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Somatic-Otolith Size Correlations for 18 Marine Fish Species and Their Importance to Age Determination

by

Kristen M. Munk

August 2012

Alaska Department of Fish and Game **Division of Commercial Fisheries**

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Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature

day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry

all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General

Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat. or long.
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Measures (fisheries)

fork length	FL
mideye-to-fork	MEF
mideye-to-tail-fork	METF
standard length	SL
total length	TL

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	log_2, etc.
minute (angular)	'
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	"
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

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ABSTRACT

Somatic and otolith measurements and their relationships are documented for 18 North Pacific marine teleost species representing 9 taxonomic families: 14 groundfish species (sablefish *Anoplopoma fimbria*, lingcod *Ophiodon elongatus*, walleye pollock *Theragra chalcogramma*, pacific cod *Gadus macrocephalus*, pacific halibut *Hippoglossus stenolepis*, and 9 rockfish species (*Sebastes* spp., *Sebastolobus alascanus*) and 4 forage fish species (Pacific sand lance *Ammodytes hexapterus*, Pacific herring *Clupea pallasi*, shiner perch *Cymatogaster aggregata*, and eulachon *Thaleichthys pacificus*). Strong positive relationships were found between somatic lengths and otolith lengths (range $r = 0.81$ to 0.98; mean $r = 0.90$) and otolith weights, and in symmetry between left and right sagittae otoliths (mean lengths $r = 0.97$; mean heights $r = 0.95$; and mean weights $r = 0.99$) for all species. Length-length (or height) relationships were generally isometric and length-weight relationships tended to be allometric; curvilinearity became more evident when the sample included juvenile and subadult specimens (which often were lacking in samples from commercial harvests). Vateritic and or dysmorphic otoliths were generally infrequent; the incidence across these 18 species ranged from 0% up to 11% (mean incidence = 3%). The strong correlation between somatic growth and otolith accretion supports the notion that incremental otolith accretion and intrinsic growth patterns might record and display that which influences somatic growth. The uniformity observed in these objective somatic-otolith relationships across 9 taxonomic families suggests that otolith accretion reference cues, which are used to interpret otolith growth patterns for age estimation, should tend toward consistency—and not divergence—amongst teleosts.

Key Words: Otoliths, age structure measurements, somatic-otolith correlation, teleosts

INTRODUCTION

Otoliths have long been the preferred age structure in order to estimate age of fish (Williams and Bedford 1974; Chilton and Beamish 1982; Campana 2005), especially for those species which are long-lived (Munk 2001). Otolith age estimates are used in age structured models for the purpose of understanding fish population dynamics and setting harvest goals (for example, Carlile 2005; Dorn et al. 2010; Ianelli et al. 2010). Age estimation, as typically applied at production age reading facilities, is the subjective process of perceiving and enumerating presumed annual growth increments through the application of standardized methods and criteria.

‘Standardized methods and criteria’ is a necessary though obfuscatory phrase referencing the synthesis of the technical and intellectual processes which result in individual specimen ages that in turn guide our understanding of species age. Collectively applied, subjective technical and intellectual processes can enable accurate age estimation; however, misapplication can result in inaccurate age estimates and subsequent misunderstanding of life history dynamics. Objectively validating the processes and methods which result in age estimates is crucial to ensuring accuracy of age data.

Today the validation of annual growth patterns is less the ‘forgotten requirement’ once heralded by Beamish and McFarlane (1983); it has since been answered by a multitude of researchers (for example, Bennett et al. 1982; Kalish 1993; Campana 1997; Andrews et al. 1999; Kerr et al. 2005, and many others). The increasing frequency of age validation has been enabled by newer and presumably better validation technologies. More age validation work is needed, including development and refinement of age validation techniques. Almost without question, published age validations and application of the techniques are accepted to confirm the reported ages and longevity of fishes. Acceptance is often despite persisting questions of the methodology and underlying assumptions which enable the validation technique. For example, the radiometric lead-radium age validation technique continues to be upheld (Whitehead and Ditchburn 1995; Baker et al. 2001), contested (West and Gauldie 1994; Gauldie and Cremer 2000), identified with ambiguous outcomes (Kastelle and Forsberg 2002)

or encouraged for technique improvement (Baker et al. 2001)—despite continued application using novel approaches (Kastelle and Kimura 2006) which increase the number of assumptions. The bomb radiocarbon chronometer (Kalish 1993) is an age validation technique that has fewer, less onerous assumptions and does have favorable application details, most notably the need for a single fish per sample (compared to a composite sample from multiple [n ~ 40] fish for the radiometric technique) with the ability to determine age to ±3 y (Campana 2001). Although accurate, the bomb radiocarbon chronometer is typically limited to discriminating birth years for a very narrow range of years; Campana (2001) states that "the years 1958 to 1965 [are] the most sensitive years for Δ^{14}C-based ageing." Regardless, age validation and improvement in the age validation techniques remain key to the process of producing age data.

Greater objectivity in growth pattern interpretation is necessary and challenging. The processes used in examining growth patterns should be rooted in objective data and established biological concepts—not unfounded traditional ideologies or biased studies. Otolith dimensions—often in relation to somatic dimensions—are objective data that can add to and inform the subjective application of 'standardized age reading criteria'.

This study was undertaken to document the relationships between objectively measured somatic and otolith dimensions for numerous teleost species, and then to combine this objective foundation along with other scientific studies that connect otolith growth patterns with environmental fluctuation or life history markers, in order to propose a general understanding of otolith accretion (annual level) in teleosts. This documentation of somatic-otolith relationships serves to broaden and deepen the objective foundation reported by many others (e.g. Frost and Lowry 1981; Boehlert 1985, Echevarria 1987; Pawson 1990; Battaglia et al. 2010).

METHODS

SOMATIC DATA AND OTOLITH COLLECTION

Commercial or research harvests of fish were conducted in the marine waters of Alaska. These harvests were randomly sampled and somatic data and sagittal otoliths (from here forward 'otolith') collected: fork length (tip of snout to fork of tail) was recorded in inches, centimeters, or millimeters (measurements were converted to millimeters as needed); whole fish weight was recorded in pounds, kilograms, and grams (weights were converted to grams as needed); otoliths were excised, the tissue, blood, and lymph were removed, and the otolith pair was placed in a dry container (coin envelope, plastic bag, or tray-cell). Otoliths were sent to the ADF&G Age Determination Unit in Juneau where the samples were inventoried and dried for at least several weeks prior to measuring.

OTOLITH MEASUREMENT

The otolith length (anterior-posterior) and height (dorso-ventral) were measured to 0.01 mm using digital calipers (Munk and Smikrud 2002 Figure 1). Otoliths from the majority of specimens were weighed on a digital balance to 0.001 g (balance resolution ±0.001 g). Very small otoliths from young fishes or species with small otoliths (for example, Pacific sand lance) were weighed on an analytical balance to 0.0001 g (balance resolution ± 0.0001 g). Otoliths were observed for the presence of vaterite and dysmorphia (a misshapen otolith per expected species shape; Figure 2) and the percentage of affected area was estimated and

recorded. Occurrence of vaterite or dysmorphia in at least one otolith of the pair was considered 'presence' for the specimen. Otoliths were identified as 'left otolith' and 'right otolith', or, 'otolith-1' and 'otolith-2' and the dimensions and attributes recorded. Prior to 2006, otolith measurements were manually entered into an EXCEL worksheet template and these data lists were then imported into a database. After 2005, the otolith length and weight measurement data were transmitted directly from the instruments to our database through custom computer interfaces collectively known as AegIS (Age Information System; AegIS 2011[1]).

Halibut otoliths (1 per fish) and somatic data were received from the International Pacific Halibut Commission (facilitated by J. Forsberg). The otolith was measured for length, height, and weight and data were recorded into an EXCEL worksheet.

DATA SET DEVELOPMENT

For this study, two standardized ACCESS queries were run against our database AegIS (AegIS 2011) and data were exported into EXCEL spreadsheets. Each query produced a discrete set of data for each species. The Otolith-Otolith data set by species was used to evaluate symmetry between left and right otoliths. The Otolith-Otolith data set required dimensions to be present for both otoliths per specimen. The Otolith-Otolith data set did not require somatic dimensions to be present for the specimen record. The Somatic-Otolith data set by species was used to document the correlation between somatic and otolith dimensions. The Somatic-Otolith data set required dimensions of fish fork length and dimensions for at least one otolith to be present; mean otolith measures were used when both otoliths had been measured. Data were examined graphically and gross outliers were checked for errors. Corrections were made when errors (for example, mismeasurement, transcription) for the original measurement effort were realized. If outliers could be evaluated and were found to not result from measurement or transcription errors they were retained in the study data set. However, if the error could not be fully evaluated then the outlier was discarded from the data set; for example, an outlier on "fish fork length" could be checked against the original field data sheet but could not be checked against the fish. Remaining outliers were retained in the study data set when field samplers had specifically noted an observation of different-sized otoliths at sampling. In either data set, specimen records indicating that one or both otoliths were vateritic or dysmorphic were excluded from calculation of correlation coefficients and relationships. However, vateritic/dysmorphic otoliths were charted to depict their general relationship to the Otolith-Otolith data set.

DATA ANALYSES

All graphical comparisons and statistical analyses were conducted using MS EXCEL (Microsoft Inc. 2003). Linear relationships were defined with the function $y=La+b$. Curvilinear relationships were defined with the common power function $y=aL^b$. Pearson correlation coefficients (r) were calculated for all visually apparent linear relationships.

[1] AegIS. 2011. Age Information System, Version 2.0. Alaska Department of Fish and Game, Juneau, Alaska.

RESULTS

A total of 18 species are presented in this study (Table 1). These species represent 9 taxonomic families, 2 general groupings (groundfishes and forage fishes), in 3 representative forms: compressiform, sagittiform, and depressiform (Bond 1979). Among the Otolith-Otolith and Somatic-Otolith data sets, sample sizes ranged from 26 to 43,081 per species (Table 2). A total of 230 data outliers (out of >80,000 specimen records) were graphically determined and researched for accuracy. Approximately 62% of researched outliers were changed and updated values entered into the data set, 24% were not changed and were retained in the data set and the remaining 14% were excluded from the data set.

The frequency of one or both otoliths containing vaterite ranged from 0% to 11% across all species (see Table 2). The left and right otoliths were highly symmetrical for all species (Figure 3). Correlation coefficients were averaged across all species: mean otolith length r = 0.97, mean otolith height r = 0.95, and mean otolith weight r = 0.99 (Table 3).

Somatic length to otolith length and height relationships for all species were generally linear (therefore, isometric; Figure 4) with r's ranging from 0.81 to 0.98 (see Table 3). Linearity was greater in samples which lacked otoliths from juvenile fish. Our samples mainly arise from commercial harvests which typically encounter larger fish, while opportunistic collections encountered either the full range in size, or, juveniles. The inclusion of younger fish introduced an inflection point in the relationship. Length (somatic, otolith) to otolith weight relationships tended to be curvilinear (therefore, allometric; Figure 4). Curvilinearity in weight to length (or height) relationships generally became more apparent upon inclusion of specimens across the complete range in size for the species. Otolith weights were transformed in an attempt to linearize these data. Iterations of log transformations were first applied and rejected due to insufficient linearity (based upon visual inspection of scatter plots, low r's, and residual plots). The square root transformation was next applied to all species. While for some species the square root transformations were an improvement over log transformations, charting of residuals of square root-transformed otolith weight to somatic length (mean r = 0.90) indicate that it did not linearize data for all species (Figure 5).

DISCUSSION

Objective somatic and otolith measurements for 18 teleosts indicate strong isometric and allometric relationships. This outcome was expected and is typical; many other researchers have reported similar relationships for somatic and otolith dimensions. For example, Echeverria (1987) reports strong correlations between total fish length and otolith length on 30 rockfish species (I present 3 rockfish species [different stocks] overlapping and in agreement with their work); Battaglia et al. (2010), 16 Mediterranean species; Boehlert (1985), 2 rockfish species; and Frost and Lowry (1981) for 3 gadids. Among these and many others, no known studies involving macrostructural (therefore, annual) accretion scale suggest nonisometric or nonallometric relationships for somatic and otolith dimensions. At a microstructural accretion level (~daily timescale), Mosegaard et al. (1988) observed an uncoupling of somatic growth and otolith accretion for arctic char in response to temperature differences. Templeman and Squires (1956), Secor and Dean (1989), and Huuskonen and Karjalainen (1998) observed that fish growth rate can influence otolith size.

The strong relationship in these somatic-otolith dimensions among these 18 species suggests that processes which influence somatic growth might also influence otolith accretion and

therefore be evident within the growth pattern. Researchers have previously documented linkages between otoliths and physiological dynamics. For example, Francis and Horn (1997) and Hutchinson et al. (2007) connect the life stanza "sexual maturity" to visible growth pattern information within the otolith. Pereira et al. (1995) and Black et al. (2005) revealed that environmental dynamics are expressed as variation in annual otolith increments. MacLellan and Saunders (1995) reported a natural tag induced in the otoliths of Pacific hake attributed to the 1982-1983 El Nino. Begg et al. (2001) distinguished between stocks using differences in internal otolith morphometrics.

Otolith accretion mirrors somatic growth for these 18 species and numerous more species reported by many others (for example Frost and Lowry 1981; Echeverria 1987; Battaglia et al. 2010), and this suggests uniformity in the otolith accretion mechanism among teleosts. Across many taxa, the physiological and environmental linkages between somatic and otolith suggest that otolith accretion, and subsequent interpretation of growth pattern details, are more likely similar than not. This implies that common otolith growth pattern interpretive details (e.g., topography, transition zones, compressed growth zones, multi-year growth cycles, etc.; Munk 2001) and their understanding, may require similar application among teleosts after taking species-specific morphological differences into account. For example, otolith patterns (annual timescale) are understood to progress from juvenile-type growth stanza through adult-type growth stanza with an intervening transition zone (Chilton and Beamish 1982; Francis and Horn 1997; MacLellan 1997; Munk 2001; Hutchinson et al. 2007). This visually interpreted transition zone marks the growth stanza when both somatic growth and otolith accretion begins to slow/lessen. Through examination of growth patterns and charted otolith dimensions, this transition zone is evidenced as the inflection point in the allometric relationship of otolith weight at somatic length. A slowing rate of accretion results in narrower annual otolith increments. An expectation of this slowing down—the transition zone—must be realized within the species-specific context of the otolith shape (therein its growth axes) and therefore within the pattern interpretation criteria, otherwise misestimation of age might result.

Scientific investigation benefits from overarching concepts. One example of an overarching concept is that teleosts which dwell in cold, deep water and share a physical environment that fluctuates, tend to be longer-lived and have environmentally mediated growth response. Longevity has been linked to fishes living (putatively evolving) in cold, deep water (Pauly 1979; Gerking 1957); an exception is made for shallow, arctic water species (Pauly 1979). Cailliet et al. (2001) synthesized information supportive of the 'long-lived' theory. Black et al. (2005) reported on the strong correlation between annual otolith growth increment width and fluctuations within the environment, for a deep water rockfish (groundfish) species. Hollowed and Wooster (1995) report synchronous recruitment pulses among groundfish species, correlated with fluctuation in their environment. These studies connect and then guide subsequent investigation relative to the broadened understanding that deep-dwelling and long-lived fishes record and reflect environmental signals in their otoliths.

Teleost otolith growth (age) pattern interpretation can benefit from an overarching concept that uses the objective somatic-otolith dimension relationships along with other otolith studies to guide age estimation and understanding of species age. This conceptual otolith accretion model (OAM)—first advanced in this paper—has three constituents:

1. Otoliths accrete as a function of somatic growth and its influences.

2. Otolith accretion mechanisms are homogeneous throughout senescence.
3. Calcium metabolism is evolutionarily conserved amongst teleosts.

This OAM states the following. (1) Otolith development mirrors somatic growth (this study; Frost and Lowry 1981; Echeverria 1987; Battaglia et al. 2010; Munk 2011; many others) and reflects that which influences somatic growth (Pereira et al. 1995; Black et al. 2005). (2) Otolith accretion (therefore addition of increments or its mass), is growth-independent and growth-dependant (Huuskonen and Karjalainen 1998), and accretion progresses in accord with (and throughout) life history growth stanzas: generally rapid growth (accretion of wider increments, with concomitant greatest annual mass) through immature, juvenile stanza; slowing or 'transitional' growth (accretion of increments with decreasing width and therefore decreasing mass) through maturing, subadult stanza; and slower maintenance growth (accretion of much narrower increments and therefore less mass) through mature, adult stanza. Annual otolith accretion is strongly correlated with somatic growth at an annual timescale (Matic-Skoko et al. 2011; Munk 2011) and is modestly variable (Pereira et al. 1995; Black et al. 2005) but not widely variable nor chaotic (Munk 2011). (3) Otoliths are primarily calcium carbonate (Degens et al. 1969), accrete through the physiological mechanism of calcium metabolism (Simkiss 1974), and, calcium metabolism is speculated to have evolved uniformly among species (Gorbman et al. 1983). The overall connectivity of these factors support the conceptual OAM, which can aid development and application of 'standardized age reading criteria' and provide consistency in the age interpretation of teleost otoliths.

In theory, applying this conceptual OAM should result in consistent understandings of general age and growth among groundfish species. However, at least one study outcome is inconsistent; Kastelle and Kimura (2006) concluded that walleye pollock aged in accord with the 'young age profile' method (termed Method A per Kastelle and Kimura 2006) was validated, thus invalidating an alternate 'old age profile' method (termed Method B per Kastelle and Kimura 2006). Yet, Method B is consistent with the OAM; it (1) utilizes otolith half sections for 100% of the specimens (not ~33% as with Method A) to enable discovery of older annuli that would not be viewable on the otolith surface (Beamish 1979; Chilton and Beamish 1982; Boehlert and Yoklavich 1984; MacLellan 1997); (2) observes and enumerates more frequent topographical ridges (annual otolith ridges) on the otolith surface which have a steadily decreasing inter-ridge spacing (while Method A does not acknowledge the same topographical periodicity as annual); and (3) recognizes senescence within the growth pattern (general rate of decline in accretion that represents fast, transitional, and slow growth stanzas). The Method B criteria also produce estimates of mean annual accretion which also reflect an understanding of senescent growth (Munk 2011), that is, a steadily decreasing rate of accretion after an early peak in accretion at age 2 y; while Method A estimates of mean yearly accretion are inconsistent with a senescent growth concept (Munk et al. 2011).

In summary, objective measurements of somatic and otolith dimensions were found to be highly correlated for 18 species—9 taxa—of groundfish and forage fishes. This outcome is consistent with numerous researchers reporting similar outcomes amongst dozens and dozens of teleosts. No contrary (nonisometric or nonallometric) somatic-otolith comparisons were evident. Documenting and understanding the fundamental connection between somatic and otolith dimensions can aid in developing and reinforcing standardized age reading criteria. The consistency in these relationships among so many teleosts directs us to uniformly interpret the features of accretion. A conceptual model, the OAM, synthesizes the fact of

otolith-somatic relationships with other studies which link otolith accretion to environmental variables, and this model can improve the understanding of growth patterns and their interpretation and perhaps result in more accurate age data.

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TABLES AND FIGURES

Table 1.– Otoliths from 18 species across 9 taxonomic families were examined for relationships between somatic and otolith dimensions.

Common Name	Scientific Name	Taxonomic Family	Species Complex	Body Form
Pacific Cod	*Gadus macrocephalus*	Gadidae	groundfish	sagittiform
Lingcod	*Ophiodon elongatus*	Hexagrammidae	groundfish	sagittiform
Black rockfish	*Sebastes melanops*	Scorpaenidae	groundfish	compressiform
Shortspine Thornyhead	*Sebastolobus alascanus*	Scorpaenidae	groundfish	compressiform
Yelloweye rockfish	*Sebastes ruberrimus*	Scorpaenidae	groundfish	compressiform
Quillback rockfish	*Sebastes maliger*	Scorpaenidae	groundfish	compressiform
Rougheye rockfish	*Sebastes aleutianus*	Scorpaenidae	groundfish	compressiform
Shortraker rockfish	*Sebastes borealis*	Scorpaenidae	groundfish	compressiform
Redbanded rockfish	*Sebastes babcocki*	Scorpaenidae	groundfish	compressiform
Dusky/Dark rockfish	*Sebastes variabilis/ciliatus*	Scorpaenidae	groundfish	compressiform
Redstripe rockfish	*Sebastes proriger*	Scorpaenidae	groundfish	compressiform
Walleye Pollock	*Theragra chalcogramma*	Gadidae	groundfish	sagittiform
Sablefish	*Anoplopoma fimbria*	Anoplopomatidae	groundfish	sagittiform
Pacific herring	*Clupea pallasi*	Clupeidae	forage fish	sagittiform
Pacific sand lance	*Ammodytes hexapterus*	Ammodytidae	forage fish	sagittiform
Shiner perch	*Cymatogaster aggregata*	Embiotocidae	forage fish	compressiform
Eulachon	*Thaleichthys pacificus*	Osmeridae	forage fish	compressiform
Pacific halibut	*Hippoglossus stenolepis*	Pleuronectidae	groundfish	depressiform

Table 2.– Two discrete data sets "Somatic - Otolith" (S-O) and "Otolith - Otolith" (O-O) for each species were used throughout comparisons; a subset of the O-O data set was used to quantify vateritic or dysmorphic (V-D) otoliths. Maximum, minimum, and mean somatic (Som) and otolith (Oto) values within these data sets are presented. Species-specific sample sizes ranged from n=26 to n=43,081, collectively over 80,000 specimens across all species.

Data Set	Somatic - Otolith										Otolith - Otolith			
Common Name	S-O n	Min Som Len mm	Max Som Len mm	Mean Som Len mm	Min Oto Len mm	Max Oto Len mm	Mean Oto Len mm	Min Oto Wt g	Max Oto Wt g	Mean Oto Wt g	O-O n	V-D n	# V-D	% V-D
Pacific cod	4539	32	960	595	1.2	24.2	17.1	0.001	1.080	0.452	3180	3519	339	9.6%
Lingcod	12,436	75	1650	959	0.8	14.5	10.2	0.0001	0.144	0.059	7782	11882	190	1.6%
Black rockfish	823	310	615	491	13.0	23.0	19.0	0.143	0.780	0.434	698	903	99	11.0%
Shortspine Thornyhead	712	119	868	546	5.3	18.5	13.0	0.019	0.647	0.240	649	817	7	0.9%
Yelloweye rockfish	10,020	246	820	555	9.8	26.5	19.2	0.067	1.445	0.448	8901	10892	330	3.0%
Quillback rockfish	2008	250	480	382	10.3	18.2	14.6	0.081	0.462	0.231	1243	1261	18	1.4%
Rougheye rockfish	2369	66	767	373	3.1	25.2	14.0	0.002	1.148	0.264	2675	3778	134	3.5%
Shortraker rockfish	2087	342	1040	680	12.0	27.7	20.1	0.167	1.892	0.769	1749	2548	101	4.0%
Redbanded rockfish	161	143	632	438	6.3	19.6	15.0	0.024	0.669	0.309	162	237	6	2.5%
Dusky/Dark rockfish	933	95	525	383	4.6	17.9	13.2	0.011	0.431	0.187	658	1141	27	2.4%
Redstripe rockfish	29	199	375	303	7.7	14.1	11.2	0.037	0.201	0.103	26	30	0	0.0%
Walleye pollock	4736	44	758	442	3.0	25.3	17.4	0.003	1.004	0.350	1350	2682	159	5.9%
Sablefish	35,004	109	1130	653	1.5	15.6	9.1	0.0005	0.199	0.033	43,081	43,360	279	0.6%
Pacific herring	329	130	265	194	2.4	4.8	3.5	0.001	0.008	0.003	200	329	13	4.0%
Pacific sand lance	113	102	213	159	1.8	3.5	2.5	0.001	0.005	0.002	102	113	0	0.0%
Shiner perch	190	57	152	95	3.0	7.2	4.6	0.005	0.040	0.014	187	190	0	0.0%
Eulachon	341	100	221	166	2.3	5.0	3.6	0.002	0.007	0.004	298	341	0	0.0%
Pacific halibut	537	300	2390	1041	6.5	21.0	13.5	0.027	1.050	0.265	-	-	-	-

Table 3.– Regression parameters (*a*, *b*) are indicated for somatic to otolith dimensions for 18 species using a linear function ($y=La+b$) and a power function ($y=aL^b$). Pearson correlation coefficients (*r*) for linear relationships indicate high correlations between somatic (Som) and otolith (Oto) lengths, and left (LS) and right sagittae (RS) otolith lengths, heights, and weights.

Common Name	Som Len - Oto Len				Som Len - Oto Ht				Som Len - Oto Wt			
	n	*r*	*a*	*b*	*n*	*r*	*a*	*b*	*n*	r^a	*a*	*b*
Pacific cod	4539	0.9094	0.0179	6.498	4539	0.9276	0.01	2.504	4539	–	3.E-06	1.856
Lingcod	12,436	0.8624	0.0081	2.4351	12,436	0.6148	0.002	1.744	12,436	–	7.E-08	1.987
Black rockfish	823	0.8949	0.0306	3.976	823	0.8405	0.012	2.544	823	–	1.E-07	2.452
Shortspine Thornyhead	712	0.9658	0.0108	7.3076	712	0.9395	0.013	2.115	712	–	1.E-05	1.593
Yelloweye rockfish	10,020	0.878	0.0241	5.8298	10,020	0.878	0.012	2.766	10,020	–	4.E-07	2.189
Quillback rockfish	2008	0.8141	0.018	0.5105	2008	0.8199	0.03	2.962	2008	–	1.E-08	2.799
Rougheye rockfish	2369	0.9631	0.0279	3.9069	2369	0.9566	0.014	2.309	2369	–	2.E-06	1.982
Shortraker rockfish	2087	0.8277	0.0082	6.0141	2087	0.742	0.018	7.678	2087	–	1.E-06	2.04
Redbanded rockfish	161	0.9462	0.0256	3.7285	161	0.9257	0.014	2.002	161	–	6.E-07	2.161
Dusky/Dark rockfish	933	0.9683	0.0297	1.7898	933	0.9639	0.015	1.014	933	–	2.E-07	2.303
Redstripe rockfish	29	0.9515	0.0304	1.9397	29	0.8783	0.016	1.052	29	–	6.E-07	2.101
Walleye pollock	4736	0.9534	0.0296	4.2979	4736	0.9628	0.013	1.314	4736	–	3.E-07	2.278
Sablefish	35,001	0.6832	0.0106	2.1195	35,008	0.4436	0.003	1.448	35,008	–	3.E-08	2.16
Pacific herring	329	0.9018	0.0143	0.6942	329	0.8972	0.006	0.448	329	–	7.E-07	1.925
Pacific sand lance	113	0.9073	0.0153	0.1147	113	0.8455	0.006	0.342	113	–	2.E-08	2.265
Shiner perch	190	0.9887	0.0463	0.2299	190	0.9818	0.024	0.79	190	–	5.E-07	2.203
Eulachon	341	0.9307	0.0194	0.4024	341	0.9139	0.011	0.607	341	–	3.E-07	1.832
Pacific halibut	537	0.9026	0.0059	7.4784	ND	ND	ND	ND	537	–	6.E-06	1.528
Mean >		0.915641				0.8805						

Common Name	Oto Len - Oto Wt				Oto Len - Oto Ht				Som Len - Square Root Oto Wt			
	n	r^a	*a*	*b*	*n*	*r*	*a*	*b*	*n*	*r*	*a*	*b*
Pacific cod	4539	–	0.0001	2.8625	4539	0.9277	0.523	-0.338	4539	0.9384	0.001	0.06
Lingcod	12,436	–	0.0002	2.4315	12,436	0.6026	0.214	1.527	12,436	0.8775	2E-04	0.004
Black rockfish	826	–	8E-05	2.9079	826	0.8187	0.354	1.925	823	0.9008	0.002	-0.14
Shortspine Thornyhead	712	–	0.0002	2.8189	712	0.7453	0.705	-0.337	712	0.9376	7E-04	0.075
Yelloweye rockfish	10,020	–	8E-05	2.9081	10,020	0.8642	0.416	1.362	10,020	0.8955	0.001	-0.07
Quillback rockfish	2008	–	6E-05	3.0952	2008	0.8019	0.473	0.512	2008	0.825	0.002	-0.19
Rougheye rockfish	2369	–	0.0002	2.6449	2369	0.971	0.503	0.458	2369	0.966	0.001	0.005
Shortraker rockfish	2087	–	0.0001	2.9453	2087	0.7221	0.363	4.314	2087	0.8452	0.001	-0.01
Redbanded rockfish	161	–	0.0001	2.9204	161	0.9404	0.536	0.193	161	0.9292	0.001	-0.05
Dusky/Dark rockfish	933	–	0.0001	2.805	933	0.9592	0.493	0.343	933	0.9516	0.001	-0.08
Redstripe rockfish	29	–	0.0002	2.5998	29	0.924	0.534	0.013	29	0.883	0.001	-0.01
Walleye pollock	4736	–	5E-05	3.0357	4736	0.959	0.427	-0.23	4736	0.9662	0.001	-0.04
Sablefish	35,001	–	0.0001	2.4586	35,008	0.3462	0.176	1.526	35,008	0.7496	3E-04	-0.02
Pacific herring	329	–	0.002	2.2576	329	0.9022	0.398	0.285	329	0.8742	3E-04	0.002
Pacific sand lance	113	–	0.0003	2.3207	113	0.8762	0.355	0.356	113	0.8583	3E-04	-0.01
Shiner perch	190	–	0.0003	2.5654	190	0.9853	0.506	0.691	190	0.9788	0.001	-0.02
Eulachon	341	–	0.0003	1.9963	341	0.947	0.525	0.451	341	0.9154	4E-04	0.005
Pacific halibut	537	–	9E-05	3.0338	ND	ND	ND	ND	537	0.9619	0.004	-0.13
Mean >						0.8408				0.903		

-continued-

Table 3.–Page 2 of 2.

Common Name	RS Oto Len - LS Oto Len				RS Oto Ht - LS Oto Ht				RS Oto Wt - LS Oto Wt			
	n	*r*	*a*	*b*	*n*	*r*	*a*	*b*	*n*	*r*	*a*	*b*
Pacific cod	3180	0.9823	0.9828	0.2919	3180	0.9637	0.958	0.341	3180	0.9878	0.993	0.004
Lingcod	7782	0.9547	0.9479	0.4903	7782	0.9264	0.917	0.297	7782	0.9854	0.666	7E-04
Black rockfish	698	0.9823	0.9761	0.4156	698	0.9471	0.929	0.608	698	0.9832	0.984	0.005
Shortspine Thornyhead	649	0.972	0.9698	0.3943	649	0.9738	0.963	0.352	649	0.9937	0.984	0.004
Yelloweye rockfish	890	0.9707	0.9725	0.4945	890	0.9622	0.949	0.457	890	0.99	0.988	0.007
Quillback rockfish	1243	0.9454	0.9536	0.6883	1243	0.945	0.955	0.381	1243	0.9833	0.985	0.004
Rougheye rockfish	2675	0.995	0.9974	0.0706	2675	0.9948	0.992	0.083	2675	0.9982	1.002	6E-04
Shortraker rockfish	1749	0.956	0.9645	0.7488	1749	0.9322	0.939	0.677	1794	0.9925	0.995	0.004
Redbanded rockfish	162	0.9826	0.9912	0.1932	162	0.9809	0.992	0.108	162	0.9967	0.995	0.002
Dusky/Dark rockfish	658	0.9905	1.0095	-0.042	658	0.9868	0.966	0.23	658	0.9964	0.983	0.003
Redstripe rockfish	26	0.9881	0.9752	0.2289	26	0.9921	0.999	-0.013	26	0.9951	0.992	7E-04
Walleye pollock	1350	0.9971	0.9952	0.0793	1350	0.996	1.002	0.019	1350	0.9982	0.998	9E-04
Sablefish	43,081	0.9176	0.9471	0.4593	43,081	0.8282	0.911	0.27	43,081	0.9762	0.098	4E-04
Pacific herring	200	0.99	0.9898	0.0363	200	0.9705	0.969	0.046	200	0.9822	0.974	9E-05
Pacific sand lance	102	0.961	0.9566	0.1235	120	0.9312	0.957	0.057	102	0.9633	0.952	1E-04
Shiner perch	187	0.9949	0.9999	-0.012	187	0.9786	0.993	0.028	187	0.9988	0.999	5E-05
Eulachon	298	0.9676	0.9694	0.1221	298	0.9096	0.921	0.2	298	0.9669	0.948	2E-04
Pacific halibut	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mean >		0.9734				0.9541				0.9875		

Note: ND= no data

[a] *r* was not calculated because it was inappropriate.

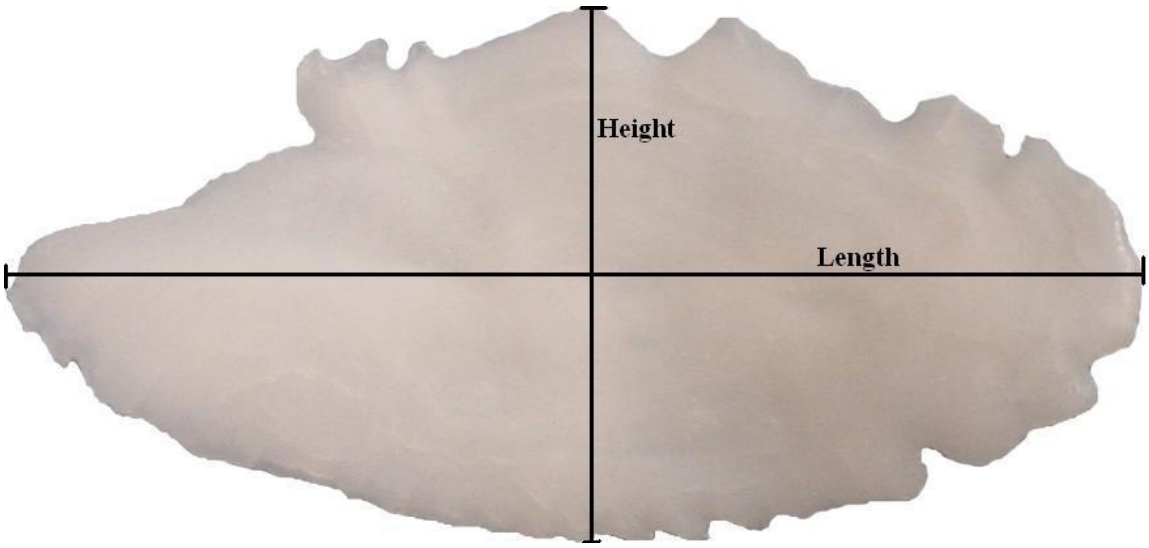


Figure 1.–Otolith dimensions measured in millimeters (mm) were length (anterior-posterior axis) and height (dorso-ventral axis).

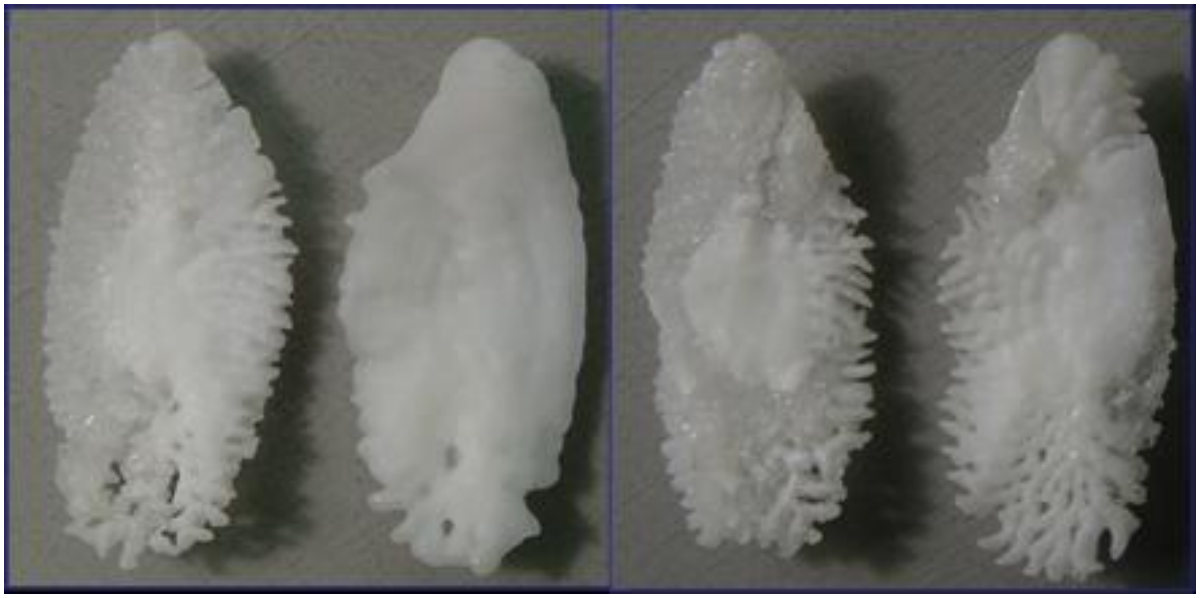


Figure 2.– Otoliths were observed for the presence of vaterite or dysmorphia (a misshapen otolith per expected species shape) and the percentage of affected area was estimated and recorded. For example, the sagittal otolith pair on the left has a normal right sagittae and a heavily vateritic (~75%) and slightly dysmorphic (~5%) left sagittae. The pair on the right are both vateritic (left ~75%; right ~50%) and dysmorphic (left ~10%; right >25%).

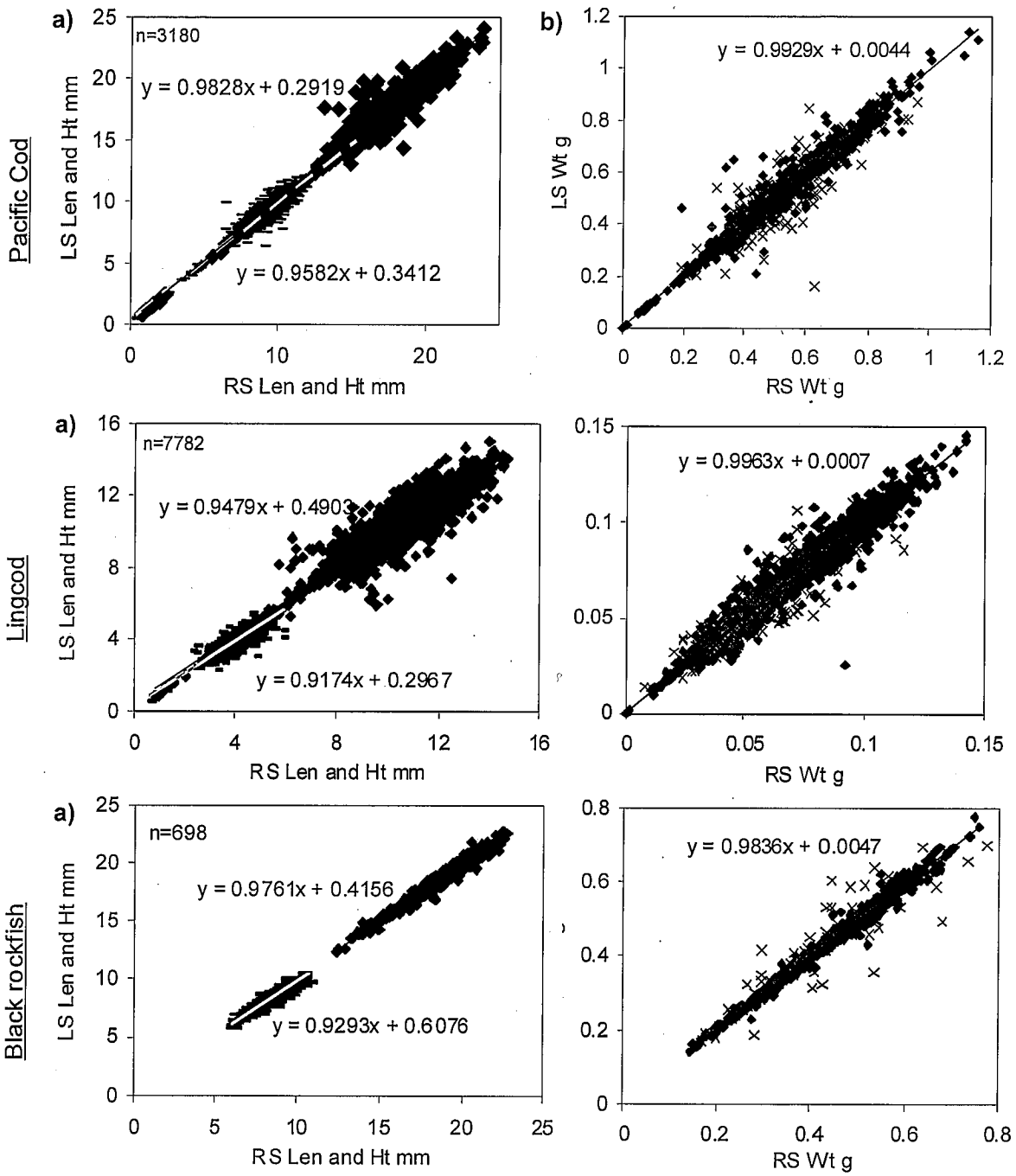


Figure 3.–Otoliths were symmetrical for the dimensions *a)* left sagittae (LS) and right sagittae (RS) otolith lengths (Len; grey diamonds), heights (Ht; black dash), and *b)* weights (Wt). Otoliths which were vateritic or dysmorphic ("X") were not included in calculation of the correlation coefficient (*r*). Measurements are in millimeters (mm) and grams (g).

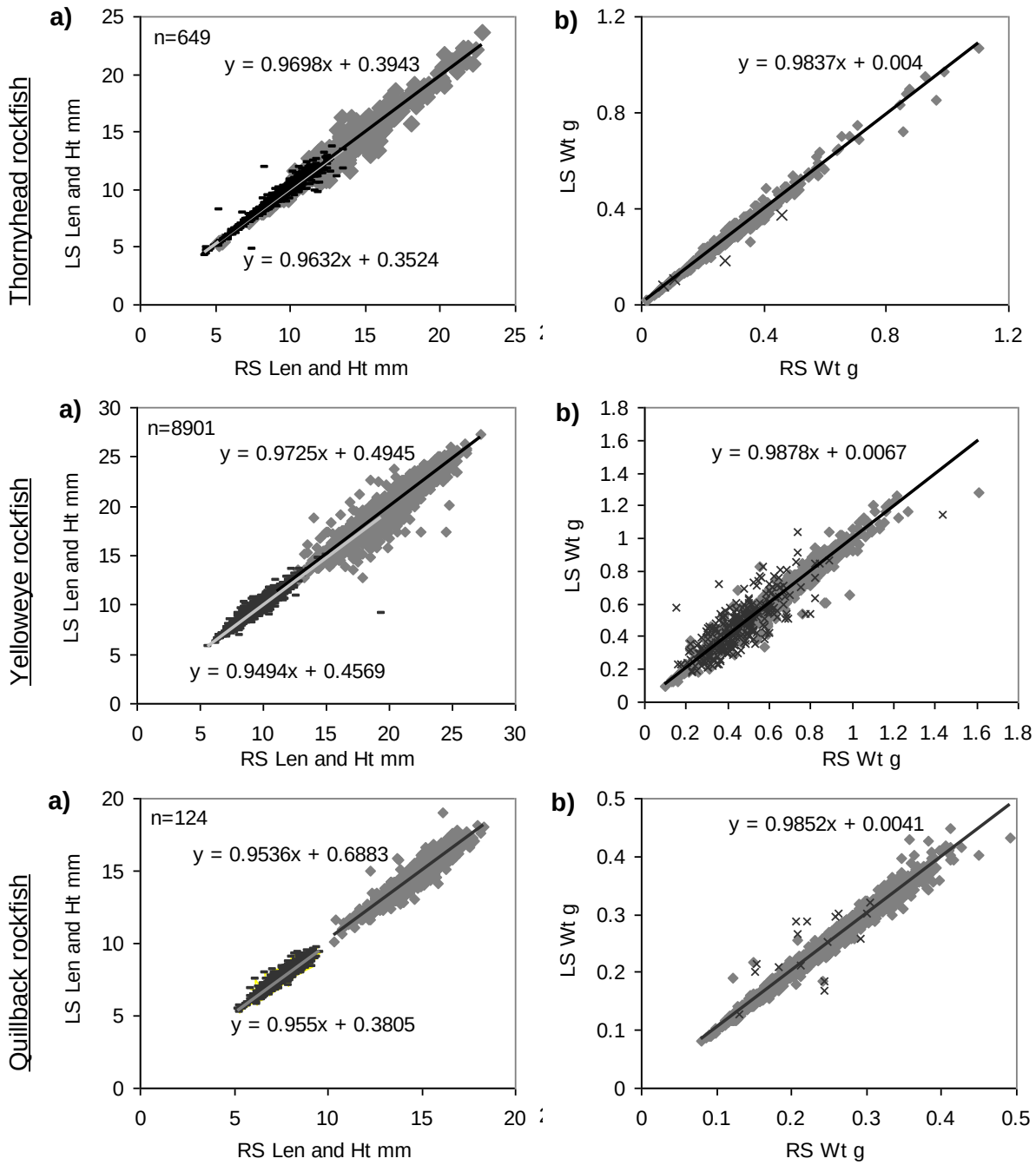


Figure. 3.–Page 2 of 6.

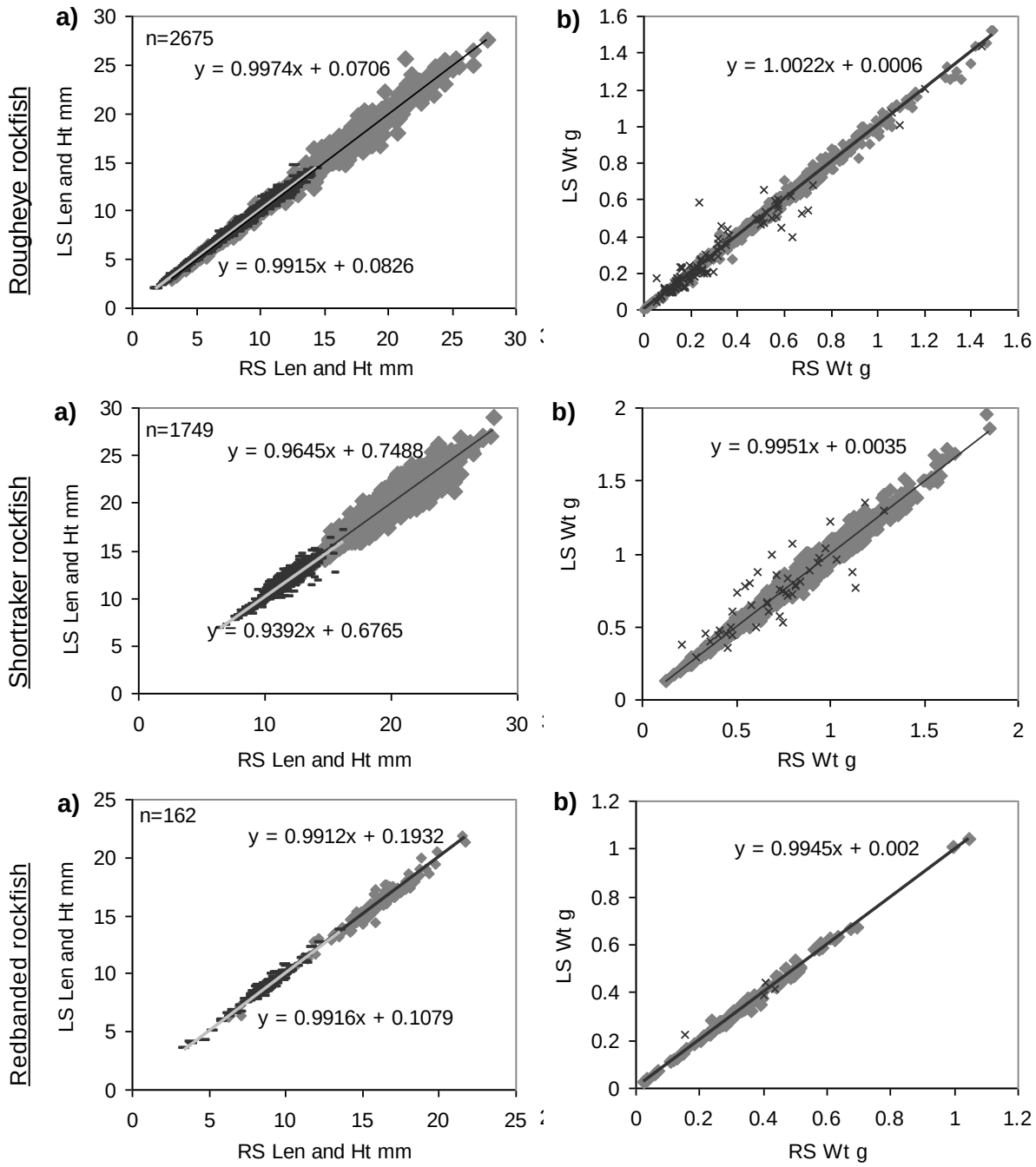


Figure 3.–Page 3 of 6.

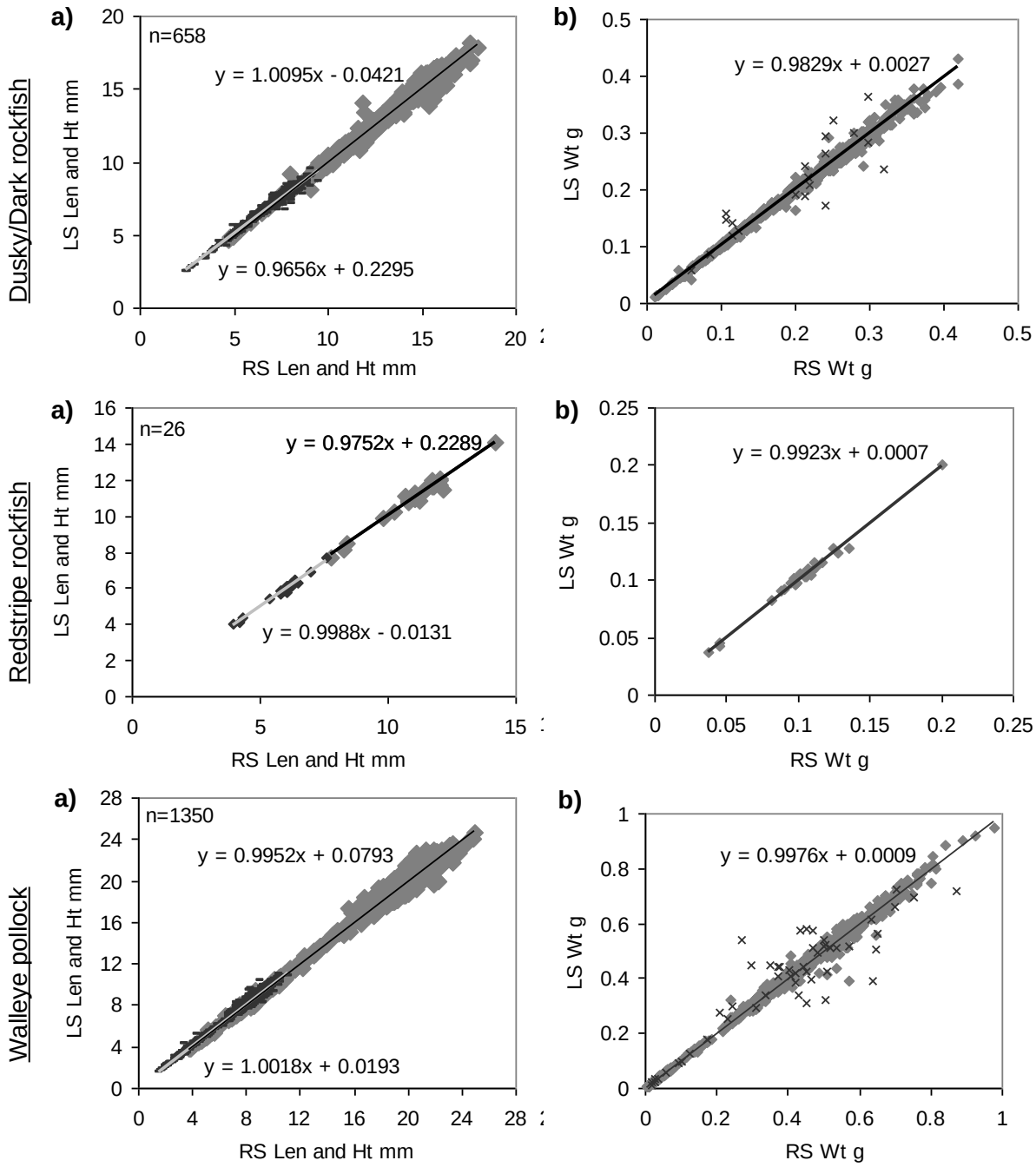


Figure 3.–Page 4 of 6.

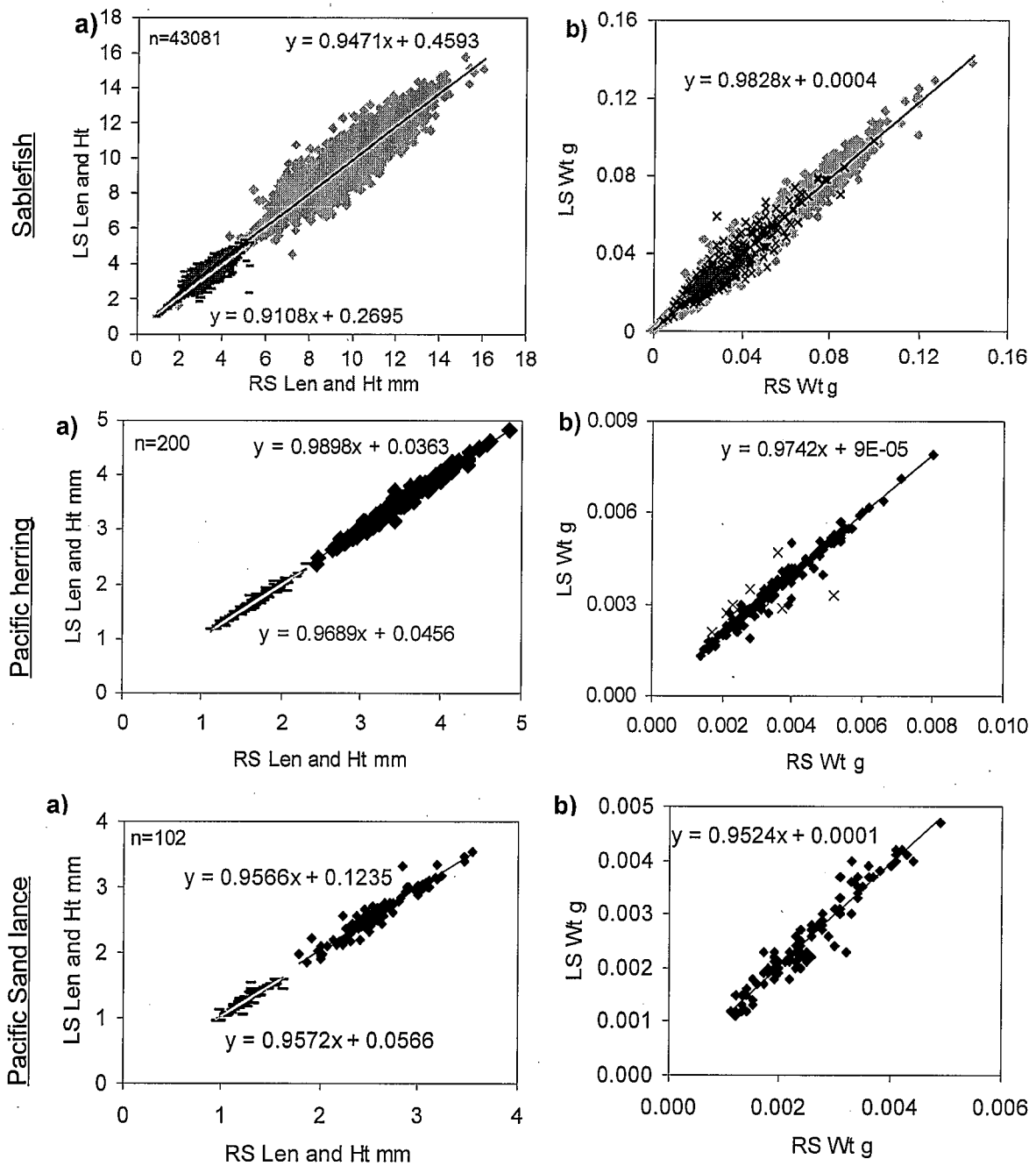
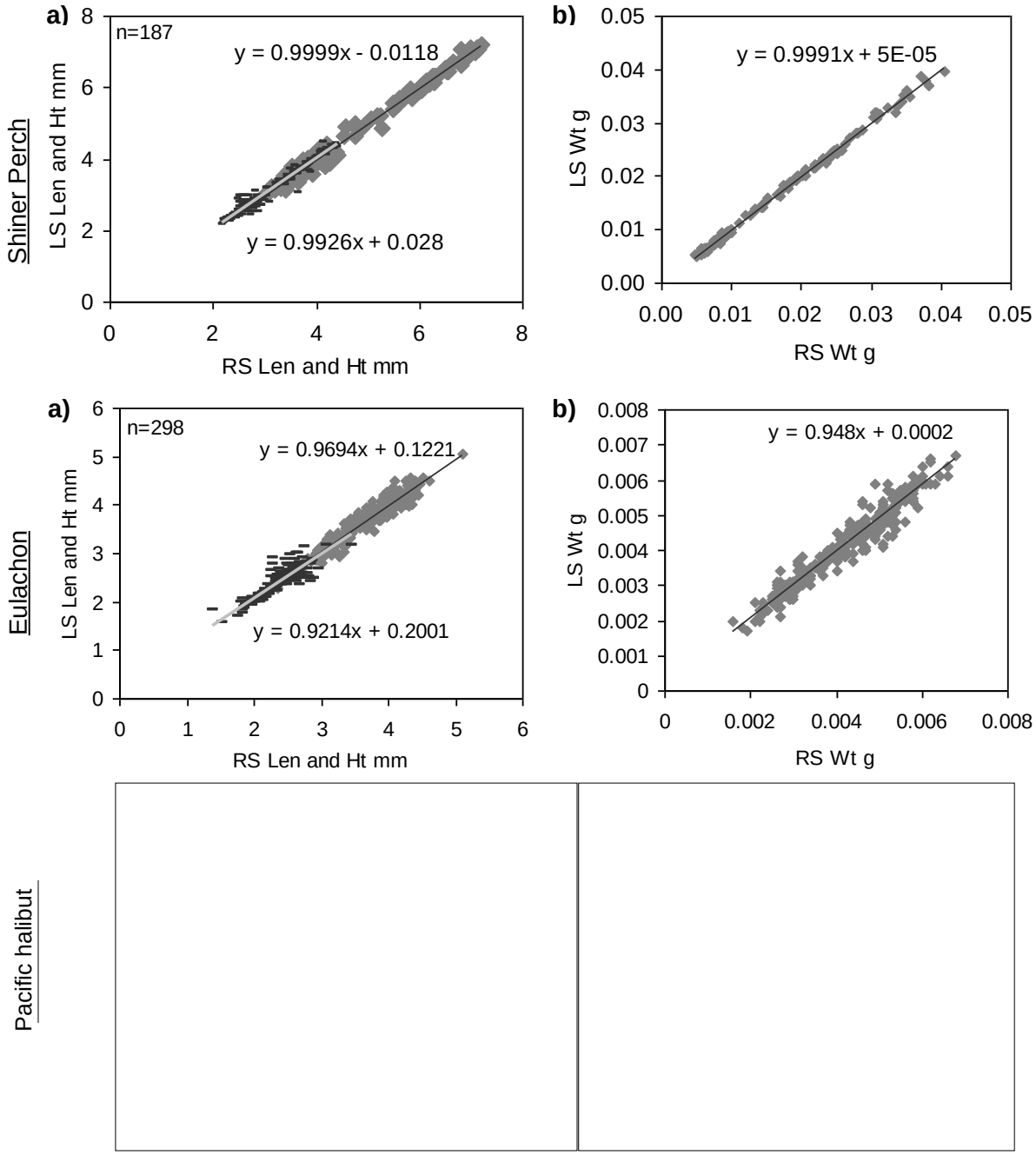


Figure 3.–Page 5 of 6.



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Note: There was no data that would allow a comparable chart be developed for Pacific halibut.

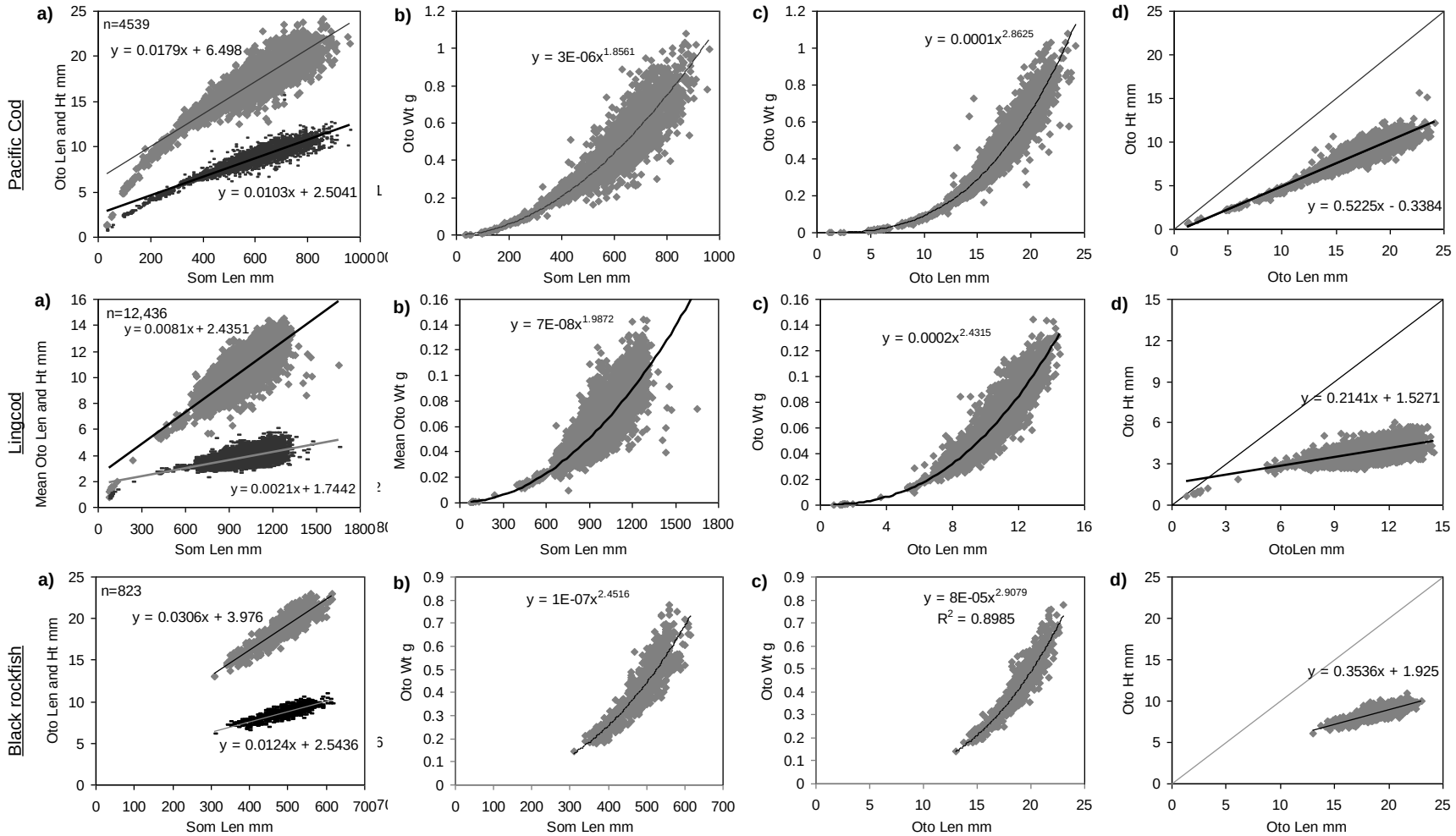


Figure 4.– Relationships were highly correlated for *a)* somatic length (Som Len) to otolith length (Oto Len), otolith height (Oto Ht), and *b)* otolith weight (Wt); and, *c)*otolith length to otolith weight. *d)* The otolith length to height relationship is plotted relative to a 1:1 line. Measurements are in millimeters (mm) and grams (g).

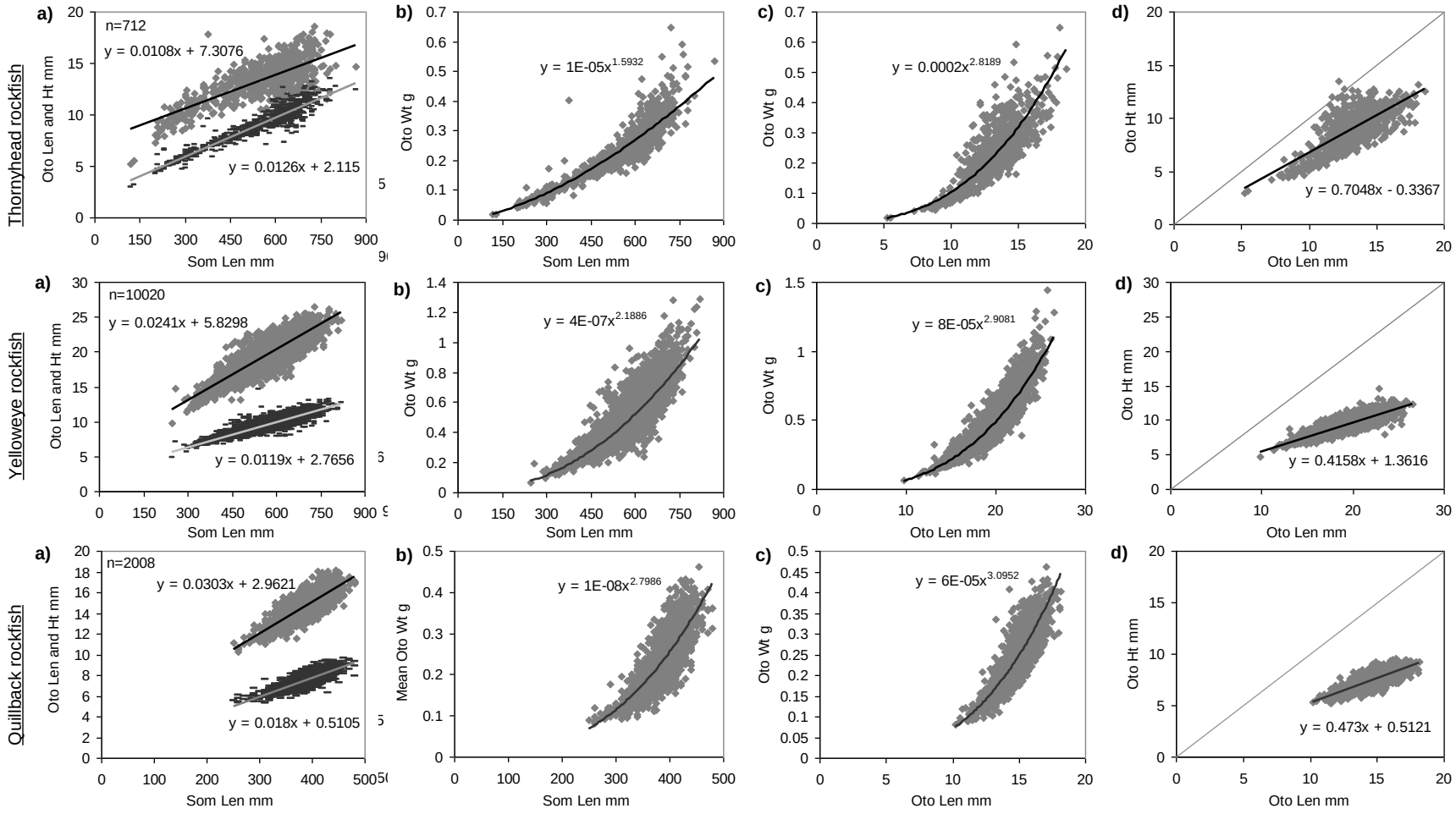
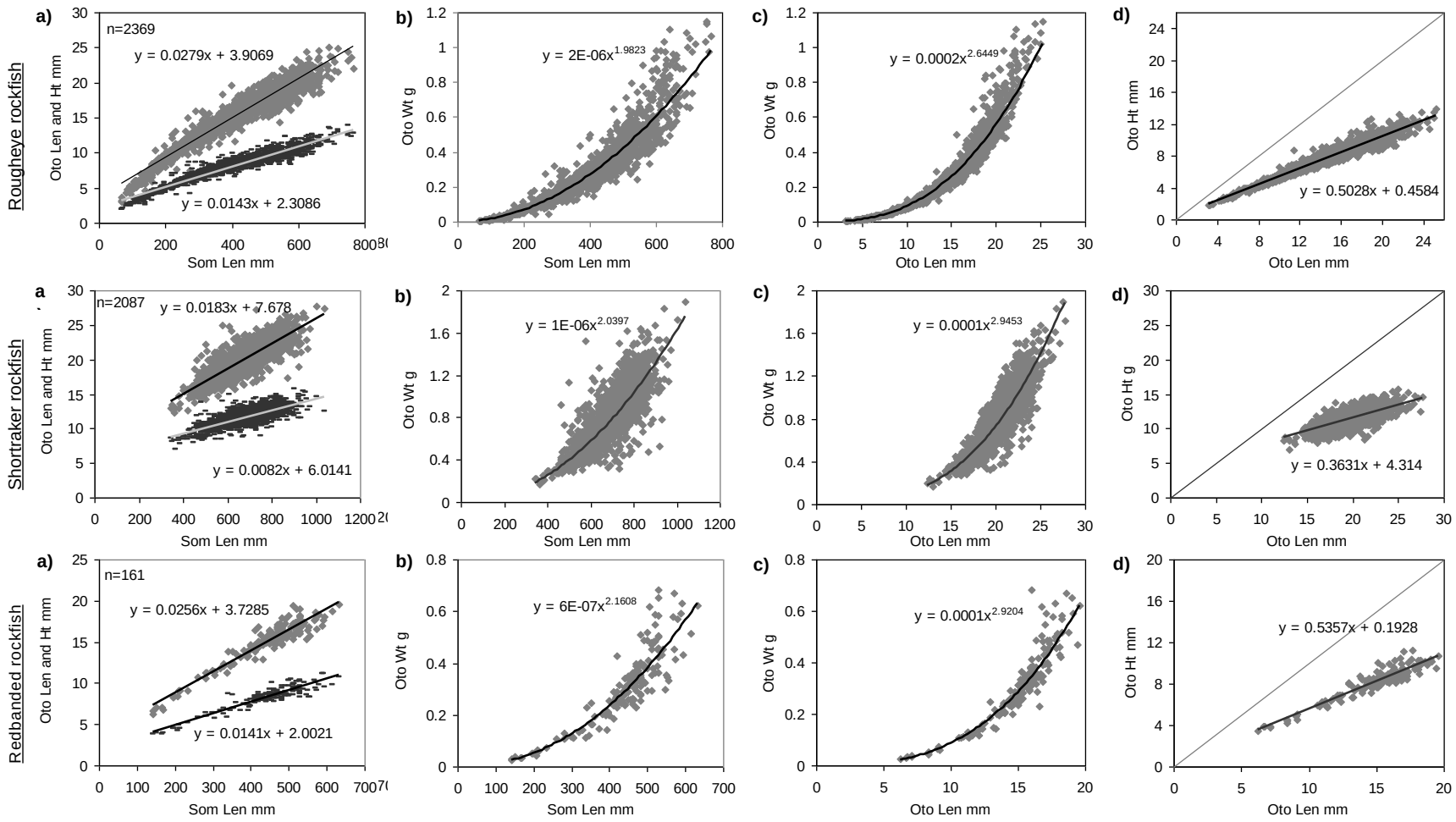


Figure 4.–Page 2 of 6.



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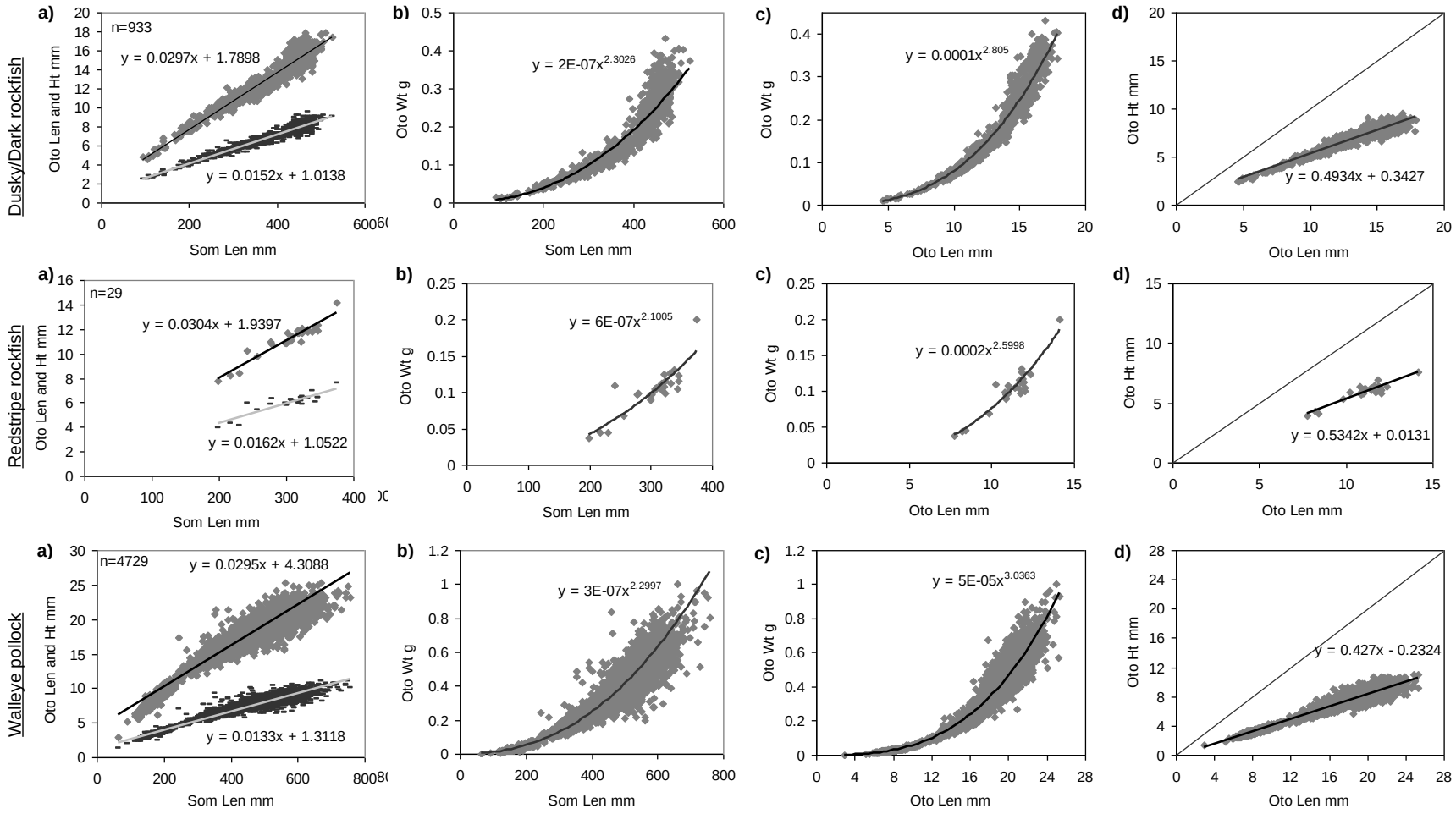

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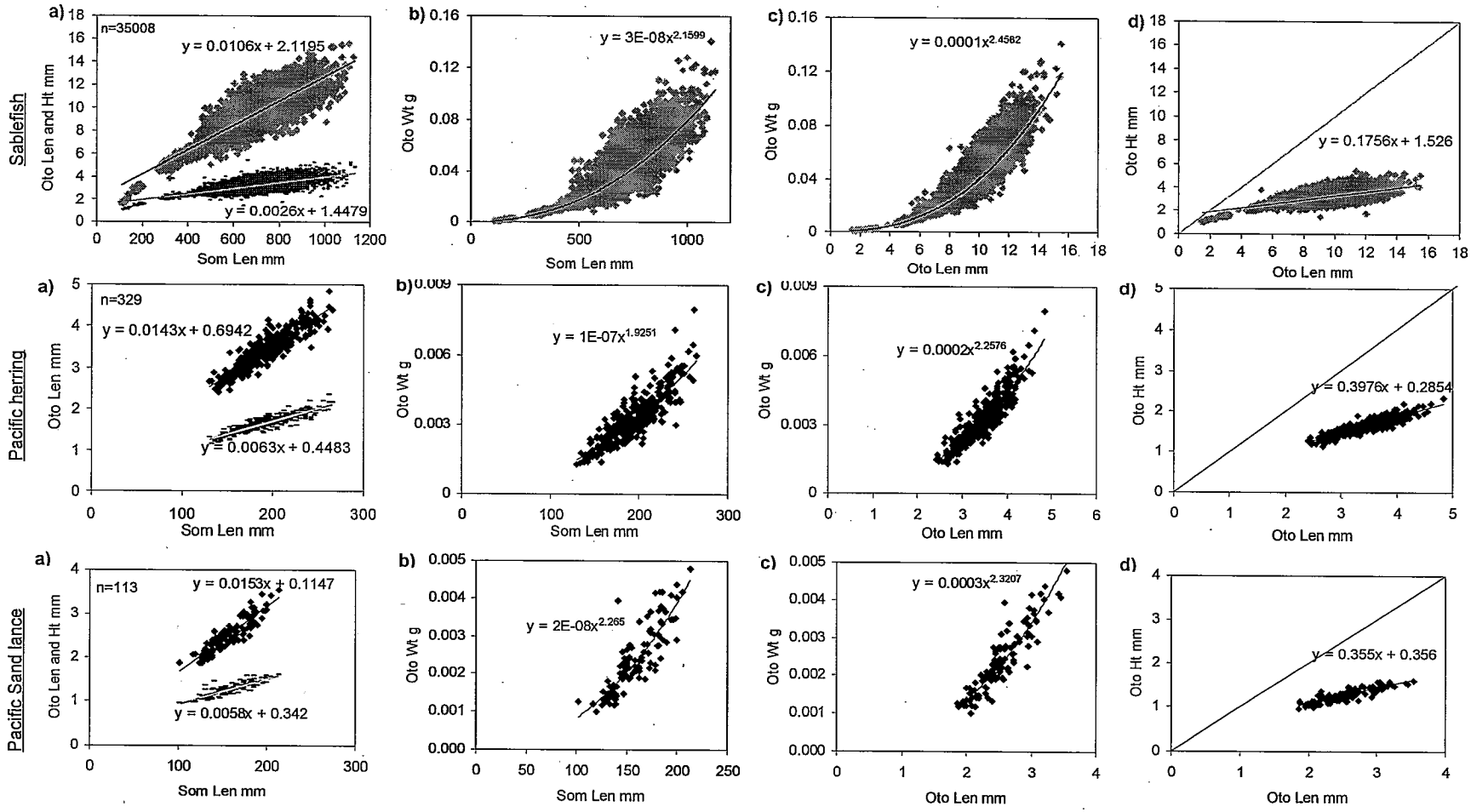
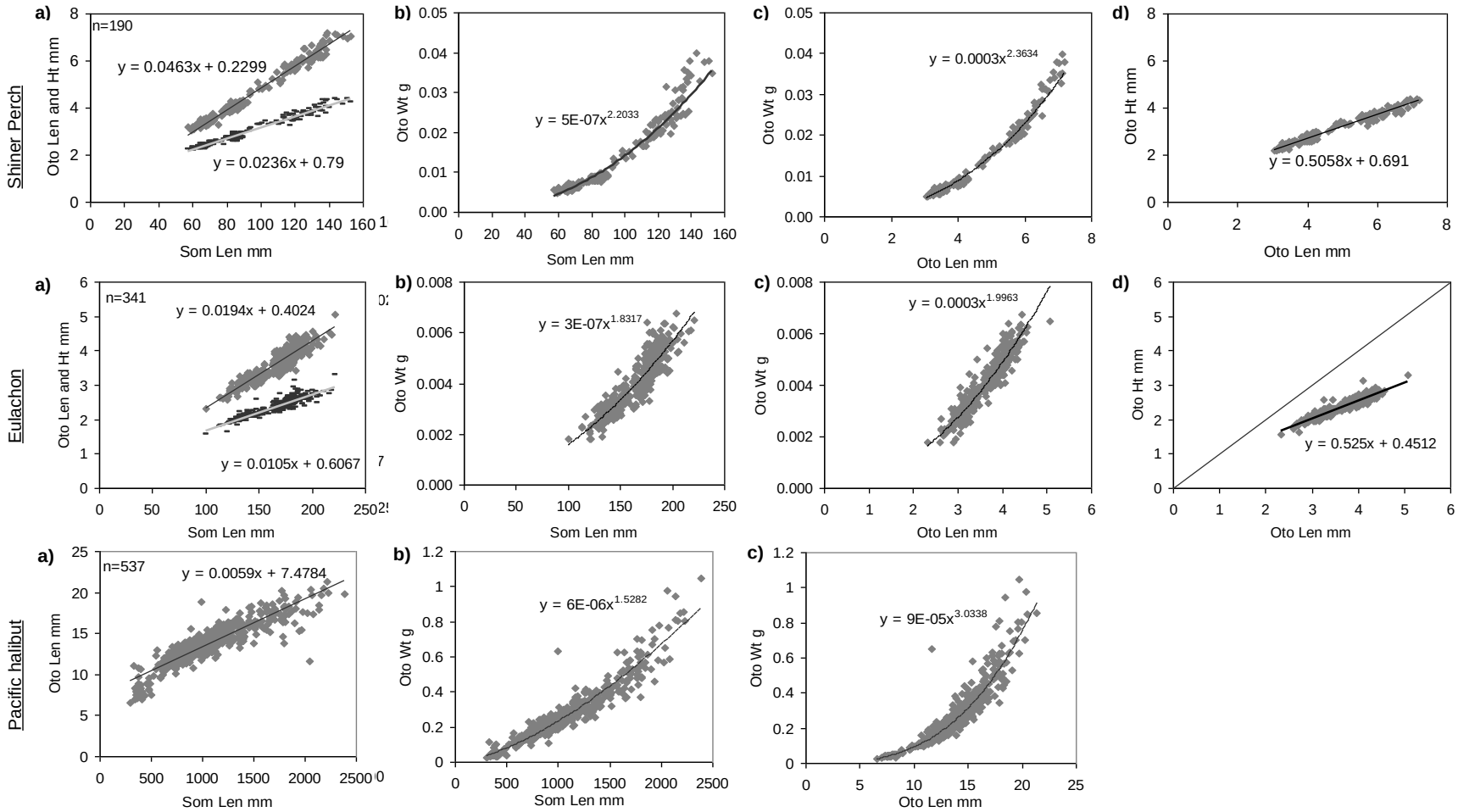


Figure 4.–Page 5 of 6.



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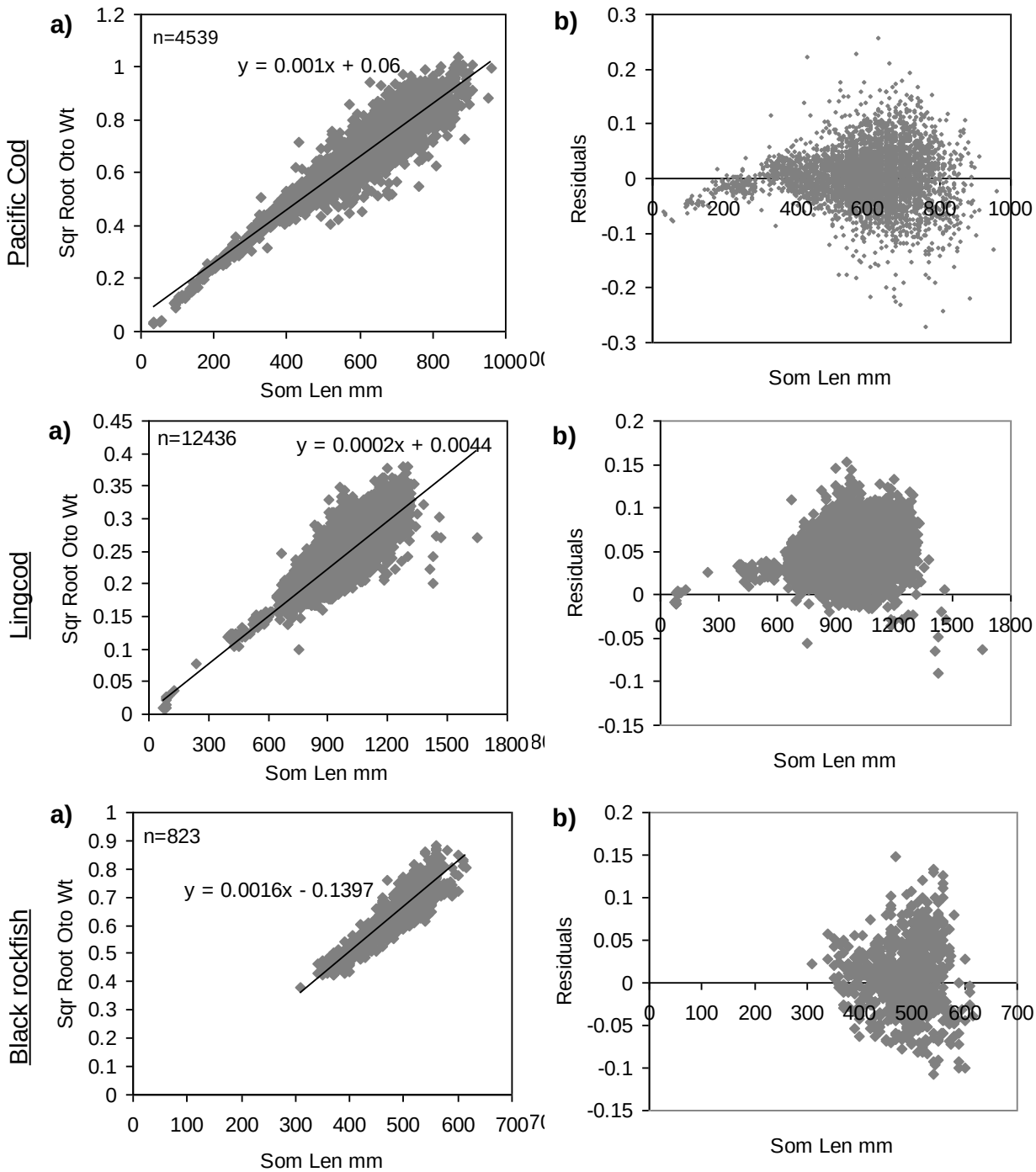


Figure 5.–Otolith weights were *a)* linearized with square root transformation and the coefficients of determination were calculated. *b*) Residuals of transformed otolith weight to somatic length convey that the square root transformation did not always produce a linear relationship. Measurements are in millimeters (mm).

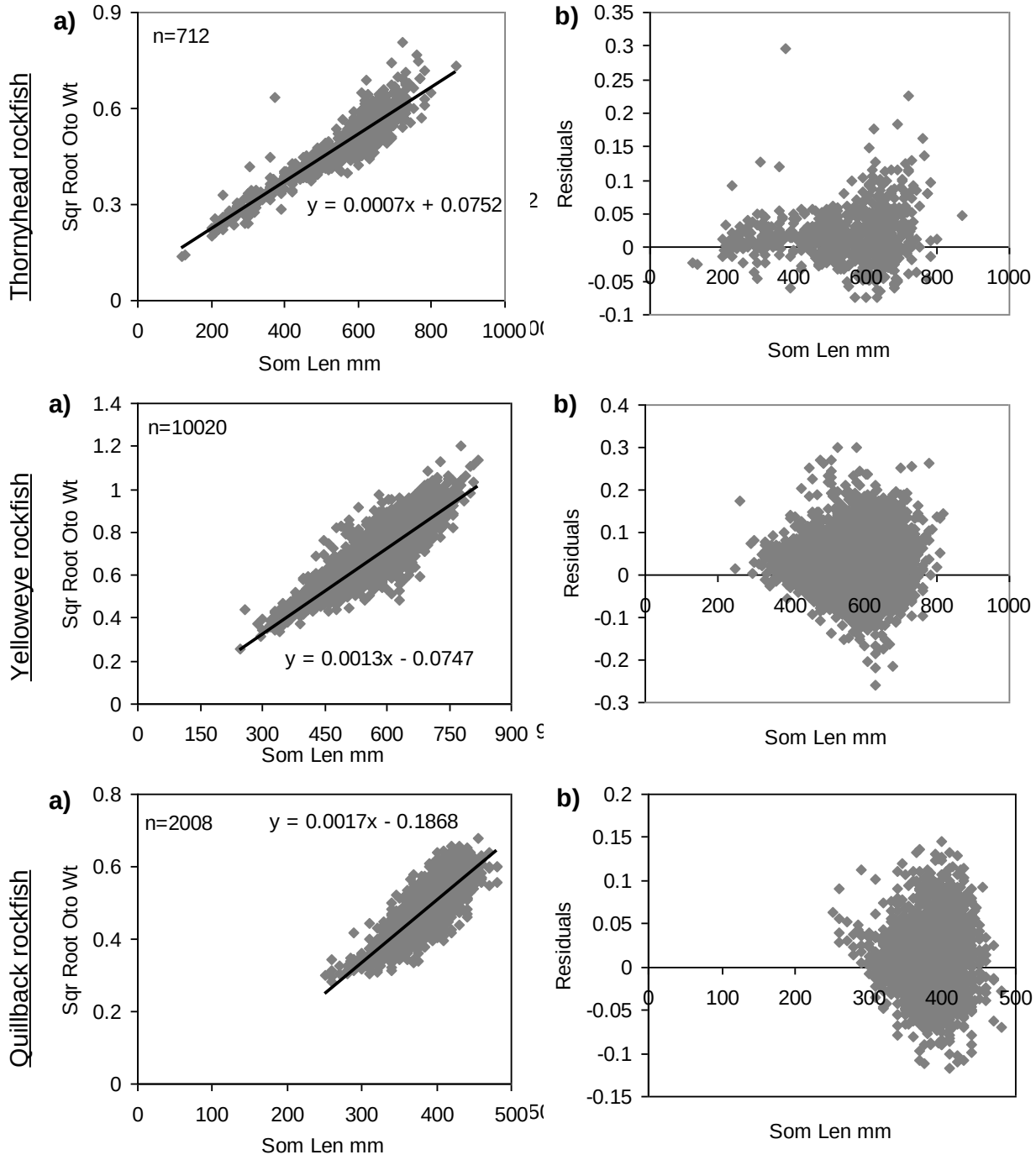


Figure 5.–Page 2 of 6.

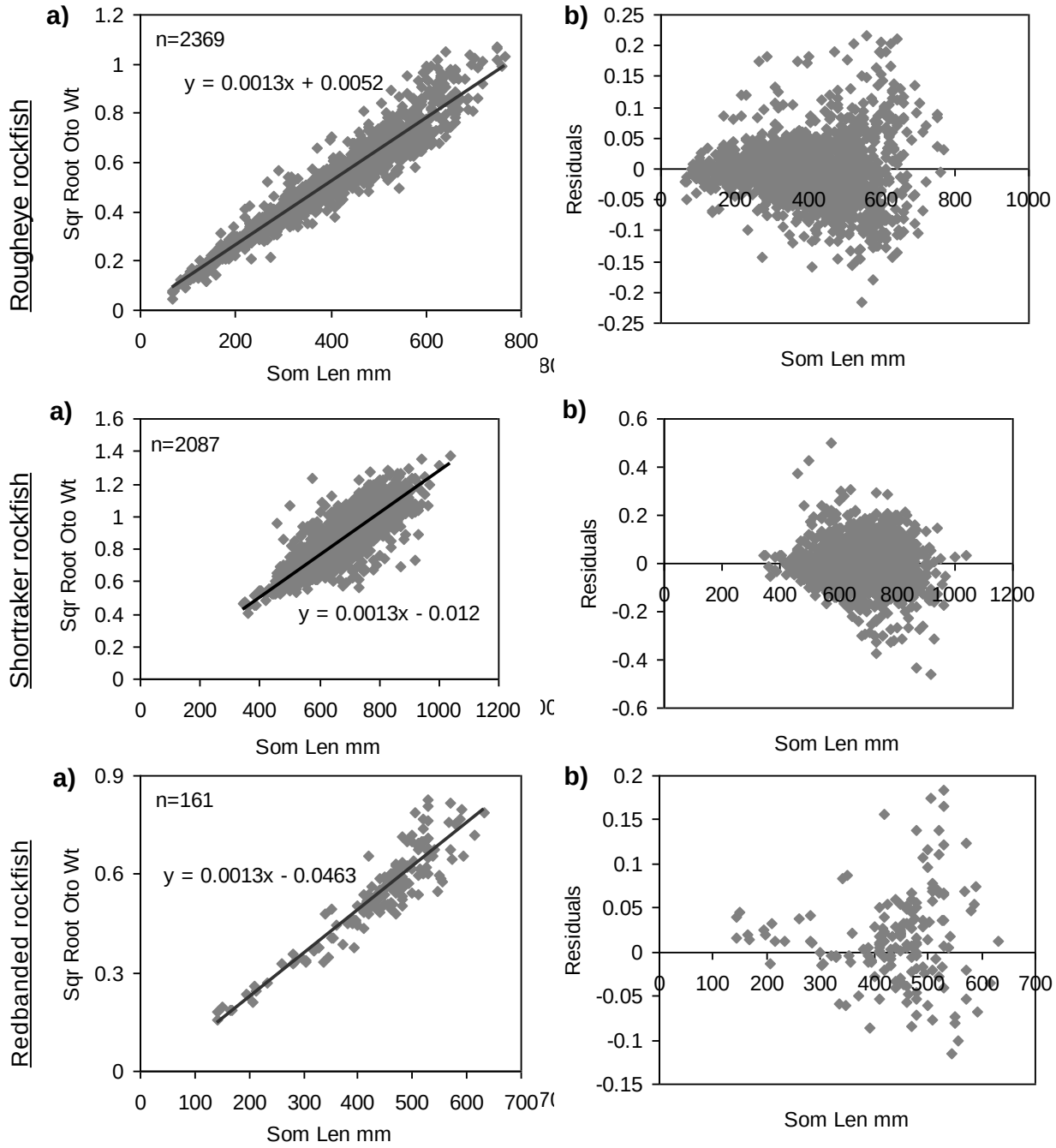
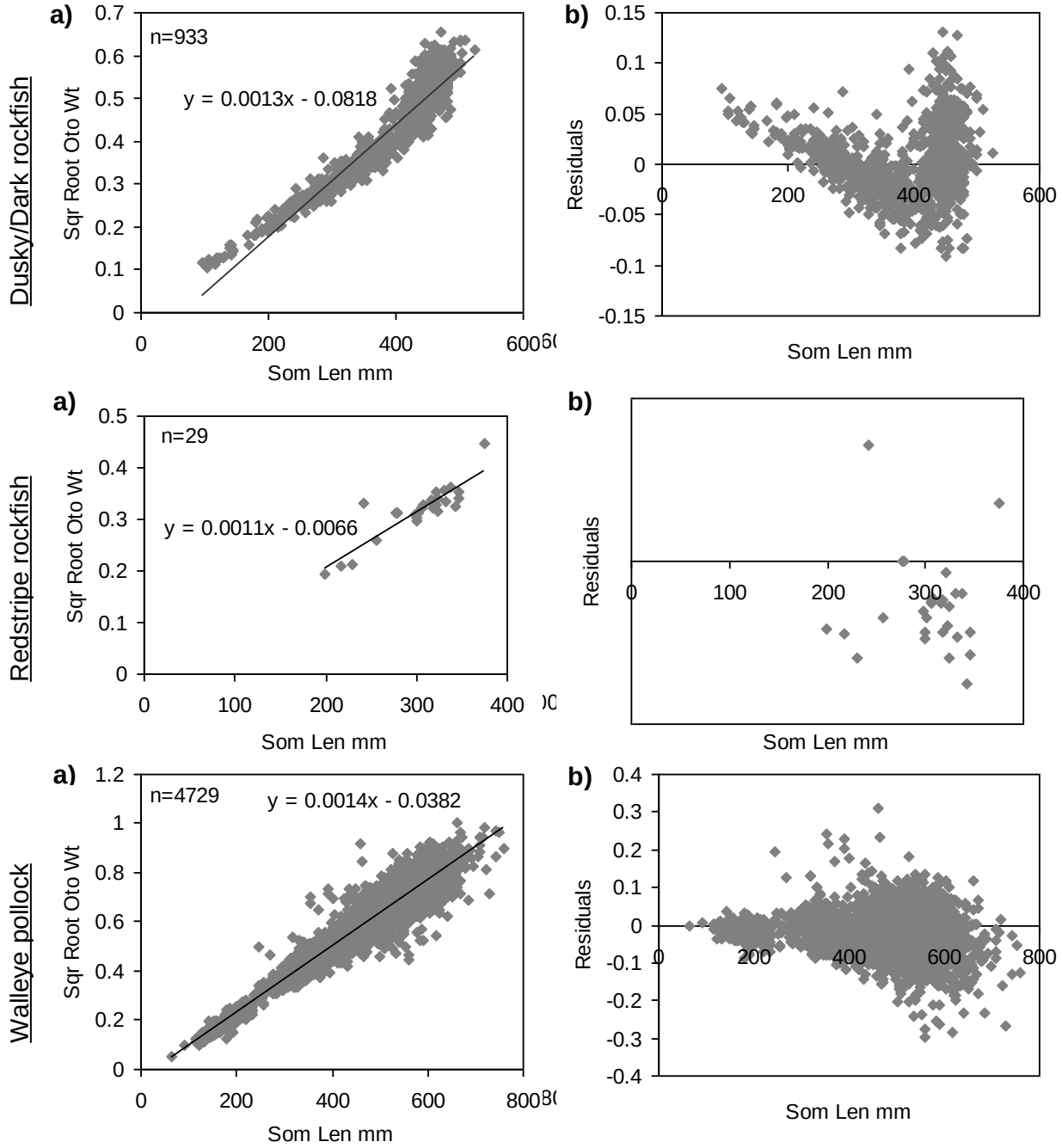


Figure 5.–Page 3 of 6.



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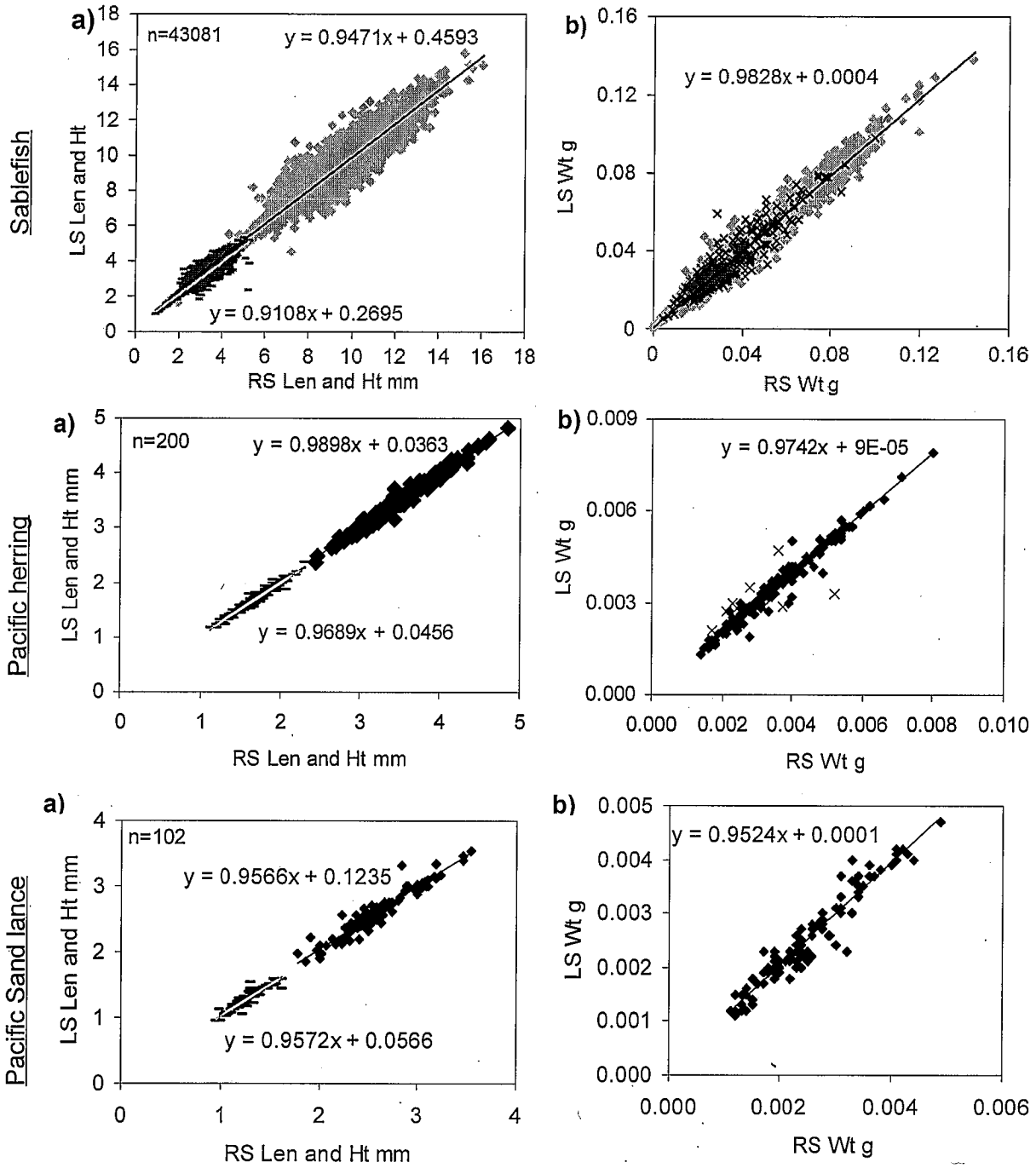

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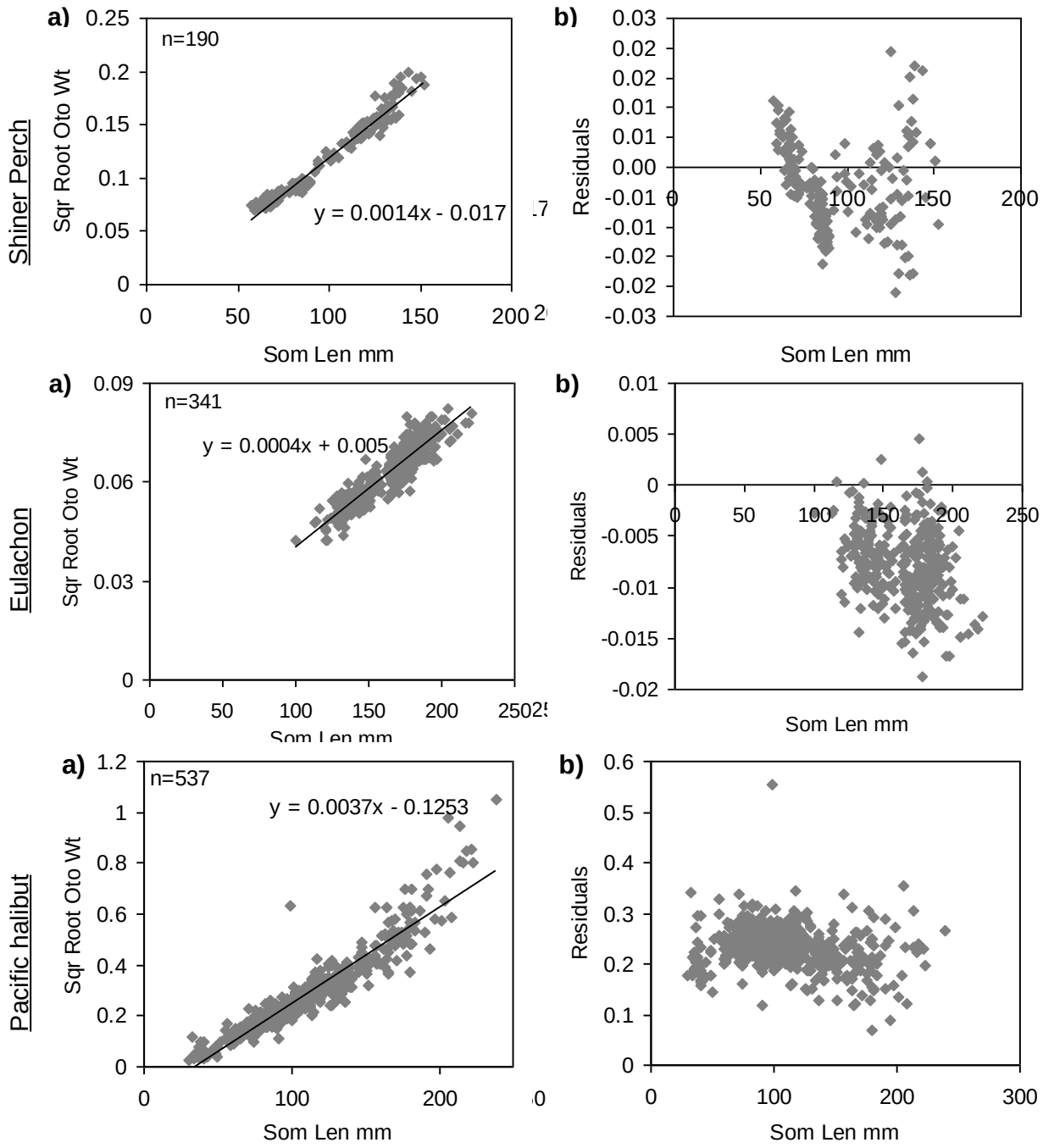

Figure 5.–Page 6 of 6.