Inclusion of ageing error and growth variability in the estimation of age composition input sample size

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# Abstract

*Why are you doing this? [context and aim]*

*What did you do?* [*methods*](#methods)

*What did you find? [core results – say something useful – no motherhood statements or deference to the main text!]*

*What does this mean? [interpretation in context]*

*What is it good for? [application]*

# Introduction

Compositional information on age and length comprise critical data products used in statistical catch-at-age assessment models, as they facilitate the tracking of year classes and size-structure over time and improve our understanding of the population dynamics (Quinn and Deriso 1999). There are two primary sources for age and length composition data used in statistical catch-at-age models: fishery-independent sources, which include some level of randomized and standardized collection of samples in a non-targeted framework, and fishery-dependent sources, in which collection of age and length samples are also randomized at some level but are obtained from hauls that are not random but rather targeted within a specific fishery. Regardless of the source of age and length composition data, it is commonly accepted that overdispersion of collections are inherent to the data due to intra-haul correlation (e.g., Pennington et al. 2000). The concept of ‘effective sample size’ has since been developed, that is smaller than the sample size collected, to reflect the increased uncertainty due to this overdispersion (e.g., McAllister and Ianelli 1997). Since modern statistical catch-at-age stock assessment models integrate multiple sources of data related to catch (e.g., fisheries catch-per-unit-effort, survey indices of abundance), life history (e.g., size-at-age, maturity-at-age, selectivity-at-age), and composition (e.g., length and age), it is imperative to consider the relative information content these data products provide to the model employed.

Because fisheries often depend on the periodic production of strong year-classes and subsequent recruitment into fishery catch, sampling efforts for age and length data, scaling of these data to the population level (‘compositional expansion’), and the weight assigned to these data products in assessment models are highly important in order to provide accurate advice for management. This is often handled through the use of data-weighting methods, checking the fit of compositional data in the model, and ensuring a good match between the variance of the data and the variance implied by the model (Francis 2017). The weight assigned to annual compositions (the ‘input sample size’) can follow a myriad of methods (e.g., fixed values as in Monnahan et al. (2021), number of samples or tows sampled upon as in Hulson et al. (2021) or Spencer and Ianelli (2022), bootstrapping compositions as in Stewart and Hamel (2014)). The primary consideration when assigning a weight to age or length composition data is to account for the potential variability and correlation in the sampling process. The method developed by Stewart and Hamel (2014) allows for resampling techniques to be employed at each level of the sampling design, and provides an objective avenue to determine input sample size that is smaller than the actual sample size based on the observation variability contained within the sampling process.

In addition to intra-haul correlation, for every fish species sampled for which age is capable of being determined from otoliths there is resulting variability in the ageing of the otolith, often called ‘ageing error’ (e.g., Punt et al. 2008). There are a number of factors that can influence the magnitude of ageing error (Nesslage et al. 2022), but inherent to obtaining ages from otoliths is variability in the age readings. To account for this source of variability, ageing laboratories regularly evaluate precision through obtaining multiple readings of the same otolith across different age readers (Morison et al. 2005). Several methods have been developed to account for ageing error in statistical catch-at-age models when fitting age composition through the use of an ageing error matrix (Punt et al. 2008, Candy et al. 2012). The essence of this approach is that the numbers-at-age estimated by the assessment model are ‘corrected’ through multiplication with an ageing error matrix, which assigns estimated numbers-at-age to adjacent age-classes depending on the magnitude of the ageing error within the specific age-class. Since the development and implementation of ageing error matrices a number of studies have been devoted to quantifying the effects of ageing error on assessment model estimates Liao et al. (2013). Within each of these studies, and in each application of an ageing error matrix within a stock assessment model, the age composition data fit will be weighted by an input sample size. As described previously, the input sample size selected would reflect the variability in the sampling process, which would also include the variability in the age readings themselves.

In the process of compositional expansion, it is often the case that an age-length key (ALK) is employed to expand population numbers-at-length to population numbers-at-age (Ailloud and Hoenig 2019). It is through the age-length key, and the subsequent age expansion, that observations of age composition are derived from fishery-independent and fishery-dependent sources. Conditional age-at-length (CAAL), in which paired age-length data are used as in indication of the age distribution for a specific length, is used to inform length-at-age and it’s related uncertainty (Taylor and Methot 2013). CAAL data can be used directly within statistical catch-at-age models to inform estimates of growth as well as composition data (Lee et al. 2019) and has been implemented in a number of operational stock assessments (e.g., McGilliard et al. 2019, Hulson et al. 2022). An intrinsic component to both the ALK and CAAL is the variability in length for a given age. Further, when using CAAL data as an additional likelihood component to a statistical catch-at-age model one must determine the input sample size to be used to weight this information.

Despite the acceptance of requiring an input sample size to weight age composition data in statistical catch-at-age models that reflects the added uncertainty caused by overdispersion common to age sampling, and the recognition of the inherent variability in the ageing process when reading otoliths and in the growth process upon which age-length keys are based, these sources of uncertainty have not been previously integrated in an objective estimation method for input sample size. In this study, we use the methods of Stewart and Hamel (2014) to estimate age composition input sample size that includes both ageing error and growth variability in the estimation process. We show, in a step-wise process, the added variability in age composition sample size from including ageing error and growth variability across a number of species that reflect differing life histories and levels of ageing difficulty. Using a current statistical catch-at-age models that are used for assessment and management as case studies we then show the effects of this added uncertainty on assessment model results.

# Methods

## Data: age collections and reader-tester agreement

In this study we used historical data collected from bottom trawl surveys conducted by the Alaska Fisheries Science Center (AFSC) in the Eastern Bering Sea (EBS: Lauth et al. 2019), Aleutian Islands (AI: von Szalay et al. 2017), and Gulf of Alaska (GOA: von Szalay and Raring 2018). Within the AFSC bottom trawl surveys both length frequency data and age specimen data are collected (in addition to other data sources including catch, effort, location, etc.). To facilitate age estimation, individual fish are processed at sea to record sex, length and weight and to remove sagittal otoliths that are sent to the AFSC Age and Growth laboratory for age determination. Periodically, a subset of these otoliths are selected for reader-tester agreement tests, which evaluates the reproducability of an age reading when two different age readers age the same fish, without knowledge of the other reader’s determined age of the otolith (Kimura and Lyons 1991). The average annual bottom trawl survey age sample sizes for the stocks selected for this analysis by region, along with the total number of otoliths that have been selected for reader-tester agreement tests across these regions is shown in Table ??). The stocks selected to use as examples for this analysis were all stocks that had greater than 5,000 reader-tester paired otolith readings. These stocks are also all assessed with statistical catch-at-age models that require input sample sizes to ‘weight’ the age composition data fit in the stock assessment models. Details of how the length frequency and age collections are expanded to population abundance-at-length and age at AFSC to then subsequently used as compositional data in stock assessment models at AFSC are provided in Hulson et al. (in review).

## Simulation-Bootstrap framework

To evaluate the effect of the inclusion of ageing error and growth variability on uncertainty in age compostion datasets we developed a bootstrap-simulation framework that allowed for the addition of these sources of error. In simple terms, the simulation framework that we developed resamples the hauls, then lengths and ages collected within the resampled hauls following from the method introduced by Stewart and Hamel (2014). To implement ageing error, for a given resampled age, the set of tester ages for that reader age were pooled and a new age was resampled from that set. To implement growth variability, for a given resampled age the lengths observed for that age were pooled by sex, and then a new length was resampled from that set of lengths.

The bootstrap-simulation framework is composed of a suite of nested resampling protocols. Functions to run the sampling protocols were developed in a compartmentalized manner to provide for substantial flexibility in exploring desired resampling protocols. The order of operations (Figure 1 *ben - we need to add where we’re doing the ageing error and growth resampling to this figure*) has the following schedule, with steps 1-2 and 4-6 being optional switches:

1. Resample hauls from the set of hauls with associated catch per unit effort (in numbers)
2. Within the resampled hauls from step 1, resample the observed lengths
3. With the resampled length frequency data from step 2, calculate population abundance-at-length
4. Within the resampled hauls from step 1, resample the observed ages from the specimen data
5. For the resampled ages in step 4, resample a length from the set of lengths observed for the given age
6. For the resampled ages in step 4, resample an age from the set of tester ages for the given age
7. With the resampled age data in steps 4-6 and the population abundance-at-length in step 3, calculate the population abundance-at-age

The core of the bootstrap-simulation function (steps 5 and 6 above) were designed to explore inclusion of ageing error and growth variability. The bootstrap-simulation then repeated steps 1-7 iteratively providing iterated population abundance-at-age that was then compared to the historical (the full sample without any resampling of data) population abundance-at-age determined by the bottom trawl surveys.

We applied the bootstrap-simulation in a step-wise manner to evaluate the consequences of adding each source of additional error to the age composition estimates across what we term ‘uncertainty scenarios’.  
First, we ran the bootstrap-simulation with the historical data without adding any extra error, thus, omitting steps 5 and 6 above (termed the ‘Base’ scenario). Next, we added ageing error (termed the ‘AE’ scenario) and growth variability (termed the ‘GV’ scenario) separately, thus, omitting either step 5 or 6 depending on the source of uncertainty that we wanted to include. Finally, we added both ageing error and growth variability (termed the ‘AE & GV’ scenario) to the bootstrap-simulation framework. To allow for the largest number of samples from which the consequences of these sources of uncertainty could be evaluated we included reader-tester data that was pooled across these three regions. To evaluate the inclusion of growth variability we pooled the sex-specific age-length pairs across all the years of the survey in order to provide the maximum influence of growth variability on the replicated sex-specific age composition estimates. We ran the bootstrap-simulation for 500 iterations, which was a level for which the variability in population abundance-at-age results had stabilized. The bootstrap-simulation was developed in R (R Core Team 2022) and is available via GitHub as an R package (<https://github.com/BenWilliams-NOAA/surveyISS>).

## Computing effective and input sample size

A useful statistic that can quantify the variability in age composition is effective sample size, introduced by McAllister and Ianelli (1997). This statistic evaluates the amount of uncertainty in an estimated composition compared to an observed composition and is given by:

where is the estimated proportion for category-*c* (which can be age or any other arbitrary category across which proportions are computed) and is the observed proportion. Here, the underlying age composition derived from the historical bottom trawl surveys with the full and unsampled data was treated as the observed proportions in equation (1). For each iteration of the bootstrap-simulation we computed an estimated proportion () that was then compared to the underlying historical age composition () to determine the effective sample size of the resampled age composition. Thus, across each iteration of the bootstrap-simulation we computed an effective sample size that indicated the amount of uncertainty in the resampled age composition.

To summarize effective sample size across iterations we used the harmonic mean, which has been shown to reduce bias in recovering the true sample size in simulations for a multinomial distribution, and due to this reduction in bias the harmonic mean has also been recommended to determine the ‘input sample size’ that is used in stock assessment models to fit compositional data (Stewart and Hamel 2014). Herein, when we use the term ‘effective sample size’ we are referring to the effective sample sizes that were computed for each iteration of the bootstrap-simulation, when we use the term ‘input sample size’ (ISS) we are referring to the harmonic mean of the iterated effective sample sizes. While we present the results of the annual ISS for each stock evaluated when incorporating ageing error, growth variability, or both, we also compute the proportion of ‘base’ ISS in order to present the relative decrease in ISS when incorporating these sources of additional uncertainty. The proportion of base ISS is computed by dividing the ISS as determined after incorporating ageing error, growth variability, or both, by the base ISS without these sources of uncertainty.

## Evaluating life-history relationships to consequences of added uncertainty

In order to quantify trends across stocks we evaluated these stocks based on their species type. Results for three species types are shown: for flatfish (arrowtooth flounder, flathead sole, northern rock sole, and yellowfin sole), for gadids (walleye pollock and Pacific cod), and for rockfish (Pacific ocean perch and northern rockfish). We also investigated the relationship between two statistics and the cases that added ageing error and growth variability. The first statistic we used to evaluate the influence of adding ageing error was the average coefficient of variation (CV) in age agreement. We computed this by computing the CV in the tester ages for a given reader age, then averaged these CVs across the reader ages. The second statistic we used to evaluate the influence of adding growth variability was the average CV in age-length data. We computed the average age-length CV by computing the CV in length for a given age, then averaging the CVs in length-at-age across age.

# Results

While the magnitude of age composition ISS was stock and region specific, the general result that was consistent across the stocks evaluated was a reduction in age composition ISS as additional sources of uncertainty were introduced in the bootstrap procedure (Figure 2). This reduction in age composition ISS resulted for both sex-specific and total (combined sex) age composition ISS. The relative magnitude of adding ageing error compared to growth variability was also stock and region specific. For example, adding ageing error to arrowtooth flounder age data resulted in smaller ISS than adding growth variability in the GOA, but larger ISS in the EBS. Variability in the age composition ISS across uncertainty scenarios evaluated was also stock and region specific, where Pacific cod and walleye pollock in the EBS resulted in the largest variability in ISS and AI Atka mackerel resulted in the smallest.

The proportional reduction in age composition ISS compared to the base case across uncertainty scenarios revealed patterns across species types within each region evaluated (Figure 3). In general, including ageing error in rockfish age data had a larger proportional reduction in age composition ISS than including growth variability. Alternatively, adding growth variability to flatfish and gadid data had a larger proportional reduction in age composition ISS than adding ageing error. Across the regions and uncertainty scenarios investigated, the largest variability in the proportional reduction in age composition ISS in any given region resulted for flatfish. Across the regions and uncertainty scenarios investigated, the largest range among the reduction in region-specific age composition ISS when adding additional sources of error resulted for gadids. For example, after adding both ageing error and growth variability the proportional reduction in age composition ISS was 85-95% of base ISS for gadids in the AI, 40-50% for gadids in the EBS, and 70-80% for gadids in the GOA. Overall, when adding both ageing error and growth variability across the regions evaluated the age composition ISS resulted in 50-90% of the base age composition ISS for flatfish, 40-90% for gadids, and 80-95% for rockfish.

For each of the uncertainty scenarios investigated the relationship between age composition ISS and the number of sampled hauls was not one-to-one for any of the species type evaluated (Figure 4). It was also the case that across the uncertainty scenarios investigated there was large variability in the age composition ISS compared to the number of sampled hauls for each species type evaluated, and any trend was difficult to distinguish. While an increasing trend resulted for rockfish and flatfish between age composition ISS and the number of sample hauls when fitting a linear model to the data, it was generally the case that the age composition ISS was larger than the number of sampled hauls for hauls less than 100-200, and smaller than the number of hauls for hauls larger than 100-200. This increasing trend for rockfish and flatfish degraded as additional sources of uncertainty were added, but for each uncertainty case the trend was not one-to-one. In each of the uncertainty scenarios investigated the trend between age composition ISS and the number of hauls for gadids was different than that for rockfish and flatfish, and while there was a slight increase in age composition ISS as the number of hauls increased, it was not as large of an increase as that which resulted for rockfish and flatfish.

For each species type there was a generally increasing trend that resulted between the number of age samples taken per haul and the age composition ISS per sampled haul (top panel of Figure 5 *i haven’t yet figured out how to match the font in the shared y-axis title with the rest of the figure*). However, as sources of uncertainty were added to age data this increasing trend was dampened for each species type; this was particularly true for gadids as compared to flatfish and rockfish. Across species types the age composition ISS per haul was around half of the number of sampled ages per haul, less for rockfish and gadids. The age composition ISS per haul was, on average, the largest for flatfish, followed by rockfish, and was the smallest for gadids (bottom panel of Figure 5). The variability in the age composition ISS per haul across years, regions, and sex categories was also the largest for flatfish compared to gadids and rockfish.

Comparing between statistics for ageing error and growth variability resulted in different trends in the proportional reduction of age composition ISS upon comparison across species types (top panels of Figure 6). The proportional reduction in age composition ISS when adding ageing error was similar when compared to the average reader-tester CV between gadids and rockfish, where the variability was smaller for rockfish (top left panel of Figure 6). While the range in average reader-tester CV was smaller for rockfish and gadids than for flatfish, the resulting range in proportional reduction in age composition ISS for gadids was larger than rockfish and flatfish. The proportional reductions in age composition ISS when adding growth variability resulted in the smallest range in both ISS reduction and average age-length CV for rockfish, but had a large range and was quite similar between flatfish and gadids (top right panel of Figure 6). On average, the proportional reduction in age composition ISS when adding both ageing error and growth variability was smallest for rockfish, intermediate for flatfish, and largest for gadids (bottom panel of Figure 6). The same trend resulted when evaluating the range in the proportional reduction in age composition ISS when both ageing error and growth variability were added.

# Discussion

[Summary para of main results]

[Cost-benefit of precision compared to survey injuries]

[Still thinking on other paras]

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# Tables

Table 1: Average age samples from the AFSC bottom trawl surveys by region (rounded to the nearest 10), and total reader-tester age pairs (rounded to the nearest 100) for the species evaluated in the bootstrap-simulation.

| Stock | Scientific name | AI | EBS | GOA | R-T |
| --- | --- | --- | --- | --- | --- |
| arrowtooth flounder | Atheresthes stomias | 450 | 480 | 850 | 6,100 |
| Atka mackerel | Pleurogrammus monopterygius | 600 | – | – | 12,900 |
| flathead sole | Hippoglossoides elassodon | – | 560 | 520 | 9,400 |
| northern rock sole | Lepidopsetta polyxystra | – | 460 | 450 | 8,900 |
| northern rockfish | Sebastes polyspinis | 570 | – | 450 | 6,400 |
| Pacific cod | Gadus macrocephalus | 800 | 1070 | 650 | 21,200 |
| Pacific ocean perch | Sebastes alutus | 940 | – | 1030 | 13,500 |
| walleye pollock | Gadus chalcogrammus | 790 | 1500 | 1300 | 84,400 |
| yellowfin sole | Limanda aspera | – | 750 | – | 10,300 |

# Figures



Figure 1: Bootstrap-simulation flow chart, the steps refer to the order of operations.

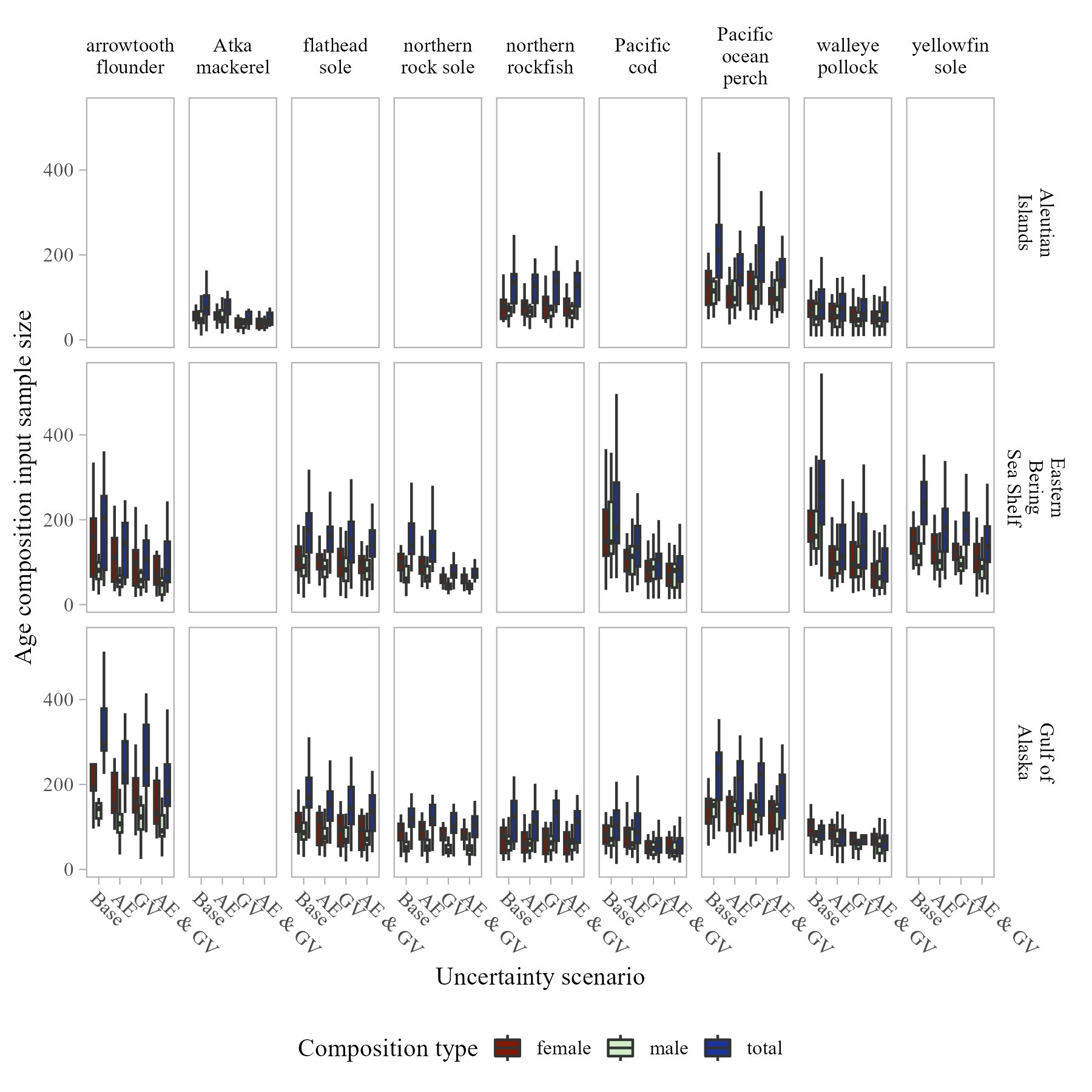


Figure 2: Age composition input sample size for the stocks and regions evaluated across uncertainty scenarios.

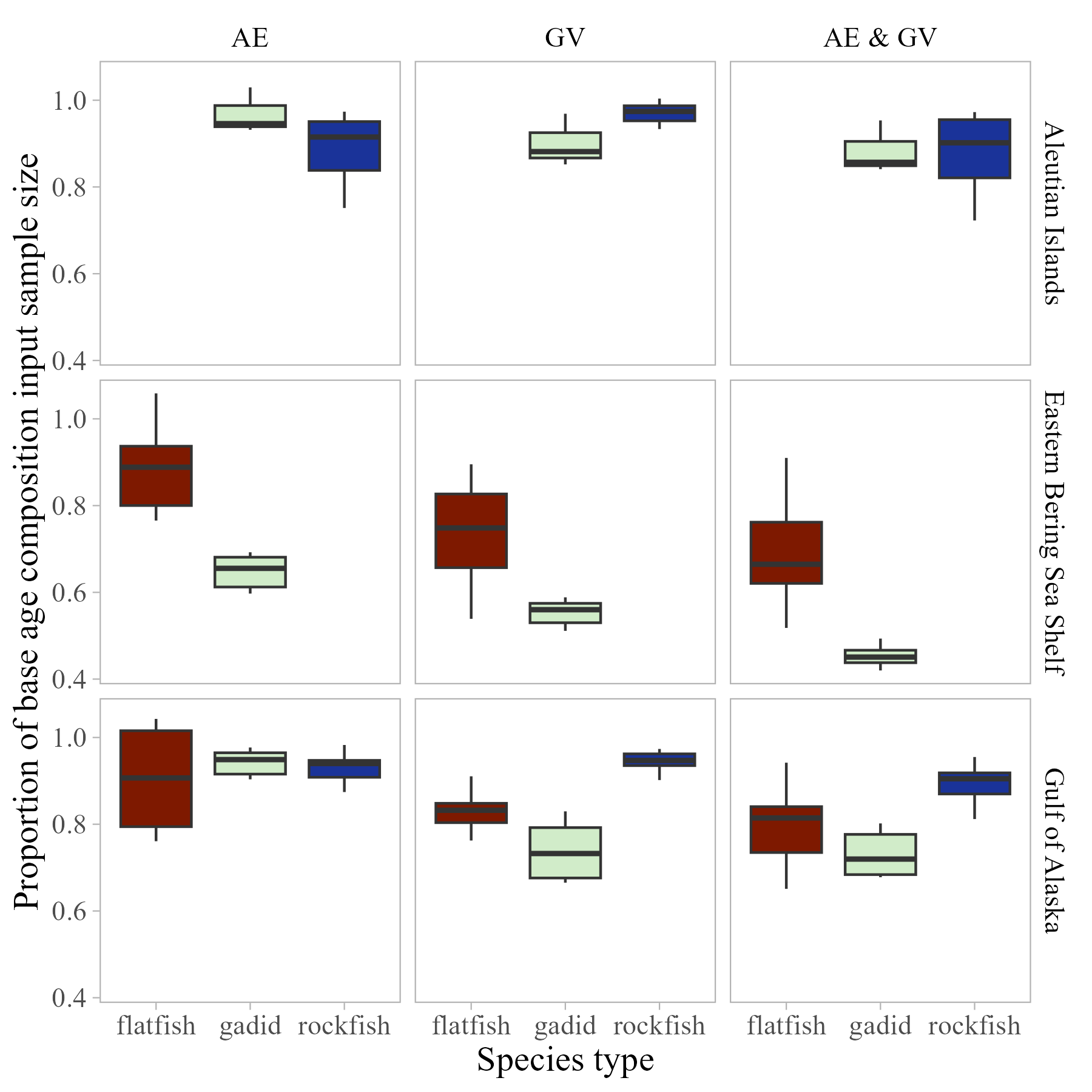


Figure 3: Proportion of base case age composition input sample size by species type across sex categories and uncertainty scenarios.

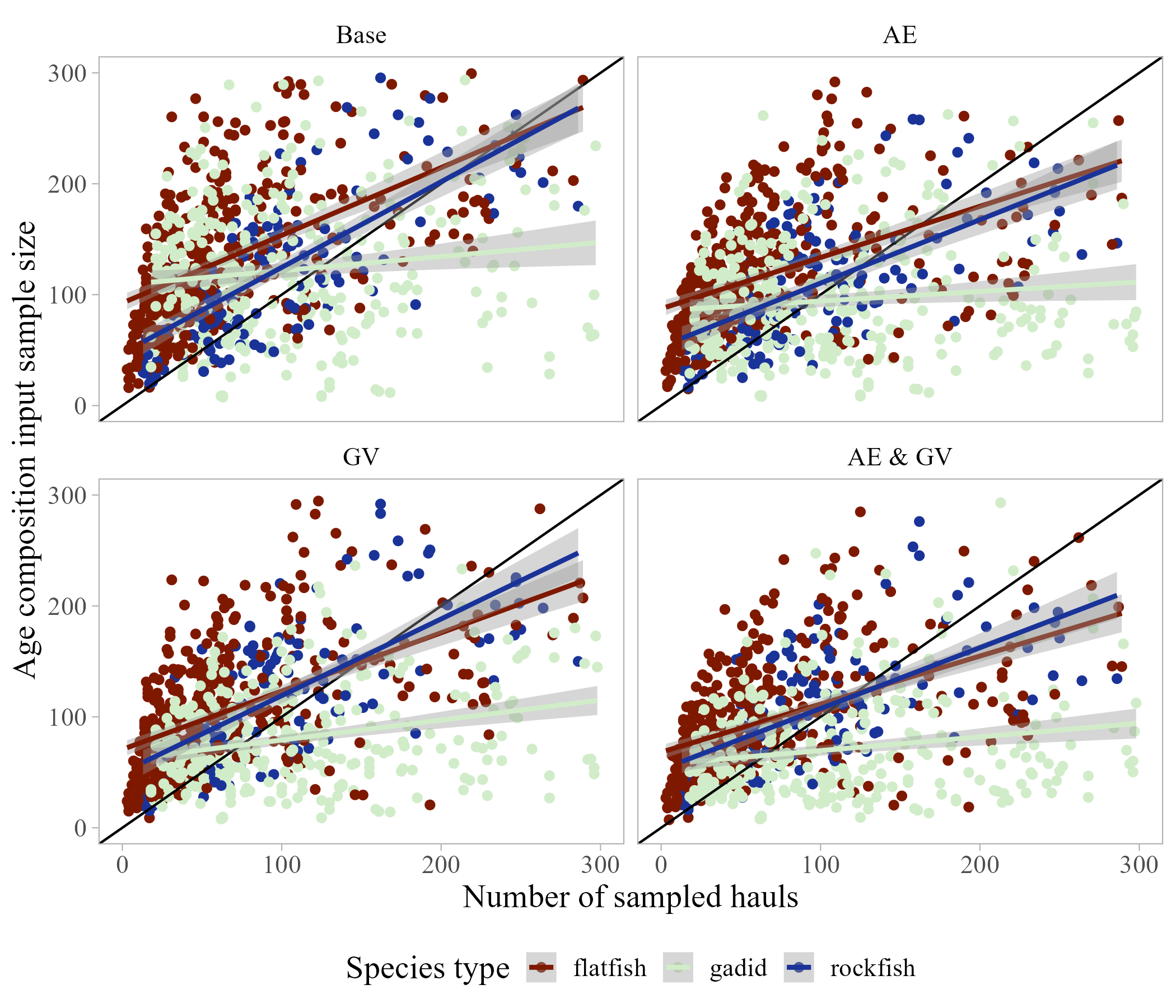


Figure 4: Age composition input sample size compared to number of sampled hauls across uncertainty scenarios and species types (linear fit by species type shown for illustration).

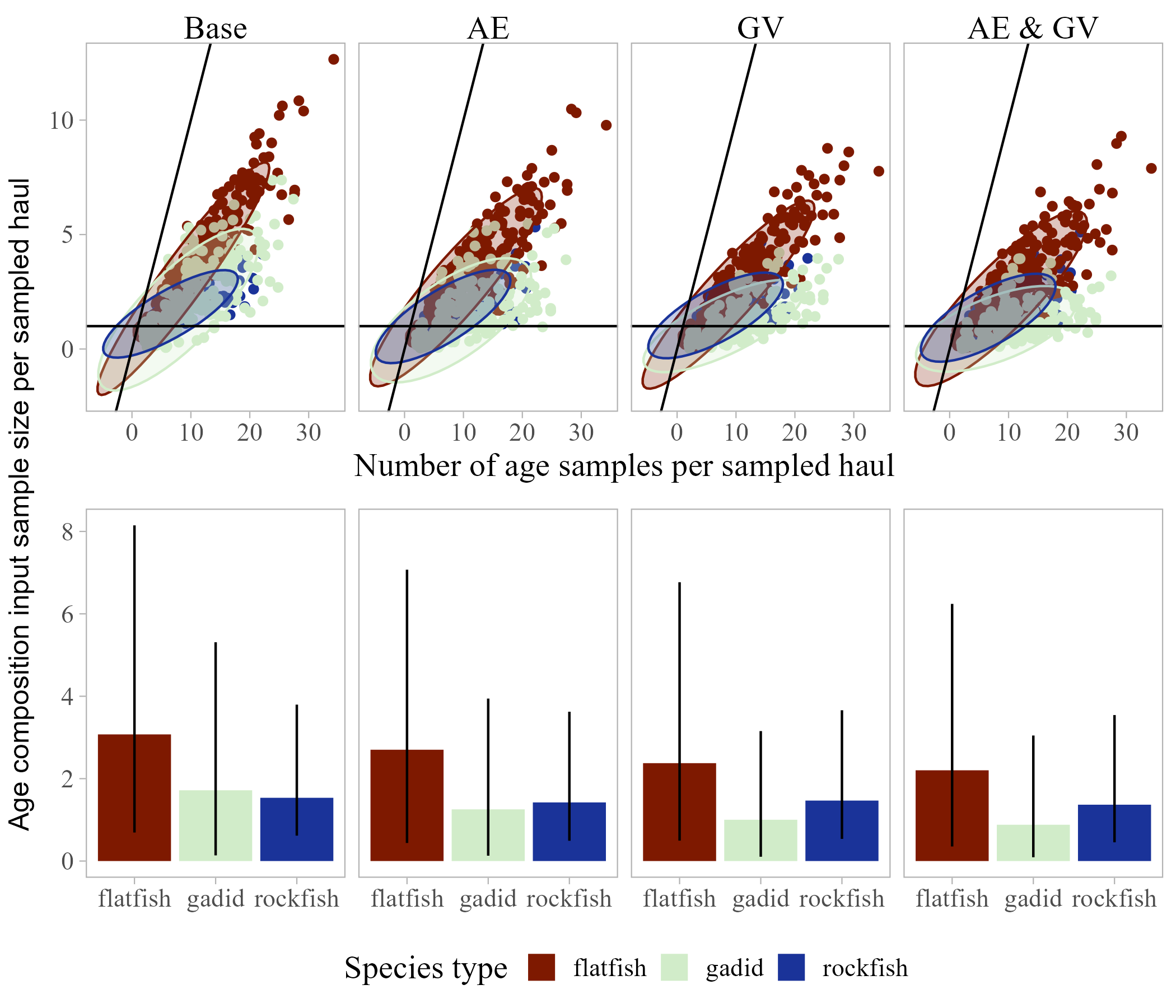


Figure 5: Age composition input sample size per sampled haul compared to number ages sampled within a haul (top panel) across uncertainty scenarios and species types (bottom panel).

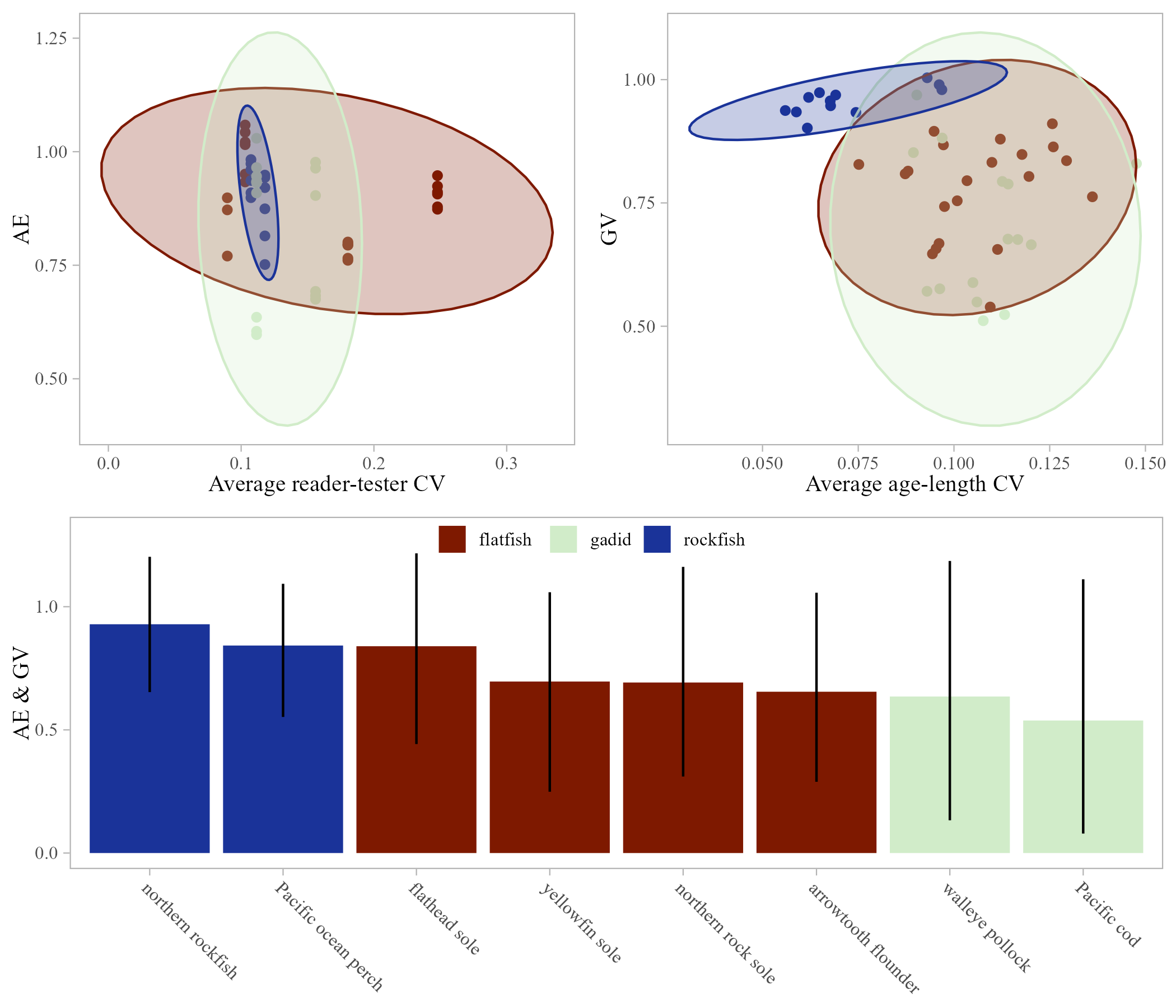


Figure 6: Proportional reduction in age composition input sample size compared to age and growth statistics (top panel) and across stocks evaluated (bottom panel).