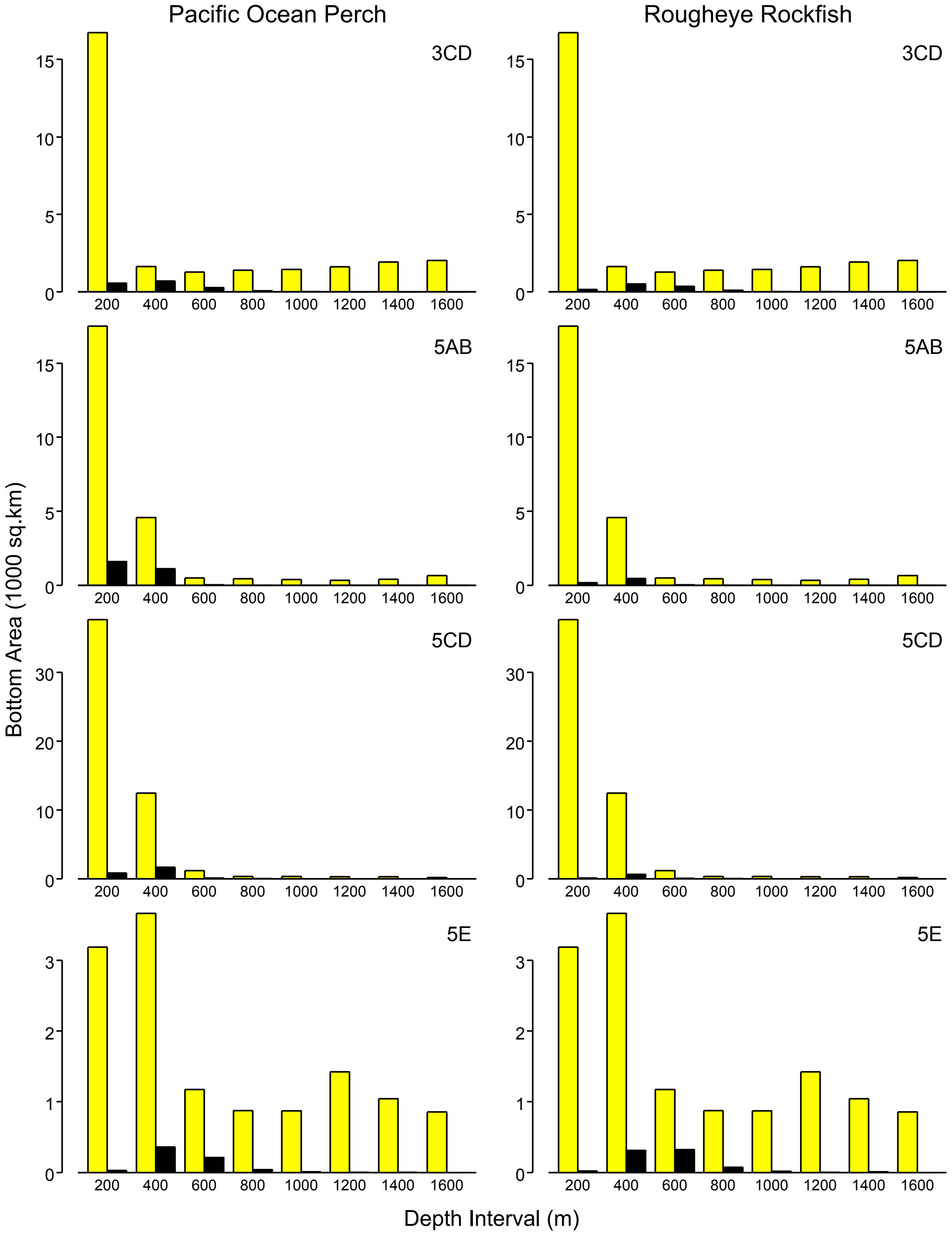

Figure 1a. Distribution of bottom area in management areas 3CD, 5AB, 5CD, and 5E at 200 m depth intervals. Within each depth stratum S_j, a light bar shows the total available area A_j, and a dark bar indicates the area A_j^* in which Pacific ocean perch or rougheye rockfish were caught between 1996 and 2000.

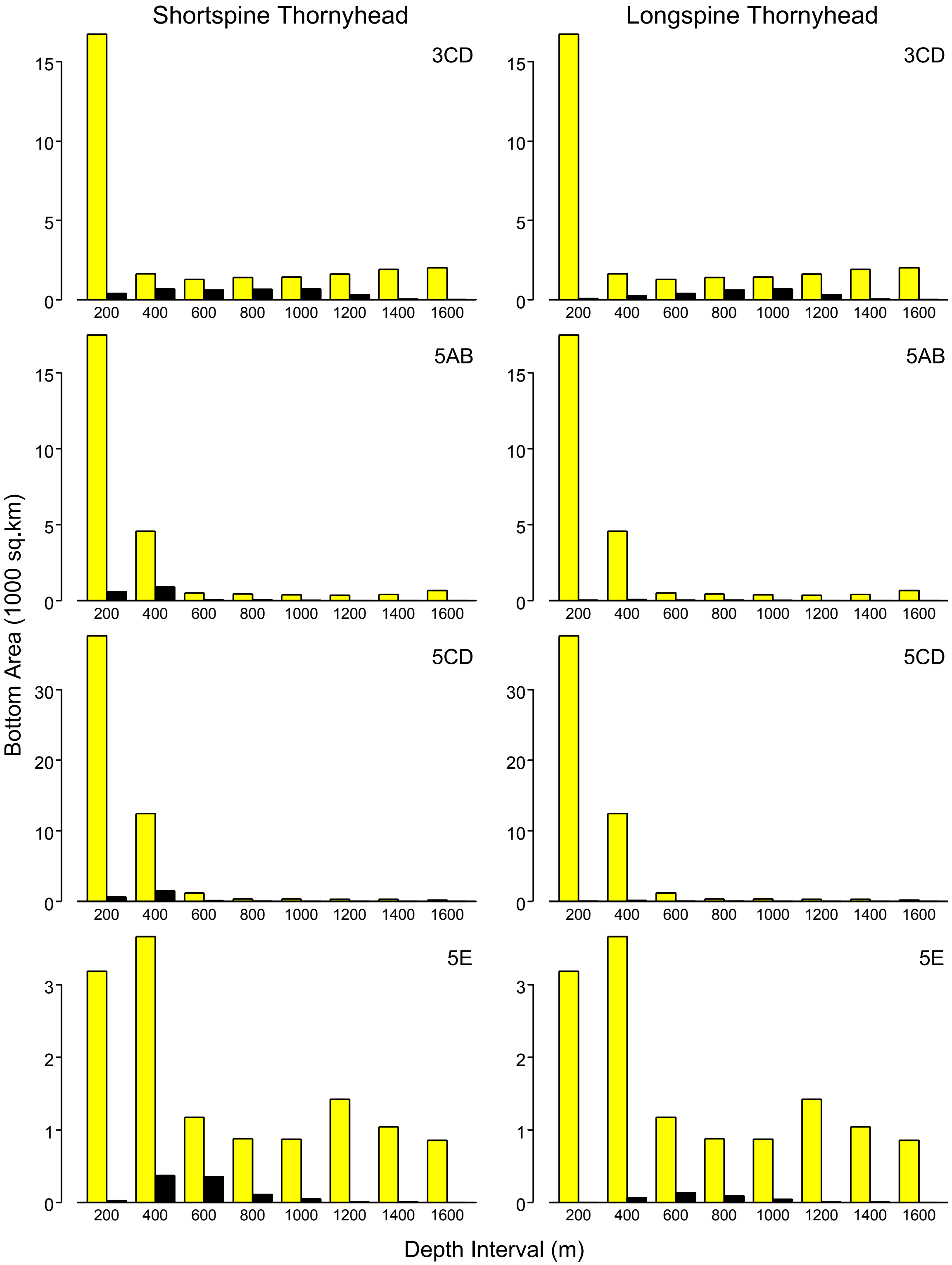

Figure 1b Distribution of bottom area in management areas 3CD, 5AB, 5CD, and 5E at 200 m depth intervals. Within each depth stratum S_j, a light bar shows the total available area A_j, and a dark bar indicates the area A_j^* in which shortspine or longspine thornyheads were caught between 1996 and 2000.

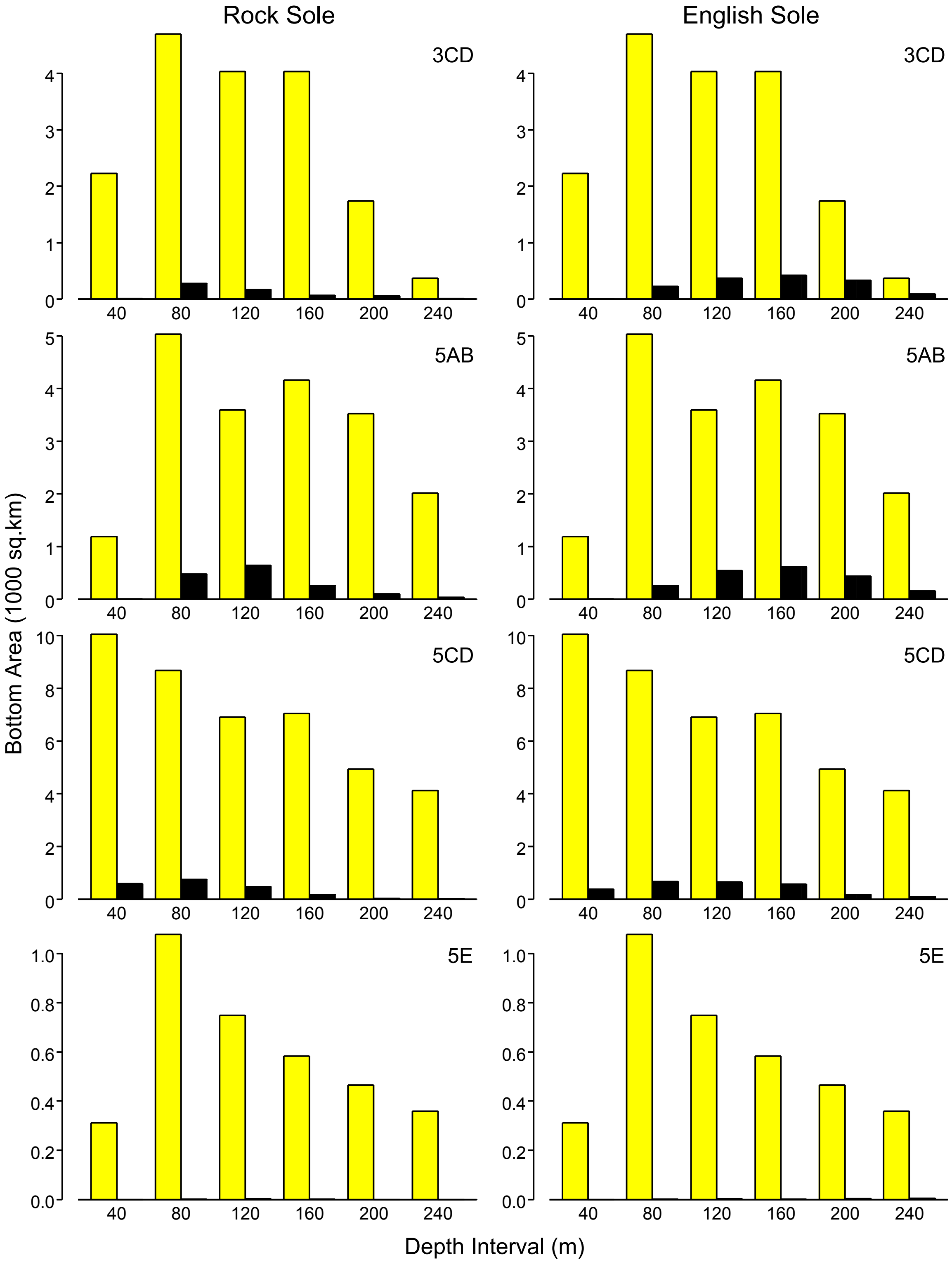

Figure 1c. Distribution of bottom area in management areas 3CD, 5AB, 5CD, and 5E at 40 m depth intervals. Within each depth stratum S_j, a light bar shows the total available area A_j, and a dark bar indicates the area A_j^* in which rock sole or English sole were caught between 1996 and 2000.

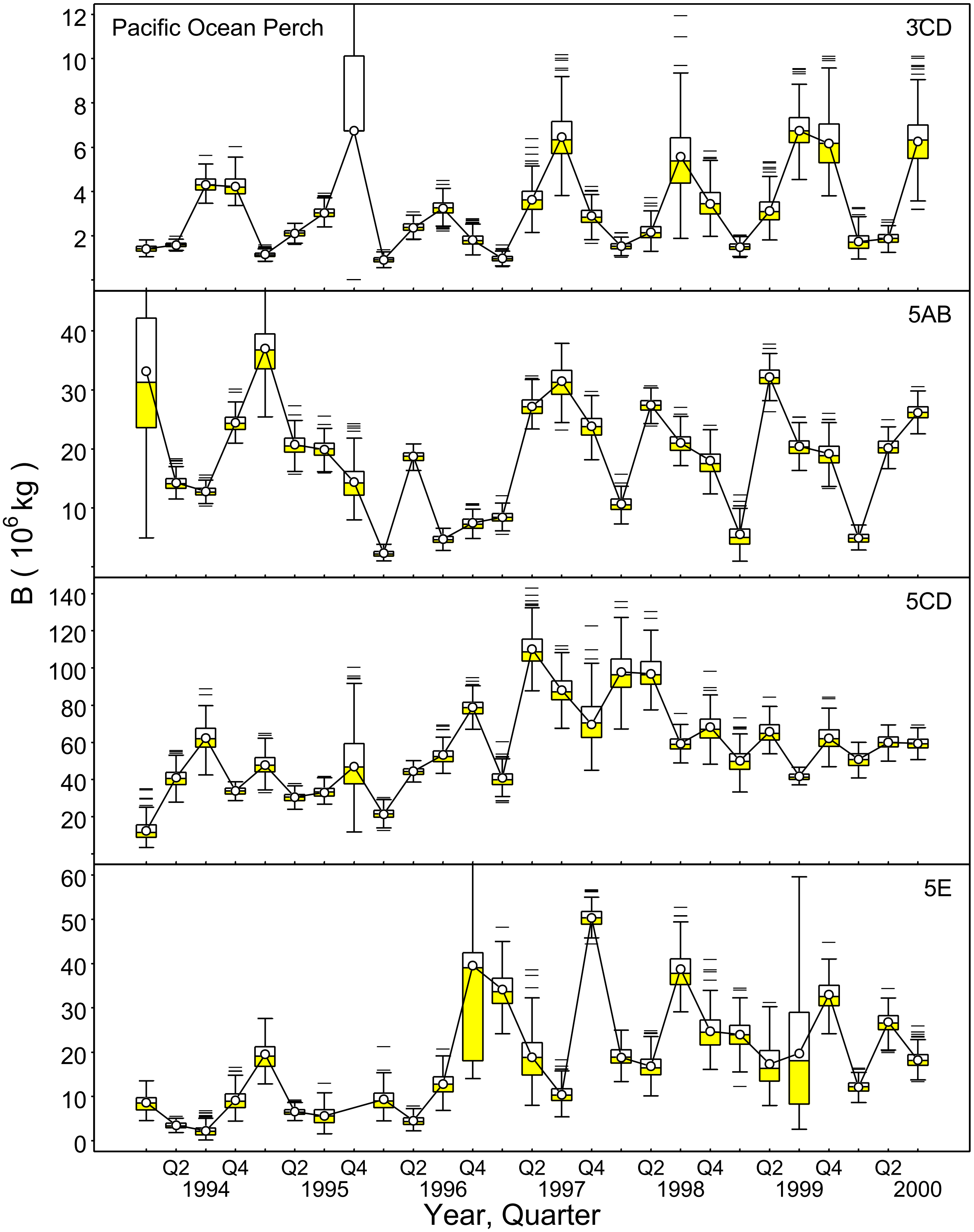

Figure 2a. Boxplots portraying the distribution of 300 bootstrapped biomass estimates *B* for Pacific ocean perch by quarter in management areas 3CD, 5AB, 5CD, and 5E, based on data from the commercial fleet. A circle in each boxplot indicates the quarterly biomass estimate.

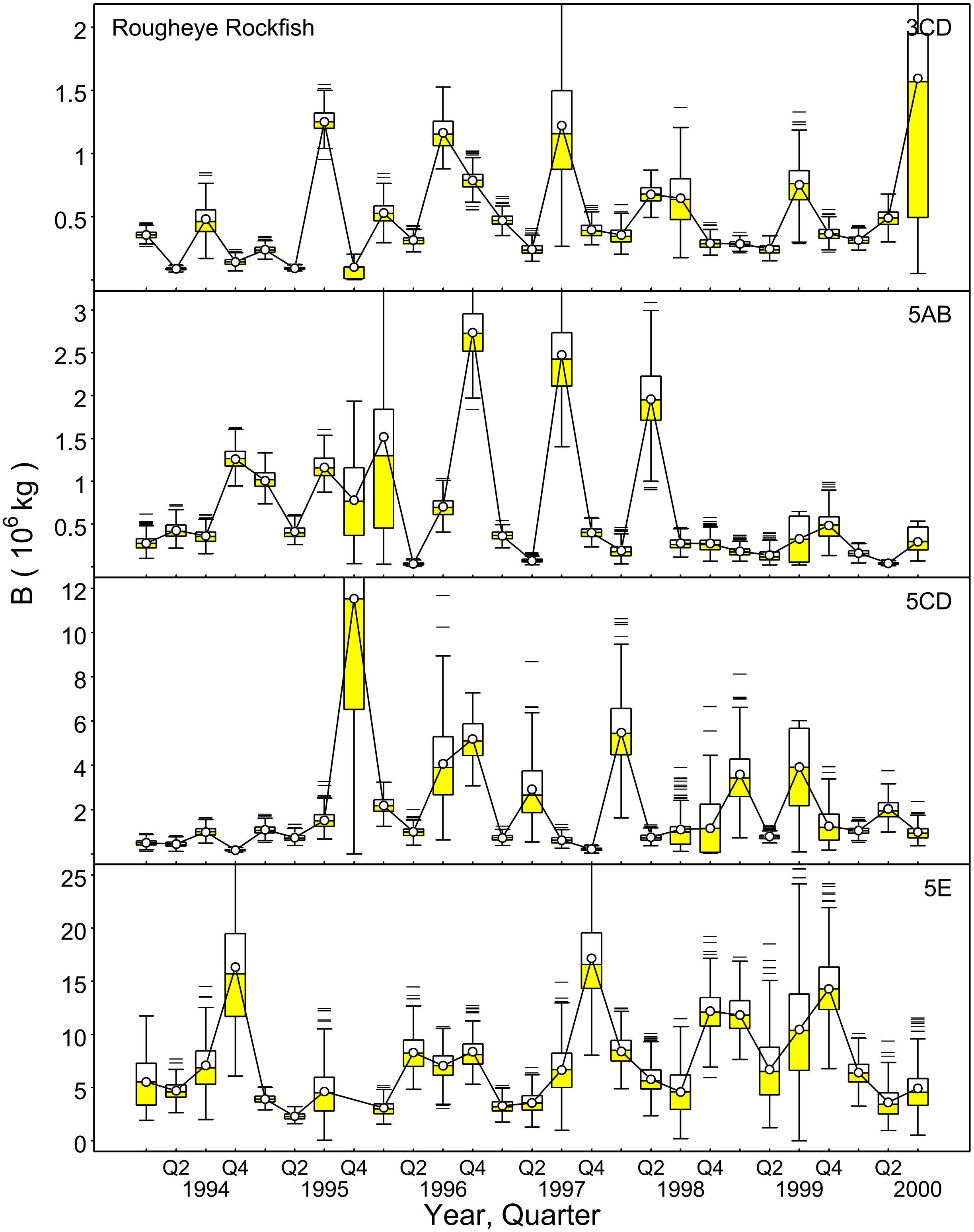

Figure 2b. Boxplots portraying the distribution of 300 bootstrapped biomass estimates *B* for rougheye rockfish by quarter in management areas 3CD, 5AB, 5CD, and 5E, based on data from the commercial fleet. A circle in each boxplot indicates the quarterly biomass estimate.

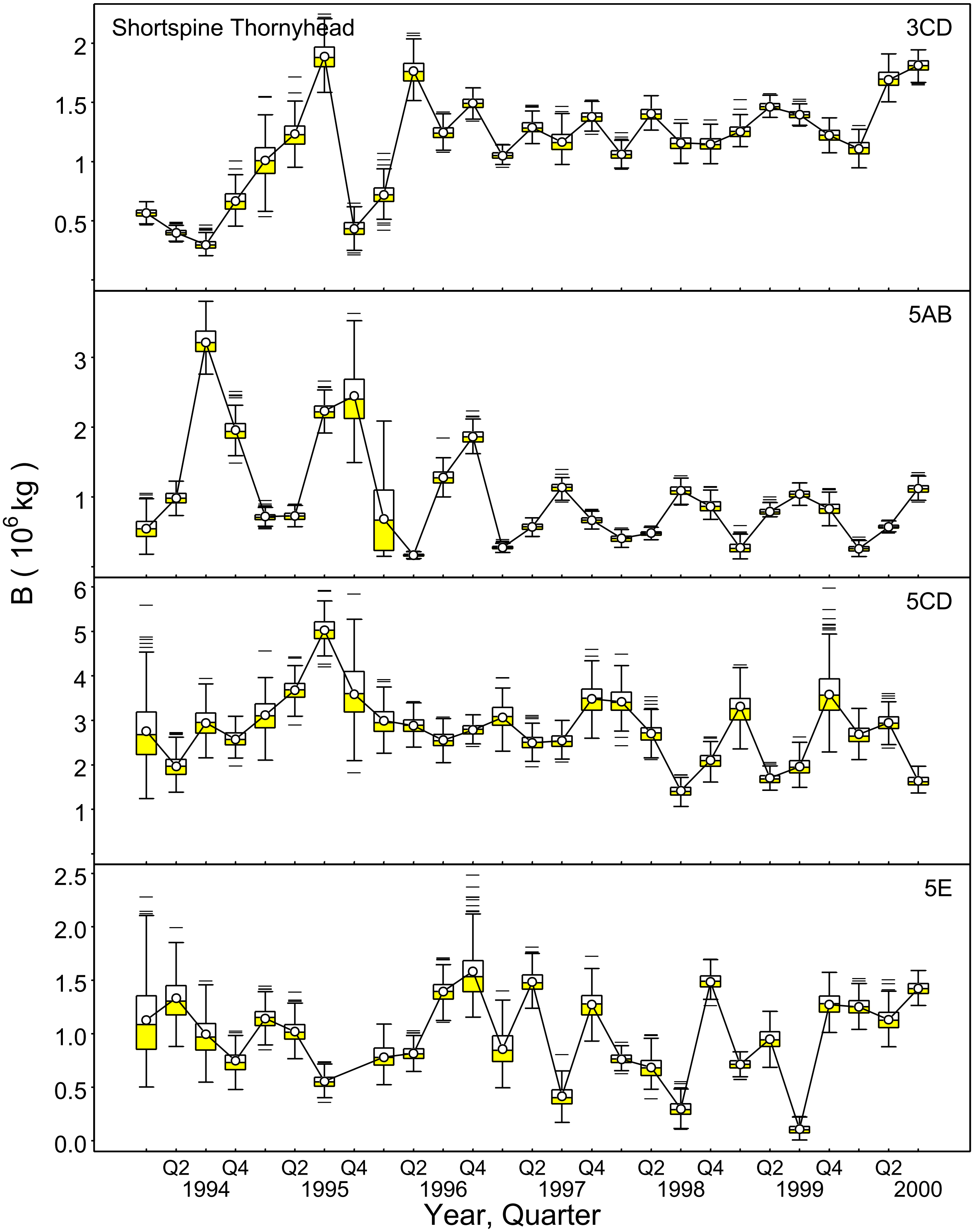

Figure 2c. Boxplots portraying the distribution of 300 bootstrapped biomass estimates *B* for shortspine thornyheads by quarter in management areas 3CD, 5AB, 5CD, and 5E, based on data from the commercial fleet. A circle in each boxplot indicates the quarterly biomass estimate.

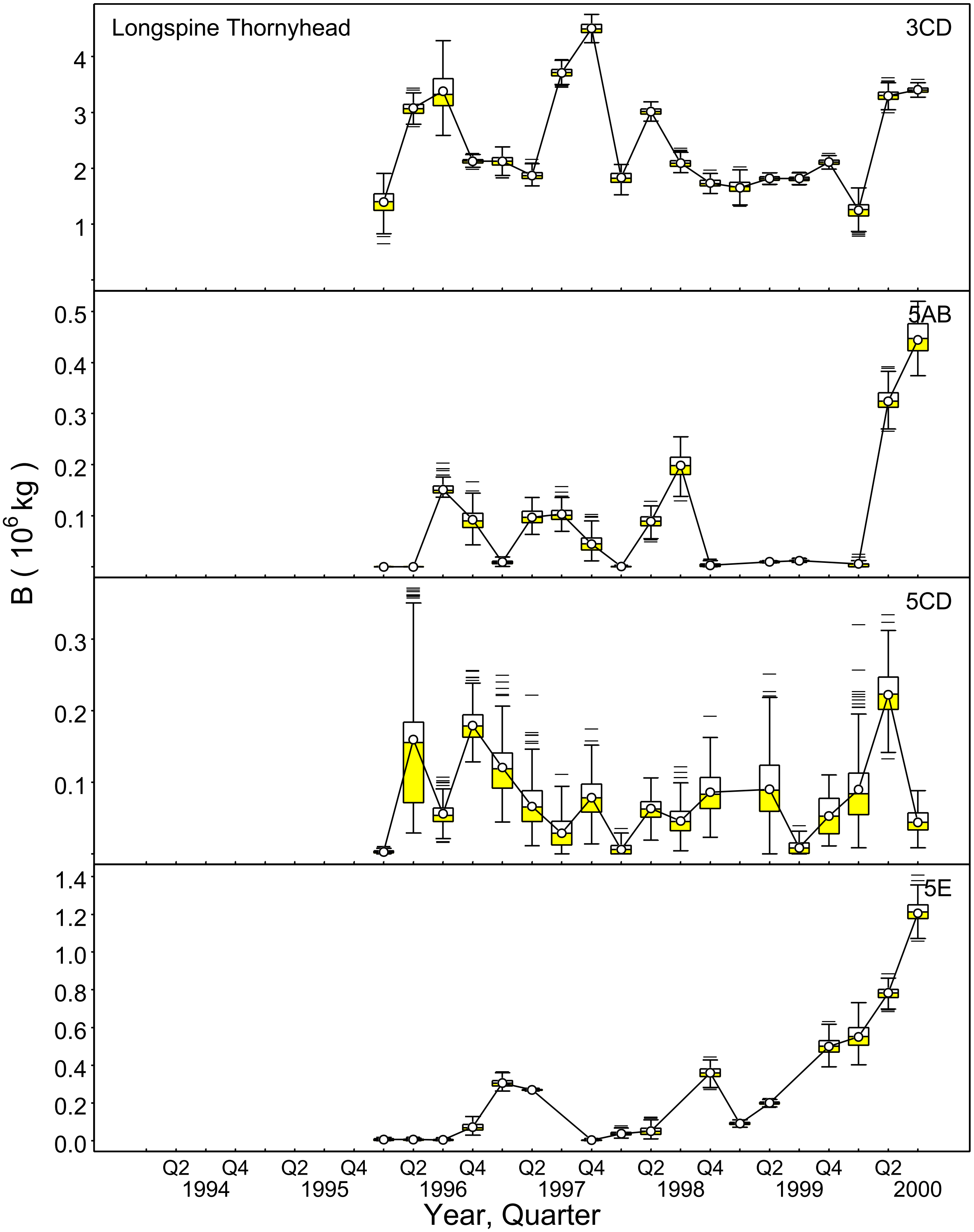

Figure 2d. Boxplots portraying the distribution of 300 bootstrapped biomass estimates *B* for longspine thornyheads by quarter in management areas 3CD, 5AB, 5CD, and 5E, based on data from the commercial fleet. A circle in each boxplot indicates the quarterly biomass estimate.

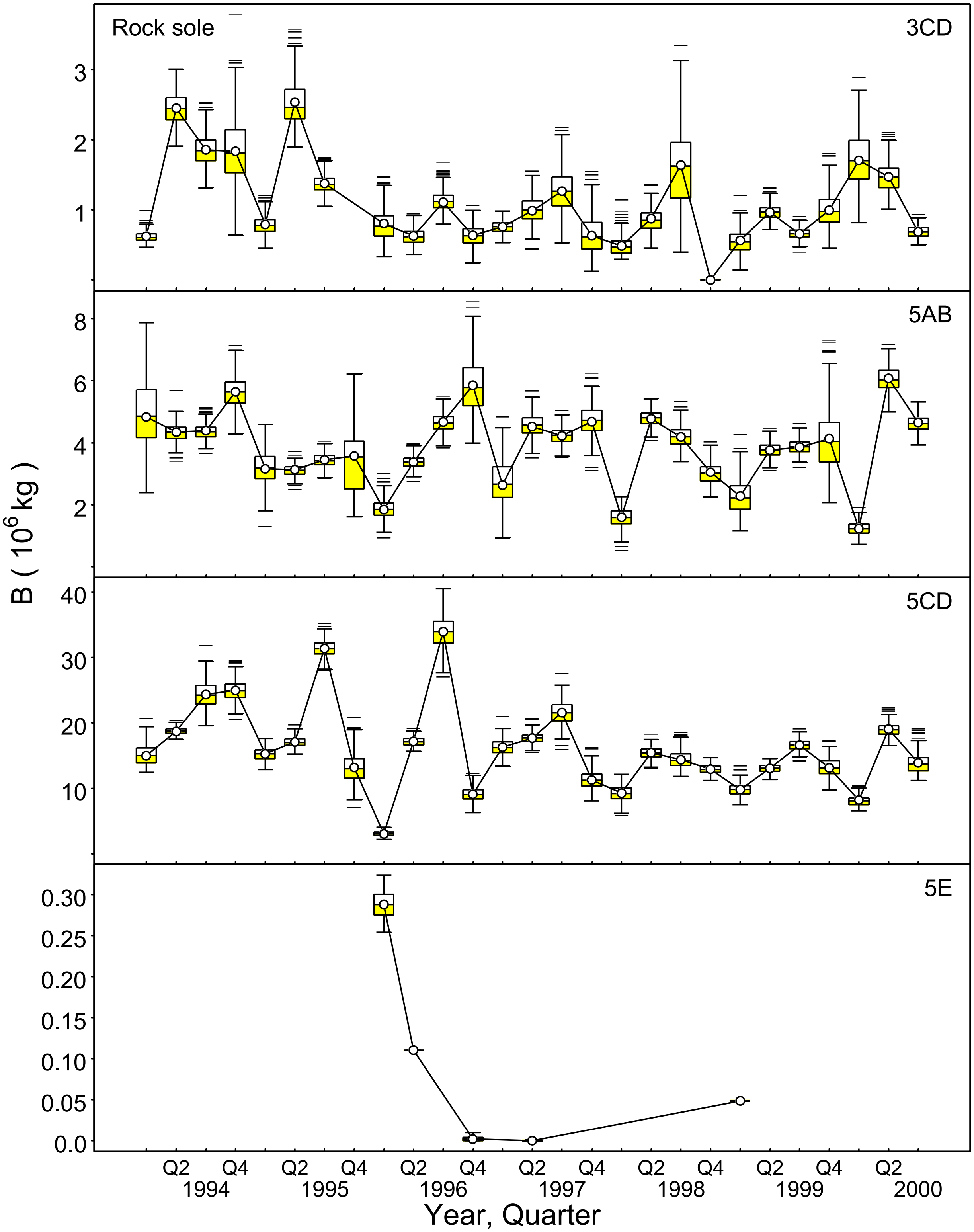

Figure 2e. Boxplots portraying the distribution of 300 bootstrapped biomass estimates *B* for rock sole by quarter in management areas 3CD, 5AB, 5CD, and 5E, based on data from the commercial fleet. A circle in each boxplot indicates the quarterly biomass estimate.

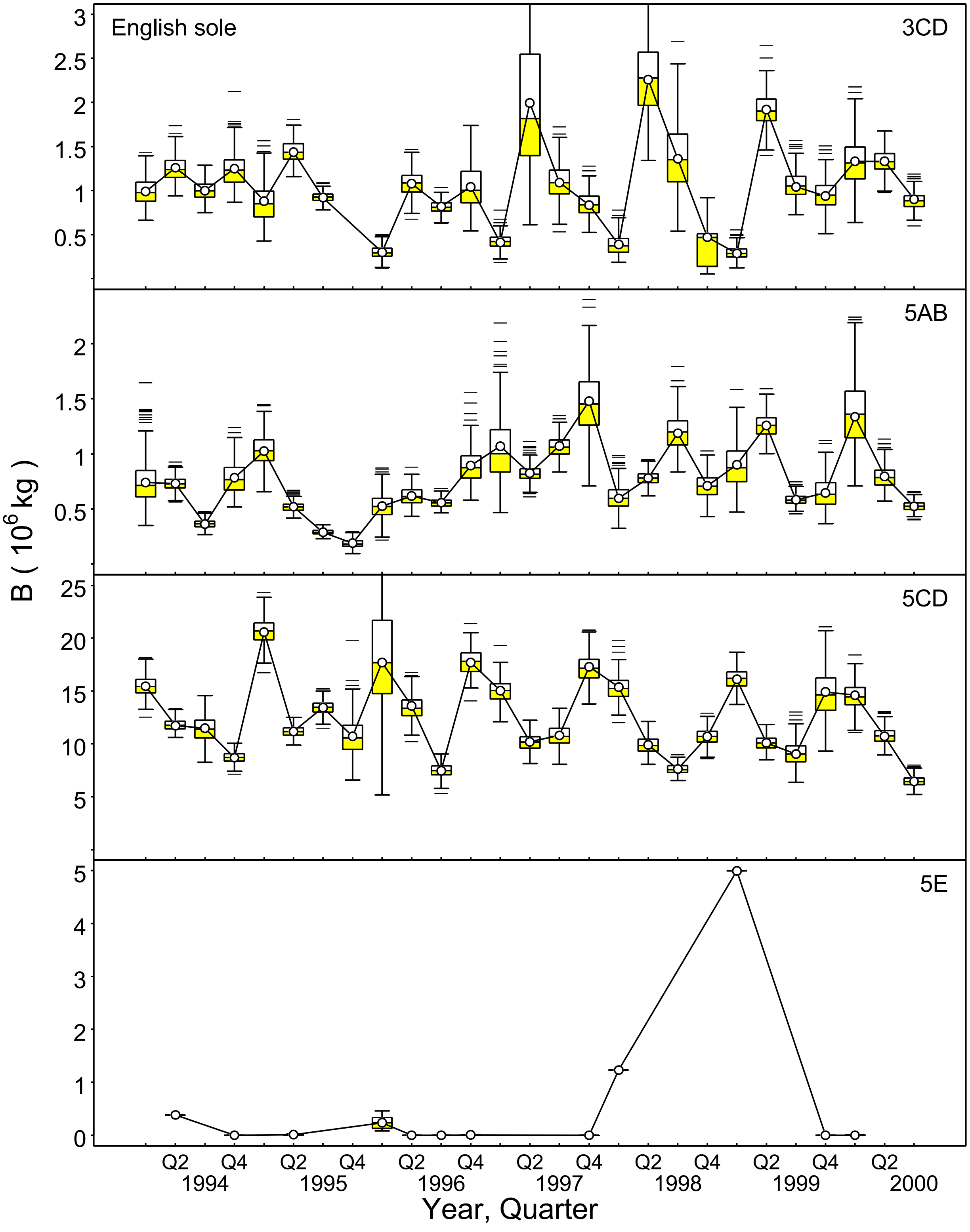

Figure 2f. Boxplots portraying the distribution of 300 bootstrapped biomass estimates *B* for English sole by quarter in management areas 3CD, 5AB, 5CD, and 5E, based on data from the commercial fleet. A circle in each boxplot indicates the quarterly biomass estimate.

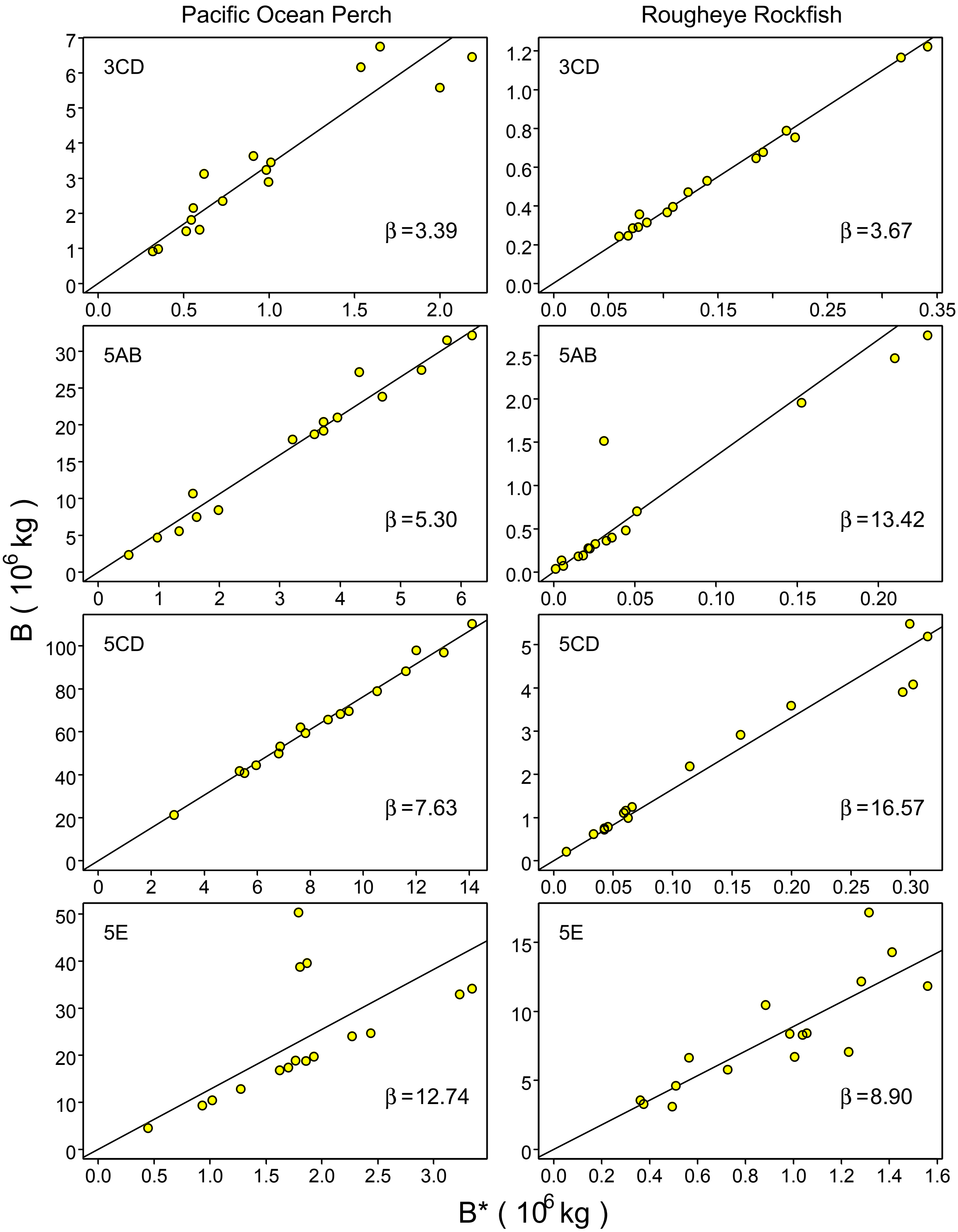

Figure 3a. Quarterly (1996-1999) biomass estimates B vs. B^* for Pacific ocean perch and rougheye rockfish in management areas 3CD, 5AB, 5CD, and 5E. The indicated line of slope β joins the origin (0,0) to the centroid of the data.

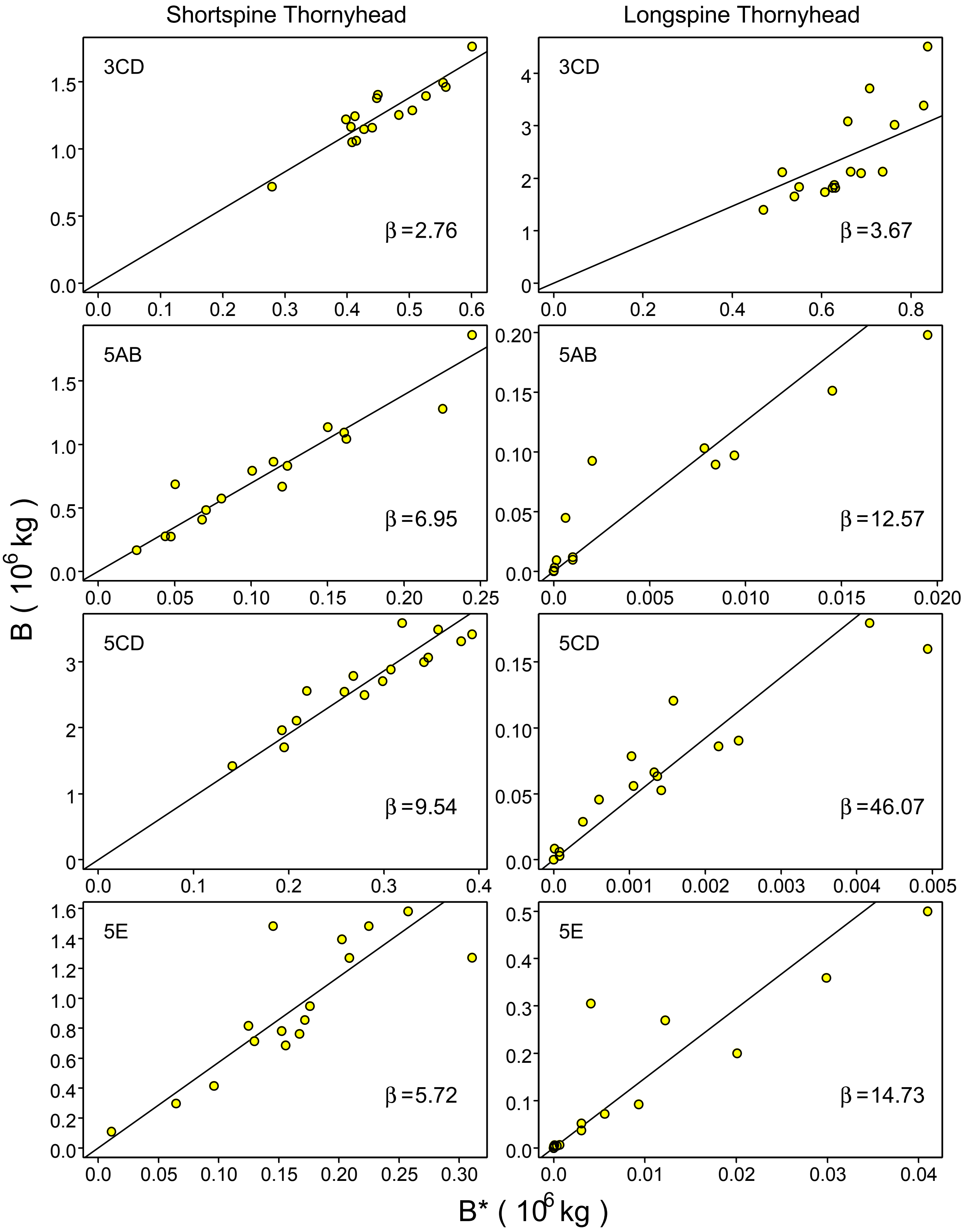

Figure 3b. Quarterly (1996-1999) biomass estimates B vs. B^* for shortspine and longspine thornyheads in management areas 3CD, 5AB, 5CD, and 5E. The indicated line of slope β joins the origin $(0,0)$ to the centroid of the data.

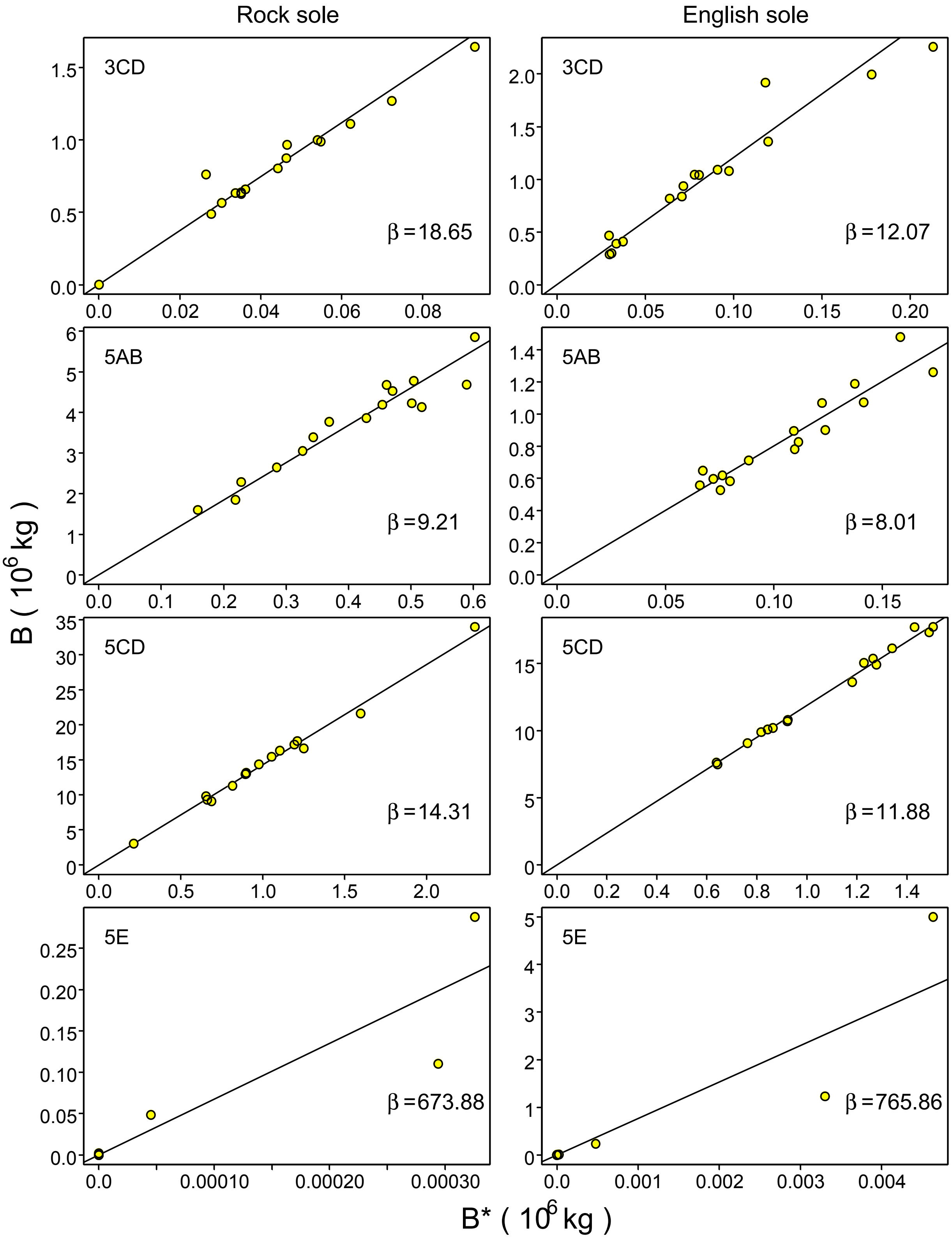

Figure 3c. Quarterly (1996-1999) biomass estimates B vs. B^* for rock sole and English sole in management areas 3CD, 5AB, 5CD, and 5E. The indicated line of slope β joins the origin (0,0) to the centroid of the data.

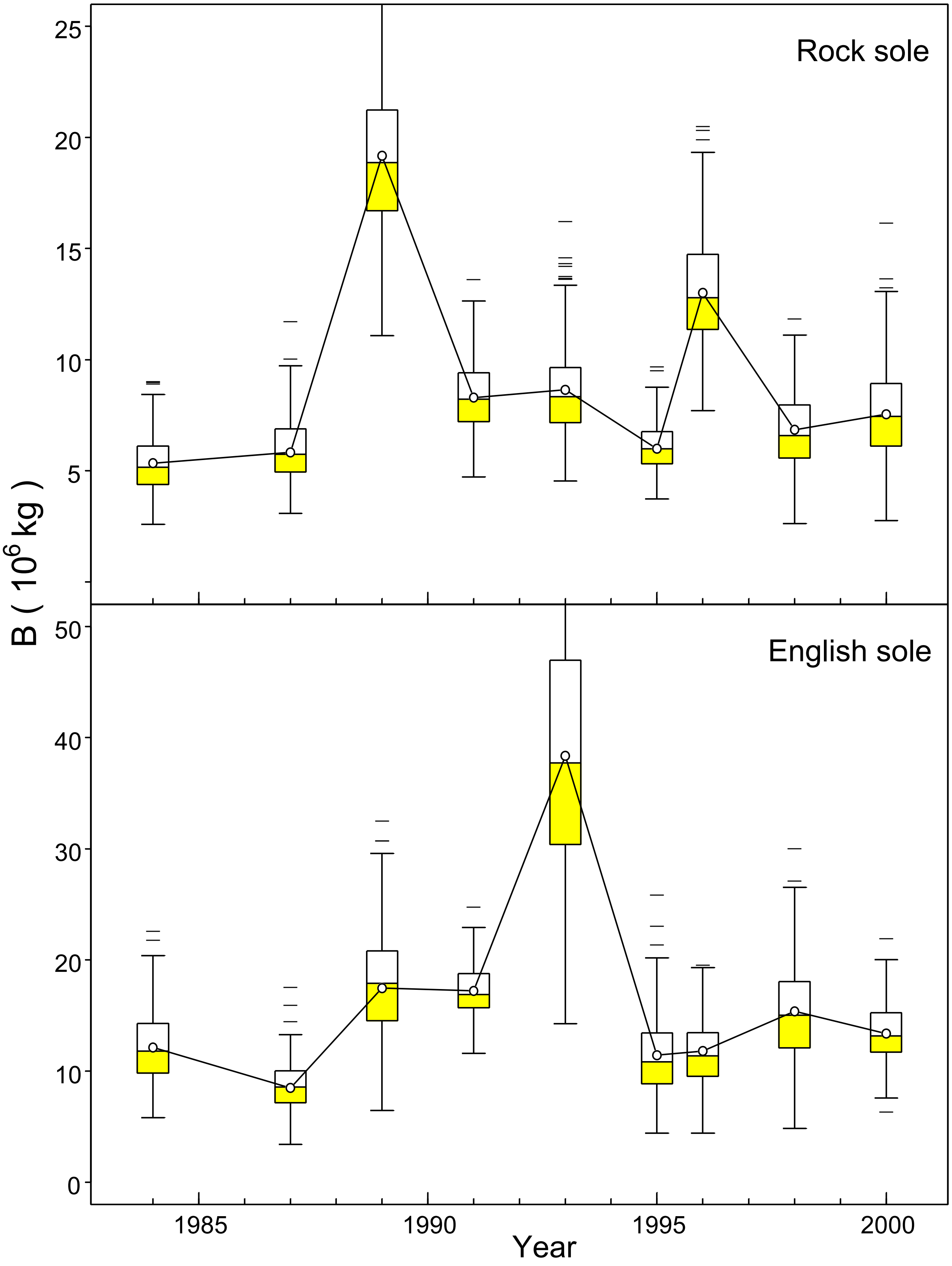

Figure 4. Boxplots portraying the distribution of 300 bootstrapped biomass estimates *B* for rock sole and English sole in area 5CD, based on data from Hecate Strait June surveys. A circle in each boxplot indicates the corresponding biomass estimate.

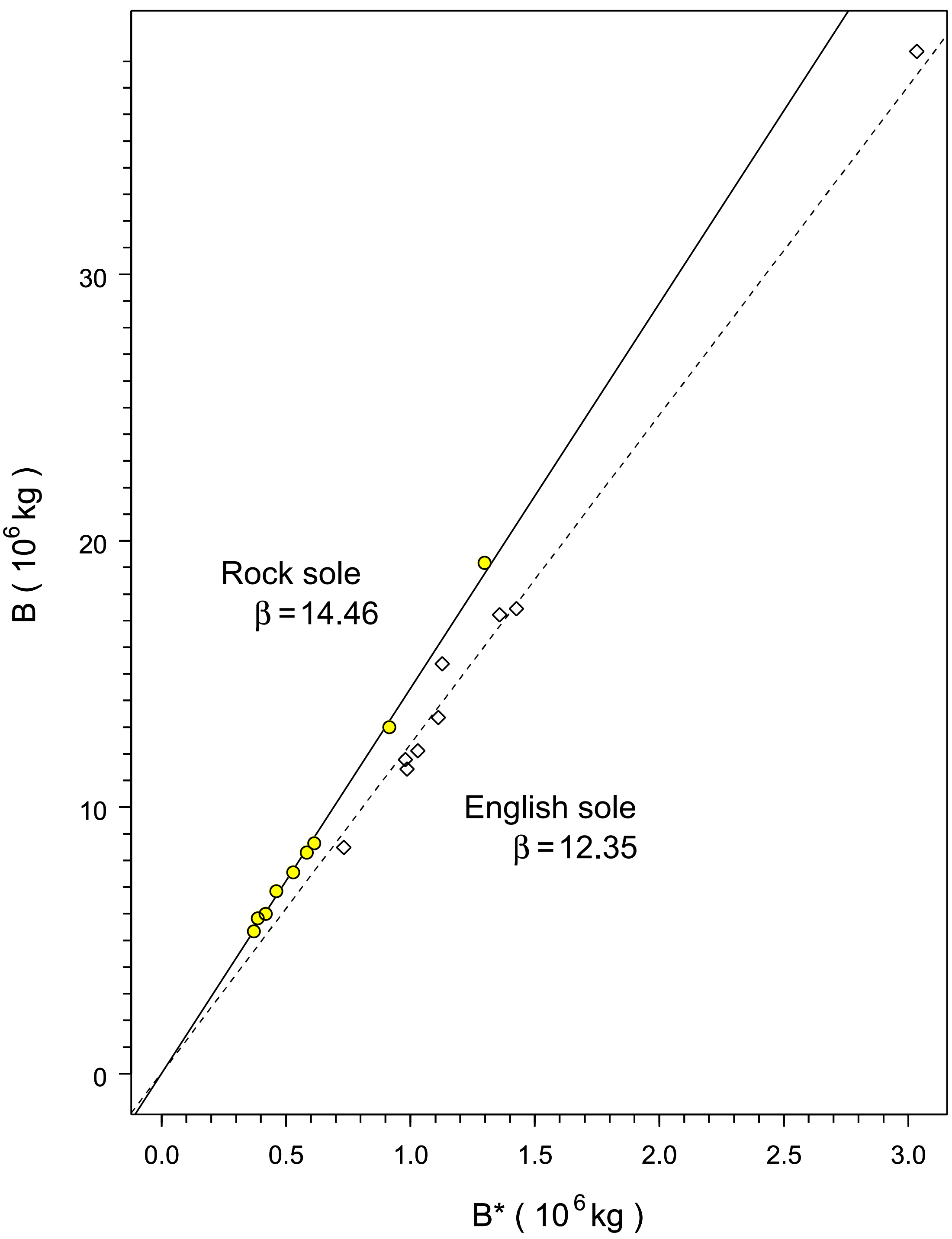

Figure 5. Biomass estimates B vs. B^* for rock sole and English sole in management areas 5CD, based on data from Hecate Strait June surveys. The indicated line of slope ***b*** joins the origin (0,0) to the centroid of the data.

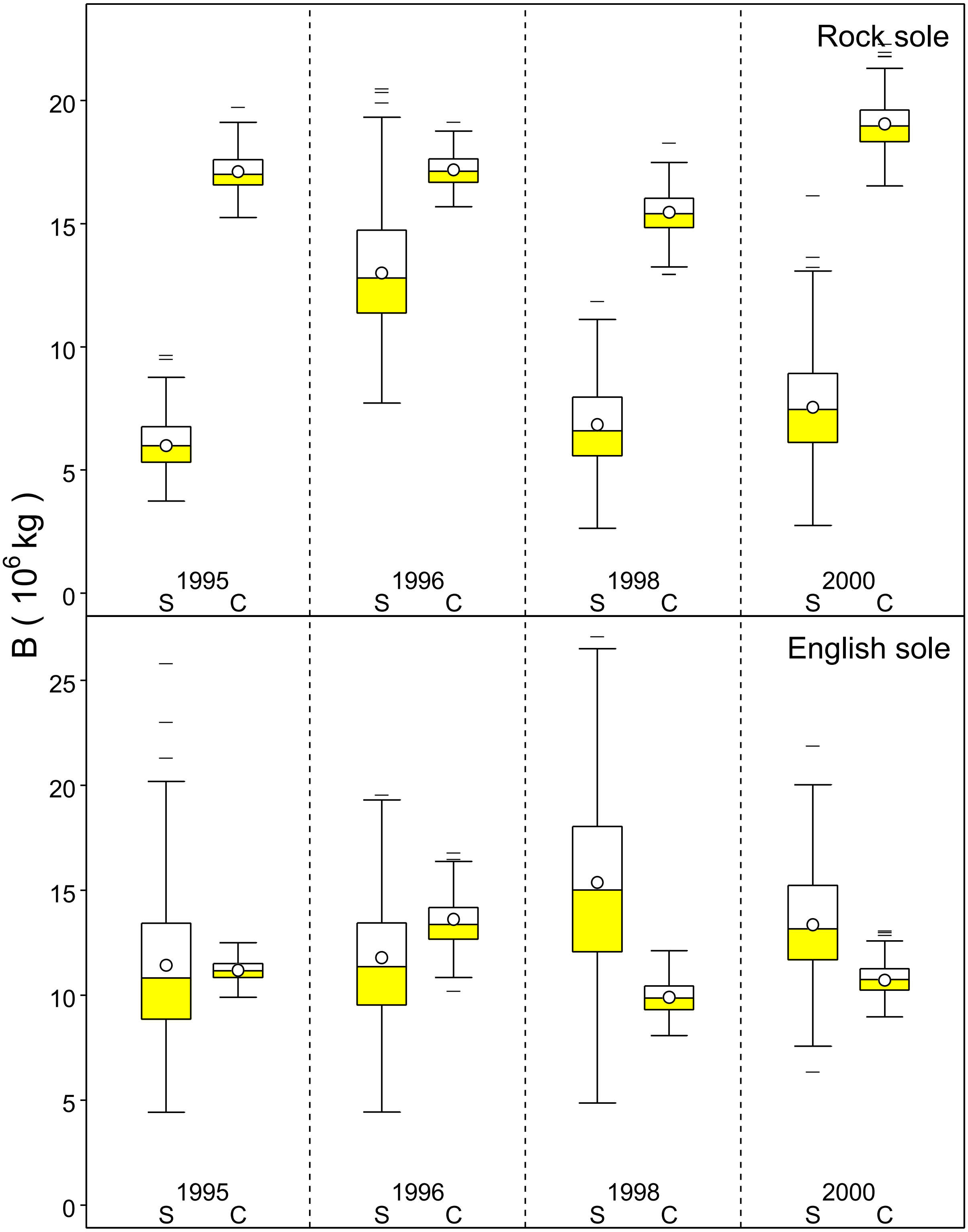

Figure 6. Comparison of bootstrapped biomass distributions from Figs. 2e, 2f, and 4. Biomass estimates *B* come from Hecate Strait research surveys in June (S) and commercial tows in the 2nd quarter (C). Comparisons are possible for the four years 1995, 1996, 1998, and 2000. A circle in each boxplot indicates the corresponding biomass estimate.

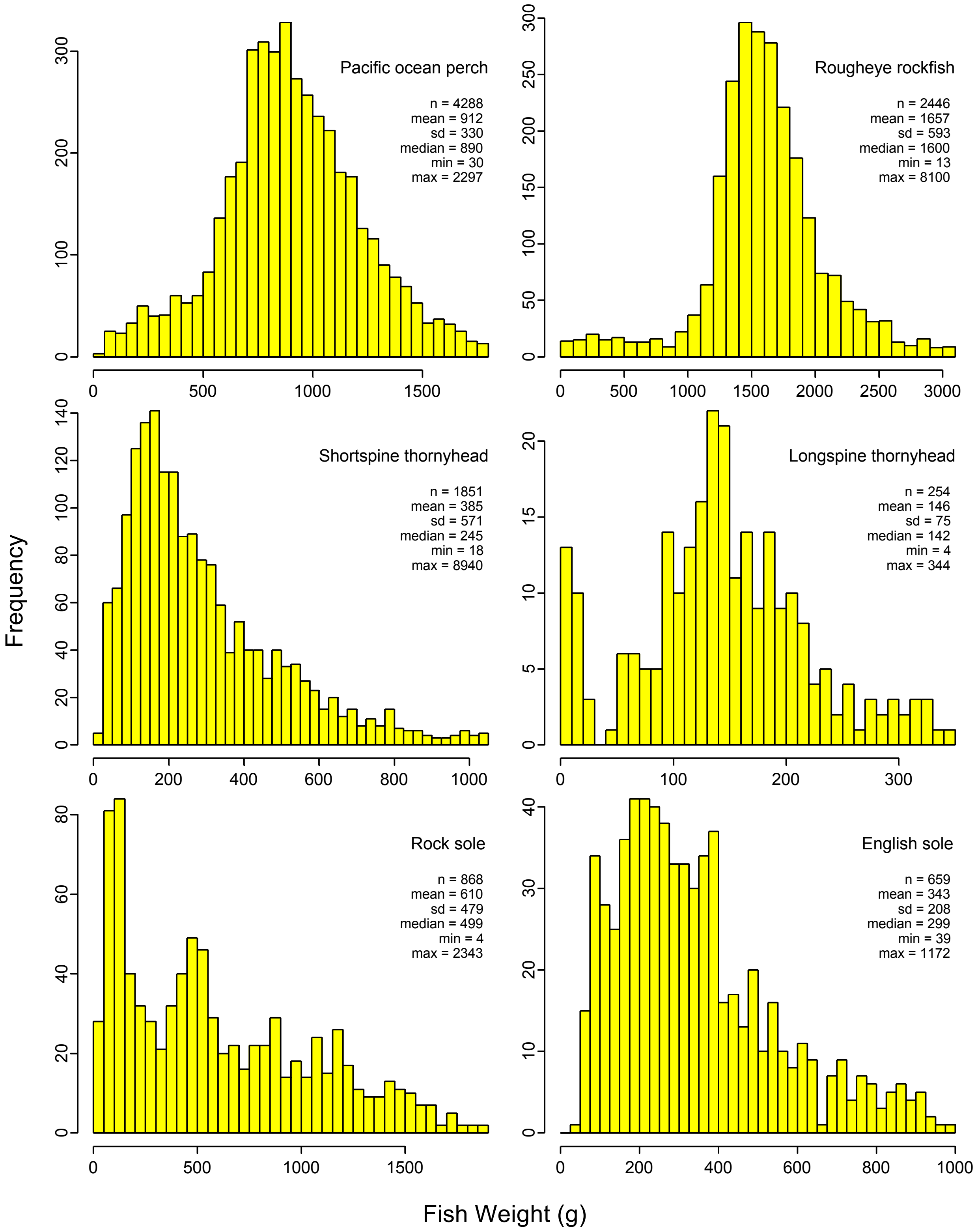

Figure 7. Weight distribution of Pacific ocean perch, rougheye rockfish, shortspine thornyheads, longspine thornyheads, rock sole and English sole. Weights (g) come from samples recorded in the GFBio database [D4], with additional data for the thornyheads from the 2000 Tanner crab survey.