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The British Columbia longspine thornyhead fishery: analysis of survey and commercial data (1996-2003)

Pêche du sébastolobe à longues épines en Colombie-Britannique : analyse des données provenant des relevés et des pêches commerciales (1996-2003)

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Abstract

This report presents an analysis of the biomass survey conducted annually in 2001-2003 on the deep-water population of longspine thornyheads (*Sebastolobus altivelis*) off the west coast of Vancouver Island (WCVI). We examine the survey data in the context of a coastwide longspine fishery that began in 1996 and extended northward from WCVI into two northern regions, Tidemarks and Rennell. Within WCVI, the survey appears to index longspine thornyhead biomass well, achieves coefficients of variation near 10%, and indicates no significant biomass change in 2001-2003. Because the survey has limited coverage in space and time, we compare that analysis with similar analyses of commercial catch per unit effort (CPUE) data in WCVI and the two northern regions, where no surveys exist. We present an integrated framework of three mathematical models for making these comparisons: (i) swept-area biomass estimates, (ii) standardized catch rates with fixed effects for various factors, and (iii) swept-area biomass estimates with standardized vessel effects. All commercial indices for the three regions show downward trends since the inception of the fishery, with the largest decline in the Rennell Sound area. The magnitude of decline depends on the model chosen for analysis. If these trends in the commercial data reflect real declines in population biomass, current removals of longspine thornyhead may not be sustainable. We conclude with recommendations for planning future surveys, integrating data from surveys and commercial fisheries, planning future reductions in the commercial fishery, and improving the basic biological information available for this species.

Résumé

Nous présentons une analyse d'un relevé de la biomasse de sébastolobe à longues épines (*Sebastolobus altivelis*) effectué chaque année de 2001 à 2003 dans les eaux profondes au large de la côte ouest de l'île de Vancouver (WCVI). Nous avons examiné les données des relevés dans le contexte d'une pêche ciblant cette espèce à l'échelle de la côte, qui a débuté en 1996 sur la WCVI pour ensuite s'étendre vers le nord jusqu'aux secteurs de Tidemarks et Rennell. Sur la WCVI, le relevé semble donner un bon indice de la biomasse; les coefficients de variation s'approchent de 10 %, et aucun changement important de biomasse ne s'est produit de 2001 à 2003. Comme la couverture du relevé est limitée dans l'espace et le temps, nous avons comparé les résultats de notre analyse à ceux d'analyses semblables de données sur les prises commerciales par unité d'effort (PUE) sur la WCVI et dans les deux secteurs nordiques, où aucun relevé n'a été effectué. Nous présentons un cadre intégré de trois modèles mathématiques pour faire ces comparaisons : (i) les estimations de la biomasse dans les aires balayées, (ii) les taux de capture normalisés avec des effets fixes pour divers facteurs et (iii) les estimations de la biomasse dans les aires balayées avec les effets normalisés du bateau. Tous les indices de la pêche commerciale dans ces trois secteurs indiquent des tendances à la baisse depuis la mise en vigueur de la pêche, le déclin le plus marqué s'étant produit dans la région de la baie Rennell. L'ampleur du déclin dépend du modèle choisi pour faire l'analyse. Si ces tendances dans les données provenant des prises commerciales reflètent un déclin réel de la biomasse de la population, il se peut que les ponctions actuelles de sébastolobe ne soient pas durables. Nous concluons par des recommandations visant la planification des relevés futurs, l'intégration des données des relevés et des pêches commerciales, la planification de futures réductions dans la pêche commerciale et l'amélioration des données biologiques de base disponibles sur cette espèce.

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1. Introduction

This report addresses questions relevant to the management of Canada's longspine thornyhead (*Sebastolobus altivelis*) fishery along the British Columbia coast. The species occurs in deep-water habitats, with most catch taken from depths below 500 m. The fishery began primarily off the west coast of Vancouver Island, but an exploratory fishery since 2000 has extended the range north to the west coast of the Queen Charlotte Islands. Current information reveals little about longspine thornyhead recruitment, growth, and other features of the population dynamics. Despite promising research into methods of ageing this species, reliable age structure information remains a goal for the future. Recent assessments (Schnute et al. 1999a, 1999b; Starr and Haigh 2000; Starr 2001) have depended significantly on biomass indices obtained from commercial fishery data.

In response to concerns that the fishery-dependent indices might be unreliable, the Canadian Groundfish Research and Conservation Society (CGRCS) initiated a fishery-independent biomass trawl survey off the west coast of Vancouver Island in 2001, with a plan to conduct two additional surveys in 2002 and 2003. All three surveys have now been completed. Furthermore, in response to a PSARC recommendation in 2001, DFO[*] staff consulted with industry to establish a management plan for the northern exploratory trawl fishery. The final agreed plan, implemented in the 2002/2003 and 2003/2004 seasons, sets a total allowable catch (TAC) of 230 t (reduced from 425 t in 2001/2002). This catch can come from three northern regions (Rennell, Tidemarks, Triangle), with another area (Flamingo) set aside as a refuge where no directed fishing is allowed. To date, Triangle also serves as a *de facto* refuge, probably because its steep bottom profile makes fishing impractical. The TAC for the southern fishery along the west coast of Vancouver Island (WCVI) remains at the 2001/2002 level of 405 t, although the boundaries for this area were moved northward in 2002. Figure 1.1 portrays these regions on a map of the BC coast.

The request for this working paper (Appendix A) asks for a review of information available from all three years of the survey, along with suggestions for possible improvement. In particular, the working paper should address three questions:

A. Does the survey have potential utility for estimating biomass?

B. Can coastwide estimates of abundance be inferred from the current survey design?

C. Are modifications required to improve survey design and provide information to support the current management plan?

The request also mentions that the working paper should assist a review of the fishing plan for the northern exploratory fishery.

Very briefly, our analyses lead to the following answers:

A. The survey appears to offer an index of biomass fluctuations in the WCVI region. Surveys generally do not give reliable estimates of absolute biomass, due to unknown vulnerability

[*] Historical acronym for the Department of Fisheries and Oceans, now called Fisheries and Oceans Canada

of fish to the gear. However, this trial three-year survey shows promise for indexing longspine thornyhead biomass in the region for which it was designed.

B. The current survey, confined to the WCVI region, does not produce a coastwide biomass index. Although a survey of the entire coast would have obviously been preferable, the planners recognized problems with such an extensive initial undertaking. Instead, they opted for a limited, more feasible survey confined to the WCVI region. Experiences from this successful initial phase bode well for future surveys of the northern areas.

C. Although the survey design worked well for the intended region, it would need extension into northern regions to provide information useful for the northern fishery plan.

These conclusions bring us full circle back to the problem that originally motivated the survey: a dependency on data from the commercial fishery. However, although we still have only commercial data for assessment in the northern regions (Tidemarks and Rennell), we can now compare commercial with survey data in the WCVI region.

The plan for this report follows logically from the available data. We use catch per unit effort (CPUE) data to produce biomass indices from four data sources: the WCVI survey and commercial fisheries in the WCVI, Tidemarks, and Rennell regions. Any analysis of CPUE data depends on assumptions that may or may not be appropriate. Although the survey follows an experimental design with a prescribed method of analysis, the commercial fishery does not. We test sensitivity to model assumptions by applying several different approaches to each data set. These include (i) swept-area biomass estimates, (ii) standardized analyses with fixed effects for factors such as depth, month, vessel, and year, and (iii) swept-area estimates with fixed effects to standardize vessels only. We compare survey with commercial data, where possible, and investigate differences due to model assumptions.

In Sections 2 and 3, we review the history of the longspine thornyhead fishery and describe the three-year WCVI survey. Section 4 discusses our data sources and explains our methods of selecting and qualifying data for various CPUE analyses. Section 5 defines the mathematical models we use for estimating biomass indices from CPUE data. In Sections 6 and 7, we present the results of our analyses for the four data sources, based on various models. The survey and commercial fishery also produce biological sample information, as we describe in Section 8. The final two sections summarize our findings and explore their consequences for fishery management.

2. History of the Fishery

Longspine thornyheads grow slowly, reaching a maximum size near 30 cm with typical ages in the range 25 to 45 years (Jacobson and Vetter 1996). This long, slow growth pattern, probably reflecting lower food availability on the continental slope (Vetter and Lynn 1997), makes the species relatively unproductive. Additionally, fishing below 500 m makes them relatively costly to catch.

Canadian fisheries for longspine thornyhead (*Sebastolobus altivelis*) and shortspine thornyhead (*S. alascanus*) evolved from a small fishery that supplied local and foreign demands with large shortspine thornyheads. Low market prices did not justify serious fishing effort, and most thornyheads appeared as bycatch in tows targeting rockfish *Sebastes* spp. Generally, fishermen did not notice thornyheads in the hold until the trip's catch was offloaded and several tonnes would be evident. Plant processors were reluctant to pay much for these fish.

Demand for thornyheads comes from Japan, where whole fish are used in wedding ceremonies and the frozen flesh is sold as an expensive delicacy. In the mid-1980s, depletion of Japan's highly valued broadbanded thornyhead *Sebastolobus macrochir* stocks (Rogers et al. 1997) created thornyhead market shortages and increased the demand for other *Sebastolobus* species along the Pacific coast of North America. Landings in BC began a substantial increase in 1993 (Fig. 2.1). The high price of longspines on world markets further encouraged rapid development of this fishery, and the introduction of freezer technology allowed fishermen to specialize in thornyheads. However, because longspines primarily inhabit deep water (700-1,200 m), vessels faced potentially expensive gear changes to participate. Today, only a few of Canada's Pacific trawlers are fully equipped for deep-water fishing. Those that do fish thornyheads retain the skills and equipment necessary for multispecies trawl opportunities at all depths along the BC coast.

Trawl records indicate that thornyheads have been harvested since 1966. Rutherford (1999) describes the historical **GFCatch** database spanning the years 1966-1995. Queries on this database show that shortspine catch records occur frequently since 1966 and appear annually from 1977 onward. However, as the thornyhead fishery expanded, the alleged shortspine catch increasingly included some catch of longspines. By 1994, fishermen began to recognize longspines as a species distinct from shortspines. Catch records on the U.S. west coast had already begun to distinguish these two species – Oregon in 1987, Washington in 1988, and California in 1995 (Rogers et al. 1997). Starr (2001) analyzed shortspine catches in BC waters prior to 1996 and concluded that the combined shortspine and longspine catch below the depth of 600 m did not exceed 100 t y^{-1} before 1995. In 1995, the total catch of these two species combined exceeded 300 t, and the longspine component probably did not exceed 200 t. In 1996, BC implemented an onboard observer program that required identification of all species captured. Consistent with this detailed catch information, DFO began issuing a separate annual quota for the two thornyhead species and created a new database, currently called **PacHarvTrawl**, to archive the detailed harvest information from the trawl fishery (Table 2.1).

Since 1996, the number of vessels capturing longspine thornyheads has declined from 57 to 20 in 2002 (Fig. 2.2A). Early on, many fishermen tried the fishery but few made the financial commitment (equipment and tactics) to make the venture profitable. The annual frequency of longspine landings has declined somewhat since 1998 as the fishery developed and management became more restrictive (Fig. 2.2B). The shortspine fishery remains a bycatch fishery despite directed quotas, and fluctuates accordingly.

Since the inception of a directed longspine thornyhead fishery in 1996, management rules have evolved to satisfy precautionary principles. Initially (1996-1999), DFO set coastwide quotas with no spatial restrictions. Despite this, vessels concentrated their effort off the west coast of Vancouver Island (Fig. 2.3). Declining catch rates in local areas (Schnute et al. 1999a, b) prompted DFO managers to cut the 2000 trawl quota on the traditional WCVI grounds to 404 t, effectively a 53% cut (Table 2.1). In compensation, they allocated a conditional quota of 425 t to an exploratory fishery north of a line drawn 230° true from Lookout Island (Fig. 1.1). The primary reason for this move was to reduce fishing pressure on WCVI stocks and explore the potential for resource development of more northerly longspine thornyhead stocks. The fishery was dubbed “exploratory” to avoid the stringent phased development proposed by Perry et al. (1999) for new fisheries (on species never commercially harvested). This strategy successfully identified two new fishing grounds, one located near a region called Tidemarks in Queen Charlotte Sound and the other off the NW coast of the Queen Charlotte Islands near Rennell Sound (Fig. 2.4). Many coastwide biological samples were collected and fishing pressure on the WCVI stock was reduced (Table 2.2).

In 2002, management stepped up its precautionary stance. The coast was divided into five longspine thornyhead management regions (Fig. 1.1). The traditional WCVI fishery was now defined to be south of 50° 30′ N. The northern fishery was designated “experimental” which meant that conditions for continuation of the fishery were more demanding. In addition to the collection of biological samples, a refuge area called Flamingo was closed to all directed longspine thornyhead fishing. (Although not officially closed, the Triangle region also acts as a refugium due to its difficult bottom topography at longspine depths.) At the time of this management shift, it was hoped that longspine biomass changes over time could be followed by some method of indexing in each of these new management regions. After the experimental fishery superseded the exploratory one, longspine density as measured by commercial CPUE declined coastwide (Fig. 2.4). Catches off the west coast of Vancouver Island increased somewhat in the 2002/03 fishing year; however, coastwide catches of longspines dropped in 2003/04 (Tables 2.1 and 2.3), probably in response to poor markets for this species, the rising value of the Canadian dollar and increased harvest costs.

Spatial shifts in commercial catch and density are apparent in latitudinal plots (Fig. 2.5). The fleet started targeting WCVI longspines in an area known as Beginner’s Ledge (grey band) and subsequently moved away from this location, possibly due to local depletion. The effect of management’s effort to spread fishing pressure away from WCVI in 2000 is also apparent.

3. WCVI Survey

Starr and Schwarz (2000) analyzed commercial trawl information, identifying both longspine and shortspine thornyheads as likely candidates for a random stratified trawl survey. These two species appear to have relatively uniform distributions on bottom compared to other slope and shelf rockfish species. Consequently, the authors anticipated reasonably precise estimates of relative biomass with their proposed survey design. After extensive consultation with various stakeholders – the Canadian Groundfish Research and Conservation Society (CGRCS), DFO science and management, fishing industry representatives, Simon Fraser University, the U.S. National Marine Fisheries Service (NMFS) – the CGRCS and DFO designed an initial three-year survey to target the longspine thornyhead resource.

A coastwide survey targeting multiple species was rejected during the initial study phase due to logistics and economics. Expanding the focus to other species would compromise the goal of reliable biomass index estimates for longspine thornyheads, given the lack of overlap in preferred depth ranges between longspines and other shelf species. Survey cost and time commitments restricted the survey to the west coast of Vancouver Island. A September time window allowed completion of the survey before fishing conditions deteriorated in the winter months.

An experienced fisherman, Brian Mose, identified six areal zones (Fig. 3.1, zones A-F) as discrete longspine thornyhead fishing grounds. A seventh zone G was added in 2002 to include the northernmost area of the newly created longspine management region WCVI (Fig. 1.1). The design used three depth strata (500-800 m, 800-1,200 m, 1,200-1,600 m), which span the normal habitat of longspine thornyheads and include a deeper, exploratory zone below 1,200 m where commercial fishermen rarely trawl. The seven areal zones A-G and three depth ranges define a total of 21 strata. The survey used randomly chosen tow locations in each stratum. Areal zones A-F had 4 tows in each of the two shallower depth zones and 2 tows in the deepest zone. The most northerly areal zone G had only 2 tows in each depth zone. This allocation gives a target of $6\times(4+4+2)+(2+2+2)=66$ tows for the survey (Starr et al. 2004). In 2001, with only 6 areal zones, this target number is reduced to 60.

In this paper, we consider the areal zones as a means for getting spatial coverage throughout the WCVI region, but we stratify the data using only the three depth zones described above. We adopt this strategy to obtain a reasonable number of tows in each stratum for bootstrapping and to deal partially with the change in areal stratification between 2001 and 2002. The data show much greater dependence on the depth strata than on the areal strata in all three surveys. Our preliminary survey biomass indices, not strictly based on the original design, will be updated in a future publication. We anticipate that these new or updated values will not differ significantly from those presented here.

Random trawl locations within defined strata were selected prior to each survey, and additional random sites were chosen as backups to be used when any primary selection proved untrawlable. Figure 3.3 shows the final site selections for each survey year. Commercial operators, who often return to known fishing grounds where they can tow for long periods, would not normally visit many of these sites. Commercial tows typically last from 4 h to 9 h or even longer. Survey tows, with a duration of only about 1 h, can occur in less desirable fishing locations and tend to produce more variable CPUE values. These bracket the observed values from the commercial fishery, which tend to be less extreme due to the averaging effect of the longer tows. Figure 3.4 illustrates this pattern within summary grid blocks. Presumably, each commercially fished block lies over a decent fishing ground and contains many more observations (tows) than an equivalent survey block.

The F/V *Viking Storm* conducted the 2001 survey, with skippers Chris Roberts and Kelly Anderson. This vessel could not complete the entire three-year contract, and was replaced by the F/V *Ocean Selector* with skipper Dave Clattenberg (Fig. 3.2) for survey years 2002 and 2003. A standard Atlantic Western II bottom trawl net was purchased in the first year specifically for this survey so that gear differences could be minimized among years. However, due to the change in survey vessel and the construction of a second Atlantic Western II trawl net in 2002, catchability and selectivity likely changed between the first and subsequent years of the survey but these differences could not be quantified. The *Viking Storm* used a net having a lighter footrope

(~300 kg), less buoyancy on the headrope (60 vs. 90 floats), shorter sweep wires, different lengthening pieces, a different codend and different doors (G. Workman, DFO, Nanaimo, pers. comm.). The survey planning team did not notice these changes until 2003 when the gear was subsequently standardized to the net used for the 2002 survey. At that time, skipper Dave Clattenberg indicated that, in his opinion, these changes would have a very minor effect on longspine catchability. However, experienced DFO field staff used both nets during the 2003 Queen Charlotte Sound survey and noticed marked differences in performance when deploying nets with the same doors, sweeps, bridles and net mensuration equipment (G. Workman, DFO, Nanaimo, pers. comm.). As stated above, these differences are not quantifiable and cannot be accounted for in the analyses presented here. In an effort to reduce or eliminate changes in survey gear catchability, future surveys must be constrained to using the same nets and rigging as initial surveys regardless of the fishing master's preferences or refinements in fishing methods and gear.

In all three years of the survey, a bottom contact sensor provided extra data for measuring the effective tow time. This sensor attaches to the footrope via two short (0.5-1.2 m) lengths of chain and hangs freely beneath the net. Every six seconds, the angle of the sensor is recorded relative to a vertical line, so that 0° indicates that the sensor hangs vertically and 90° indicates that it is horizontal. While the net sinks, the sensor dangles vertically from the footrope. When the net contacts bottom, the sensor drags horizontally behind the footrope. Consequently, bottom contact normally corresponds to a sharp change from 0° to 90° in the tilt angle. Sensor data (Fig. 3.5) often show considerable and highly variable delays between the time that winches were locked to begin a fishing event and the time that the net made initial contact with the bottom. Similar variable delays occurred between times of winch release during trawl retrieval and final lift-off from the bottom. With fairly smooth bottom topography, the sensor trace exhibits a regular pattern (Figs. 3.5A, D, E). Over rougher bottoms, the trace clearly shows that the sensor bounces off the bottom frequently (Figs. 3.5B, G). Some tows exhibit a combination of rough and smooth bottoms (Fig. 3.5H). Analyses in the report use tow times estimated from initial and final moments of achieving the critical angle 45°, as illustrated in Fig. 3.5.

In 2002 and 2003, net monitoring equipment from SCANMAR (Scanmar AS, Norway, http://www.scanmar.no/) displayed fishing characteristics of the net while a tow progressed. The system includes four sensors mounted on the net and trawl doors, plus associated receiver and processing equipment on the bridge. The display shows real-time data for the doorspread, wingspread, headline height, water temperature at the net, water velocity at the net, and net depth. Because no provisions for electronic data capture existed in 2002, staff manually transcribed the desired sensor readings to a log form every 5-10 minutes during the tow. Readings began when the net reached bottom (based on readings from the net sensors) and ceased when the winch released for net retrieval. Log sheets also recorded interval data (from SCANMAR, GPS, and other sensors) for: date, time, bottom depth, latitude, longitude, warp length, vessel direction, and vessel towing speed. Manual data logging continued for the first 37 tows of the 2003 survey, after which a live computer feed captured data for the remaining tows.

Each valid survey tow has an average vessel speed calculated from recorded speeds at time intervals during that tow. The mean speed of all survey tows is

(3.1) $v = 4.48826 \text{ km h}^{-1}$.

In 2002 and 2003, SCANMAR measurements of doorspread provide a consistent estimate of net width, with an average value for each tow computed from numerous individual values. The mean doorspread width of all tows is

(3.2) $w = 56.3607$ m.

For survey tows with missing data and all commercial tows, we use (3.1)-(3.2) as default values of vessel speed and net width.

Following techniques of sampling theory (Section 5 below), the survey gives a biomass estimate $\hat{B}$, along with an estimated variance $\hat{\mathrm{V}}[\hat{B}]$ and coefficient of variation (CV)

(3.3) $$\hat{\rho} = \frac{\sqrt{\hat{\mathrm{V}}[\hat{B}]}}{\hat{B}},$$

sometimes called the *relative error*. According to initial plans, the survey design should produce an estimate $\hat{\rho} \le 20\%$ for each thornyhead species. In fact, the 2001 survey produced smaller values $\hat{\rho} \le 10\%$ (Starr et al. 2002). Reasonable precision ($\hat{\rho}$ between 13% and 22%) in the biomass estimates for sablefish *Anoplopoma fimbria* and Dover sole *Microstomus pacificus* demonstrated the survey's utility for other commercial groundfish species. Similar results came from the 2002 and 2003 surveys (Starr et al. 2004). In this report, we apply a single methodology to obtain swept-area biomass estimates from all three survey years, and we compare these results with similar estimates from commercial data.

4. Data Sources

The commercial trawl fishery data are currently maintained in the DFO database **PacHarvTrawl**, which contains information on all fishing events and species catches since 1996. We derive total removals (Table 2.1) by summing catch for archived tows without using specific filters. The landed catch from trips without log records cannot be assigned to any specific region. At the time of writing, there were 18,170 fishing events that reported some catch of longspine thornyhead, based on commercial data ending October 15, 2003.

For analyses of commercial CPUE data, we first consider all available tows (including tows with no catch of longspine thornyheads) that meet the following minimal criteria:

- observer log record (log code = 1);
- bottom trawl gear (gear type = 1);
- no water hauls (success code = 0 or 1);
- effort greater than 0 h, but less than or equal to 24 h;
- total tow catch weight (all species) greater than 0 kg;
- tow location in management region WCVI, Tidemarks, or Rennell (Fig. 1.1);
- fishing depth greater than 500 m, but less than or equal to 1,600 m.

Currently, the database lists 16,754 tows that meet these minimal qualifications. They occur between May 1, 1996 and October 15, 2003.

When applying our models to CPUE data, we impose two additional criteria that fully qualify tows for inclusion in our analyses:

- month in the period May-October (six months);
- vessel included among the 14 fishing vessels that caught longspine thornyhead in at least 6 of the 8 years (1996-2003) coastwide.

This additional filter qualifies 9,893 tows (Table 4.1). All 14 vessels participated in the WCVI fishery. Only 11 of these fished in Tidemarks, and a different set of 11 vessels fished in Rennell. The majority (80%) of tows occurred in WCVI, with 7% in Tidemarks and 13% in Rennell.

The WCVI survey conducted 211 bottom tows over the three years, 192 of which we use for CPUE analysis (Table 4.1). We exclude invalid tows that encountered problems due to the net snagging on the bottom, doors crossing, excessively strong tides, and insufficient bottom contact time. Of the useable tows, 189 were sampled for fish biometrics: length, weight, sex, maturity, otoliths (Table 4.2). Cruise details and biological data are housed in DFO's **GFBio** database. The 2001-2003 surveys have trip identification codes 42252, 45780, and 50220, respectively. The total longspine thornyhead catch from the three surveys is 3.5 t, 5.3 t, and 3.6 t, each representing roughly 1% of the annual longspine thornyhead catch in the WCVI region.

Some of our models require areas associated with various depth zones. We obtain these data using a standard algorithm for computing the area inside a polygon (Schnute et al. 2003, p. 8), based on polygonal lines that defined depth contours. Thus, the areas used here correspond to measurements of ocean surface above specified depth zones. We lack three-dimensional data adequate to give us realistic estimates of area along the convoluted sea floor. Furthermore, we restrict our analyses to the rectangular area portrayed in Figure 1.1, where the southern and western boundaries constrain the extent of some depth zones.

As a condition for continuing the longspine thornyhead fishery, DFO requires the collection of biological samples from commercial tows to help determine population status in the three major regions (WCVI, Tidemarks, Rennell). The sampling rate increased notably in 2000, the year that the exploratory fishery was implemented (Table 4.2), but since then the rate has declined to more practical levels. Available data reflect the fact that fish lengths are by far the easiest metric to collect. Length frequencies are not as powerful for determining longspine population status as age frequencies, but they provide a potential indicator of length-based selectivity in the fishery. Weight measurements come entirely from the survey, with no samples taken from the commercial fishery. Although it is difficult to distinguish between the sexes for fish smaller than 20 cm, sex information is available for many specimens. Maturity readings, on the other hand, are difficult because no standard maturity guides exist for this species. Many otolith pairs have been collected from the commercial fishery, especially at the beginning of the exploratory fishery, and from the WCVI survey (Table 4.2). At the present time, however, no generally accepted protocols are available for age determination of longspine thornyheads, and otolith sampling has been scaled back in the commercial fishery.

5. Models for CPUE Data

5.1. Model Concepts and Notation

The introduction mentions three methods of estimating a biomass index from CPUE data:

- swept-area biomass estimates;
- standardized analyses with fixed effects for various factors, such as year, month, depth and vessel;
- swept-area estimates with fixed effects to standardize vessels only.

This section provides a conceptual framework for all three models and a systematic notation that allows us to state each one in a manner comparable with the others. We begin with idealized statements of the mathematical models (Sections 5.1 to 5.4), but we examine their assumptions more completely in Section 5.5.

Schnute and Haigh (2000) discuss the key idea that a single tow along the sea floor theoretically gives an estimate of biomass density for each species caught:

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

To be precise, suppose that a vessel tows a net of width w at speed v. If the tow lasts for time 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 density measurement is

(5.2) $$y = \frac{C}{vwE} = \frac{1}{vw} U ,$$

where $U = C / E$ is the catch per unit effort (CPUE). In a typical situation, the quantities in (5.2) might have the units listed below:

Quantity	**Notation**	**Units**
catch	C	kg
effort	E	h
CPUE	U	kg h^{-1}
net width	w	m
vessel speed	v	km h^{-1}
density	y	t km^{-2}

These units, with mixed choices for biomass (1 t = 1,000 kg) and distance (1 km = 1,000 m), remain consistent in (5.2) because the two factors 1,000 cancel. Our analyses assume that vessel speeds and net widths are always known, so that CPUE (kg h^{-1}) can readily be scaled to biomass density (t km^{-2}). For example, the default values (3.1)-(3.2) imply the correspondences

$$100 \text{ kg h}^{-1} \leftrightarrow 0.395 \text{ t km}^{-2}, \quad 25.3 \text{ kg h}^{-1} \leftrightarrow 0.1 \text{ t km}^{-2}.$$

In practice, tows occur in various contexts associated with different years, months, depths, vessels, and survey strata. We indicate these factors with subscripts, as follows:

- h – stratum,
- i – year,
- j –month,
- k – depth,
- l – vessel,
- n – tow number (within the relevant categories).

In particular, we always treat depth as a factor defined by specified depth ranges, rather than a continuous variable. Each factor has a number of possible levels, which we denote with a corresponding uppercase letter. For example, H denotes the number of strata, I the number of years, J the number of months, and so on.

Depending on the context, a model may include one or more factors. The subscript n enumerates tows within the relevant categories, and we use the upper case letter N to denote the number of tows within a particular category. Thus, N_{ijkl} represents the number of tows conducted by vessel l in year i, month j, and depth zone k. Similarly, N_{ikl} indicates the number of tows by vessel l in year i and depth zone k, regardless of the month; consequently,

$$N_{ikl} = \sum_j N_{ijkl} \ .$$

Other examples include N_{ik} (the total number of tows in year i and depth zone k, regardless of month or vessel) and N_i (the total number of tows in year i, regardless of month, depth, or vessel). With no subscript, the symbol N denotes the total number of tows used in the model.

In principal, the notation developed here allows each depth zone k to be divided into strata h. However, for the applications here, we always use depth to define areal strata, so that one of the indices h or k can be dropped from the analysis.

5.2. Swept-area Biomass Estimates

If the area of available fish habitat is known, then the logic of (5.1) extends to give an estimate of stock biomass by the simple formula

$$\text{biomass} = \text{density} \times \text{habitat area} \ . \tag{5.3}$$

We can apply this idea to a simple stratified design, where stratum h has known area A_h $(h = 1, \ldots, H)$ and y_{hn} denotes the density measurement from tow n $(n = 1, \ldots, N_h)$ in stratum h. Define the usual sample mean and variance estimates for stratum h:

$$\bar{y}_h = \frac{1}{N_h} \sum_{n=1}^{N_h} y_{hn} \;, \quad s_h^2 = \frac{1}{N_h - 1} \sum_{n=1}^{N_h} (y_{hn} - \bar{y}_h)^2 \;. \tag{5.4}$$

Then, by the logic of (5.3), the sum

$$\hat{B} = \sum_{h=1}^{H} A_h \, \bar{y}_h \tag{5.5}$$

gives an estimate of total biomass in all strata. Furthermore, the variance of $\hat{B}$ can be estimated as

$$\hat{\mathrm{V}}[\hat{B}] = \sum_{h=1}^{H} A_h^2 \, \frac{s_h^2}{n_h} \,, \tag{5.6}$$

where s_h^2 / n_h estimates the variance of $\bar{y}_h$. Combining (5.5)-(5.6) gives an estimated coefficient of variation $\hat{\rho}$ defined in (3.3).

Bootstraps provide an alternative method of estimating uncertainty in the estimate (5.5). This technique samples the raw data y_{hn} $(n = 1, \ldots, N_h;\ h = 1, \ldots, H)$ with replacement from each stratum and generates a distribution of corresponding estimates (5.5). Schnute and Haigh (2003) describe the method more completely and discuss improvements using bias correction and acceleration.

5.3. Standardized CPUE Analysis

The swept-area model in Section 5.2 takes account of differences among strata, but ignores any dependencies on year, month, depth, and vessel. This works well for a survey by a single vessel during a specific year and month, particularly if depth zones define the strata. In the commercial fishery; however, vessels can fish differently from each other, density can vary by month, and these factors can influence the apparent population trend from one year to the next. For example, consider an unchanging population that experiences fishing by a highly efficient vessel the first year and a less efficient vessel the next. A corresponding drop in CPUE from the first to the second year would make it appear that the population had declined. Scientifically, population changes become confounded with changes in the method of measurement.

One possible solution to this problem puts different measurements on a standard scale. For example, the CPUE from a highly efficient vessel would count more than the same CPUE from a less efficient vessel. The additive lognormal model

(5.7) $$\log y_{hijkln} = \mu_h + \alpha_i + \beta_j + \gamma_k + \delta_l + \sigma\,\varepsilon_{hijkln}$$

implies a standard scale for each factor, where

(5.8) $$\sum_i \alpha_i = \sum_j \beta_j = \sum_k \gamma_k = \sum_l \delta_l = 0$$

and the residuals

(5.9) $$\varepsilon_{ijkln} \sim \mathrm{N}(0,1)$$

are independent standard normal variables with mean 0 and variance 1. Model (5.7) assigns an overall mean μ_h to each stratum *h*, with a fixed effect for each factor. For example, a vessel *l* with $\delta_l > 0$ performs better than average, and a vessel with $\delta_l = 0$ provides a standard.

The standardized measurement

(5.10) $$y'_{hijkln} = y_{hijkln}\, e^{-\beta_j - \gamma_k - \delta_l}$$

is adjusted in stratum *h* and year *i* to correct for effects due to month *j*, depth *k*, and vessel *l*. Assumptions (5.7)-(5.10) imply that $\log y'_{hijkln}$ has a normal distribution with mean $\mu_h + \alpha_i$ and variance σ^2, independent of *j*, *k*, or *l*. Known properties of the lognormal distribution (Aitchison and Brown 1957, p. 8) imply that standardized measurements have mean and variance given by

(5.11) $$\mathrm{E}[y'_{hijkln}] = e^{\mu_h + \alpha_i + \sigma^2/2}$$ and

(5.12) $$\mathrm{V}[y'_{hijkln}] = e^{2(\mu_h + \alpha_i) + \sigma^2}(e^{\sigma^2} - 1).$$

Model (5.7)-(5.9) belongs to a class of general linear models (GLMs) with well-known theoretical properties. Most statistical software packages, such as R or S-Plus (Appendix B), routinely provide estimates of the model parameters $(\mu_h, \alpha_i, \beta_j, \gamma_k, \delta_l, \sigma)$ from a given set of observations y_{hijkln}, along with estimates of their standard errors. In this paper, estimates of α_i play a key role, because they presumably track population changes across years.

If the standardized model is correct, then statistical properties (5.11)-(5.12) of adjusted measurements y'_{hijkln} depend only on stratum *h* and year *i*. Consequently, we can ignore indices *j*, *k*, and *l*, and regard y'_{hin} as a sequence of observations in stratum *h* and year *i*, indexed by *n*. Following the logic of (5.4)-(5.5), define the mean

(5.13) $$\bar{y}'_{hi} = \frac{1}{N_{hi}} \sum_{n=1}^{N_{hi}} y'_{hin}$$

and swept-area biomass estimate for year i

(5.14) $$\hat{B}'_i = \sum_{h=1}^{H} A_h \, \bar{y}'_{hi} \; .$$

It follows from (5.11) and (5.13)-(5.14) that

(5.15) $$\mathrm{E}\,[\hat{B}'_i] = e^{\alpha_i} \sum_{h=1}^{H} A_h \, e^{\mu_h + \sigma^2/2} \; .$$

Thus, the standardized model gives swept-area biomass estimates $\hat{B}'_i$ proportional to e^{α_i}. Strictly speaking, this analysis applies only to *non-zero* observations $y'_{hin} > 0$. The next section describes an alternative that includes observations with no catch.

5.4. Swept-area Biomass Estimates with Standardized Vessel Data

The standardized analysis in Section 5.3 makes the assumption (5.7) that factors act independently in their influence on CPUE. We show in Section 7 that this assumption usually is violated by the data sets examined here; consequently, results from this model cannot be trusted completely. In this section, we weaken the model to allow only for vessel effects. Our analysis uses only the indices

- stratum h, which also acts as a surrogate for depth;
- year i;
- vessel l.

Note that we ignore any month effect. The standardized model, comparable with (5.7)-(5.8), now becomes

(5.16) $$\log y_{hiln} = \mu_{hi} + \delta_l + \sigma\,\varepsilon_{hiln}$$

with the constraint

(5.17) $$\sum_l \delta_l = 0 \, .$$

This model weakens the assumption that strata h and year i have independent effects. Instead, we assume an interaction term μ_{hi} (with HI parameters), which may not take the more parsimonious form $\mu_h + \alpha_i$ (with $H + I - 1$ parameters). Following ideas developed in Section 5.3, we define a four-step algorithm for generating a biomass estimate $\hat{B}'_i$ for year i based on measurements standardized for each vessel:

1. Apply model (5.16)–(5.17) to all available *non-zero* observations $y_{hil\,n} > 0$. This gives estimates $\hat{\delta}_l$ of relative fishing power based on tows that actually caught the species of interest.
2. Use these estimates $\hat{\delta}_l$ to compute $y'_{hil\,n} = y_{hil\,n}\, e^{-\hat{\delta}_l}$, and then ignore the index *l* by combining all observations in stratum *h* and year *i*. This calculation includes *all* observations, even those with $y_{hil\,n} = 0$, where $y'_{hil\,n} = 0$ if $y_{hil\,n} = 0$.
3. As in (5.13), compute the mean standardized density $\bar{y}'_{hi}$ for each stratum *h* and year *i*.
4. Finally, define the estimate

(5.18) $$\hat{B}'_i = \sum_{h=1}^{H} A_h\, y'_{hi}\ .$$

To assess uncertainty in this estimate, bootstraps need to follow a similar process. When repeating step 1, sample non-zero observations with replacement for each vessel *l*, preserving the total number of tows for each vessel. In step 2, use the estimates $\hat{\delta}_l$ from step 1, but resample with replacement by preserving the number of tows in stratum *h* during year *i*.

5.5. Model Assumptions

All models described above begin with the assumption that a tow measures fish density, as in (5.1). In practice, investigators prefer the weaker assumption that the measurement of biomass per unit area only *indexes* the true density:

(5.19) $$\text{measured density} = \frac{\text{biomass captured}}{\text{area swept by the net}} = q \times \text{true density}\,,$$

where the catchability constant *q* relates to the proportion of fish actually captured. For example, if a tow causes fish to swim away from the net, then the measured density is less that the true density and $q < 1$. Similarly, if a tow herds fish into the net from outside the track line, then $q > 1$. Combining (5.19) with (5.2) shows that

(5.20) $$\text{true density} = \frac{1}{v(qw)}U = \frac{1}{v w_{\text{effective}}}U\,,$$

where a calculation with the effective net width ($w_{\text{effective}} = qw$) gives the true biomass density. Often the appropriate choice of net width *w* remains a subject for speculation, and investigators choose a particular value *w* with the understanding that a different choice would only alter the catchability

(5.21) $$q = \frac{w_{\text{effective}}}{w}\,.$$

In the present context, the logic of (5.19) implies particularly that q truly remains constant across all tows, regardless of stratum, year, month, depth, vessel, or tow number. Thus, q does not depend on the various indices (h, i, j, k, l, n).

Commercial tows may fail to meet the assumptions in the previous paragraph. A fisherman can direct a tow to influence the catch of a particular species. As a result, the apparent density can increase or decrease, and the "constant" q can then vary by year, month, or depth. No amount of "standardization" can correct this problem. An analysis of commercial data might reveal patterns in CPUE, but these imply nothing about the underlying population without assumptions comparable to (5.19)–(5.20) that CPUE relates to actual biomass density. We recognize this problem but, lacking independent data in various regions and years, we apply our models as if commercial data reflect actual changes in longspine thornyhead biomass.

Density measurements from (5.19) take random values from a distribution whose mean can vary by stratum, year, month, depth, or vessel. In applications here, the swept-area model (5.5)–(5.6) assumes that for a given year, the mean changes only by stratum (or equivalently, depth). Tows must represent the entire distribution for each stratum, as in a survey with tow locations chosen randomly for complete spatial coverage. If the fish population moves rapidly enough to redistribute itself throughout each stratum between tows (an unlikely scenario), then spatial coverage becomes less important. Commercial tows usually achieve limited coverage, because fishermen focus on grounds that produce the best fisheries. Plots that represent tow locations on a map can shed light on the issue of spatial coverage.

The standardized models (5.7)–(5.9) and (5.16)–(5.17) make the explicit mathematical assumption that some factors have multiplicative (or logarithmically additive) effects on the mean CPUE. Textbooks (e.g., Steel and Torrie 1960) routinely recommend that this assumption can and should be tested before trusting model results. In our applications, we provide interaction plots useful for investigating this issue. As in the swept-area model, coverage also plays a role, where each combination of factors (e.g., year-month-depth-vessel) should ideally be represented by available data. In some cases, the data may not be adequate to estimate all model parameters.

All models have the common feature that estimates of biomass or CPUE come from linearly weighted density observations y or $\log y$. The swept-area model (5.4)–(5.5) weights the mean density $\bar{y}_h$ from stratum h by the area A_h. The standardized model (5.7)–(5.9) assigns the same weight to each stratum, but also weights each observation equally. Thus, the least-squares estimates $(\hat{\mu}_h, \hat{\alpha}_i, \hat{\beta}_j, \hat{\gamma}_k, \hat{\delta}_l)$ come from a procedure that gives greater weight to factor values with more available data. The formula (5.14) converts the results from standardized analysis to a biomass estimate with densities weighted by stratum area A_h.

A survey usually takes place in a short time frame, with relatively few controlled tow locations. By contrast, a commercial fishery typically conducts a much larger number of tows over an extended time period. To derive sensible results from commercial data, investigators usually restrict the analysis to tows that meet various *qualification* criteria. In effect, the qualification process gives *a priori* weight 0 to observations that fail to meet the prescribed criteria. Similar analyses take place in the financial world, where a particular bundle of stocks (like the Dow Jones Industrial Average) is chosen to represent a component of the market place. Indices may or may not exhibit similar patterns, and analysts typically investigate numerous indices for a better understanding of the complete picture. In this paper, we take a similar view by investigating patterns obtained from a variety of indices derived from commercial data.

5.6. Index Trends

Regardless of the data and model, all the analyses discussed here generate an index X_i that typically varies among years *i*. For example, $X_i = \hat{B}_i$ in the context of a swept-area model, or $X_i = \exp(\hat{\alpha}_i)$ in a standardized CPUE analysis. Because X_i provides an index only, rather than an absolute measurement of biomass, it describes only relative changes in the population over time. The logarithmic variable $Y_i = \log_2 X_i$ transforms relative change to a convenient linear scale, where doubling *X* corresponds to increasing *Y* by one unit:

$$\log_2(2X) = \log_2 2 + \log_2 X = 1 + Y \,.$$

The choice of logarithmic base essentially defines a scale of units for the analysis (analogous to choosing kilograms or pounds), where the constant $\log_\alpha \beta$ converts from base β to base α:

(5.21) $$\log_\alpha X = \log_\alpha \beta \, \log_\beta X \,.$$

In the applications here, we generally have short time series with overall upward or downward trends, as in the linear model

(5.22) $$\log_2 X_i = a + bi \,.$$

A linear regression through the data points $(i, \log_2 X_i)$ with $i = 1, \ldots, I$ gives a slope estimate $\hat{b}$ that provides a summary statistic for the entire series of *I* observations. Furthermore, regardless of the model and data set, bootstrapping can be used to assess the uncertainty of $\hat{b}$ in a two-step process. First, for each year *i*, generate a bootstrap estimate $\hat{X}_i$ from a sample (with replacement) of the raw data. Second, use regression on this set of *I* estimates to produce a bootstrap estimate $\hat{b}$. Repeating this process many times gives a bootstrap distribution for $\hat{b}$.

If the linear model (5.22) were exactly true, then for each year *i*

$$b = \log_2 X_{i+1} - \log_2 X_i = \log_2\left(\frac{X_{i+1}}{X_i}\right).$$

Consequently, b represents the annual logarithmic growth rate. For example, the index grows or declines by a factor of 2 if $b = 1$ or $b = -1$, respectively. The parameter b also defines the annual relative growth rate

(5.23) $$r = 2^b - 1 = \frac{X_{i+1} - X_i}{X_i}$$

and the accumulated relative change

(5.24) $$R_I = 2^{b(I-1)} - 1 = \frac{X_I - X_1}{X_1}$$

during a time series of I observations. In particular, (5.23) implies a positive, zero, or negative growth rate r when b is positive, zero, or negative, respectively. The result (5.24) reflects the fact that a series of I observations includes only $I - 1$ time steps. In particular, $R_2 = r$.

In practice, a time series X_i $(i = 1, \ldots, I)$ never follows the exact linear trend (5.22) and the regression estimate $\hat{b}$ provides only a rough measure of overall trend. The definitions (5.23)-(5.24) then give corresponding estimates $\hat{r}$ and $\hat{R}_I$. Furthermore, all these quantities reflect the chosen index X, which may pertain to biomass, density, or merely CPUE. For example, commercial CPUE might experience increases or decreases that do not reflect changes in the underlying population. As we have emphasized earlier, our use of commercial CPUE stems from the fact the fishery-independent survey covers a very limited range in space and time.

6. Swept-area Analyses

We begin with visual images of the raw data, prior to conducting analyses that depend on model assumptions. Swept-area biomass estimates (5.5) use CPUE directly, although standardized analyses use a logarithmic scale. Our exploratory plots use both scales to represent the data distribution from both points of view. Our longest time series comes from the commercial fishery, where we consider two qualification levels (Section 4) for including tows in CPUE data analysis. The first essentially requires successful tows deeper than 500 m, and the second restricts the data further to 14 consistently active vessels during the six-month period May to October. Figure 6.1 shows individual WCVI CPUE values through time for the first qualification level using (A) the original CPUE scale and (B) a logarithmic scale with base 10. Panel B excludes zero values, but panel A does not. Loess-smoothed lines in each panel show a slow declining CPUE trend, produced mainly by a declining frequency of tows with high CPUE.

For easy comparison, two loess lines appear in each panel (Fig. 6.1): the line appropriate to the panel itself and a transformed version of the line from the other panel. In this case, the line for panel A lies somewhat below the line for panel B, perhaps due to the presence of zero tows in panel A that are not represented in panel B. At the second level of qualification (Fig. 6.2), the two lines almost coincide. Also, data from experienced vessels during May-October (Fig. 6.2) show a more regular pattern with less scatter that data for any month by all vessels that fish below 500 m (Fig. 6.1).

Figures 6.3-6.6 show similar analyses from the Tidemarks and Rennell regions, where tows take place less frequently than in WCVI and fishing begins in year 2000 (rather than 1996). The spotty data in Tidemarks show no clear trend, but CPUE does appear to decline in Rennell, due particularly to a reduced frequency of the high CPUE values that occurred in the initial year 2000. As in WCVI, data from experienced vessels show a more coherent pattern with loess lines essentially independent of linear or logarithmic scales.

Our swept-area biomass estimates use fishing depth as the key variable for stratifying tows. We consider two possible schemes, each with three ranges for depth D:

1. $500\text{ m} \le D \le 700\text{ m}$, $700\text{ m} < D \le 900\text{ m}$, $900\text{ m} < D \le 1{,}200\text{ m}$;
2. $500\text{ m} \le D \le 800\text{ m}$, $800\text{ m} < D \le 1{,}200\text{ m}$, $1{,}200\text{ m} < D \le 1{,}600\text{ m}$;

We apply the first scheme to the commercial fishery, where very few operators fish depths below 1,200 m. The second scheme corresponds to depth zones chosen for the WCVI survey (Section 3). Table 6.1 lists bottom areas for all these strata in each of the three management regions (WCVI, Tidemarks, Rennell). These give the stratum areas A_h required for the estimates (5.5) and (5.6). The calculation of area between bottom contours uses PBS Mapping (Schnute et al. 2003), a software package for R/S-Plus. We assume a flat surface projection, so our area estimates can be considered minimal.

Consistent with goals described in the introduction to this report, we try to make “apples with apples” comparisons between the commercial fishery and the survey wherever possible. For example, because the commercial fishery is stratified by scheme 1, we also examine the survey from this point of view. Furthermore, we present a time series from commercial data in September for WCVI to compare with the survey estimates from the same month. Table 6.2 shows results from all these swept-area calculations, based on (5.5)-(5.6) and (3.3). Notice that survey biomass estimates $\hat{B}$ from stratification scheme 1 (commercial) are smaller than those from scheme 2 (survey), because the latter includes extra habitat area in the depth zone below 1,200 m. Our coefficient of variation estimates $\hat{\rho}$ from the survey stratified with scheme 2 lie near 10% for all three years, similar to those reported by Starr et al. (2002, 2004), based on strata that include areal zones A-G.

Figure 6.7 represents graphically the four analyses in Table 6.2 for WCVI (commercial fishery with two qualifications by month and survey with two depth stratifications), where uncertainty estimates come from bootstraps rather than the formulas (5.6) and (3.3). The swept-area estimates indicate a declining trend in biomass since 1996 (Fig. 6.7A). The commercial September index, with greater uncertainty due to fewer available tows, tells a different story, with a sudden increase in 2002 followed by a decline in 2003 (Fig. 6.7B). This up-down pattern agrees with the survey results (Figs. 6.7C-D).

In our discussion we deal with the problem of interpreting these results, where only Fig. 6.7D (the survey with its original strata) represents proper design. We can, however, take the extra step of attempting to standardize CPUE from different commercial vessels by the techniques described in Section 5.4. Furthermore, we can extend the analysis to the northern regions (Tidemarks, Rennell), where only commercial data are available. Figure 6.8 shows the results of these analyses, based on months May-October. As in Fig. 6.7, we use bootstraps to assess uncertainty. Estimates with standardized vessel effects show little difference from estimates that ignore these effects in WCVI (Figs. 6.8E-F), although temporal trends in Tidemarks (Figs. 6.8C-D) and Rennell (Figs. 6.8A-B) are altered somewhat by including vessel effects in the analysis. Note that Fig. 6.8E repeats the content of Fig. 6.7A, although different scales of the axes give somewhat different appearances.

The ultimate value of a survey lies in its ability to detect changes in the underlying biomass. The trend analysis described in Section 5.6 gives us a formal method of addressing this issue. Figure 6.9 shows a bootstrap distribution of the slope $\hat{b}$ derived from all three years of longspine survey data, based on swept-area estimates with the designed depth stratification scheme 2 listed above. The result very closely approximates a normal distribution with mean 0 and standard deviation 0.088. Consequently, with 95% confidence, $\hat{b}$ lies in the interval

$$(-1.96 \times 0.088, 1.96 \times 0.088) = (-0.17,\ 0.17)\,,$$

as indicated by the 2.5% and 97.5% quantiles in Fig. 6.9B. From (5.23), this shows that the estimated growth rate $\hat{r}$ lies in the interval

$$(2^{-0.17} - 1,\ 2^{0.17} - 1) = (-0.11,\ 0.13)\,.$$

In summary, the three-year survey shows no evidence of biomass change, but the population could have declined by as much as 11% per year or increased as rapidly as 13% per year.

7. Standardized CPUE Analyses

We conduct standardized analyses for each of the longspine thornyhead management regions (WCVI, Tidemarks, Rennell), using fully qualified commercial data (Section 4, tows by 14 experienced vessels during the months May-October). Our calculations use logarithms with base 2, so that one unit upward on the log scale corresponds to a doubling of CPUE. Following model (5.7), we estimate the following parameters:

- μ – the overall mean;
- α_i – year effect (1996-2003 in WCVI, 2000-2003 in Tidemarks and Rennell);
- β_j – month effect (May-October);
- γ_k – depth effect (500-599 m, 600-699 m, 700-799 m, 800-899 m, 900-999 m, 1,000 m or greater);
- δ_l – vessel effect (1-14, ranked within each region from highest to lowest CPUE), where not all vessels fish in every region.

The index h does not appear in this application of (5.7), so that μ has no subscript. We could let h denote the region and conduct a single coastwide analysis, but instead we analyze each region independently from the others. For ease of interpretation, our analyses use logarithms to the base 2, as discussed in Section 5.6. Figures 7.1-7.3 summarize our results. Panel A of each figure shows the year effect ($2^{\mu+\alpha_i}$) on the original CPUE scale. Panels B-D show multiplicative effects (2^{β_j}, 2^{γ_k}, 2^{δ_l}) due to month, depth, and vessel. A consistent scale from 0 to 2 makes it easy to compare the relative importance of these effects.

For the WCVI region, the parameter estimates α_i indicate a declining trend in CPUE during the period of $I = 8$ years from 1996 to 2003. From the analysis described in (5.22)-(5.24), we obtain the following estimates of slope, annual growth, and accumulated change:

(7.1) $$\hat{b} = \text{-}0.0968\,,\ \hat{r} = -0.0649\,,\ \hat{R}_8 = -0.375\,.$$

This annual rate of decline (6.5%) slightly exceeds the rate (5%) reported earlier by Starr and Haigh (2000) and by Starr (2001). The month effect suggests that CPUE is highest in June and lowest in August (Fig. 7.1B), although the differences in CPUE among months are not great. As expected from earlier work by Haigh and Schnute (2003), CPUE increases with depth (Fig. 7.1C). The multiplicative factor increases threefold from about 0.5 to 1.5 as depth increases from 500 m to 1,000 m. The 14 fishing vessels exhibit significant differences in their catchability of longspine thornyheads (Fig. 7.1D), with the highest to lowest catch rates varying by a factor of 2.

In the Tidemarks region, directed longspine thornyhead fishing occurred only in the most recent four years (2000-2003). The parameters α_i show a small declining trend over this period, giving the trend parameter estimates

(7.2) $$\hat{b} = \text{-}0.0434\,,\ \hat{r} = -0.0296\,,\ \hat{R}_4 = -0.0863\,.$$

The month effect shows a consistent decline from June to September (Fig. 7.2B). Conversations with fishermen suggest that vessels participating in the experimental longspine fishery move from northern fishing grounds to southern ones as the weather gets rougher from spring/summer to fall/winter. As in WCVI, the Tidemarks CPUE increases with depth, but the effect is less pronounced in this region (Fig. 7.2C vs. 7.1C). Of the 14 vessels, only 11 fished in Tidemarks, where catchability again varies by a factor of 2 (Fig. 7.2D). Vessel numbers do not match between Figs. 7.1D and 7.2D.

As in Tidemarks, Rennell only has four years of useful CPUE data. The apparent CPUE decline is greatest in this region, with parameter estimates

(7.3) $$\hat{b} = \text{-}0.391\,,\ \hat{r} = -0.237\,,\ \hat{R}_4 = -0.556\,.$$

The month effect appears strongest in this region with a consistent decline from May to October (Fig. 7.3B). Again, this probably corresponds to the southward migration of fishermen participating in the experimental fishery during the course of the year. Among the three regions, the depth trend in Rennell is least pronounced (Fig. 7.3C). The noticeable decrease in the strength of the depth effect from south to north might reflect fishing patterns, where fewer deep tows occur in the northern fisheries. As in other regions, vessel catchability varies two-fold (Fig. 7.3D), though different vessels dominate in the different regions.

Results in Figs. 7.1-7.3 from the standardized model (5.7) depend on the assumption that the factors act independently of each other. We examine this assumption for the Rennell data in Fig. 7.4, where six panels portray all possible pairwise interactions between year *i*, month *j*, and depth *k*. The model (5.7) suggests that the traces within each panel should show the same trend and appear parallel to each other (with vertical offsets determined by $\alpha_i, \beta_j,$ or γ_k). In fact, traces cross each other frequently. For example, in most years CPUE declines as the season progresses; however, in 2001 it did not (Fig. 7.4C). This panel also illustrates that data do not exist for all combinations of factors. For example, no tows occurred during October (month 10) in year 2000. Effectively, the model extrapolates effects in these missing cells from the available combinations.

Figure 7.5 extends this analysis to three-way interactions among year, month, and depth in the Rennell data. We examine five months (May-September) and five depth zones (100 m intervals starting at 500 m to 900 m) to obtain 25 combinations, for which we plot the time trend of CPUE during the four years 2000-2003. Some combinations have data for only one, two, or three of these years, as shown. In all but one case, we have adequate data to obtain a trend estimate $\hat{b}$ and corresponding growth rate $\hat{r}$ from (5.23). Of the 24 time trends, 22 are negative. Estimates $\hat{r}$ range from $-51.2\,\%$ (Aug-500 m) to 33.8% (Jun-900 m), with an average value $-15.5\,\%$. This disperse range of estimates provides another illustration of factor interactions in the Rennell data.

Further statistical tests (not presented here) show that all two-factor and most three-factor interactions among year, month, depth, and vessel are significant for the Rennell data. We find similar results for the WCVI and Tidemarks regions. This means that the independent trends for each of these four factors portrayed in Figs. 7.1-7.3 don’t adequately represent the data. We need to interpret the results from standardized analysis with caution. Steel and Torrie (1960, chapter 11) provide a clear, intuitive discussion of the role of interactions in factorial models.

As in Section 6, we try to make “apples with apples” comparisons between commercial and survey data wherever possible. Although not designed for this purpose, we can perform a standardized analysis of the survey taking account of two main effects: year and depth. Because we do not have enough data to partition by 100-m intervals, we use the four intervals 500-699 m, 700-899 m, 900-1,199 m, and 1,200-1,600 m, which combine stratification schemes 1 and 2 in Section 6. This analysis (not presented here) suggests that longspine densities are noticeably lower in the shallowest and deepest strata. Figure 7.6 portrays this feature in the distributions of survey CPUE data by year and depth interval. As in the commercial fishery, CPUE increases with depth to 1,200 m, but then shows a marked decline in the 1,200-1,600 m interval. Although the survey shows that longspine thornyheads live at these depths, low biomass densities and the extra cost of deep tows perhaps deter fishermen from harvesting them.

8. Biological Samples

Although designed primarily to index longspine thornyhead biomass, the survey also provides a valuable source of biological data. Tables 4.1-4.2 summarize the numbers of samples and specimens available from both the survey and commercial fishery, as archived in the **GFBio** database. Samples have *categories* that describe the portion of commercial catch examined, where

- “unsorted” refers to a sample from the raw catch before any discarding,
- “kept” refers to a sample from catch retained for sale, and
- “discarded” refers to a sample from catch not retained for sale.

All biological samples from the WCVI survey belong to the “unsorted” category. Samples also have *types* related to the method of selecting individual fish to be sampled, where

- “total” indicates that all fish within the category have been sampled,
- “random” indicates a sample of fish chosen randomly,
- “selected” indicates fish chosen for some explicit purpose,
- “stratified” indicates fish selected to represent a range of factors, usually length intervals, and
- “unknown” refers to an unknown method of fish selection.

Table 8.1 lists coastwide samples available by category and type. Similarly, Tables 8.2-8.4 break down the commercial samples by individual management regions (WCVI, Tidemarks, Rennell). Although dockside sampling programs exist for some species, almost all longspine samples come from the commercial observer program or the WCVI survey. Commercial sample abundance peaked at 885 in 2000 (Table 8.1) when observers began sampling catches in the Tidemarks and Rennell regions as the fishery expanded to the north. By 2002, frequencies decreased to more reasonable levels of 200 samples. A rather staggering collection of 34,370 otoliths (Table 4.2) provides an excellent pool of ageing structures for future research.

Longspine specimens from commercial samples in the **GFBio** database have a maximum length 72 cm. This lies well beyond the maximum size reported elsewhere (36 cm in Jacobson and Vetter 1996; 38 cm in Hart 1973). We believe that alleged longspine thornyheads with large reported lengths are probably shortspines that have been incorrectly identified. Our analyses deal with this potential problem by filtering out all specimens with length greater than 34 cm.

All available specimen weight data come from the WCVI survey. From this source, lengths and weights of 3,700 fish (Table 4.2) allow us to estimate the relationship

(8.1) $$\log_{10} w = -5.579 + 3.282 \ \log_{10} l$$

between length l (mm) and weight w (g), after removing 55 specimens taken from unsuccessful tows and an additional 54 specimens with weights that lie beyond ±3 standard deviations from the line. Figure 8.1 shows a reasonably tight log-linear relationship, where the line (8.1) implies the exponential relationship

(8.2) $$w = 2.636 \times 10^{-6} l^{3.282}.$$

We use this relationship in commercial samples to convert lengths to weights. Incidentally, this section uses mathematical notation that should not be confused with others sections. (For example, w in Section 5 refers to net width.)

To develop annual length distributions from commercial data in the three management regions, we need an algorithm for combining individual samples. Fish lengths are normally measured to the nearest cm. Let j denote the length class ($j = 1, \ldots, 34$), where a fish in class j has length $l_j = 10j$ mm $= j$ cm. The relationship (8.2) implies a corresponding weight w_j for fish of this length. Suppose that tow i produces a total catch weight W_i of longspine thornyheads and that a sample of fish from this catch gives n_{ij} fish in length class j. This gives the estimated proportion

(8.3) $$p_{ij} = \frac{n_{ij}}{\sum_j n_{ij}}$$

of fish from tow i in length class j and the estimated mean fish weight

(8.4) $$\overline{w}_i = \sum_j p_{ij} w_j .$$

Within tow i, the total catch weight W_i and mean fish weight $\overline{w}_i$ imply the estimated number

(8.5) $$N_i = \frac{W_i}{\overline{w}_i}$$

of fish in the tow. Weighting the proportions (8.3) by the numbers (8.5) gives the final estimate

(8.6) $$\hat{p}_j = \frac{\sum_i p_{ij} N_i}{\sum_i N_i}$$

of the proportion of fish in length class j from all tows combined. Within the population of fish caught by sampled tows, the numerator of (8.6) represents the total number of fish with length l_j and the denominator is the total number of fish caught.

In our analyses (8.3)-(8.6) of commercial longspine length distributions, we use only random samples from kept or unsorted catch. The estimated distributions have a degree of irregularity below 25 cm, due partly to the 1-cm length classes selected for analysis (Fig. 8.2). Cumulative plots (Fig 8.3) and bubble plots (Fig. 8.4) provide additional representations of annual differences. Survey length distributions show only minor variations across years (Fig. 8.2A, Fig. 8.3A, 8.4A).

Length distributions from annual commercial samples (Figs. 8.3B-D) appear much more variable than distributions from surveys (Fig. 8.3A). In 1996, a noticeable peak in the WCVI length distribution (Fig. 8.2B) and an absence of fish smaller than 10 cm (Fig. 8.4B) occurs because only the kept portion of the WCVI catch was sampled that year (Table 8.2). Extremely small longspines appear in the 1999 commercial WCVI catch (Figs. 8.2B, 8.4B). Among the commercial regions, a possible decline in mean size occurs in WCVI (Figs. 8.4B-D). Tidemarks samples suggest a smaller average size in 2001 compared to other years (Figs. 8.2C, 8.4C). In contrast, Rennell distributions have similar mean size and range across years (Fig. 8.4D), but proportions of large and small fish are reduced in 2001 (Figs. 8.2D, 8.4D). A comparison of survey and commercial distributions in the WCVI region shows a consistently greater abundance of smaller fish in the survey (Fig. 8.5). The survey uses a fine-mesh codend liner in the net. The current commercial fishery has an effective minimum size limit of 19 cm, imposed by market demands (Schnute and Haigh 2003).

9. Results

To address issues raised by the request for this report (Appendix A), we provide an analysis of the three-year longspine survey in WCVI, along with comparable analyses of commercial fishery data in WCVI and two northern regions (Tidemarks, Rennell). We consider a variety of models, including smooth lines through the raw CPUE data, swept-area biomass estimates, and standardized analyses that account for factors that might influence CPUE. We develop a common mathematical framework that makes it possible to compare these models with one another logically, and our repeated analyses give results that we can compare empirically.

Standardized analysis makes particular assumptions that can be tested by routine methods (e.g., Steel and Torrie 1960) applied directly to the data. When we perform these tests, we find that the data do not conform to the model assumptions. Of course, if a model with testable assumptions proves wrong, this does not imply the validity of another model with assumptions that can’t be tested so easily. For example, swept-area estimates depend on experimental design assumptions that are hopefully addressed by the survey, but certainly not by the commercial fishery. Given a fixed data set, each model tells a story about it from a certain point of view. By listening to all these stories, we can look for common features and differences that illuminate our understanding of the information available.

To compare biomass indices, we scale each of them relative to their mean, which is assigned the standard level 1 (Figs. 9.1, 9.2). The two survey indices show an upward trend from 2001 to 2002, followed by a downward trend in 2003 (Fig. 9.1A). Bootstrapped confidence limits for the primary survey index (based on survey depth strata) show that there is general agreement with the two primary commercial indices for the period 2001-2003. All WCVI commercial indices show a steady decline from 1996 to 2003 (Fig. 9.1B). Although the September swept-area biomass index deviates substantially from the others, it does uniquely show the pattern in the survey data: upward from 2001 to 2002 and downward from 2002 to 2003.

In Tidemarks, all indices show a downward trend from 2000 to 2002 with an upward tick in 2003 (Fig. 9.2A). The 2003 index value is heavily leveraged by one tow that caught 1,661 kg in 5 h (Fig. 6.4). Despite this, the overall time trend is relatively flat compared to the other two regions, and we can say little about the biomass trend in Tidemarks. By contrast, Rennell presents a notably steep downward trend according to all indices, although the estimated rate of decline varies considerably (Fig. 9.2B).

The trend analysis in Section 5.6 gives us a simple tool for comparing results from all analyses in this paper. For each index we have considered, Table 9.1 summarizes the trend statistics $(\hat{b}, \hat{r}, \hat{R}_I)$ derived from I years of data. Rows in this table correspond to curves in Figs. 7.5, 9.1, and 9.2 as follows:

- 2 rows for WCVI (Fig. 9.1A),
- 5 rows for WCVI (Figs. 9.1A and 9.1B),
- 4 rows for Tidemarks (Fig. 9.2A),
- 4 rows for Rennell (Fig. 9.2B),
- 25 rows for Rennell, grouped by depth zones (Fig. 7.5, grouped by rows).

In particular, the estimates (7.1)-(7.3) correspond to standardized CPUE analyses in WCVI, Tidemarks, and Rennell, respectively. Although Table 9.1 shows that the index trend varies considerably with the choice of model and data, some generalizations do emerge from this meta-analysis. In WCVI, commercial estimates of annual declines around 6% per year accumulate to give an overall decline near 40% during the eight-year period 1996-2003. Declines in the Tidemarks region appear to be fairly small. Annual declines in Rennell vary considerably around a central value near 20%, obtained from the mean annual CPUE. At this annual rate, the population would decline by about 50% during the four year period 2000-2003. In brief, the commercial data suggest a reduction to roughly half the initial stock size in WCVI since 1996 and in Rennell since 2000.

Because of the survey's coverage, restricted to the WCVI region in the most recent three years, we have extended our analyses to include commercial data with greater spatial and temporal extent. If we found convergence between commercial and survey data where they coexist, this would lend support to the use of commercial data elsewhere. Given the confidence bounds on the survey index, we cannot at this point say that the survey index differs greatly from the commercial ones. Obviously, more years of survey data are necessary before drawing any firm conclusions about their relationship to commercial data. Commercial indices reflect factors other than the available biomass, and industry representatives have suggested several reasons that might explain recent downward trends in longspine CPUE. These include:

1. Fishermen have experienced a recent increase in sablefish bycatch when fishing for longspines, especially in the north. Without adequate sablefish quota, skippers must seek out fishing opportunities where tows are less productive for sablefish.

2. In the early years of the fishery, observers did not always sample to determine the species split between shortspine and longspine thornyheads, relying instead on information from the factory. More recent samples attempt to identify the complete species composition of each tow. This change in behaviour has possibly introduced a bias across years.

3. Fuel costs have increased substantially. The fishery on longspines ranks high in fuel consumption among all the groundfish fisheries, with tow durations in the range 4-12 h. Higher fuel costs and lower profit margins tend to discourage directed or exploratory fishing on the resource.

4. The price of thornyheads has declined substantially in the last year, partly due to an increase in the Canadian dollar relative to the US dollar and Japanese yen. Again, a reduced profit margin tends to discourage directed fishing.

The Rennell analysis illustrates the fact that different models sometimes produce different answers. The swept-area estimates give highest weight to the deepest depth zone. This happens to be the depth zone with the least decline in CPUE. By contrast, the standardized model assumes that the CPUE trend does not vary with depth, and it gives highest weight to factor levels with the most data, which correspond here to shallower depth zones with the greatest number of tows. Both analyses have problems. The standardized model assumes a consistent pattern among depth zones not evidenced by the data. On the other hand, the swept-area model assumes that the mean density measured by the commercial fleet applies to the area defined by the bathymetry. In fact, the deepest depth stratum with the smallest decline in CPUE also has the fewest observations, the least amount of fishing effort, and the lowest spatial coverage (Fig. 9.3). The full distribution of longspine thornyheads can be determined only with a survey of the Rennell region. Even if the severity of any real decline is not well specified at present, we flag the index declines in Rennell as a matter for concern.

A survey in Rennell could benefit from further probing of the commercial data before it commences. For example, Fig. 9.3 represents longspine thornyhead CPUE in this region using a fine-scale grid. Because longspine tows have lengths that typically exceed 10 km, a 2 km×2 km grid cell will greatly underestimate the effort spatially. To rectify this, we have taken the vector connecting a tow's start and end positions and assigned the tow's CPUE to points every 2 km along the tow vector. In effect, we are assuming that the density remains the same along the length of the tow. This assumption finds support in the relatively uniform distribution characteristics of this species. Effectively, the algorithm treats each long tow as if it were a series of short tows, and Fig. 9.3 summarizes the mean CPUE on a fine-scale grid.

Aside from obvious errors in geo-referencing (errant strands of gridded CPUE) outside the main fishing region, this exercise shows at least two features of the Rennell fishery. First, there appear to be two target populations, probably separated by a region of steep bathymetry. The highest CPUE levels shift from the northern group in 2000 to the southern group in 2001. In 2002–2003, both populations show signs of declining density from the initial years. Secondly, fishing remains largely confined to relatively shallow depths in the range 500–800 m. If the

Rennell and WCVI ecosystems are comparable, we would expect greatest longspine thornyhead density between 800 and 1200 m. If so, Rennell fishermen have not accessed large portions of this optimal habitat. Instead, they may have targeted shallower species like shortspine thornyhead, or avoided regions with high sablefish density. Whatever the case, a survey would yield information not currently available from commercial data.

10. Summary and Recommendations

The WCVI survey has produced high-precision relative biomass estimates for the longspine thornyhead population. The three surveys in years 2001-2003 achieved coefficients of variation 8.6%, 10.3%, and 10.9%, respectively (Table 6.2). A photo of the 2003 crew and research staff (Fig. 3.2) reminds us of the human effort behind this successful collaboration between DFO and the Canadian Groundfish Research and Conservation Society (CGRCS). The survey shows a small biomass increase from 2001 to 2002, followed by a small decrease in 2003 (Fig. 6.7E). Measurement error makes it impossible to detect any definite upward or downward trend, but the three-year survey does indicate that the annual biomass growth rate is restricted to the interval $(-0.11, 0.13)$ with 95% confidence. In other words, any decline is probably less than 11% per year, and any growth is probably less than 13% per year.

Tows conducted in an exploratory stratum deeper than 1,200 m consistently indicate the presence of longspine thornyheads, although at relatively low densities. Currently, this depth zone acts as a *de facto* refugium because commercial vessels rarely conduct such deep tows. In depths between 500 m and 1,200 m, the spatial distribution of the survey approximately matches that of the WCVI commercial fishery (Fig. 3.4). The survey uses short tows of duration about 1 h, compared with commercial tows in the range 4-12 h, and the survey removes only about 1% of the biomass caught commercially. From this point of view, the survey has a relatively minor impact on the longspine thornyhead population.

We have detailed commercial data on the longspine fishery since 1996, and the coastwide fishery extends to regions north of WCVI. In this sense, the survey offers very limited coverage of the fishery in space and time. To achieve a broader perspective, we are forced to examine commercial fishery data, while recognizing all the usual limitations imposed by factors that influence fishing behaviour. In all three management regions (WCVI, Tidemarks, Rennell), we find declining CPUE since the inception of the fishery. However, the proportion of each regional decline directly attributable to biomass depletion remains unknown. The largest CPUE decline occurs in Rennell, although the estimated magnitude depends on the analysis. We investigate several model frameworks to explore relationships between model assumptions and conclusions. Often our conclusions are robust to the model choice, and we obtain similar index trends regardless of the assumptions. In other cases, the choice can make a big difference. When dealing with commercial data, we try to achieve consistency through data qualification, in which selection criteria determine tows for the analysis.

Biological data from the survey give us a useful relationship between longspine thornyhead lengths and weights (Fig. 8.1), which we use to combine sample information from various tows. The three annual surveys give highly consistent length distributions (Fig. 8.3A), and variable commercial length distributions (Figs. 8.3B-D) stem partly from samples that may or may not include discarded fish (unsorted category). Due to net design, the survey captures larger proportions of small fish than the commercial fishery (Fig. 8.4). At present, the biological data offer very little to detect changes in population structure. However, a huge collection of 34,370 otolith pairs presents a golden opportunity for investigating age structure, provided that ageing methods can be perfected and replicated by staff members dedicated to this task.

In an ideal world, we would base all groundfish stock assessments on reliable survey data that provide a credible biomass index. The longspine thornyhead example, however, illustrates that even a good three-year survey in a major region leaves us far from that goal. We have no fishery independent method of validating apparent biomass declines since the start of the fishery in all three regions. In retrospect, we might have preferred three WCVI surveys that cover a longer time period, such as surveys in 1996, 1999, and 2003. But this comment ignores an important fact about the actual survey: it served as a training exercise to verify that we can actually do it and obtain consistent, reasonable results.

We have limited knowledge of longspine thornyhead age structure, and our ability to maintain a viable stock while removing a sustainable catch depends critically on monitoring the stock status. The 2001-2003 survey demonstrates at least some ability to achieve this goal by conducting surveys. But they need consistent application and coastwide coverage. For example, one might consider a rotational system in which WCVI, Tidemarks, and Rennell are covered every third year.

Surveys cost money, probably enough to bankrupt the fishery if we tried to achieve the “ideal world” mentioned above. Blended analyses of survey and commercial data, like those presented here, will doubtless continue to play a role in groundfish stock assessments. But this still leaves key questions to answer. How many surveys do we require? Where and when should they take place? In approaching such questions, managers and industry need to consider a cost-benefit analysis. For example, does the revenue from the Rennell longspine fishery justify a cost similar to that of the WCVI survey? How would market conditions influence this decision? Should industry conduct a Rennell survey in 2004, even if market conditions don’t justify the cost of fishing in Rennell, to create a baseline reference level for fishing in the future when market conditions improve? All these questions lie beyond the scope of this paper and require economic data not available here. Furthermore, questions about longspine surveys need integration with questions about groundfish surveys generally. For example, do economic conditions justify a survey of some other species in some other area, rather than longspine thornyheads in Rennell, even if the Rennell fishery needed to be closed due to the absence of monitoring information?

From a science perspective, we only highlight these questions and confine our recommendations to questions raised in the request for this report (Appendix A):

1. Based on the success of the WCVI survey, we recommend continued survey monitoring of the longspine thornyhead fishery. This requires a regular pattern covering the WCVI, Tidemarks, and Rennell regions. For the present, we suggest a three-year cycle, with a 2004 survey in Rennell, a 2005 survey in Tidemarks, and the next WCVI survey in 2006.

2. To reduce survey costs, it may be possible to blend the use of commercial and survey data. For example, in the small Tidemarks fishery, it might be adequate to conduct specialized commercial tows that conform to rigorous standards. We recommend that managers and industry discuss such alternatives in planning future monitoring programs.
3. Because surveys are becoming a central component of the management of numerous other groundfish species, we recommend setting priorities for deep-water longspine thornyhead surveys in the context of other planned groundfish surveys.
4. Because long-term downward CPUE trends in the commercial fishery suggest that current longspine thornyhead removals may not be sustainable, we recommend that management and industry discuss plans for scaling back the fishery in future years.
5. We recommend that research on ageing longspine thornyheads be completed, communicated to experienced readers, and used to begin production ageing of the existing otolith archive.

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Appendix A. Request for Working Paper

<u>Source:</u> This request comes from the Groundfish Management Unit.

<u>Rationale:</u>

Based on PSARC recommendations in 2000, the Canadian Groundfish Research and Conservation Society (CGRCS) initiated a fishery-independent biomass trawl survey off the west coast of Vancouver Island (WCVI) for longspine thornyheads (*Sebastolobus altivelis*), beginning in 2001. The survey, to be conducted annually for a three year period, was initiated in response to concerns that the fishery-dependent biomass indices were unreliable due to a lack of information on growth rates and productivity.

In response to a PSARC recommendation in 2001, an experimental trawl fishing plan was designed and agreed to by DFO Science and Fisheries Management, in consultation with industry. This plan, implemented for the 2002/2003 and 2003/2004 seasons, set a TAC of 230 t (reduced from 425 t) for the northern fishery, and divided it by three areas (Rennell, Tidemarks, Triangle) to keep estimated harvest rates to the same as or less than estimates for the fishery off WCVI. Additionally, a refuge area (Flamingo) was set aside where no directed fishing would occur.

Given that the thornyhead survey has now been conducted for three years, a working paper that reviews the survey is requested to determine its utility for future management and to assist in the evaluation of the current management plan.

<u>Objectives of Working Paper:</u>

This document will:

1. Review the three years of survey information on thornyheads to determine whether it met the program objective of estimating biomass.
2. Suggest additional or modified approaches to improve survey design.

Question(s) to be addressed in the Working Paper:

A. Does the data collected to date by the survey indicate a potential utility for estimating biomass?

B. Can coastwide estimates of abundance be inferred from the current survey design?

C. Are modifications required to improve survey design and provide information to support the current management plan?

Stakeholders Affected: Primarily commercial trawl licence holders.

How Advice May Impact the Development of a Fishing Plan: The advice is will assist in the review of the current thornyhead trawl experimental fishing plan.

Timing Issues Related to When Advice is Necessary: The advice is required for development of the 2004/2005 experimental trawl fishing plan for thornyheads.

Appendix B. Standardized Models in R/S-Plus

R and S-Plus implement the model (5.7)-(5.9) with the command `lm` that creates a list object of class "lm". This command supports a variety of constraints, like (5.8), on the factor coefficients. The estimated quantities are called "contrasts". To implement (5.8), we use the "sum" contrast. For a factor with n levels and coefficients a_i $(i = 1, \ldots n)$, this treats the first $n-1$ coefficients as unknowns, and computes the final coefficient as

(B.1) $$a_n = -\sum_{i=1}^{n-1} a_i$$

From (B.1), it follows that

(B.2) $$\mathrm{V}[a_n] = \sum_{i=1}^{n-1}\sum_{j=1}^{n-1} \mathrm{Cov}[a_i, a_j] = \sum_{i=1}^{n-1}\sum_{j=1}^{n-1} \sqrt{\mathrm{V}[a_i]\mathrm{V}[a_j]}\,\mathrm{Cor}[a_i, a_j],$$

where V[], Cov[], and Cor[] denote the variance, covariance, and correlation, respectively, and the square root of the variance corresponds to the standard deviation.

From the output object produced by `lm`, a user can extract parameter coefficients, their standard deviations, and correlation matrix. The following simple code also uses (B.1)-(B.2) to estimate the final coefficient and its standard error to create a complete coefficient vector `fcoef` and a corresponding standard error vector `fserr`. The code assumes an initial data frame, called `datafile`, with response variable "lnU" and factors "year", "month", "dzone", and "cfv". The code produces a coefficient vector for "year" only.

```
# Set the contrast option to “sum”
# --------------------------------
csum   <- c("contr.sum", "contr.sum")
names(csum) <- c("factor", "ordered")
options(contrasts = csum)

# Run the linear model to estimate log CPUE
# -----------------------------------------
lmres  <- lm(lnU ~ year + month + dzone + cfv, data=datafile)

# Get parameter coefficients, their standard errors, and correlation matrix
# -------------------------------------------------------------------------
coeffs <- lmres$coefficients
stderr <- summary(lmres)$coeff[,"Std. Error"]
correl <- summary(lmres)$correlation

# Extract coefficients and calculate missing last coefficient
# -----------------------------------------------------------
fact   <- “year”
z      <- is.element(substring(names(coeffs),1,nchar(fact)),fact)
fcoef  <- coeffs[z]
fcont  <- lmres$contrasts[[fact]]
fcoef  <- fcont %*% fcoef
fcoef  <- as.vector(fcoef)

# Extract standard errors and calculate missing last standard error
# -----------------------------------------------------------------
fserr  <- stderr[z]
fcorr  <- correl[z,z]
errZ   <- sqrt(fserr %*% fcorr %*% fserr)
fserr  <- c(fserr,errZ)
```

Table 2.1. Historical quota and catch for the longspine thornyhead fishery. South (S) refers to the traditional fishery – 2000-2001: south of a line 230° True from Lookout Island (49° 59′ 52.2″ N, 127° 26′ 57.3″ W); 2002-2003: south of latitude 50° 30′ N. North (N) refers to fisheries north of the traditional fishery – 2000-2001: exploratory fishery (Table 2.2); 2002-2003: experimental fishery (Table 2.3). Additionally, catch comes from areas unknown (Unk) due to dockside landings with no matching observer records. Unless otherwise noted, fishing years run from April 1 to March 31. Values of 0 indicate catch less than 0.5 t.

Fishing	Quota (t)			Catch (t)			
Year	S	N	Total	S	N	Unk	Total
1996[1]			800				877
97[2]							293
1997			860				577
1998			861				840
1999			855				913
2000	404	425	829	389	516	5	909
2001	405	425	830	351	299	0	650
2002	405	230	635	466	191	13	670
2003[3]	405	230	635	207	145	22	374

[1] Fishing year: Feb 15, 1996 – Dec 31, 2003
[2] Interim period: Jan 1, 1997 – Mar 31, 1997
[3] Catches only for Apr 1-Oct 15, 2003

Table 2.2. Longspine thornyhead catch (t) in traditional and exploratory areas during management years 2000-2001. The boundary between the traditional WCVI fishery and the exploratory fishery is described in Table 2.1 and Figure 1.1. The region referred to as 3D is one of the Pacific Marine Fisheries Commission (PMFC) areas (Tagart 1991).

Fishing Year	S of 230° True	N of 230° in 3D	N of 3D
2000	389	286	230
2001	351	105	194

Table 2.3. Longspine thornyhead catch (t) in traditional and experimental areas during management years 2002-2003. The boundaries delimiting these areas are illustrated in Figure 1.1 and correspond to lines of latitude – WCVI (48° 05′ N to 50° 30′ N); Triangle (50° 30′ N to 51° 00′ N); Tidemarks (51° 00′ N to 51° 56′ N); Flamingo (51° 56′ N to 53° 05′ N); Rennell (53° 05′ N to 54° 40′ N). Values of 0 indicate catch < 0.5 t.

Fishing Year	WCVI	Triangle	Tidemarks	Flamingo	Rennell
2002	466	0	75	0	116
2003*	207	0	75	0	70

*Catches only for Apr 1-Oct 15, 2003

Table 2.4. Longspine thornyhead catch (t) in the current management regions (for this species) applied across all years since 1996. The boundaries delimiting these areas are illustrated in Figure 1.1 and correspond to lines of latitude outlined in Table 2.3. Unless otherwise noted, fishing years run from April 1 to March 31. Values of 0 indicate catch < 0.5 t.

Fishing Year	WCVI South	WCVI North	Triangle	Tide-marks	Flamingo	Rennell	Unknown	Total
1996[1]	862	1	0	3	0	1	10	877
97[2]	291	0	0	0	0	1		293
1997	564	1	0	8	0	2	1	577
1998	823	0	0	6	0	9	1	840
1999	732	160		1	0	19	1	913
2000	389	286		85	0	144	5	909
2001	351	105	0	49	1	144	0	650
2002	428	38		75	0	116	13	670
2003[3]	167	40		75		70	22	374

[1] Fishing year: Feb 15, 1996 – Dec 31, 2003
[2] Interim period: Jan 1, 1997 – Mar 31, 1997
[3] Catches only for Apr 1-Oct 15, 2003

Table 4.1. Summary of commercial and survey tows by thornyhead management area plus their associated sample and specimen frequencies. Minimally qualified commercial tows include successful bottom tows deeper than 500 m with under 24 h effort and reported catch > 0 kg. These tows are reported as observer logs. Fully qualified commercial tows were completed by the 14 vessels. Minimally qualified survey tows include those tows that were attempted, including aborted or rejected tows. Fully qualified survey tows are successfully completed to survey protocol standards and are accepted for biomass estimation. The numbers of survey samples and specimens are obtained from fully qualified tows.

		WCVI	Tidemarks	Rennell	Total
Commercial	Tows (Min Qual)	14,044	819	1,891	16,754
	Tows (Full Qual)	7,891	733	1,269	9,893
	Samples	1,362	176	365	1,904
	Specimens	137,711	10,254	27,880	175,856
Survey	Tows (Min Qual)	211	0	0	211
	Tows (Full Qual)	192	0	0	192
	Samples	189	0	0	189
	Specimens	19,020	0	0	19,020

Table 4.2. Biological sampling summary from the 2001-2003 longspine thornyhead biomass surveys plus commercial tows off the BC coast from 1996-2003. Commercial samples extend to September 29, 2003 due to delayed entry of commercial samples collected since that date. Numbers of samples are provided annually by longspine thornyhead management zone. Samples include 5 survey and 170 commercial sets deemed unsuccessful for modeling consideration due to set qualification criteria. Other categories refer to numbers of specimens having recorded measurements or structures collected.

		Survey	Commercial					Combined
	Year	**WCVI**	**WCVI**	**Tidemarks**	**Flamingo**	**Rennell**	**All Areas**	**All Areas**
Samples	1996		8				8	8
	1997		8				8	8
	1998		120				120	120
	1999		229			4	233	233
	2000		532	130	1	222	885	885
	2001	62	265	19		46	330	392
	2002	62	130	15		55	200	262
	2003	65	70	12		38	120	185
Lengths	1996		653				653	653
	1997		1,051				1,051	1,051
	1998		20,423				20,423	20,423
	1999		34,225			364	34,589	34,589
	2000		23,180	2,943	11	6,134	32,268	32,268
	2001	6,884	25,735	2,582		7,109	35,426	42,310
	2002	6,952	21,462	2,294		8,877	32,633	39,585
	2003	5,184	10,982	2,435		5,396	18,813	23,997
Weights	1996		0				0	0
	1997		0				0	0
	1998		0				0	0
	1999		0			0	0	0
	2000		0	0	0	0	0	0
	2001	1,094	0	0		0	0	1,094
	2002	1,333	0	0		0	0	1,333
	2003	1,273	0	0		0	0	1,273
Sexed	1996		653				653	653
	1997		274				274	274
	1998		1,008				1,008	1,008
	1999		1,146			0	1,146	1,146
	2000		10,425	2,739	11	3,532	16,707	16,707
	2001	6,072	6,153	403		773	7,329	13,401
	2002	6,955	2,159	398		829	3,386	10,341
	2003	5,178	1,089	0		484	1,573	6,751
Maturities	1996		200				200	200
	1997		0				0	0
	1998		0				0	0
	1999		0			0	0	0
	2000		0	0	0	0	0	0
	2001	5,534	0	0		0	0	5,534
	2002	5,734	0	0		0	0	5,734
	2003	4,006	0	0		0	0	4,006
Otoliths	1996		100				100	100
	1997		220				220	220
	1998		919				919	919
	1999		1,242			0	1,242	1,242
	2000		9,655	2,688	0	3,420	15,763	15,763
	2001	1,094	6,257	403		773	7,433	8,527
	2002	1,333	2,170	397		853	3,420	4,753
	2003	1,273	1,089	0		484	1,573	2,846
Total Samples		**189**	**1,362**	**176**	**1**	**365**	**1,904**	**2,093**
Total Lengths		**19,020**	**137,711**	**10,254**	**11**	**27,880**	**175,856**	**194,876**
Total Weights		**3,700**	**0**	**0**	**0**	**0**	**0**	**3,700**
Total Sexed		**18,205**	**22,907**	**3,540**	**11**	**5,618**	**32,076**	**50,281**
Total Maturities		**15,274**	**200**	**0**	**0**	**0**	**200**	**15,474**
Total Otoliths		**3,700**	**21,652**	**3,488**	**0**	**5,530**	**30,670**	**34,370**

Table 6.1. Bottom area (km^2) used for the calculation of depth-stratified, swept-area biomass estimates. Stratification scheme 1 refers to a commercial fishery depth stratification scheme while scheme 2 refers to the longspine thornyhead survey depth stratification scheme. Bathymetry contours are derived from interpolation of Canadian Hydrographic Service data using ArcView software (ESRI 1996). Bottom areas are calculated using PBS Mapping software (Schnute et al. 2003).

Stratification Scheme	Areal Zone	Areal Name	Depth Zone	Depth Interval	Bottom Area (km^2)
1	1	WCVI (48°05'-50°30'N)	1	500-700m	1,416
1	1	WCVI (48°05'-50°30'N)	2	700-900m	1,236
1	1	WCVI (48°05'-50°30'N)	3	900-1200m	2,265
1	2	Tidemarks (51°00'-51°56'N)	1	500-700m	667
1	2	Tidemarks (51°00'-51°56'N)	2	700-900m	588
1	2	Tidemarks (51°00'-51°56'N)	3	900-1200m	717
1	3	Rennell (53°05'-54°40'N)	1	500-700m	802
1	3	Rennell (53°05'-54°40'N)	2	700-900m	550
1	3	Rennell (53°05'-54°40'N)	3	900-1200m	1,181
2	1	WCVI (48°05'-50°30'N)	1	500-800m	2,044
2	1	WCVI (48°05'-50°30'N)	2	800-1200m	2,873
2	1	WCVI (48°05'-50°30'N)	3	1200-1600m	3,270
2	2	Tidemarks (51°00'-51°56'N)	1	500-800m	968
2	2	Tidemarks (51°00'-51°56'N)	2	800-1200m	1,004
2	2	Tidemarks (51°00'-51°56'N)	3	1200-1600m	937
2	3	Rennell (53°05'-54°40'N)	1	500-800m	1,127
2	3	Rennell (53°05'-54°40'N)	2	800-1200m	1,406
2	3	Rennell (53°05'-54°40'N)	3	1200-1600m	586

Table 6.2. Stratified, swept-area biomass estimates (t) and their CVs (%). S-Strat = survey depth stratification scheme (500-800m, 800-1200m, 1200-1600m); C-Strat = commercial depth stratification scheme (500-700m, 700-900m, 900-1200m).

Biomass (tonnes)	Year	Survey		Commercial	
		S-Strat	C-Strat	May-Oct	Sep
WCVI	1996			1,393	1,741
	1997			1,118	1,171
	1998			1,270	1,341
	1999			1,124	1,069
	2000			1,186	1,086
	2001	1,698	1,312	1,030	651
	2002	1,814	1,610	931	1,362
	2003	1,656	1,385	874	872
Tidemarks	2000			452	
	2001			408	
	2002			380	
	2003			489	
Rennell	2000			528	
	2001			456	
	2002			351	
	2003			342	

CV (%)	Year	Survey		Commercial	
		S-Strat	C-Strat	May-Oct	Sep
WCVI	1996			4.6	14.0
	1997			4.5	4.6
	1998			2.0	6.5
	1999			1.7	4.4
	2000			2.7	3.3
	2001	8.6	8.3	4.0	14.0
	2002	10.3	11.3	2.7	11.1
	2003	10.9	14.0	3.1	11.7
Tidemarks	2000			5.9	
	2001			9.3	
	2002			9.7	
	2003			12.3	
Rennell	2000			3.0	
	2001			3.7	
	2002			5.1	
	2003			8.3	

Table 8.1. Distribution of biological samples coastwide by category, type and year from the longspine thornyhead biomass surveys and the commercial fishery. ‘Kept’ or ‘Discarded’ sample categories apply to commercial samples where specimens are measured respectively from the harvested or discarded portion of the catch. Unsorted samples come from the entire catch. Sample type refers to the method of selecting specimens from the catch for the purpose of biological sampling. Samples include 5 survey and 170 commercial sets deemed unsuccessful for modeling consideration since they failed to meet qualification criteria.

Sample origin	Sample category	Sample type	Year 1996	1997	1998	1999	2000	2001	2002	2003	All Years
Survey	Unsorted	random						37	40	47	124
		total						25	22	18	65
	Total (survey)							**62**	**62**	**65**	**189**
Commercial	Unsorted	random		7	27	104	799	329	200	120	1,586
		selected						1			1
		total				1	4				5
		unknown			2						2
	Kept	random	8	1	75	57	40				181
		stratified				1					1
	Discarded	random			16	70	42				128
	Total (commercial)		**8**	**8**	**120**	**233**	**885**	**330**	**200**	**120**	**1,904**
Combined Total			**8**	**8**	**120**	**233**	**885**	**392**	**262**	**185**	**2,093**

Table 8.2. Commercial sample breakdown for WVCI region. See Table 8.1 for explanations of sample categories and sample types.

Sample Origin	Sample category	Sample type	Year 1996	1997	1998	1999	2000	2001	2002	2003	All Years
Commercial	Unsorted	random		7	27	104	474	265	130	70	1,077
		total				1	2				3
		unknown			2						2
	Kept	random	8	1	75	57	21				162
		stratified				1					1
	Discarded	random			16	66	35				117
Total			**8**	**8**	**120**	**229**	**532**	**265**	**130**	**70**	**1,362**

Table 8.3. Commercial sample breakdown for Tidemarks region. See Table 8.1 for explanations of sample categories and sample types.

Sample Origin	Sample category	Sample type	Year 1996	1997	1998	1999	2000	2001	2002	2003	All Years
Commercial	Unsorted	random					111	19	15	12	157
	Kept	random					17				17
	Discarded	random					2				2
Total							**130**	**19**	**15**	**12**	**176**

Table 8.4. Commercial sample breakdown for Rennell region. See Table 8.1 for explanations of sample categories and sample types.

Sample Origin	Sample category	Sample type	Year 1996	1997	1998	1999	2000	2001	2002	2003	All Years
Commercial	Unsorted	random					213	45	55	38	351
		selected						1			1
		total					2				2
	Kept	random					2				2
	Discarded	random				4	5				9
Total						**4**	**222**	**46**	**55**	**38**	**365**

Table 9.1. Summary of index slopes b (linear fit through $\log_2$-transformed index) and annual rates of change $r = 2^b - 1$. Type: S = Survey, C = Commercial. I = Number of years in the index. Overall change in the index over I years is calculated $R_I = 2^{b(I-1)} - 1$.

Region	Type	Index	*I*	*b*	*r*	R_I
WCVI	S	Swept-area biomass using survey depth strata	3	-0.018	-1.3%	-2.5%
WCVI	S	Swept-area biomass using commercial depth strata	3	0.039	2.8%	5.6%
WCVI	C	Mean annual CPUE (May-Oct)	8	-0.128	-8.5%	-46.4%
WCVI	C	Standardized CPUE (GLM, May-Oct)	8	-0.097	-6.5%	-37.5%
WCVI	C	Swept-area biomass (May-Oct)	8	-0.082	-5.5%	-32.7%
WCVI	C	Swept-area biomass (May-Oct), standardized vessel	8	-0.098	-6.6%	-37.8%
WCVI	C	Swept-area biomass (Sep)	8	-0.107	-7.2%	-40.5%
TM	C	Mean annual CPUE (May-Oct)	4	-0.002	-0.1%	-0.4%
TM	C	Standardized CPUE (GLM, May-Oct)	4	-0.043	-3.0%	-8.6%
TM	C	Swept-area biomass (May-Oct)	4	0.024	1.7%	5.1%
TM	C	Swept-area biomass (May-Oct), standardized vessel	4	-0.011	-0.8%	-2.3%
REN	C	Mean annual CPUE (May-Oct)	4	-0.325	-20.2%	-49.1%
REN	C	Standardized CPUE (GLM, May-Oct)	4	-0.391	-23.7%	-55.6%
REN	C	Swept-area biomass (May-Oct)	4	-0.226	-14.5%	-37.4%
REN	C	Swept-area biomass (May-Oct) with standardized vessel	4	-0.213	-13.7%	-35.8%
REN	C	Mean annual CPUE (May, 500-600m)	4	-	-	-
REN	C	Mean annual CPUE (Jun, 500-600m)	4	0.118	8.5%	27.7%
REN	C	Mean annual CPUE (Jul, 500-600m)	4	-0.510	-29.8%	-65.4%
REN	C	Mean annual CPUE (Aug, 500-600m)	4	-1.034	-51.2%	-88.3%
REN	C	Mean annual CPUE (Sep, 500-600m)	4	-0.061	-4.2%	-12.0%
REN	C	Mean annual CPUE (May, 600-700m)	4	-0.071	-4.8%	-13.8%
REN	C	Mean annual CPUE (Jun, 600-700m)	4	-0.318	-19.8%	-48.3%
REN	C	Mean annual CPUE (Jul, 600-700m)	4	-0.502	-29.4%	-64.8%
REN	C	Mean annual CPUE (Aug, 600-700m)	4	-0.538	-31.1%	-67.3%
REN	C	Mean annual CPUE (Sep, 600-700m)	4	-0.048	-3.3%	-9.6%
REN	C	Mean annual CPUE (May, 700-800m)	4	-0.204	-13.2%	-34.5%
REN	C	Mean annual CPUE (Jun, 700-800m)	4	-0.222	-14.2%	-36.9%
REN	C	Mean annual CPUE (Jul, 700-800m)	4	-0.296	-18.5%	-45.9%
REN	C	Mean annual CPUE (Aug, 700-800m)	4	-0.263	-16.6%	-42.1%
REN	C	Mean annual CPUE (Sep, 700-800m)	4	-0.054	-3.7%	-10.7%
REN	C	Mean annual CPUE (May, 800-900m)	4	-0.245	-15.6%	-40.0%
REN	C	Mean annual CPUE (Jun, 800-900m)	4	-0.293	-18.4%	-45.6%
REN	C	Mean annual CPUE (Jul, 800-900m)	4	-0.341	-21.1%	-50.8%
REN	C	Mean annual CPUE (Aug, 800-900m)	4	-0.464	-27.5%	-61.9%
REN	C	Mean annual CPUE (Sep, 800-900m)	4	-0.525	-30.5%	-66.4%
REN	C	Mean annual CPUE (May, 900-1000m)	4	-0.054	-3.7%	-10.6%
REN	C	Mean annual CPUE (Jun, 900-1000m)	4	0.420	33.8%	139.6%
REN	C	Mean annual CPUE (Jul, 900-1000m)	4	-0.131	-8.7%	-23.8%
REN	C	Mean annual CPUE (Aug, 900-1000m)	4	-0.309	-19.3%	-47.4%
REN	C	Mean annual CPUE (Sep, 900-1000m)	4	-0.520	-30.3%	-66.1%

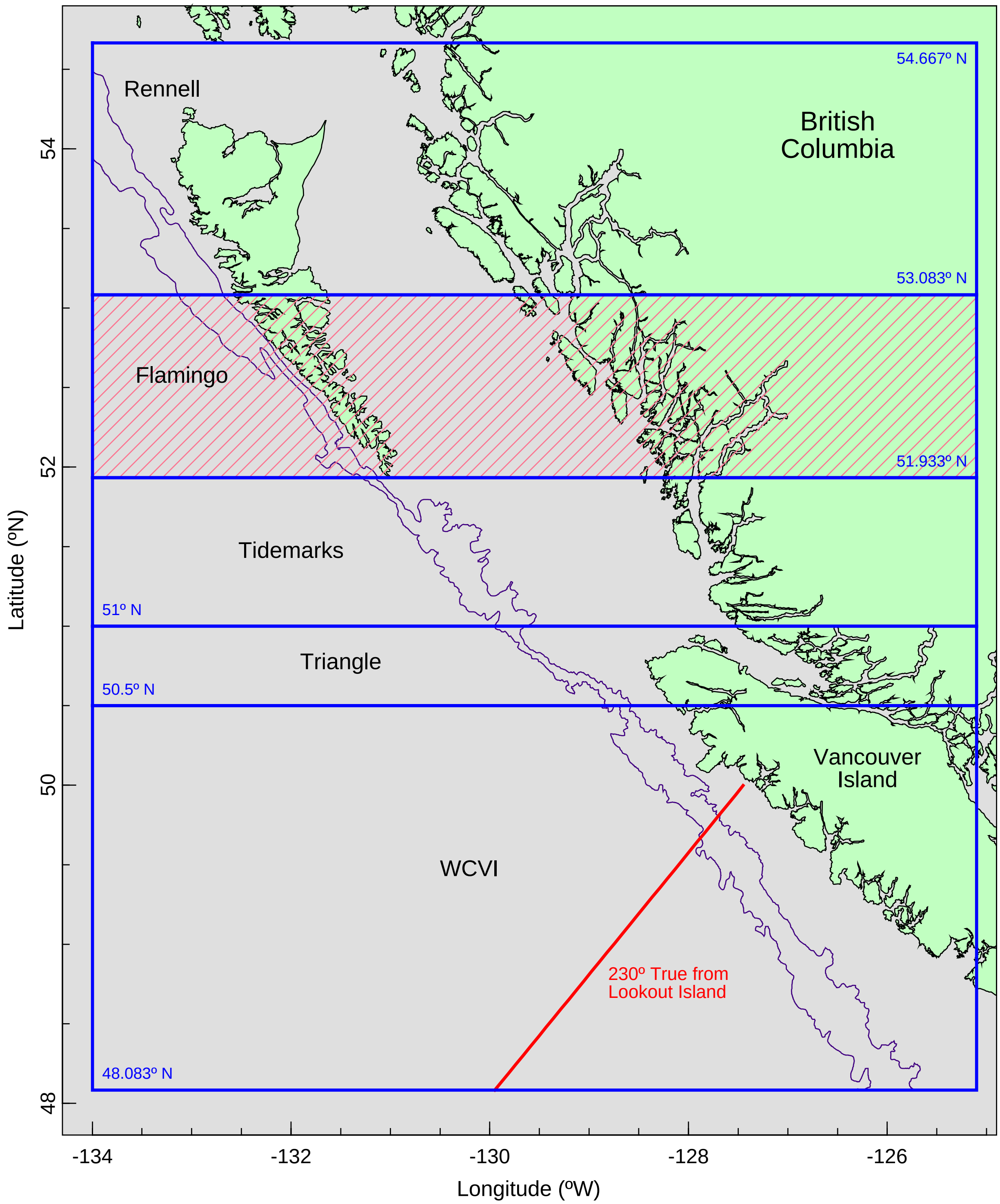

Figure 1.1. Management regions for the longspine thornyhead fishery: 1996-1999 – no boundaries, coastwide quota ≥ 800 t; 2000-2001 – boundary at 230°true from Lookout Island, quota south of line = 405 t, quota north of line = 425 t; 2002-2003 – boundaries fixed at various latitudes, quota south of 50.5°N = 405 t, quota north of 50.5°N = 230 t, Flamingo region closed to fishing.

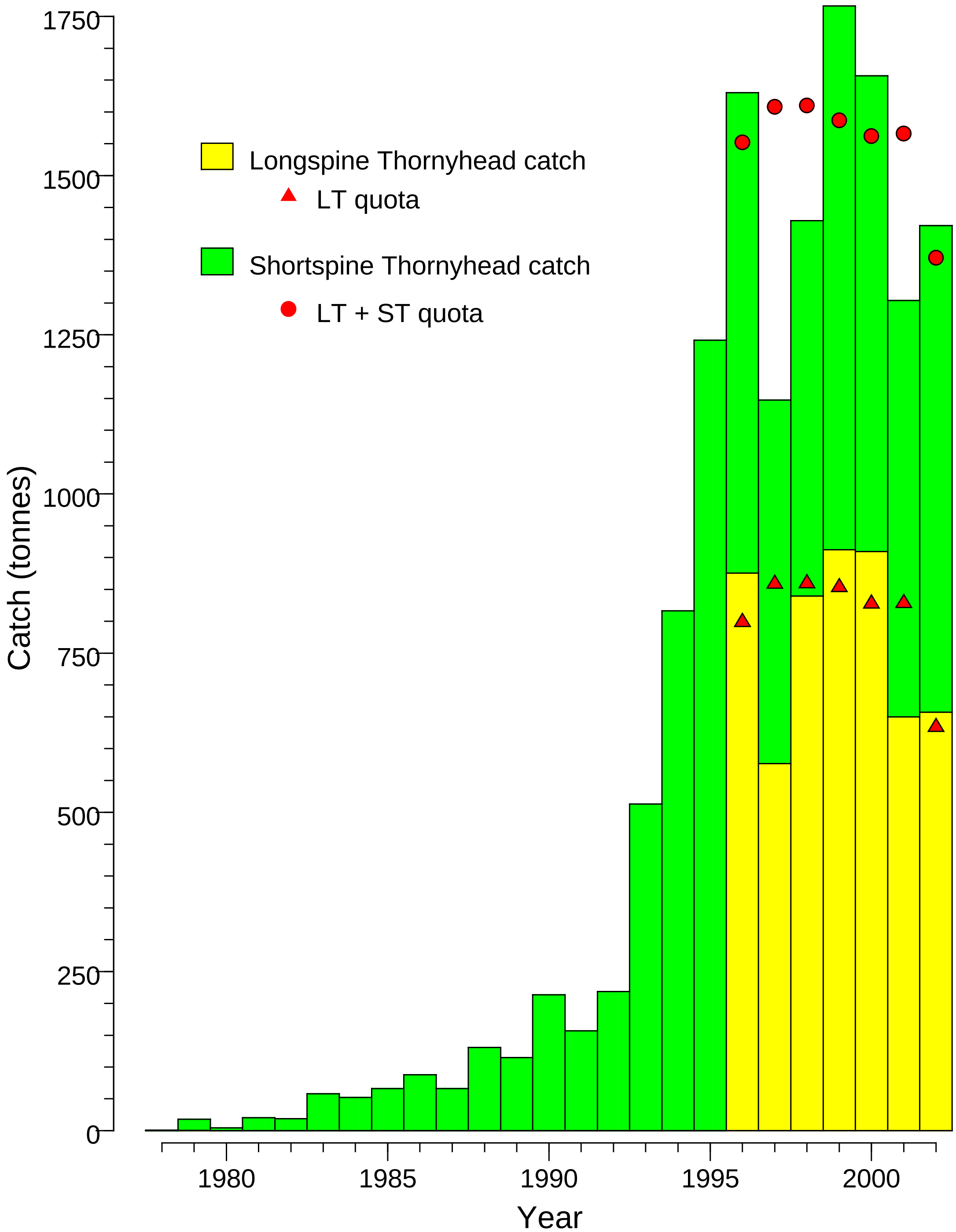

Figure 2.1. History of thornyhead landings on the BC coast. From 1978 to 1995, thornyheads were recorded as an aggregate. In 1996, longspine thornyheads (LT) were distinguished from shortspine thornyheads (ST) and each given a separate quota. Landed values prior to 1996 come from fishermen's logs and sales slips (Leaman and Hamer 1985; Rutherford 1999). Landings from 1996 to 2002 come from the dockside monitoring program. Quotas for thornyheads appear in Canadian Department of Fisheries and Oceans assessment reports (Richards and Olsen 1996; Richards et al. 1997; Schnute et al. 1999a, 1999b). Catches and quotas are reported in tonnes.

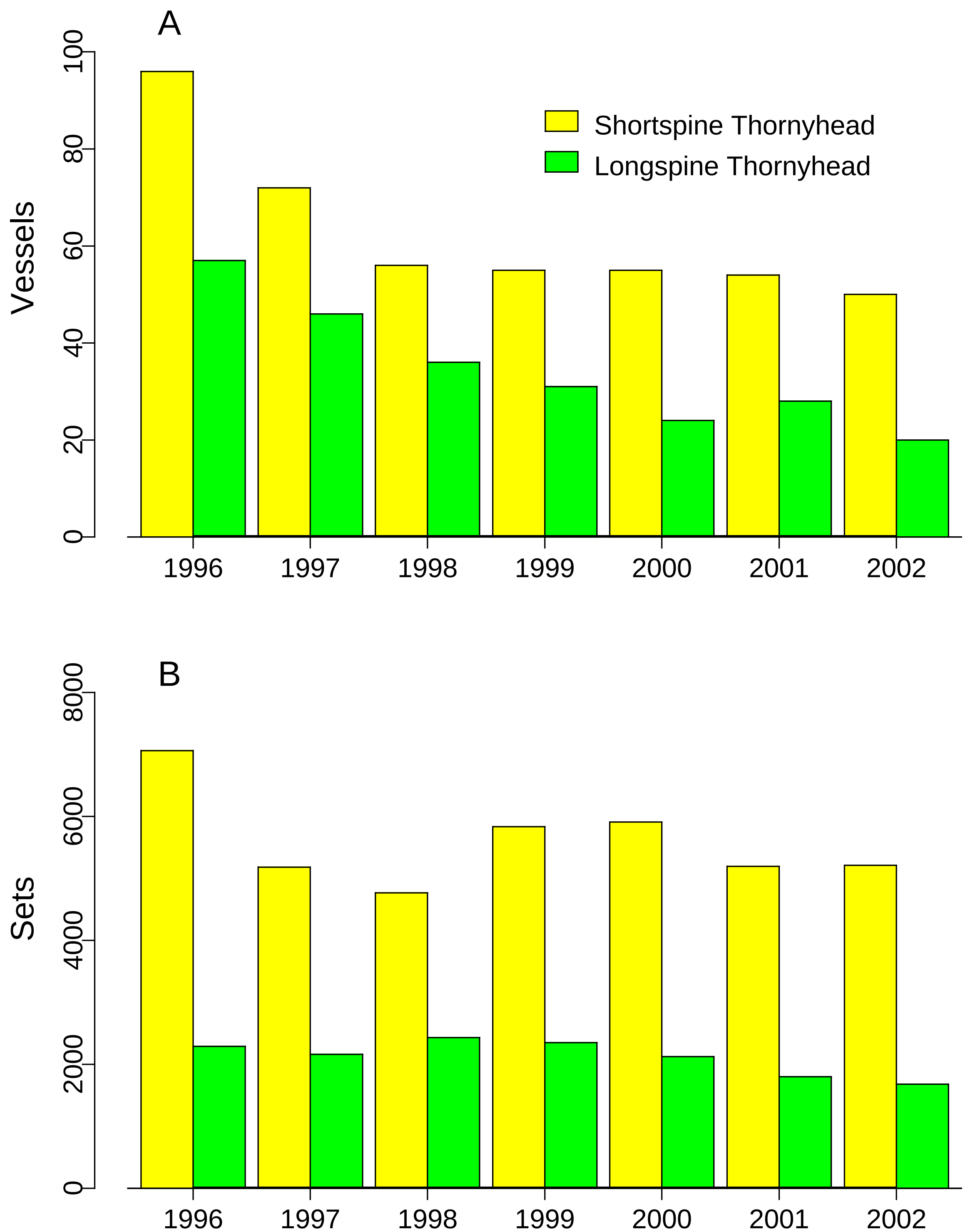

Figure 2.2. Trends in coastwide vessel participation and landing frequencies for the longspine and shortspine thornyhead fisheries. (A) number of unique vessels reporting thornyhead landings annually; (B) number of sets reporting thornyhead landings.

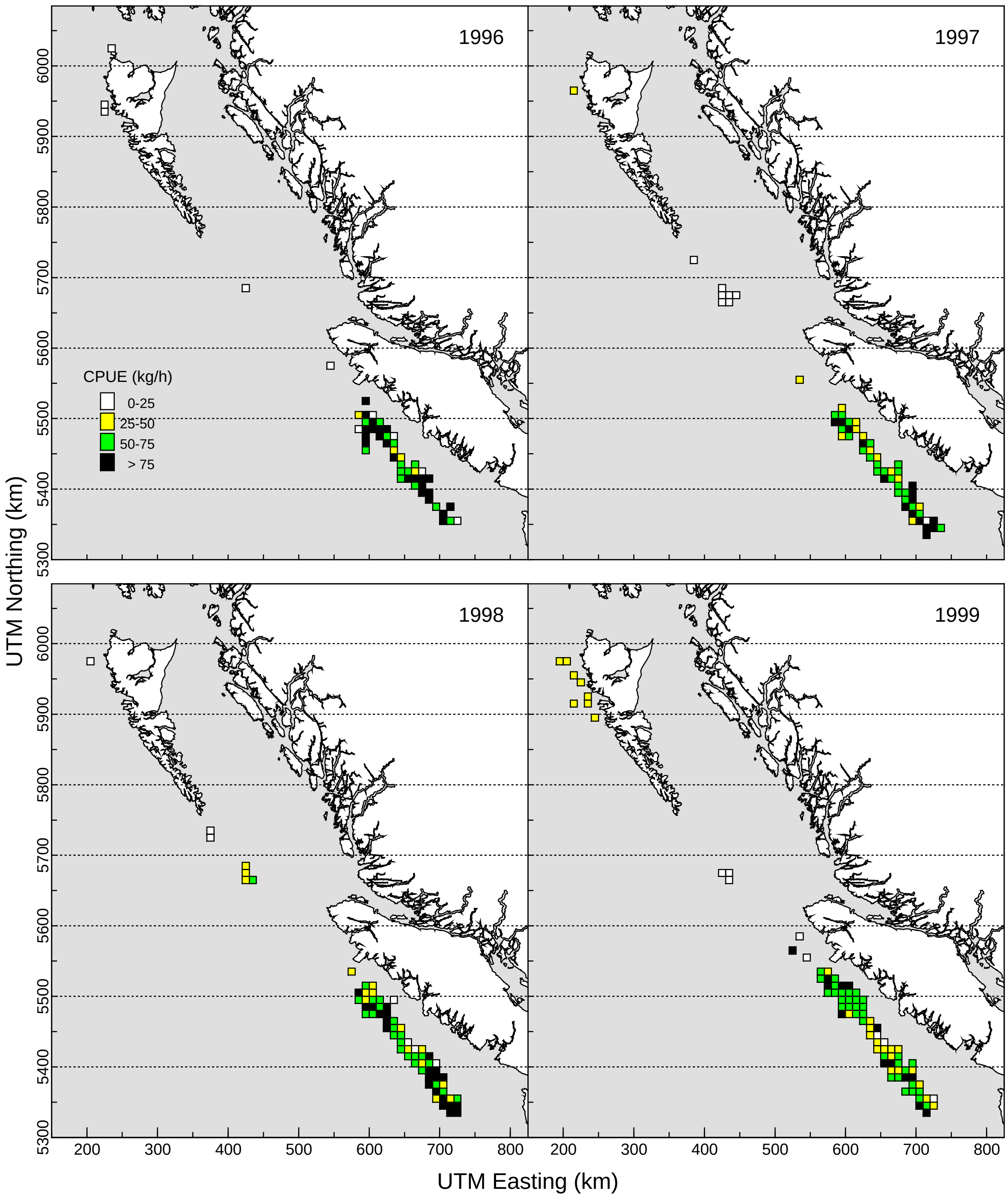

Figure 2.3. Mean CPUE in 10km × 10km grid blocks for fishing years 1996-1999. Tows used: bottom trawls >500 m with an onboard observer, May 1-Oct 31, vessels in fishery for at least 6 of the 8 years (1996-2003).

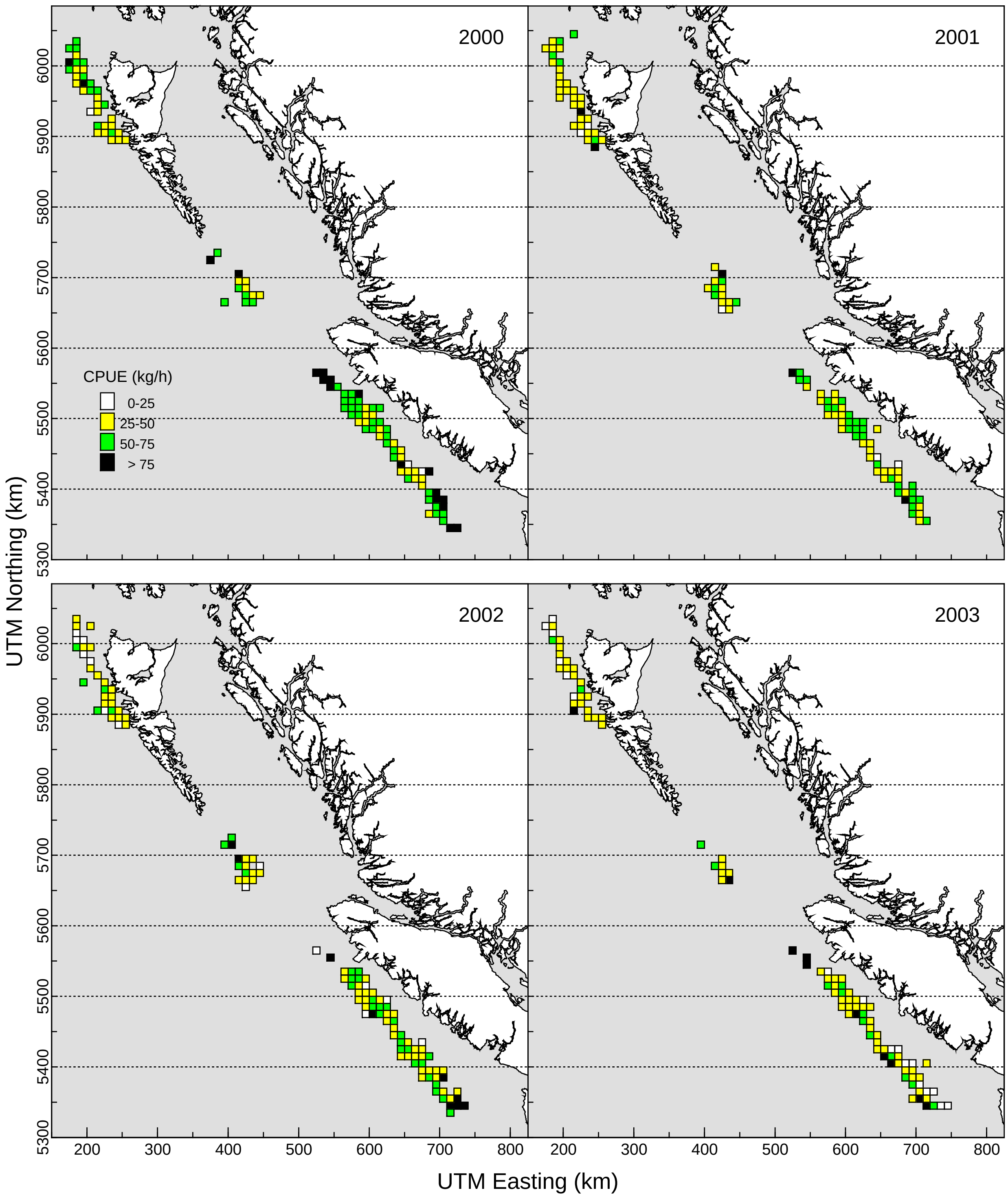

Figure 2.4. Mean CPUE in 10km × 10km grid blocks for fishing years 2000-2003. Tows used: bottom trawls >500 m with an onboard observer, May 1-Oct 31, vessels in fishery for at least 6 of the 8 years (1996-2003).

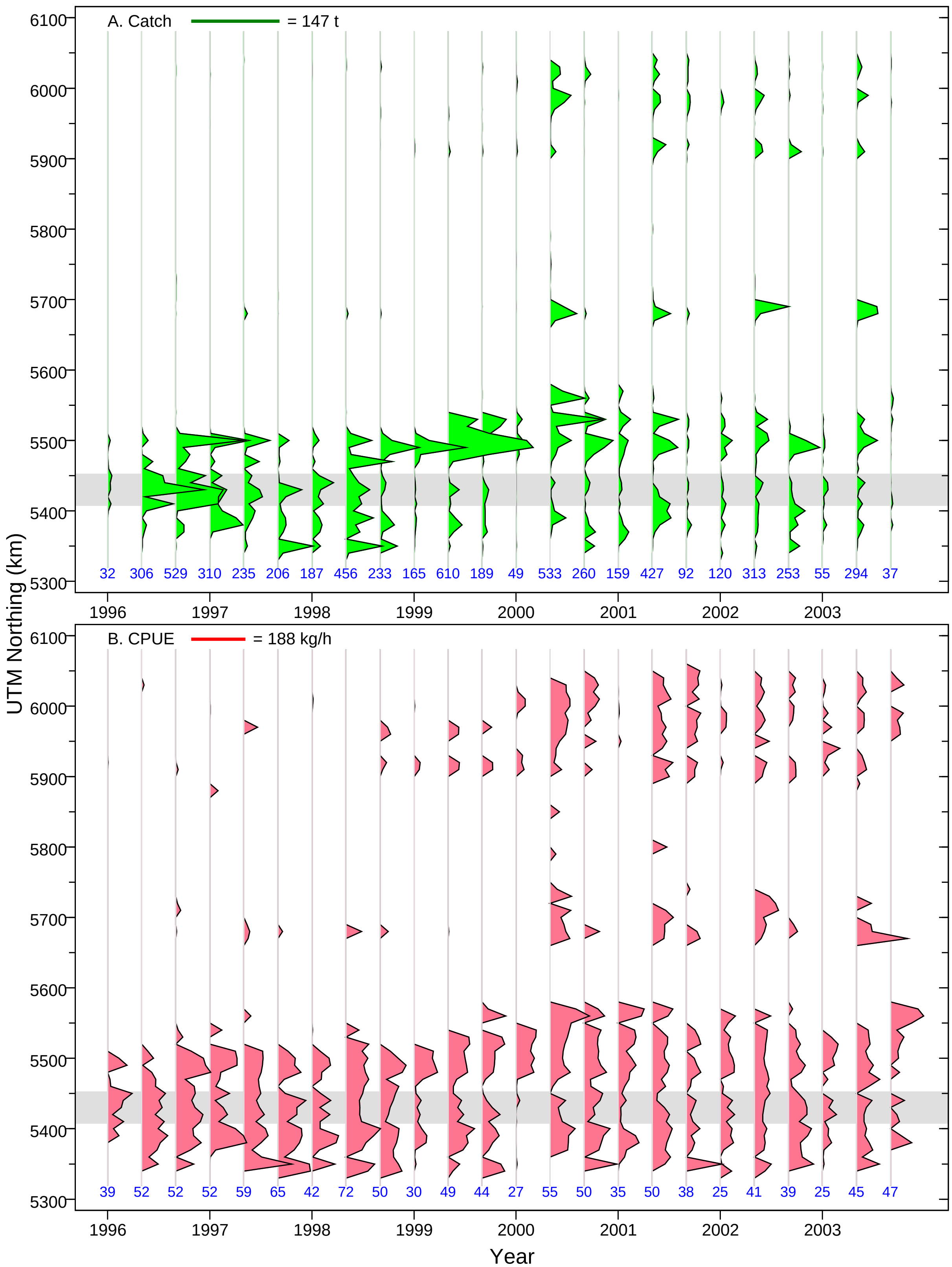

Figure 2.5. Latitudinal spread of catch and CPUE over time along the BC coast using 10-km UTM northing intervals and 4-month periods. All tows catching longspine thornyhead are used to summarize catch. CPUE is calculated using bottom trawl tows below 500 m with an onboard observer. Total catch and mean CPUE are indicated for each 4-month period.

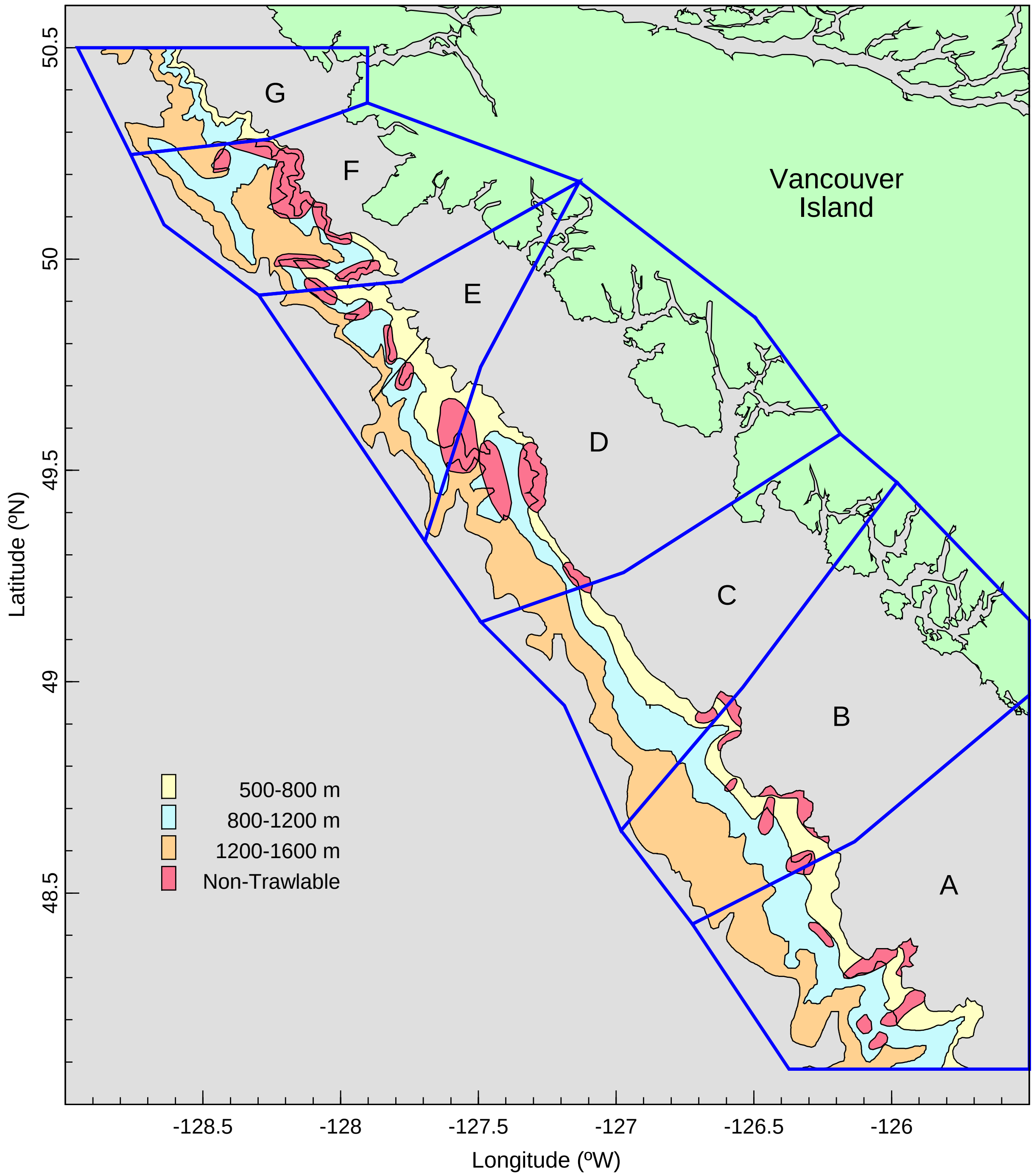

Figure 3.1. Map of the WCVI longspine thornyhead survey strata. Areal zones correspond to fishing grounds outlined by Brian Mose (fisherman). Depth zones are defined by isobaths derived from interpolated Canadian Hydrographic Service data (Schnute et al. 1999b). Non-trawlable areas are defined by Chris Roberts (fisherman).

Figure 3.2. F/V *Ocean Selector* crew plus research staff participating in the 2003 thornyhead biomass survey. From left to right: Mike Orcutt (AMR), Daryl Heinrich, Dean Gaidica (AMR), John O'Driscol, Dave Clattenberg (skipper), Paul Fraser, Ed Choromanski (DFO), Hank Hemstra, Brian Krishka (DFO), Nev Venables (Nev's Groundfish Research) (missing: Paul Starr CGRCS). (AMR - Archipelago Marine Research, DFO - Fisheries & Oceans Canada, CGRCS - Canadian Groundfish Research and Conservation Society). Photo credit: Jody Riley.

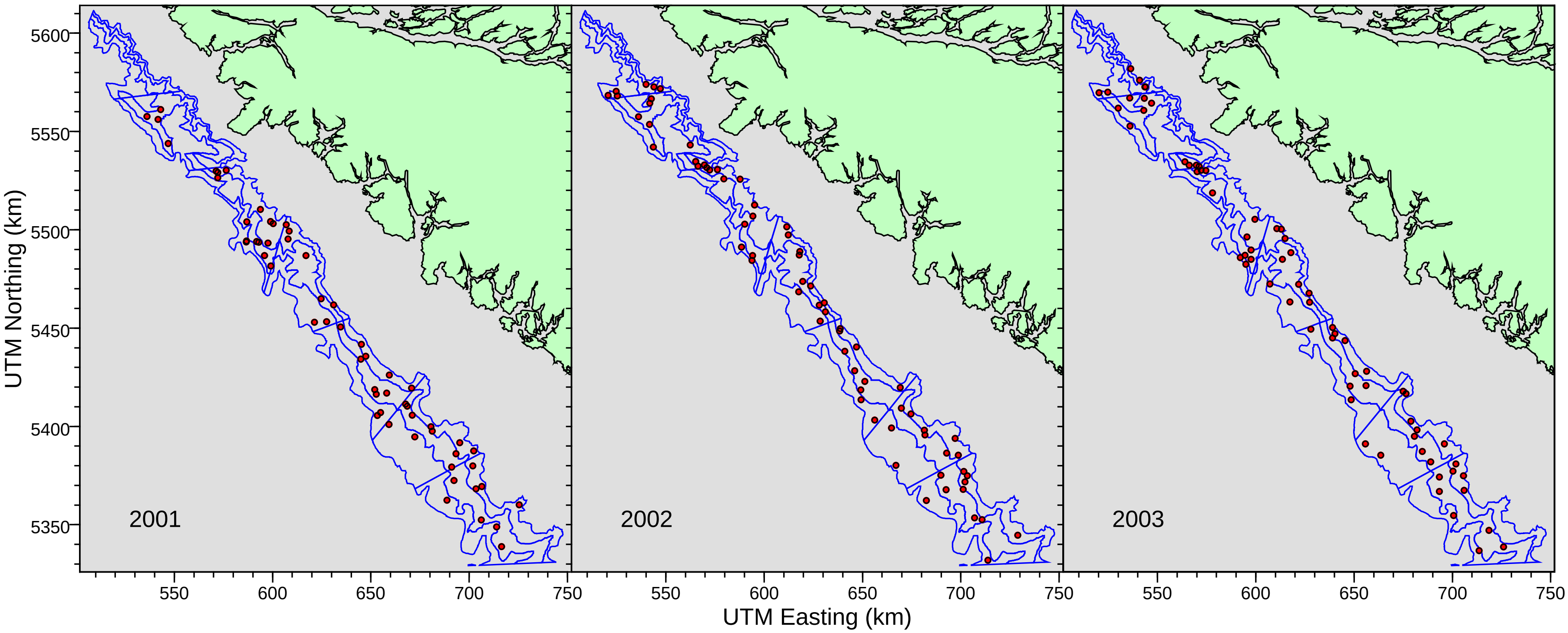

Figure 3.3. Longspine thornyhead survey tow locations in each of the 3 years (2001-2003).

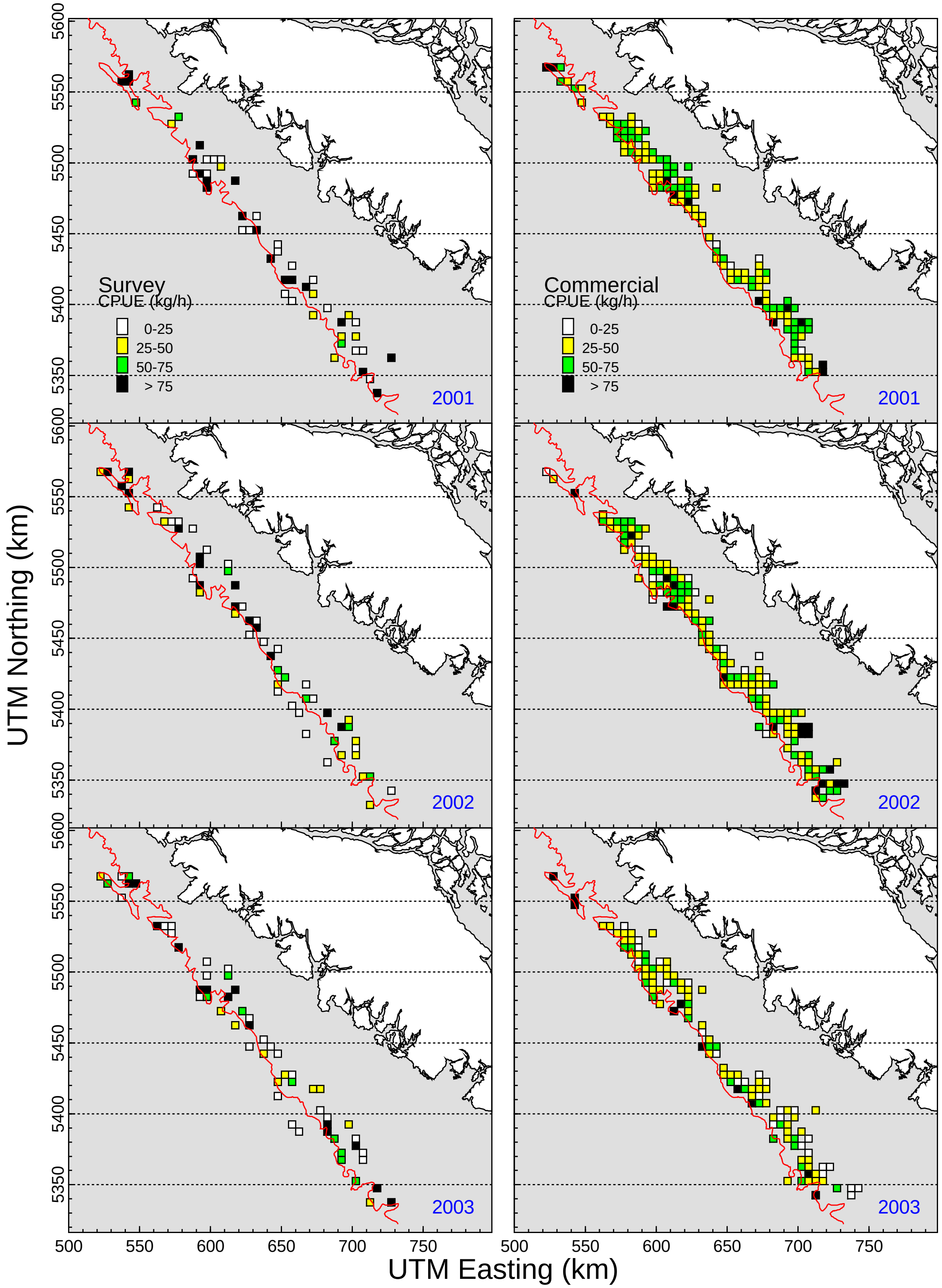

Figure 3.4. Mean CPUE in 5km×5km grid blocks for each year of the survey (2001-2003); left panels = survey, right panels = commercial. Commercial tows used: bottom trawls >500 m with an onboard observer, May 1-Oct 31, vessels in fishery for at least 6 of the 8 years (1996-2003). Red line indicates the 1,200 m isobath.

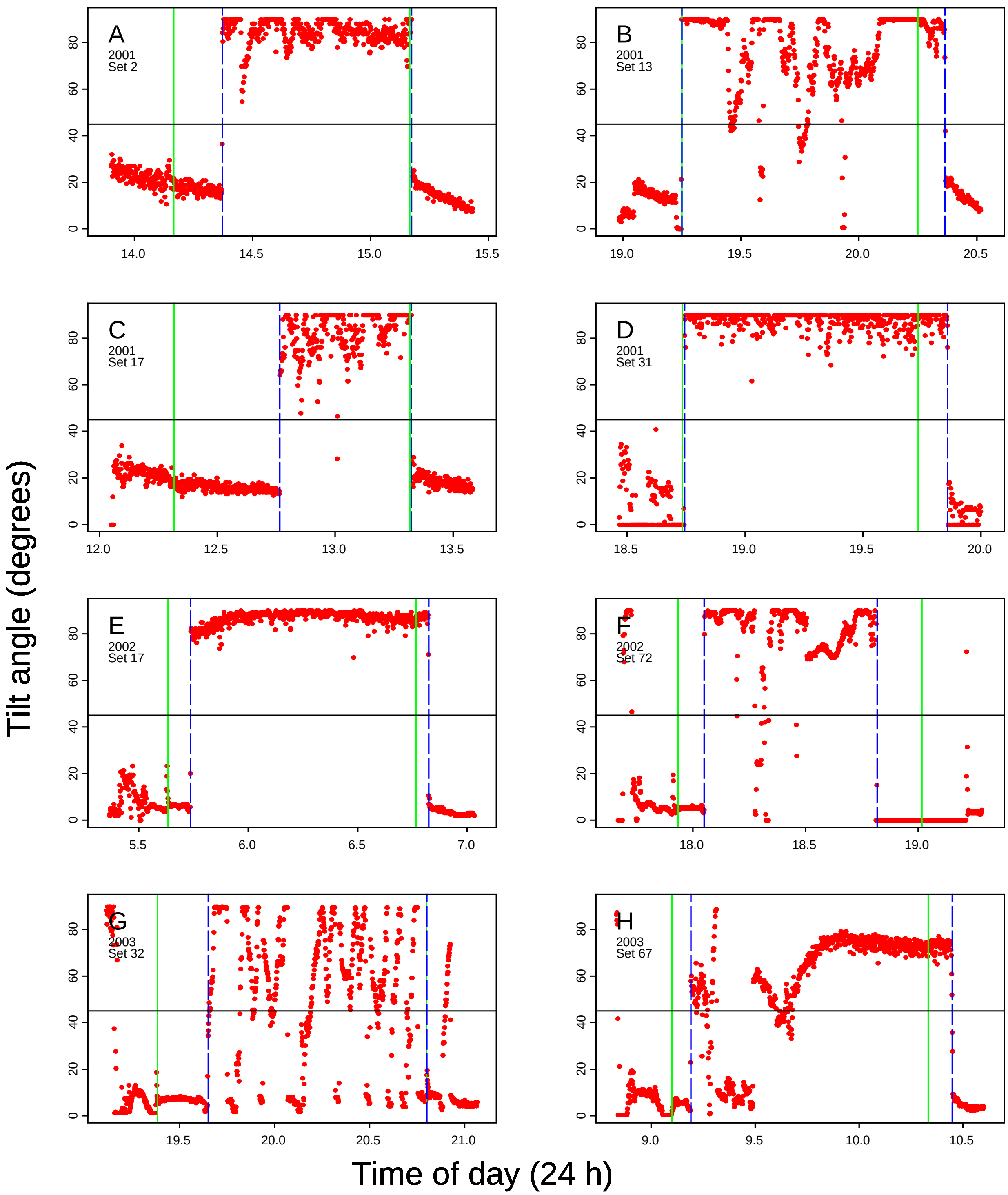

Figure 3.5. Examples of bottom contact sensor profiles from the WCVI longspine survey. The horizontal line defines the 45° tilt angle criterion for the start/end of bottom contact. Solid vertical green lines indicate winch lockup and winch release times. Dashed vertical blue lines represent start and end times for bottom contact. Four tows (A-D) from 2001 have elapsed winch-lockup-to-retrieval times of 1 h but show a wide range of bottom contact times (Set 2: 0.80 h; Set 13: 1.12 h; Set 17: 0.56 h; Set 31: 1.12 h). Panels E-H illustrate the variety of profiles obtained using the sensor: good (E), net off bottom before winch release (F), highly irregular (G), and mixed (H).

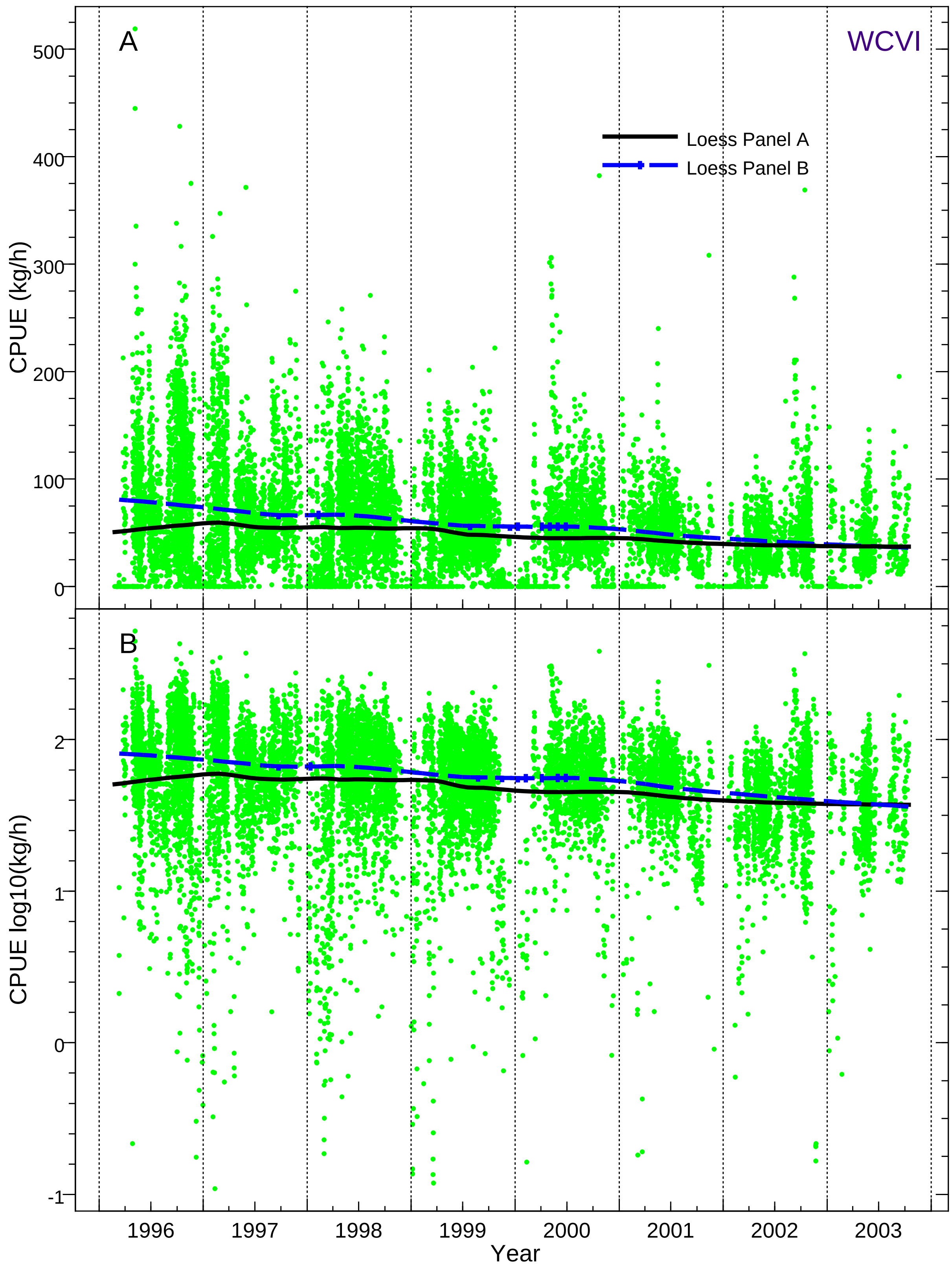

Figure 6.1. Scatter plots of commercial CPUE in the WCVI longspine thornyhead management region for 1996-2003. Commercial tows used: bottom trawls >500 m with an onboard observer. (A) CPUE including zero-catch tows; (B) $\log_{10}$ CPUE excluding zero-catch tows. The loess-smoothed line for each panel is also drawn on the other panel.

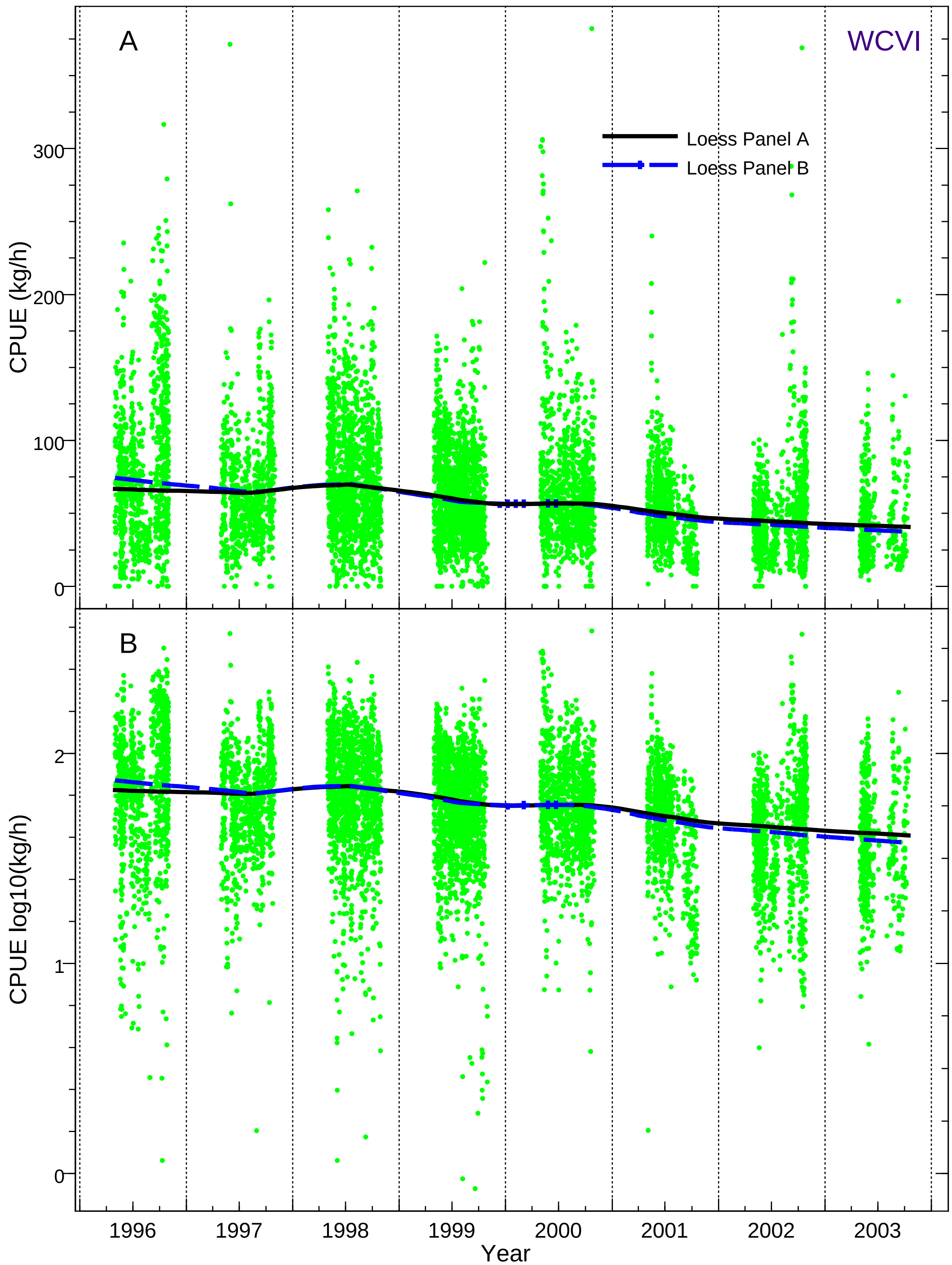

Figure 6.2. Scatter plots of commercial CPUE in the WCVI longspine thornyhead management region for 1996-2003. Commercial tows used: bottom trawls >500 m with an onboard observer, May 1-Oct 31, vessels in fishery for at least 6 of the 8 years (1996-2003). (A) CPUE including zero-catch tows; (B) $\log_{10}$ CPUE excluding zero-catch tows. The loess-smoothed line for each panel is also drawn on the other panel.

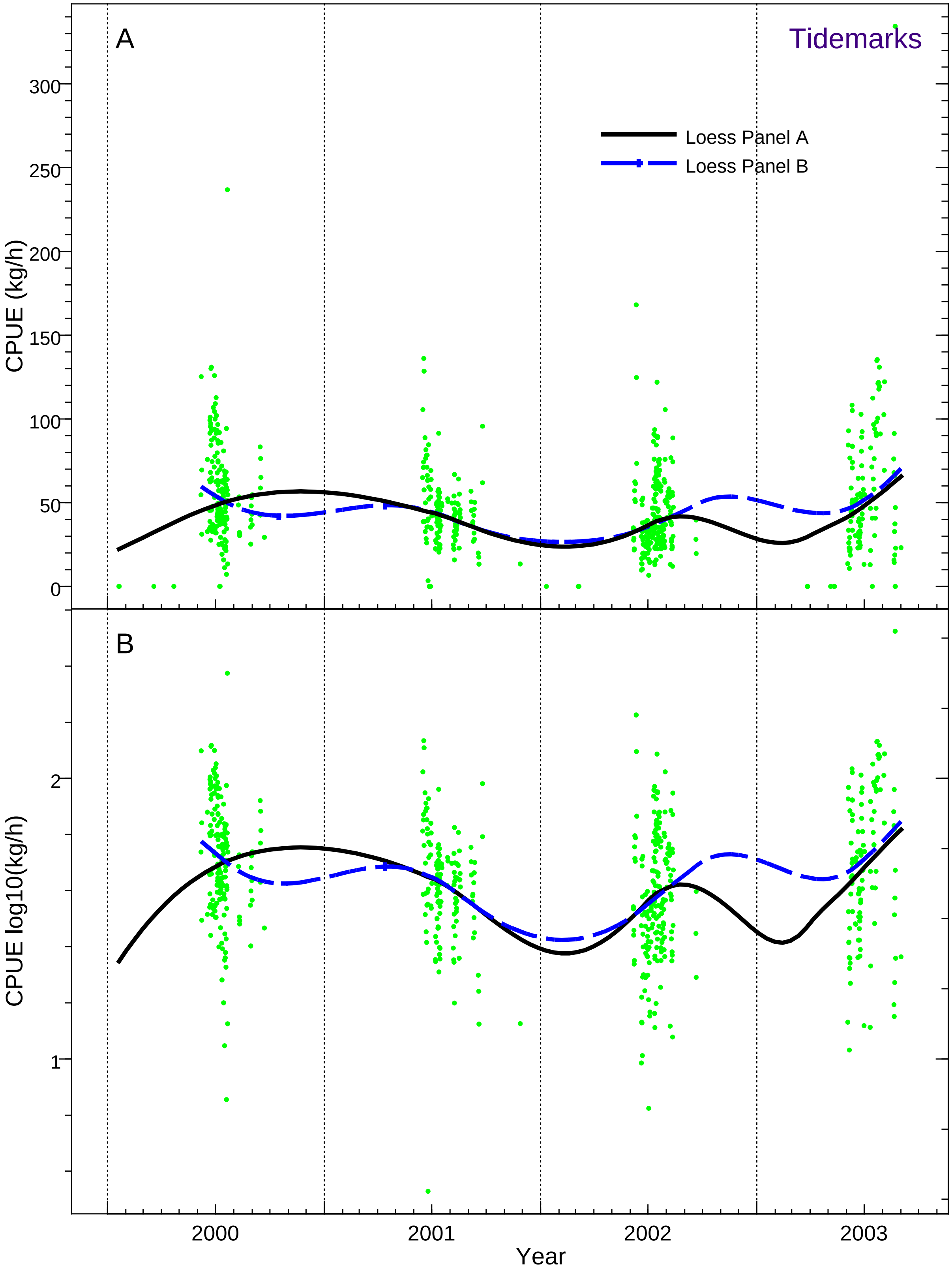

Figure 6.3. Scatter plots of commercial CPUE in the Tidemarks longspine thornyhead management region for 2000-2003. Commercial tows used: bottom trawls >500 m with an onboard observer. (A) CPUE including zero-catch tows; (B) $\log_{10}$ CPUE excluding zero-catch tows. The loess-smoothed line for each panel is also drawn on the other panel.

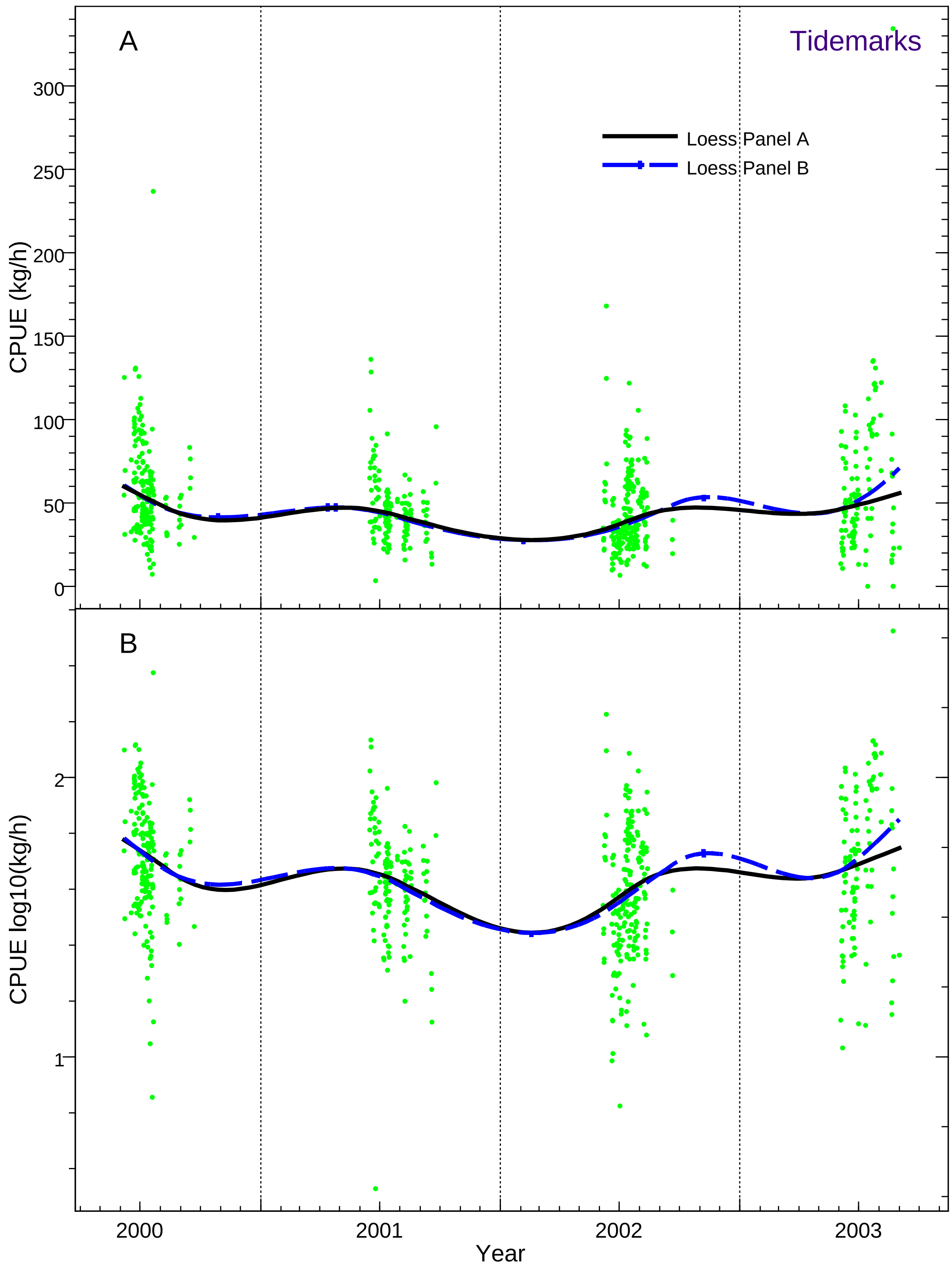

Figure 6.4. Scatter plots of commercial CPUE in the Tidemarks longspine thornyhead management region for 2000-2003. Commercial tows used: bottom trawls >500 m with an onboard observer, May 1-Oct 31, vessels in fishery for at least 6 of the 8 years (1996-2003). (A) CPUE including zero-catch tows; (B) $\log_{10}$ CPUE excluding zero-catch tows. The loess-smoothed line for each panel is also drawn on the other panel.

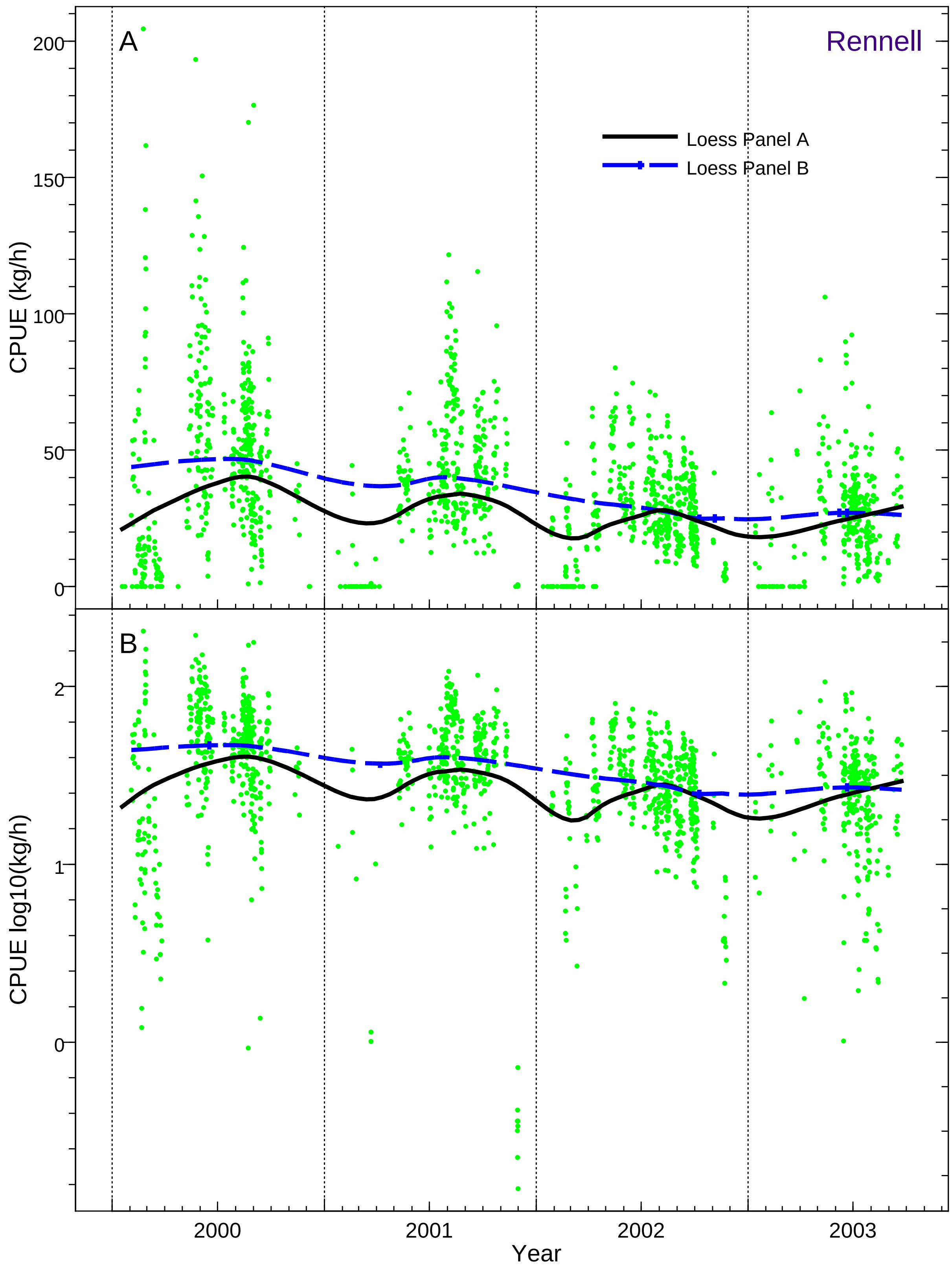

Figure 6.5. Scatter plots of commercial CPUE in the Rennell longspine thornyhead management region for 2000-2003. Commercial tows used: bottom trawls >500 m with an onboard observer. (A) CPUE including zero-catch tows; (B) $\log_{10}$ CPUE excluding zero-catch tows. The loess-smoothed line for each panel is also drawn on the other panel.

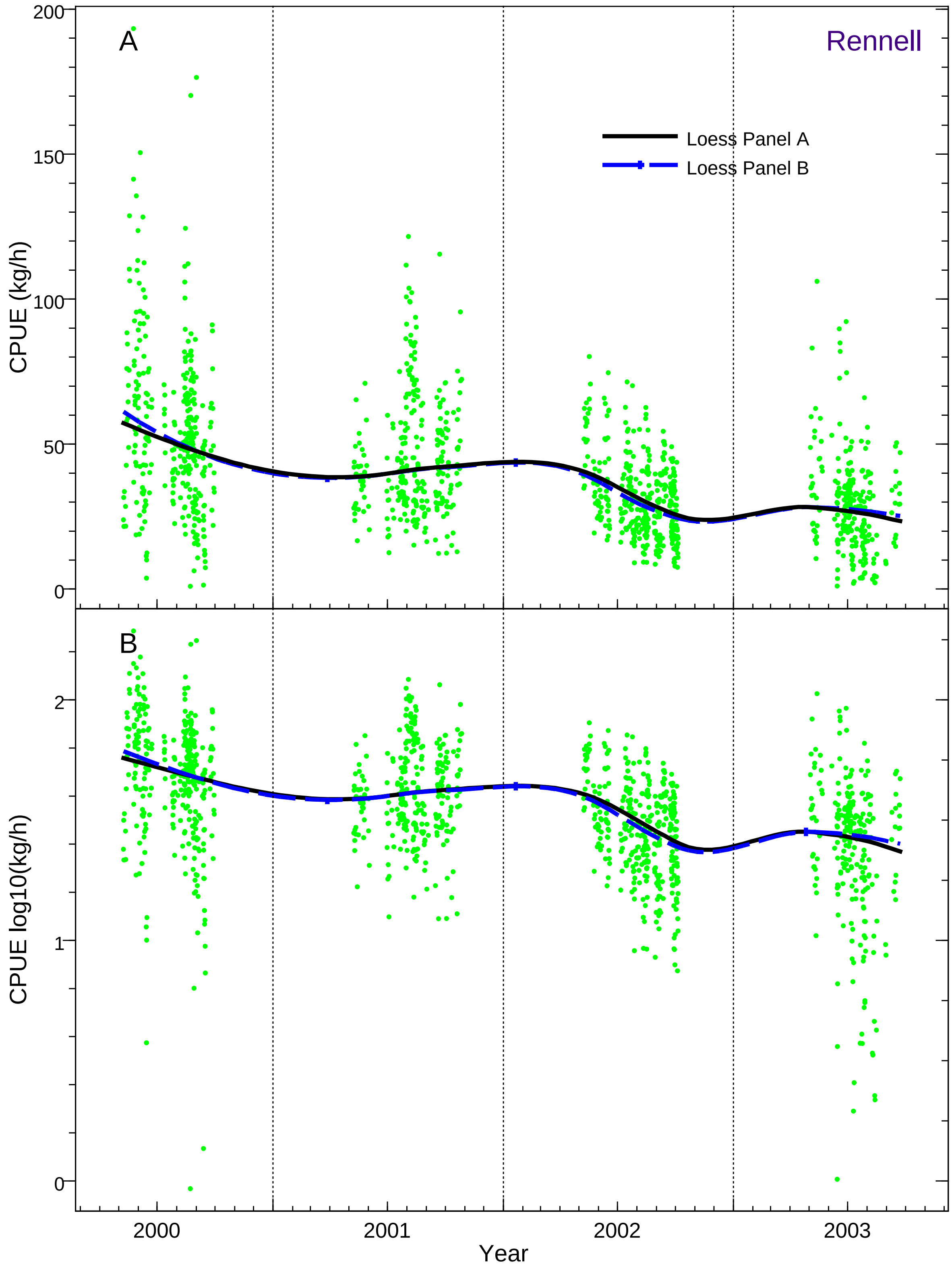

Figure 6.6. Scatter plots of commercial CPUE in the Rennell longspine thornyhead management region for 2000-2003. Commercial tows used: bottom trawls >500 m with an onboard observer, May 1-Oct 31, vessels in fishery for at least 6 of the 8 years (1996-2003). (A) CPUE including zero-catch tows; (B) $\log_{10}$ CPUE excluding zero-catch tows. The loess-smoothed line for each panel is also drawn on the other panel.

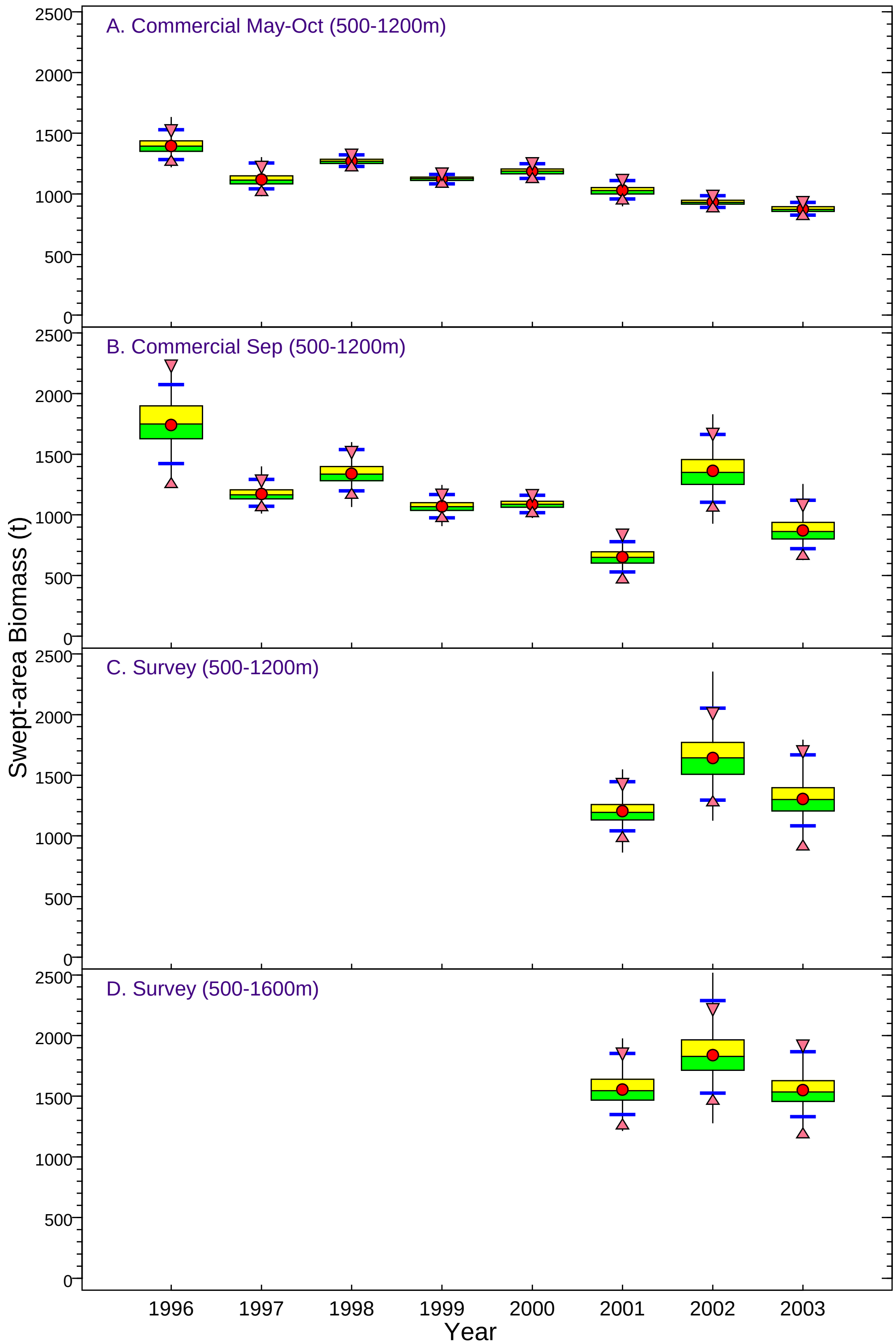

Figure 6.7. Annual swept-area biomass estimates from commercial and survey data for the WCVI longspine thornyhead management region. Commercial tows used: bottom trawls >500 m with an onboard observer, vessels in fishery for at least 6 of the 8 years (1996-2003). Panels: (A) commercial tows May-Oct, depth strata 500m < 1 ≤ 700m < 2 ≤ 900m < 3 ≤ 1200m; (B) commercial tows Sep, depth strata as in (A); (C) survey tows, depth strata as in (A); (D) survey tows, depth strata 500m < 1 ≤ 800m < 2 ≤ 1200m < 3 ≤ 1600m. Horizontal lines denote 95% bias-corrected, accelerated limits. Triangles denote moment 95% confidence limits.

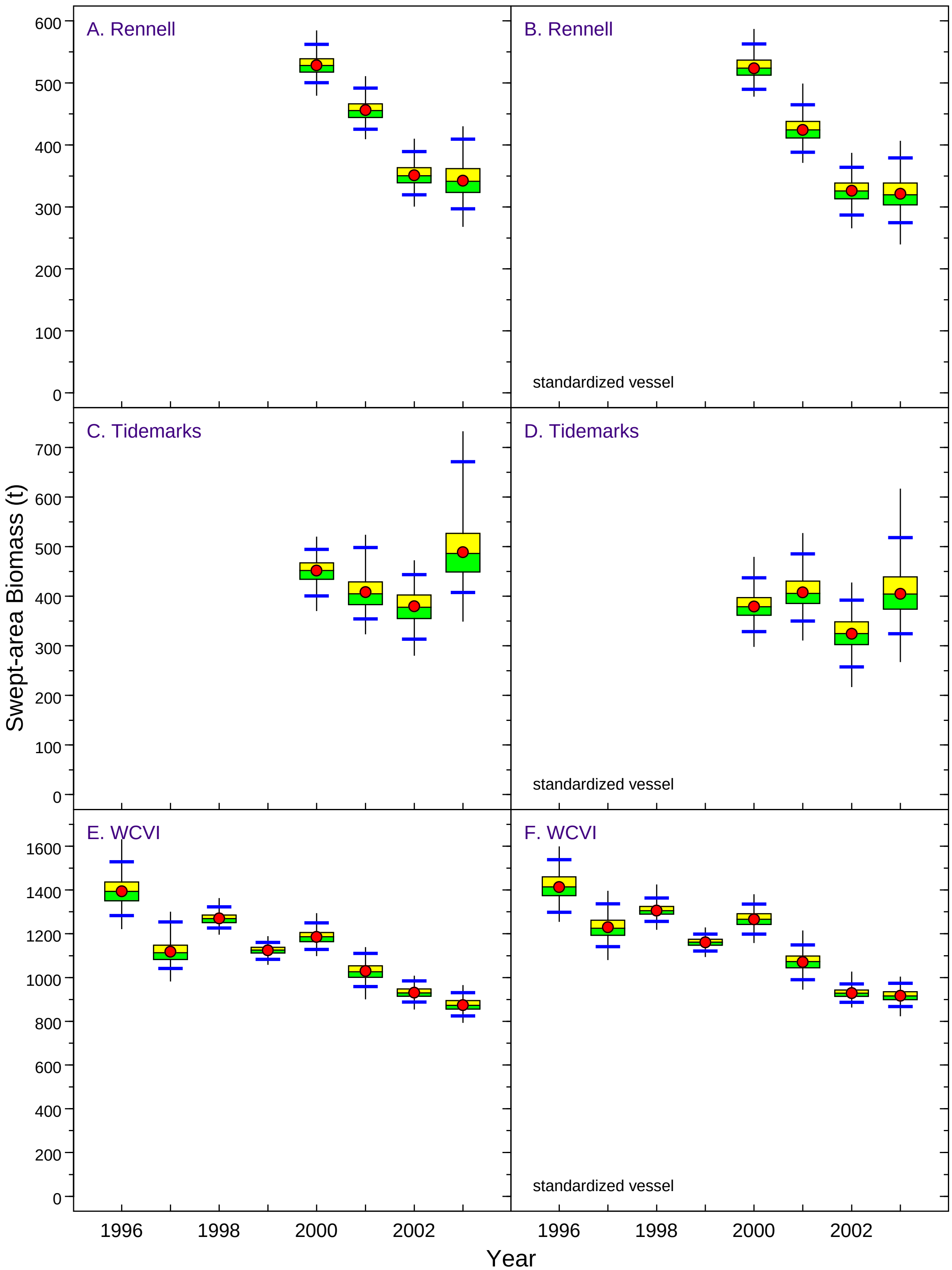

Figure 6.8. Annual swept-area biomass estimates from commercial data for the longspine thornyhead management regions Rennell, Tidemarks, and WCVI. Panels on left show normal estimates, panels on right show standardized estimates adjusted for vessel effect. Commercial tows used: bottom trawls >500 m with an onboard observer, May-Oct, vessels in fishery for at least 6 of the 8 years (1996-2003). Depth strata 500m < 1 ≤ 700m < 2 ≤ 900m < 3 ≤ 1200m. . Horizontal lines denote 95% bias-corrected limits, accelerated in panels A, C, and E.

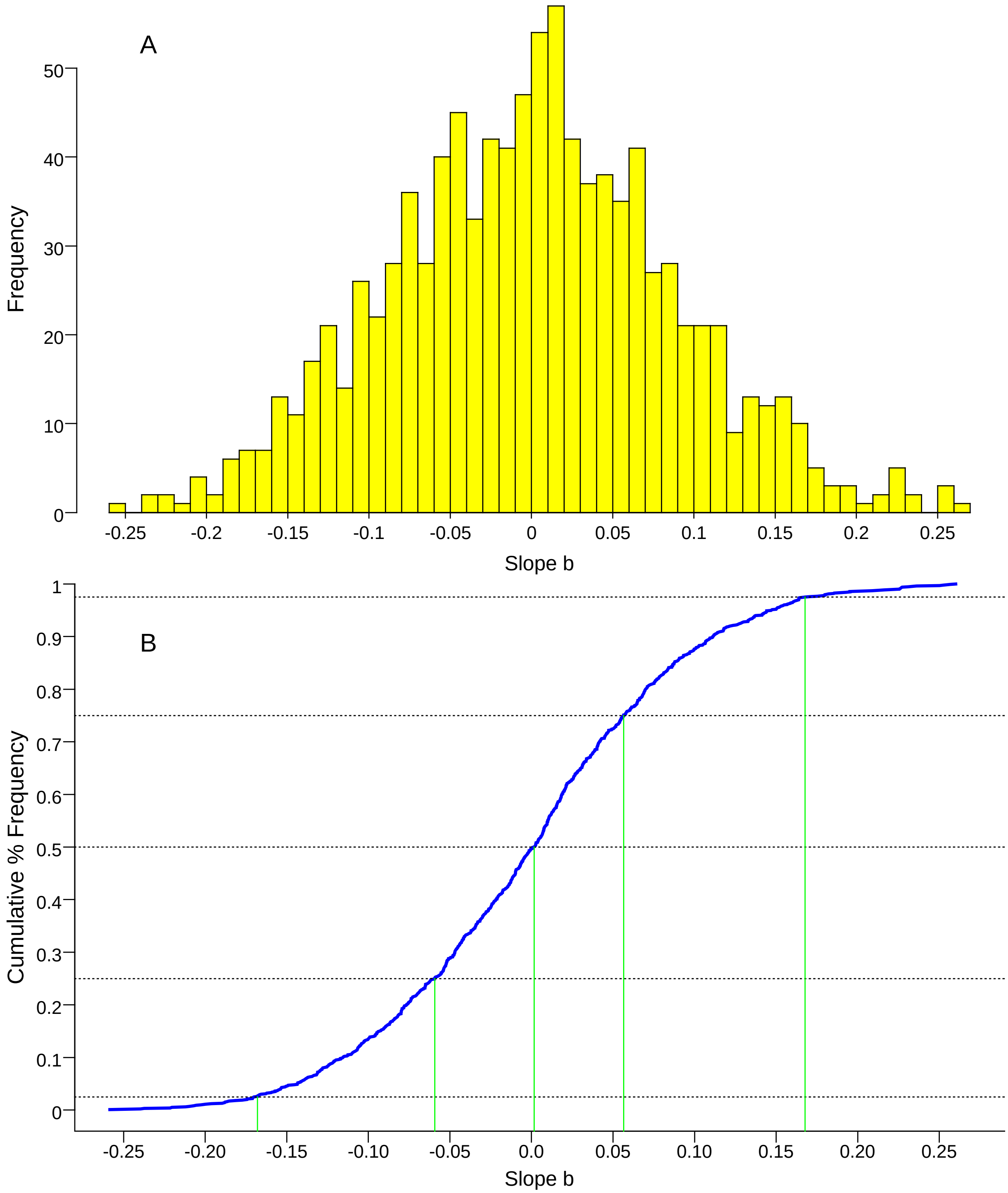

Figure 6.9. Distribution of slopes obtained from bootstrapping the WCVI survey biomass estimates. Slopes represent the linear fit to the biomass index (transformed by $\log_2$) over time. (A) Frequency distribution of 1000 bootstrap replicates; (B) cumulative percent frequency.

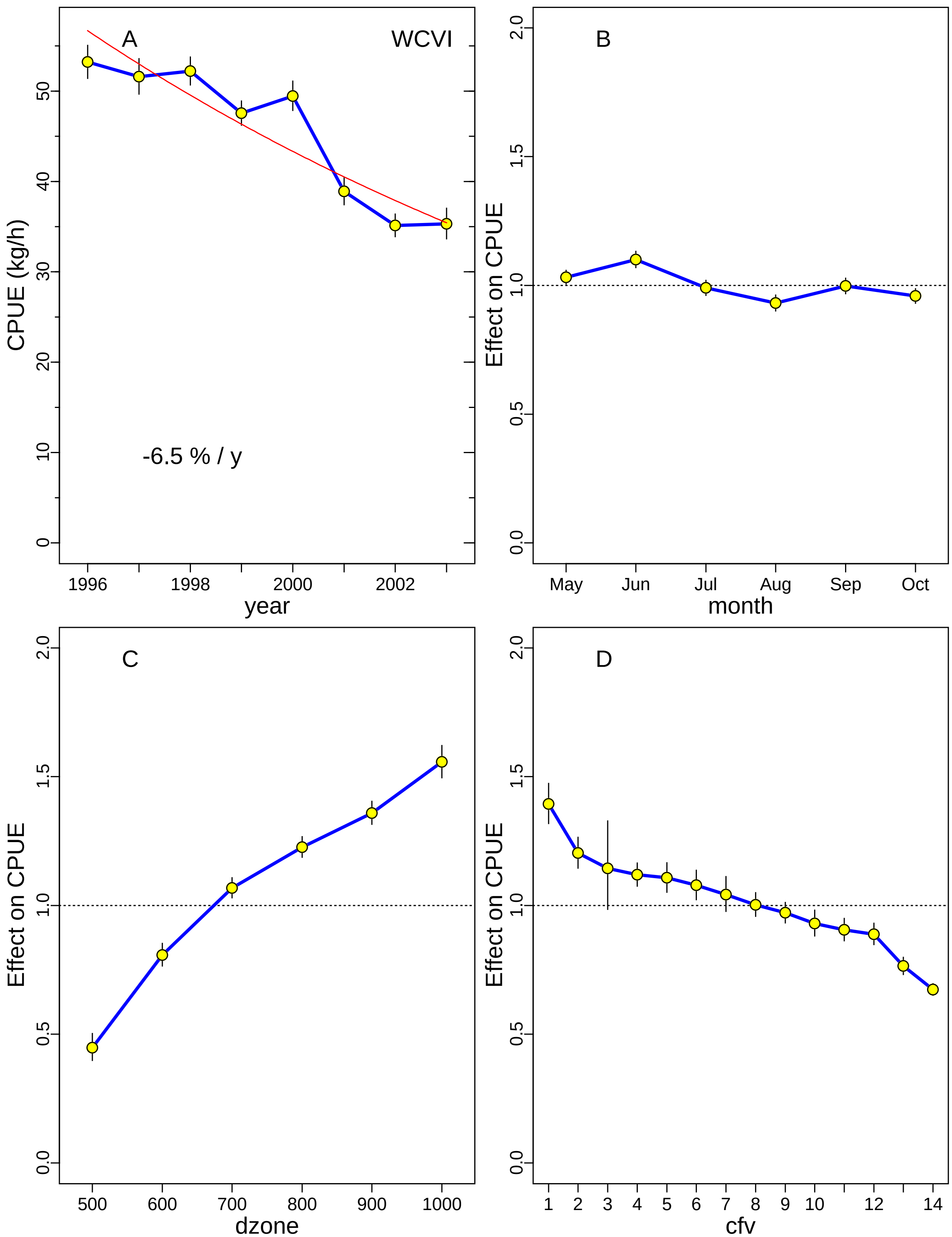

Figure 7.1. Commercial longspine thornyhead CPUE U (kg h^{-1}) estimated from (5.7) as $\log_2 U$ in the WCVI region: (A) year as $2^{\mu+\alpha_i}$, (B) month as 2^{β_j}, (C) depth zone (100-m intervals) as 2^{γ_k}, and (D) vessel as 2^{δ_l}. Vertical error bars indicate 95% confidence limits. Red line in (A) shows the back-transformed linear fit through α_i; implies an annual loss of 6.5 % $\cdot y^{-1}$.

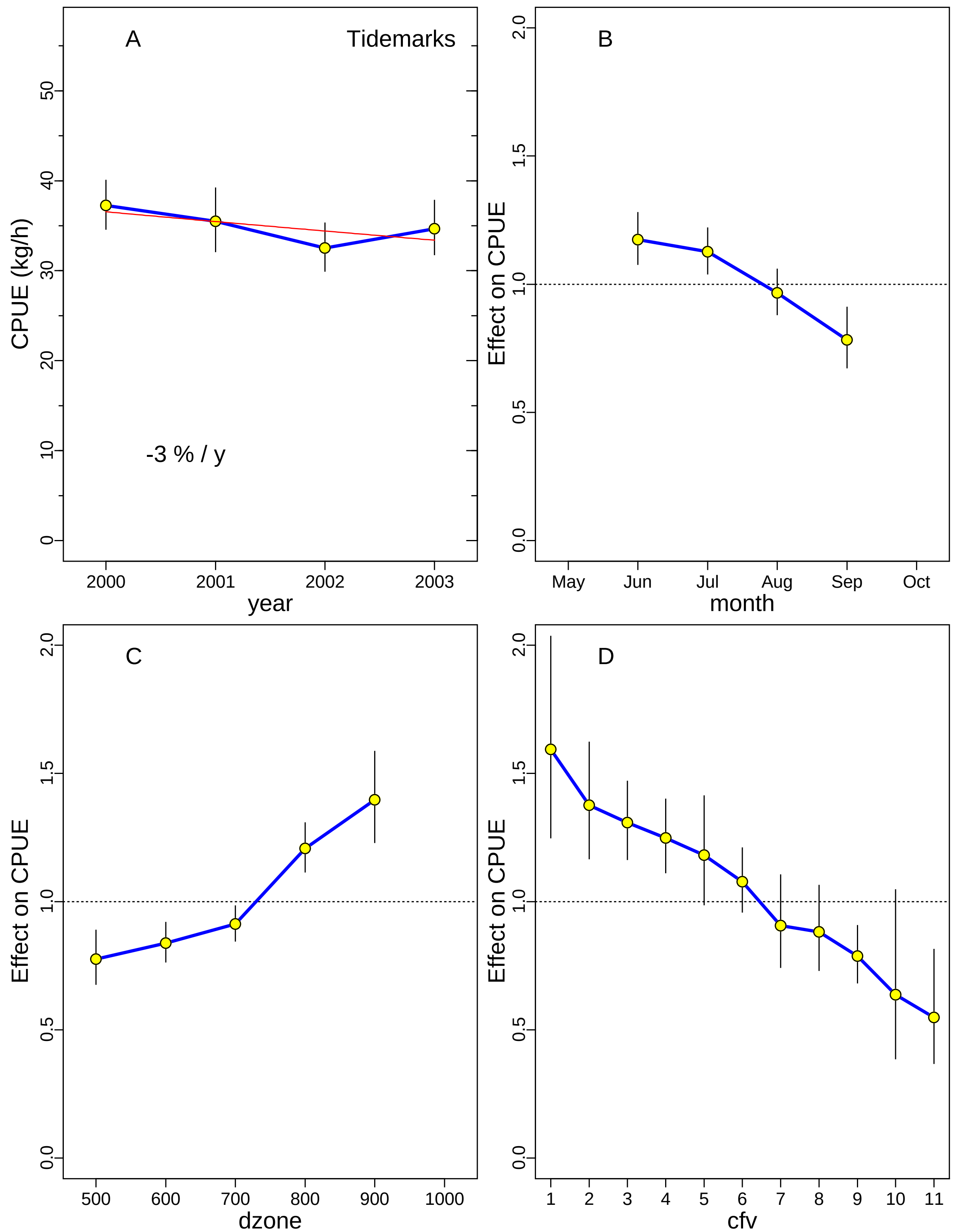

Figure 7.2. Commercial longspine thornyhead CPUE U (kg h^{-1}) estimated from (5.7) as $\log_2 U$ in the Tidemarks region: (A) year as $2^{\mu+\alpha_i}$, (B) month as 2^{β_j}, (C) depth zone (100-m intervals) as 2^{γ_k}, and (D) vessel as 2^{δ_l}. Vertical error bars indicate 95% confidence limits. Red line in (A) shows the back-transformed linear fit through α_i; implies an annual loss of 3.0 % $\cdot y^{-1}$.

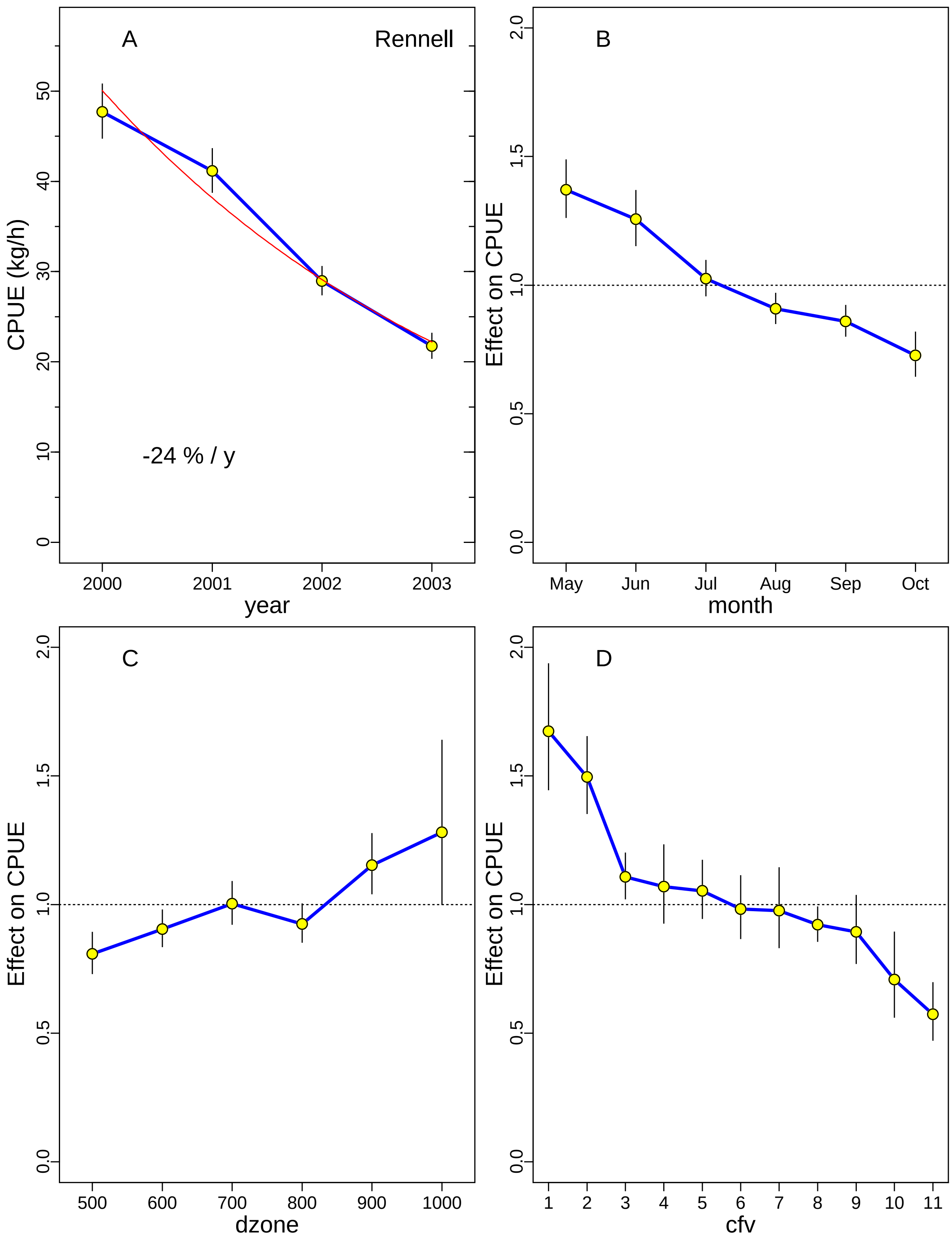

Figure 7.3. Commercial longspine thornyhead CPUE U (kg h^{-1}) estimated from (5.7) as $\log_2 U$ in the Rennell region: (A) year as $2^{\mu+\alpha_i}$, (B) month as 2^{β_j}, (C) depth zone (100-m intervals) as 2^{γ_k}, and (D) vessel as 2^{δ_l}. Vertical error bars indicate 95% confidence limits. Red line in (A) shows the back-transformed linear fit through α_i; implies an annual loss of 24 % $\cdot y^{-1}$.

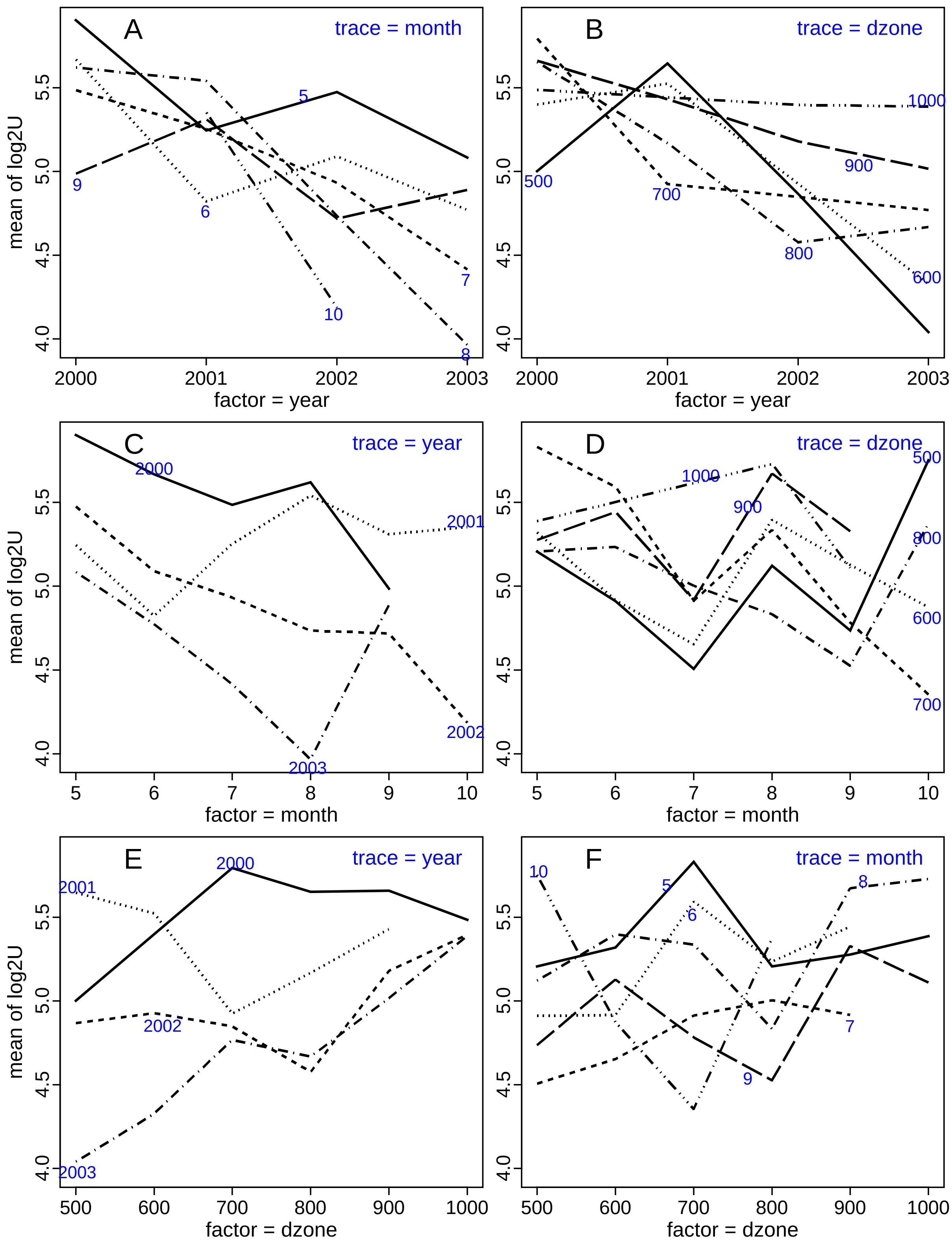

Figure 7.4. Interaction plots for three factors affecting longspine thornyhead commercial CPUE as $\log_2 U$, where $U = \text{kg h}^{-1}$, in the Rennell management region. Interactions: (A) year-month, (B) year-depth, (C) month-year, (D) month-depth, (E) depth-year, and (F) depth-month.

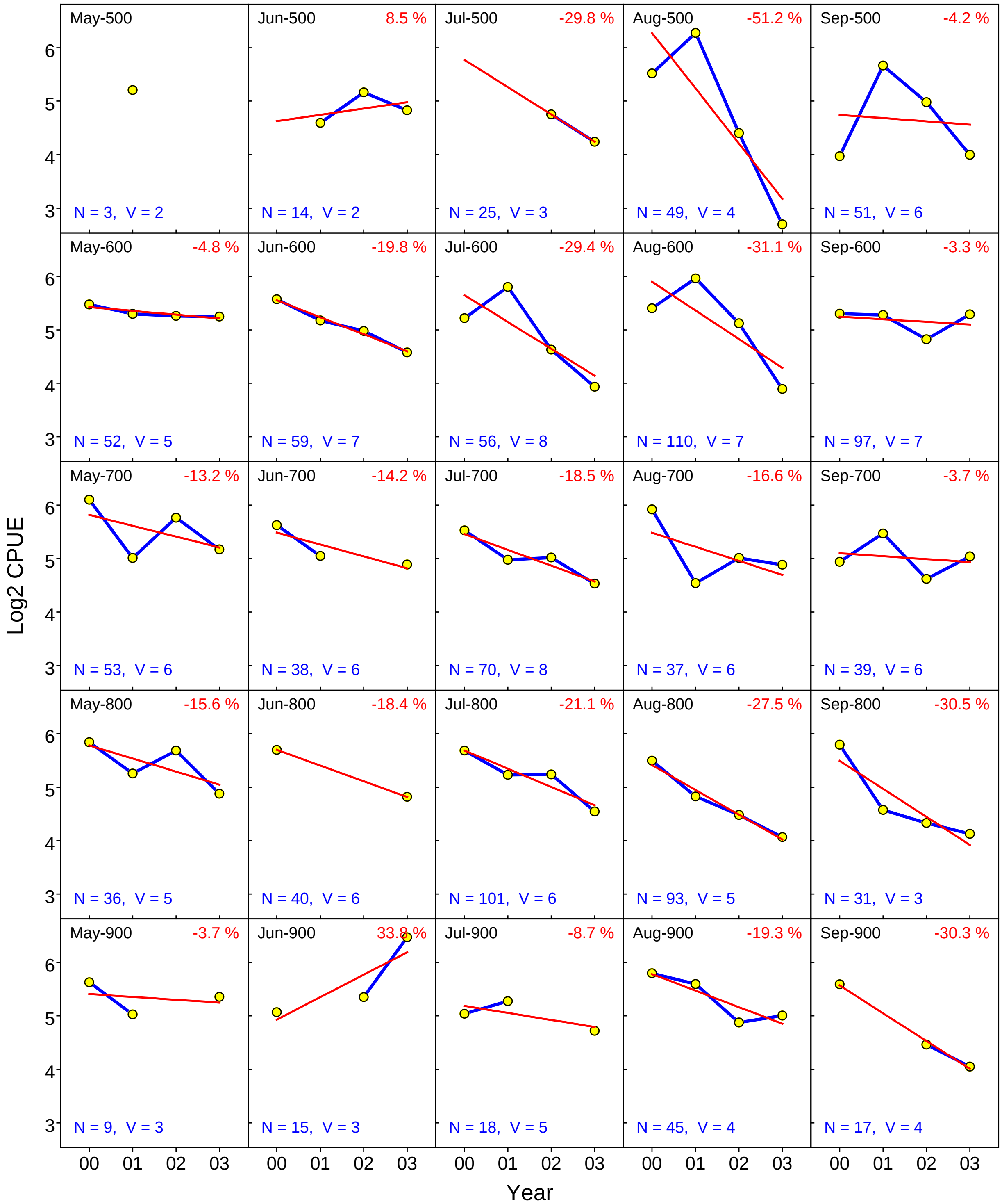

Figure 7.5. Annual time trends of longspine thornyhead commercial CPUE ($\log_2$ kg h^{-1}) partitioned by month and 100 m depth intervals (e.g., 500 designates 500-600 m) for the Rennell region. Annual CPUE change is calculated $r = 2^b - 1$, where b is the slope of the linear fit (red line) through the mean annual log-transformed CPUE. Text in the lower left of each month-depth panel indicates the numbers of tows N and vessels V.

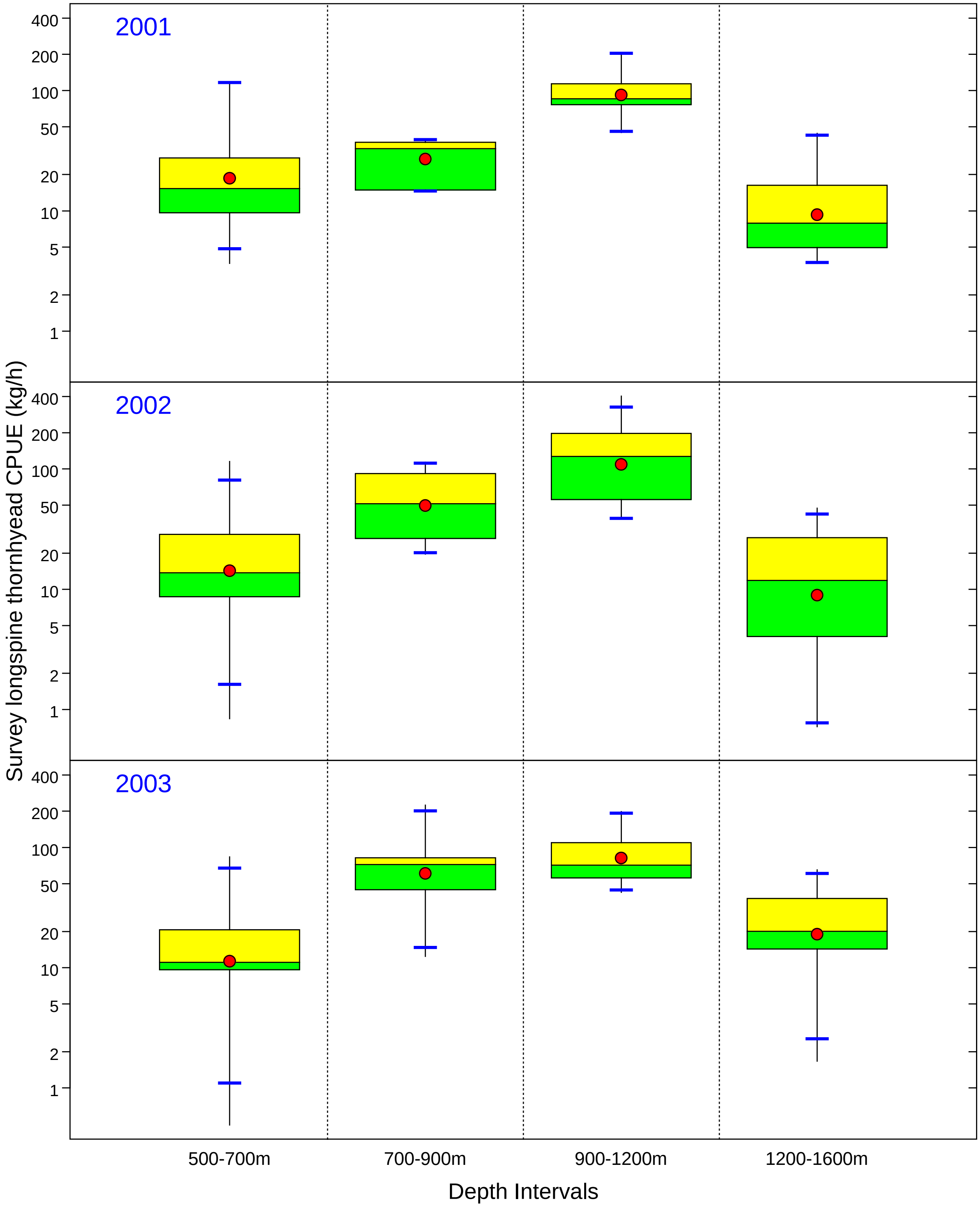

Figure 7.6. Distribution of longspine thornyhead CPUE U (kg h^{-1}) by depth interval for each year of the WCVI survey. Four zero-catch tows are excluded. Boxplot details: 25-50% quantile range (green shading), 50-75% quantile range (yellow shading), mean U (red circle), 2.5% and 97.5% quantiles (horizontal blue lines).

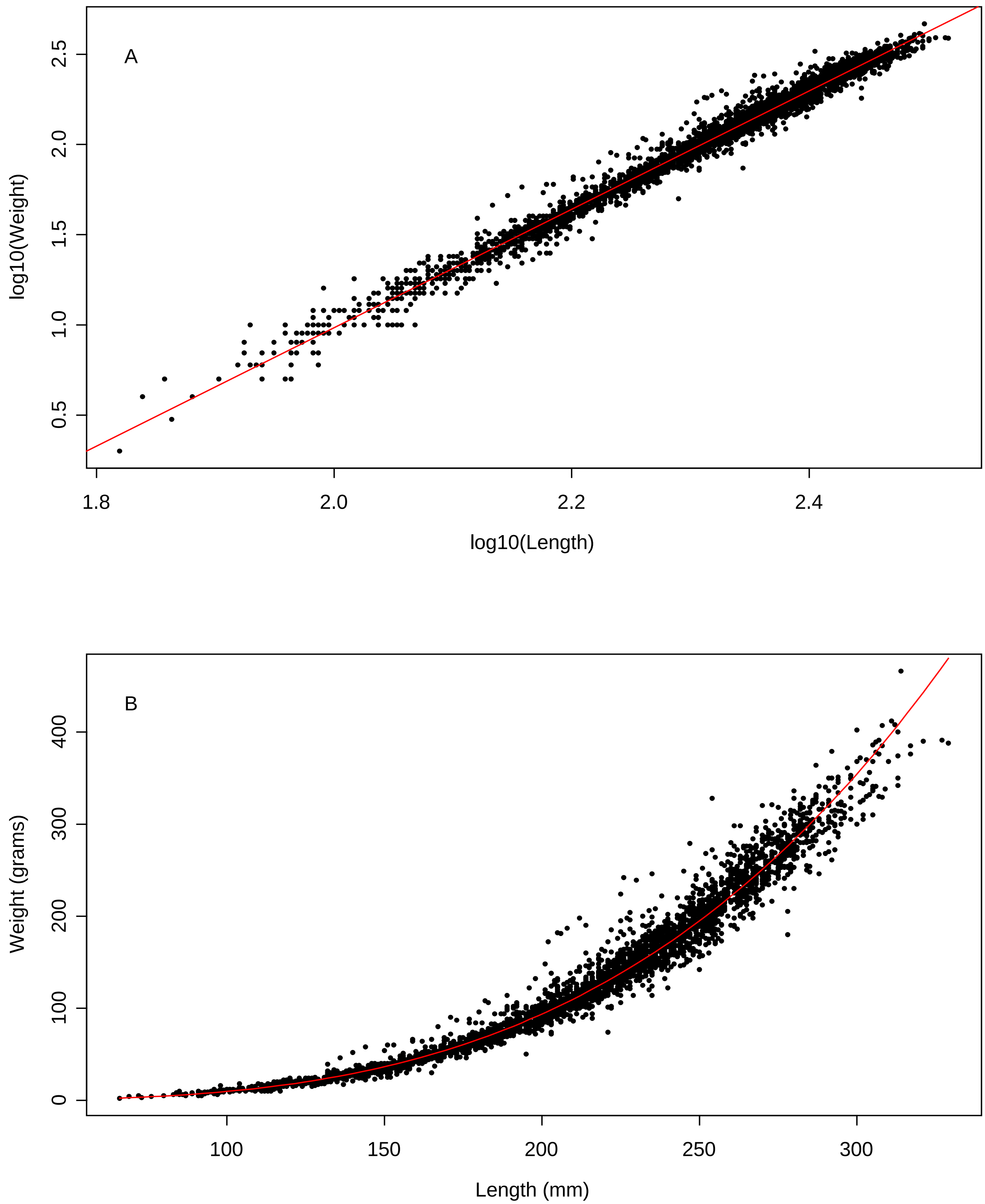

Figure 8.1. Weight-length regression (red line) for longspine thornyhead from combined survey data for 2001-2003 ($\log_{10}W = -5.579 + 3.282\log_{10}L$, $R^2 = 0.9839$, $N = 3591$), where W = round weight (grams) and L = total fish length (mm). Data include 3,645 specimens from valid survey sets, minus 54 outlier weights (greater than ±3SE). (A) $\log_{10}$-$\log_{10}$ relationship, (B) linear relationship.

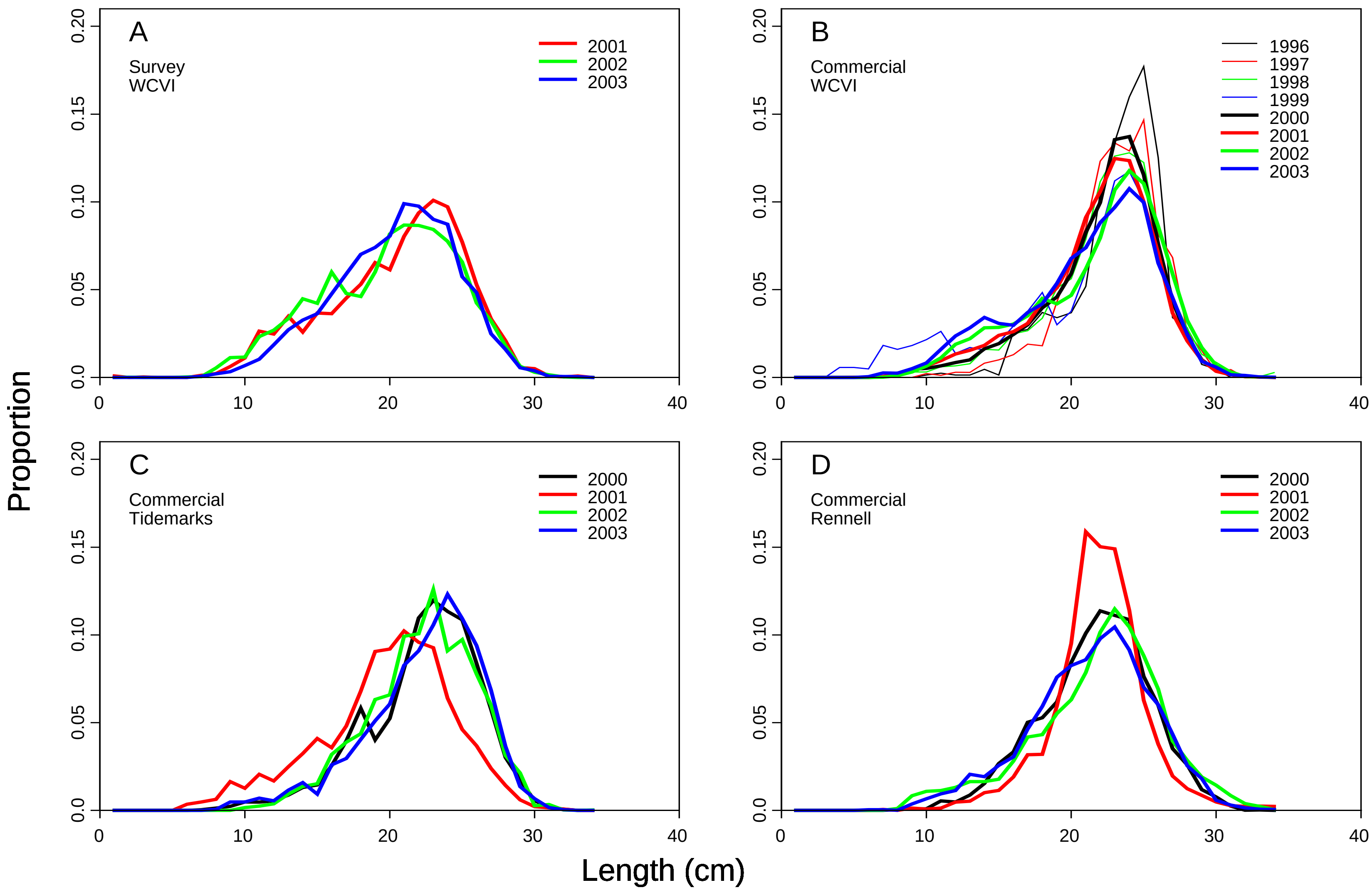

Figure 8.2. Longspine thornyhead length distributions by year: (A) survey in WCVI management region, (B) commercial in WCVI, (C) commercial in Tidemarks, and (D) commercial in Rennell.

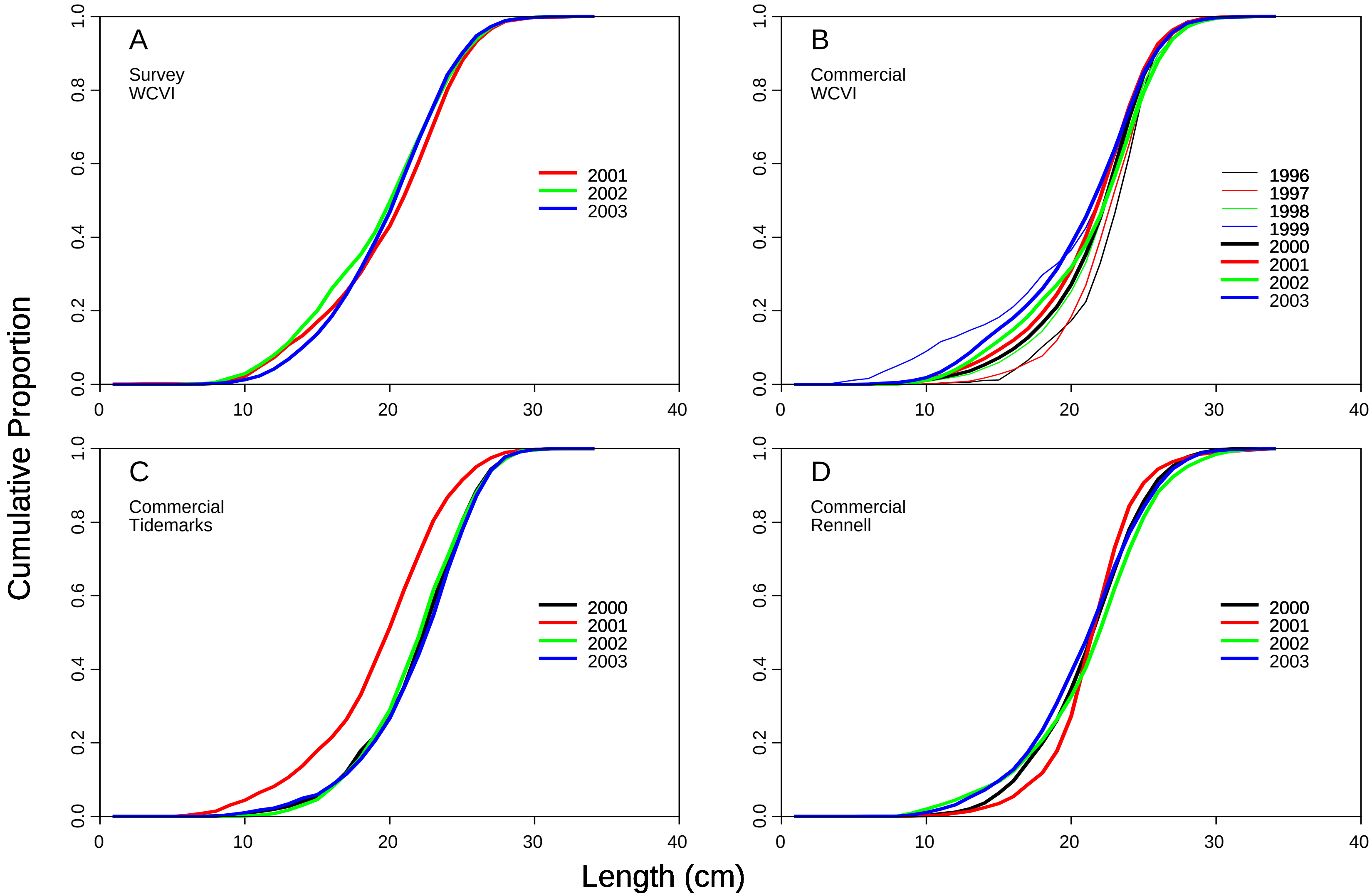

Figure 8.3. Longspine thornyhead cumulative length distributions by year: A) survey in WCVI management region, (B) commercial in WCVI, (C) commercial in Tidemarks, and (D) commercial in Rennell.

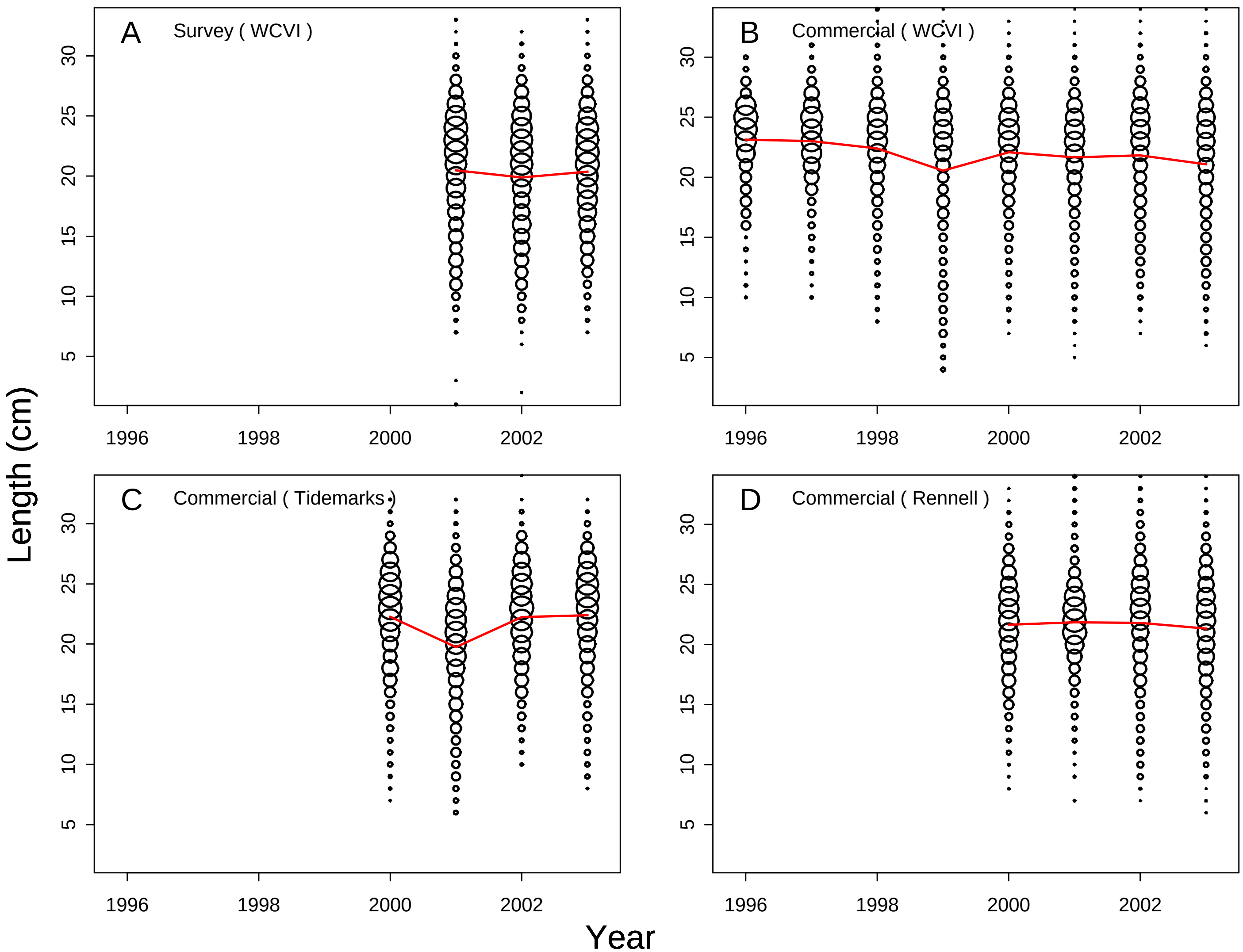

Figure 8.4. Longspine thornyhead length proportions estimated from survey and commercial samples for: (A) Survey (WCVI), (B) Commercial (WCVI), (C) Commercial (Tidemarks), and (D) Commercial (Rennell). Bubble areas represent relative annual proportions. Red lines indicate annual mean lengths. All samples are from “unsorted” catches except for 1996 where all WCVI samples come from “kept” portions of commercial catches.

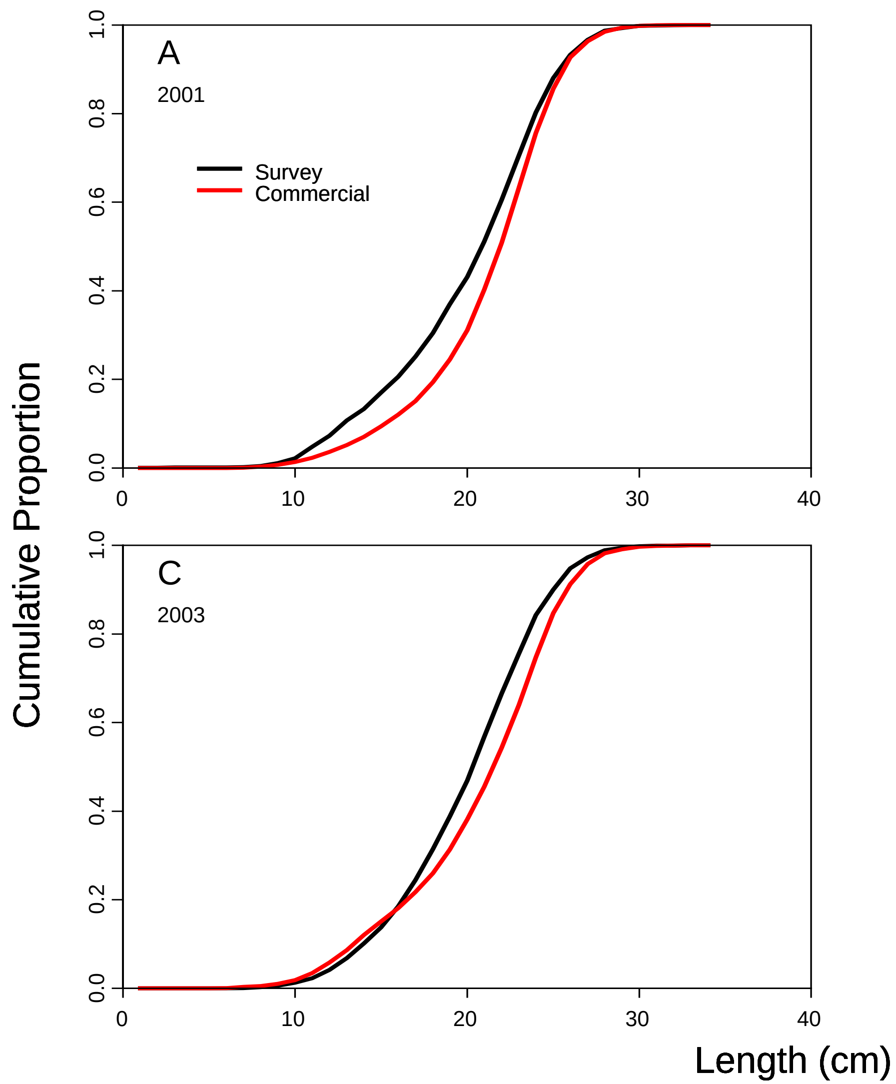

Figure 8.5. Longspine thornyhead cumulative length distributions from survey and commercial samples in WCVI management region for: (A) 2001, (B) 2002, and (C) 2003.

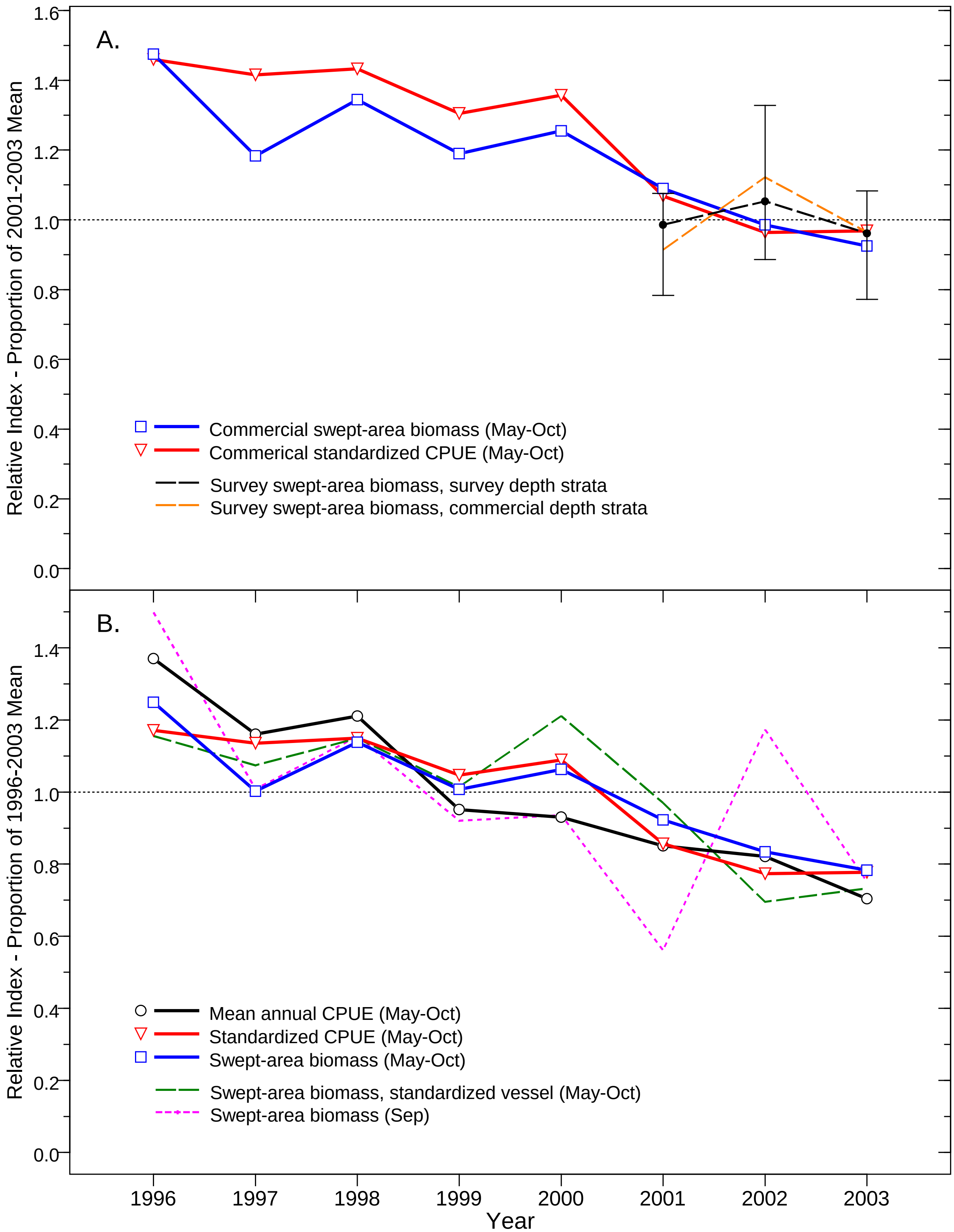

Figure 9.1. Comparison of annual abundance indices for the WCVI region: (A) commercial vs. survey indices, each standardized to its 2001-2003 mean, (B) commercial indices, each standardized to its 1996-2003 mean.

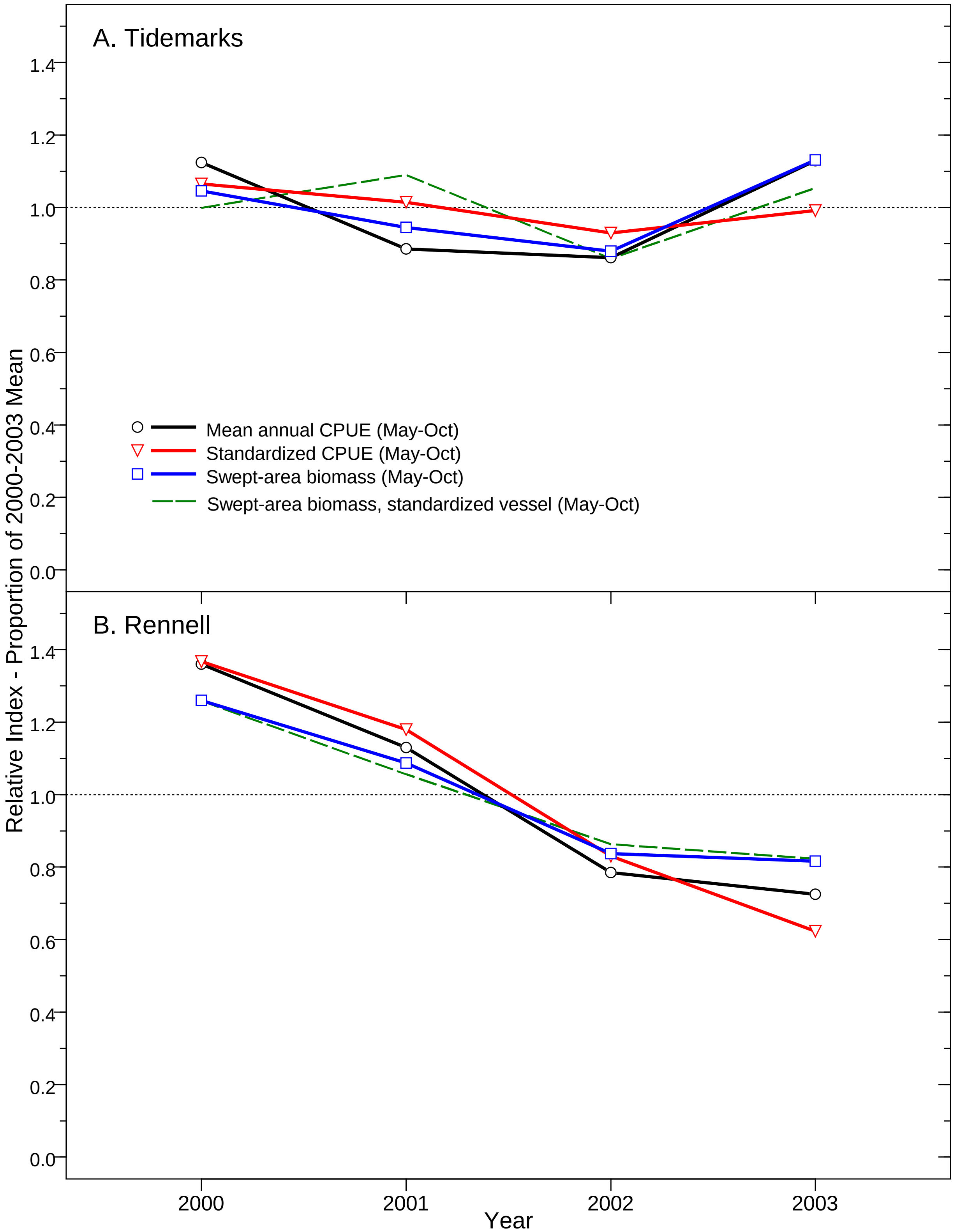

Figure 9.2. Comparison of annual abundance indices, each standardised relative to its 2000-2003 mean; (A) commercial indices for the Tidemarks region, (B) commercial indices for the Rennell region.

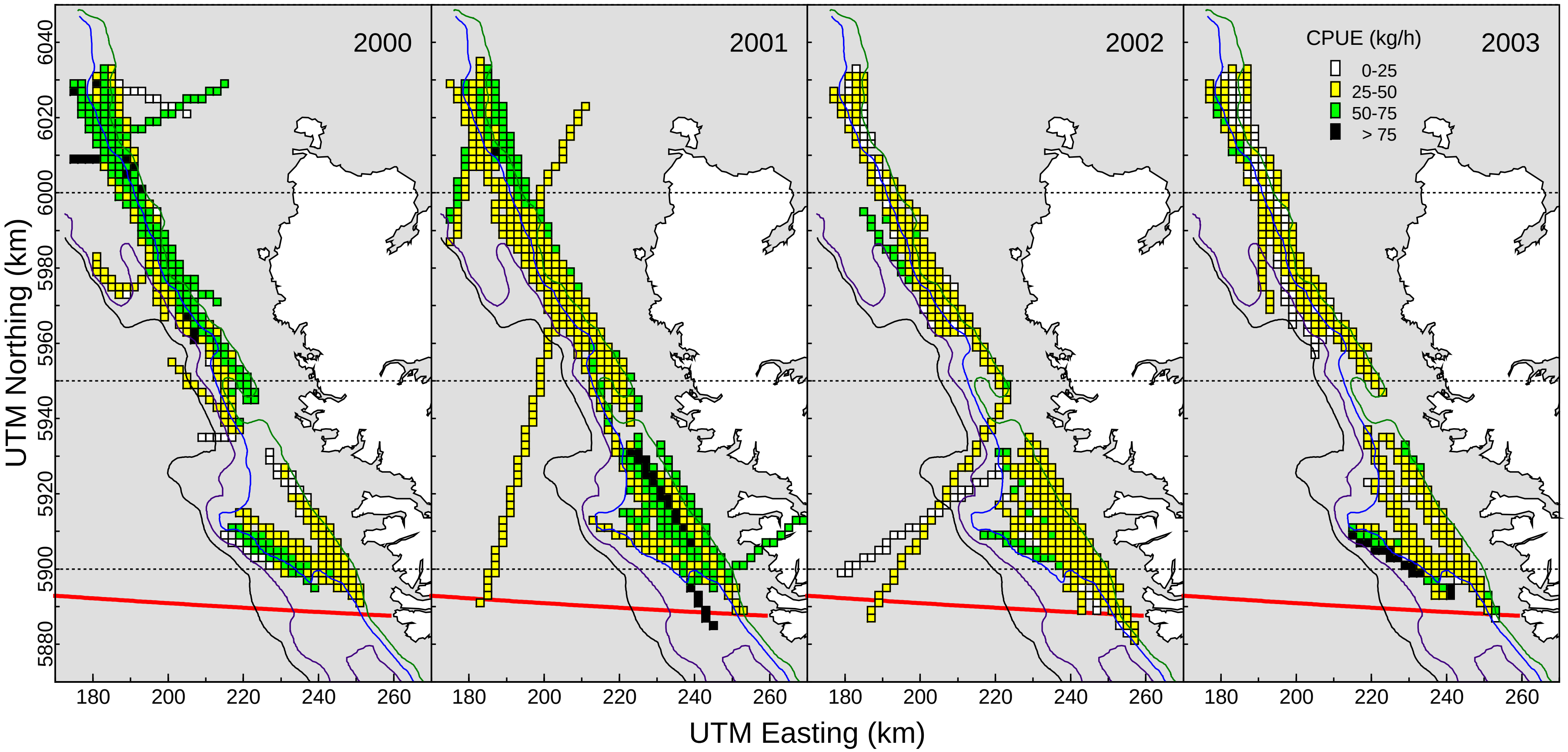

Figure 9.3. Mean longspine thornyhead CPUE (kg/h) in 2 km × 2 km grid cells in the Rennell region (May-Oct) for 2000-2003. For each tow, the CPUE was repeated every 2 km along a vector connecting the tow start and end positions before gridding. Errors in geo-referencing become obvious by strands of grid cells away from the main tow grounds. Isobaths shown (500, 800, 1200, and 1800 m) approximate survey regions comparable to those in Fig. 3.1 for the WCVI. The Rennell-Flamingo boundary is shown in red.