Appendix S1:

High variation in handling times confers 35-year stability to predator feeding rates despite community change

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Ecology

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Section S1.1 Species identifications

Three things are worth noting in regards to species identifications of key taxa:

(i) The whelk referred to as *Neothais scalaris* in the only paper that Paine published of his New Zealand work (Paine, 1971) is now called *Dicathais orbita*. Among its differences from *H. haustorium* is that *Dicathais* occurs on more exposed shores where its apparent diet consists primarily of *Perna* mussels.

(ii) Although Paine (1971) mentions having observed *Dicathais* at multiple (unspecified) sites, and to have estimated its density to be 17 m^{-2} at Red Beach, Whangaparoa Peninsula, specifically, I observed few to no *Dicathais* at the sites which I resurveyed, including the Red Beach, Whangaparoa Peninsula site that I surmised Paine to have surveyed for *H. haustorium*. I nonetheless consider it unlikely that Paine mistook small *H. haustorium* or *Paratrophon* spp. — which can appear similar to small *Dicathais* and which I did observe at Red Beach — for *Dicathais*.

(iii) It is possible that the prey species *H. scobina* reported on here (and in Novak (2010; 2013) for sites around the South Island) is conflated with the sister taxon *H. albomarginatum* (Barco *et al.* 2015; but see O'Mahoney 2020; Tan 2003).

Section S1.2 Supplementary tables

Table S1: The locations where Paine and I surveyed *Haustrum haustorium*'s diet and the abundances of its prey in 1968-9 and 2004 for which data are posted to the public repositories indicated in the main text. Missing coordinates are unknown.

			Feeding		**Abundance**	
Site	Latitude	Longitude	1968-9	2004	1968-9	2004
Waikuku Bay	−34.4720	173.0079	x			
Leigh - Waterfall Rocks	−36.2688	174.8060	x	x	x	x
Leigh Goat Island Reserve	−36.2688	174.8060	x			
Leigh - Echinoderm Reef	−36.2696	174.7937	x	x		
Leigh - Tabletop Rocks and Boulders	−36.2701	174.8025	x	x		
Leigh Harbour	−36.2881	174.8080	x			
Red Beach - Whangaparaoa	−36.6007	174.7092	x	x	x	x
Rangitoto Island - Whites Beach	−36.7754	174.8334	x	x	x	x
Takapuna	−36.8160	174.8087	x			
Kaikoura Paine's			x			
Waikukua Bay-2			x			
Whangarei			x			
Tapotupotu Bay West	−34.4347	172.7129		x		
Leigh Shadow Rocks	−36.2715	174.8091		x		
Tungutu Point	−36.5075	174.7231		x		
Red Beach Cliff	−36.6003	174.7075		x		
Opunake	−39.4597	173.8485		x		
Pourere Tuingara Point	−40.1376	176.8650		x		
Castle Point Cave	−40.8997	176.2310		x		
Castle Point Boulders	−40.9006	176.2302		x		
Island Bay Lab Rocks	−41.3490	174.7649		x		
Matakitakiakupe Cape Palliser	−41.6125	175.2742		x		
Cape Foulwind NWPlatform	−41.7461	171.4666		x		
Cape Foulwind	−41.7526	171.4586		x		
Tauranga Bay North	−41.7653	171.4560		x		
Tauranga Head	−41.7738	171.4555		x		
Tauranga Head West	−41.7764	171.4514		x		
Tauranga Head SWcorner	−41.7768	171.4523		x		
Ward Beach	−41.8483	174.1836		x		
Charleston Joyce Bay	−41.9022	171.4350		x		
Memorial Garden Rocks	−42.4044	173.6851		x		
Whakatu Point	−42.4143	173.7062		x		
Avoca Point North	−42.4161	173.7076		x		
Lighthouse Reef	−42.4239	173.7169		x		
First Bay	−42.4261	173.7143		x		
Limestone Bay Point	−42.4267	173.6872		x		
Raramai	−42.4586	173.5520		x		
Oaro South	−42.5239	173.5050		x		

Table S2: Prey for which *Haustrum haustorium*'s prey-specific detection times had not been measured in the laboratory experiments of Novak (2013) were assigned the regression coefficients of prey species for which they had been measured.

Unmeasured		**Matched to measured**	
Predator	Prey	Predator	Prey
H. haustorium	Atalacmea fragilis	H. haustorium	Cellana radians
H. haustorium	Cellana stellifera	H. haustorium	Cellana radians
H. haustorium	Chamaesipho columna	H. haustorium	Chamaesipho spp
H. haustorium	Cominella adspersa	H. haustorium	Haustrum scobina
H. haustorium	Crassostrea gigas	H. scobina	Mytilus galloprovincialis
H. haustorium	Dicathais orbita	H. haustorium	Haustrum scobina
H. haustorium	Diloma bicanaliculata	H. haustorium	Diloma aethiops
H. haustorium	Diloma nigerrima	H. haustorium	Diloma aethiops
H. haustorium	Diloma zelandica	H. haustorium	Diloma aethiops
H. haustorium	Fossarina rimata	H. haustorium	Risellopsis varia
H. haustorium	Haustrum haustorium	H. haustorium	Haustrum scobina
H. haustorium	Mytilus galloprovincialis	H. scobina	Mytilus galloprovincialis
H. haustorium	Nerita atramentosa	H. haustorium	Diloma aethiops
H. haustorium	Notoacmea parviconoidea	H. haustorium	Notoacmea spp
H. haustorium	Paratrophon patens	H. haustorium	Haustrum scobina
H. haustorium	Trimusculus conicus	H. haustorium	Siphonaria australis
H. haustorium	UNID Chiton	H. haustorium	Plaxiphora caelata
H. haustorium	UNID Diloma	H. haustorium	Diloma aethiops
H. haustorium	UNID Limpet	H. haustorium	Notoacmea spp
H. haustorium	UNID Notoacmea	H. haustorium	Notoacmea spp
H. haustorium	UNID Snail	H. haustorium	Diloma aethiops
H. haustorium	Zeacumantus subcarinatus	H. haustorium	Austrolittorina cincta

Section S1.3 Detection-time sensitivities

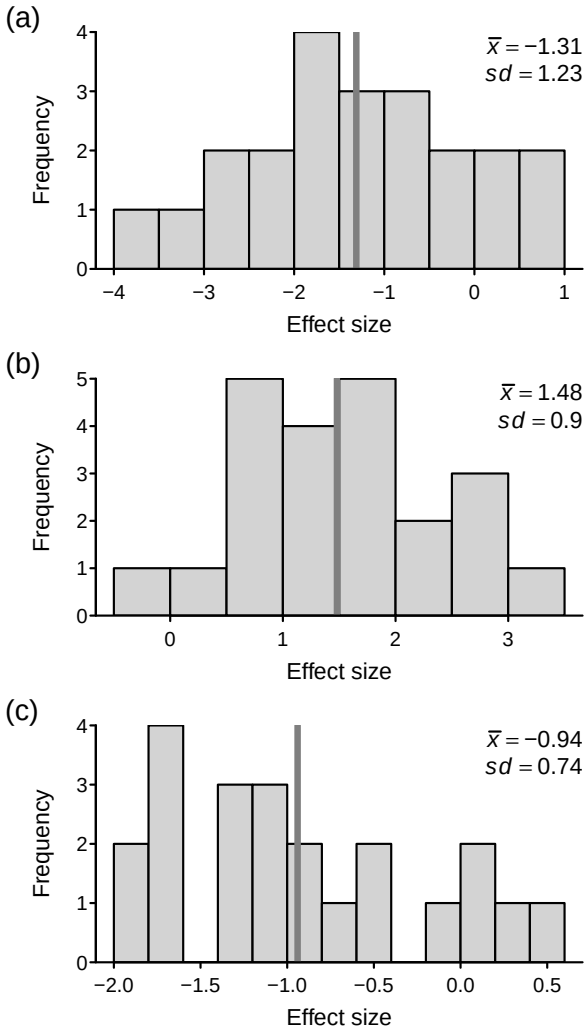

Figure S1: Histograms of the prey-specific regression coefficients from Table S3.3 of Novak (2013) characterizing the sensitivity of detection times to variation in (a) *Haustrum* whelk size, (b) prey size, and (c) temperature, with all variables log_e-transformed. Note that, because of the nonlinear power-relationship between variables and detection times, the sensitivity of detection times to each of the variables is size-dependent when considered on the natural (non-logarithmic) scale and, when compared between species, is also dependent on the modeled intercept (Menge *et al.*, 2018).

Section S1.4 Regression summary tables

Table S3: Summary table for the regression of predator size on prey size.

	Estimate	Std. Error	t value	Pr(>—t—)
(Intercept)	2.336	0.0466	50.1	$9.17e-170$
log(PreySize)	0.456	0.0182	25.1	$9.61e-83$

Table S4: Summary table for the regression of predator size on prey size and time period (*Year*).

	Estimate	Std. Error	t value	Pr(>—t—)
(Intercept)	2.670792	1.307244	2.043	$4.17e-02$
log(PreySize)	0.453821	0.020303	22.352	$3.00e-71$
Year	−0.000166	0.000647	−0.257	$7.98e-01$

Table S5: Summary table for the regression of predator size on prey size, time period (*Year*), and their interaction.

	Estimate	Std. Error	t value	Pr(>—t—)
(Intercept)	0.491060	5.83524	0.0842	0.933
log(PreySize)	1.357255	2.35701	0.5758	0.565
Year	0.000932	0.00294	0.3174	0.751
log(PreySize):Year	−0.000456	0.00119	−0.3833	0.702

Table S6: Summary table for the regression of prey-specific feeding rate on prey-specific abundance, time period (*Year*), and their interaction.

	Estimate	Std. Error	t value	Pr(>—t—)
(Intercept)	15.36190	30.2353	0.508	0.617
log10(N.mean)	−9.84166	21.3753	−0.460	0.650
Year	−0.00888	0.0152	−0.583	0.566
log10(N.mean):Year	0.00522	0.0108	0.485	0.633

Table S7: Summary table for the regression of prey-specific feeding rate on prey-specific abundance and time period (*Year*).

	Estimate	Std. Error	t value	Pr(>—t—)
(Intercept)	2.18267	13.03154	0.167	0.86851
log10(N.mean)	0.52616	0.18387	2.862	0.00907
Year	−0.00224	0.00657	−0.341	0.73652

Table S8: Summary table for the regression of prey-specific feeding rate on prey-specific abundance.

	Estimate	Std. Error	t value	Pr(>—t—)
(Intercept)	−2.257	0.254	−8.89	$6.70e-09$
log10(N.mean)	0.521	0.180	2.90	$8.08e-03$

Section S1.5 Additional measures similarity

The correlation and distance-based comparisons of the main text included only prey species which both Paine and I observed *H. haustorium* feeding on at a given site. To compare *H. haustorium*'s apparent diet and each site's community structure between time periods more generally (i.e. including species incidences), I performed additional analyses that also (*i*) included prey species which only one of us observed in our feeding surveys and (*ii*) included prey species which only one of us observed as well as additional (non-prey) mobile species which we observed in our abundance surveys.

To assess time-period similarities in diet and prey abundances at all five sites where both Paine and I performed feeding surveys, I used the classic incidence-based Jaccard index (J_{class}), the abundance-based Jaccard index (J_{abd}), and the estimator for the abundance-based Jaccard index ($\hat{J}_{abd}$) (Chao *et al.*, 2005). While J_{class} quantifies compositional similarity (species overlap), J_{abd} reflects the probability that two randomly chosen individuals, one from each time period, both belong to any of the shared species seen in both time periods (not necessarily to the same shared species). The estimator $\hat{J}_{abd}$ attempts to account for shared but rare species that were not observed due to incomplete sampling. Overall, these analyses indicate low to intermediate levels of similarity in the composition of *H. haustorium*'s apparent diet and community that were driven by changes in the occurrence of low-frequency prey/species; for most sites, similarities were higher when considering prey frequency/species abundance and differed little between J_{abd} and $\hat{J}_{abd}$ (Table S9).

To visualize similarities in community structure, I performed a two-dimensional non-metric multi-dimensional scaling analysis with the *vegan* `R`-package (Oksanen *et al.*, 2020) using the Bray-Curtis metric to quantify distances between surveyed quadrats. This analysis indicated that all three sites surveyed by both Paine and me have changed in their community structure, with my surveys indicating more similar communities (both within and between sites) than did Paine's surveys (Fig. S2).

Table S9: The between time period similarity of *Haustrum haustorium*'s apparent diet – at the sites where Paine and I performed either feeding surveys only or both feeding and abundance surveys – as quantified by the incidence-based Jaccard index (J_{class}), as well as the abundance-based Jaccard index (J_{abd}) and the estimator for the abundace-based Jaccard index ($\hat{J}_{abd}$).

	Feeding observations			**Prey abundances**		
Site	J_{class}	J_{abd}	$\hat{J}_{abd}$	J_{class}	J_{abd}	$\hat{J}_{abd}$
Leigh - Echinoderm Reef	0.50	0.78	0.80	-	-	-
Leigh - Tabletop Rocks and Boulders	0.38	0.30	0.32	-	-	-
Leigh - Waterfall Rocks	0.50	0.87	0.98	0.77	0.92	0.92
Rangitoto Island - Whites Beach	0.50	0.74	0.81	0.33	0.45	0.45
Red Beach - Whangaparaoa	0.25	0.74	0.74	0.4	0.81	0.81

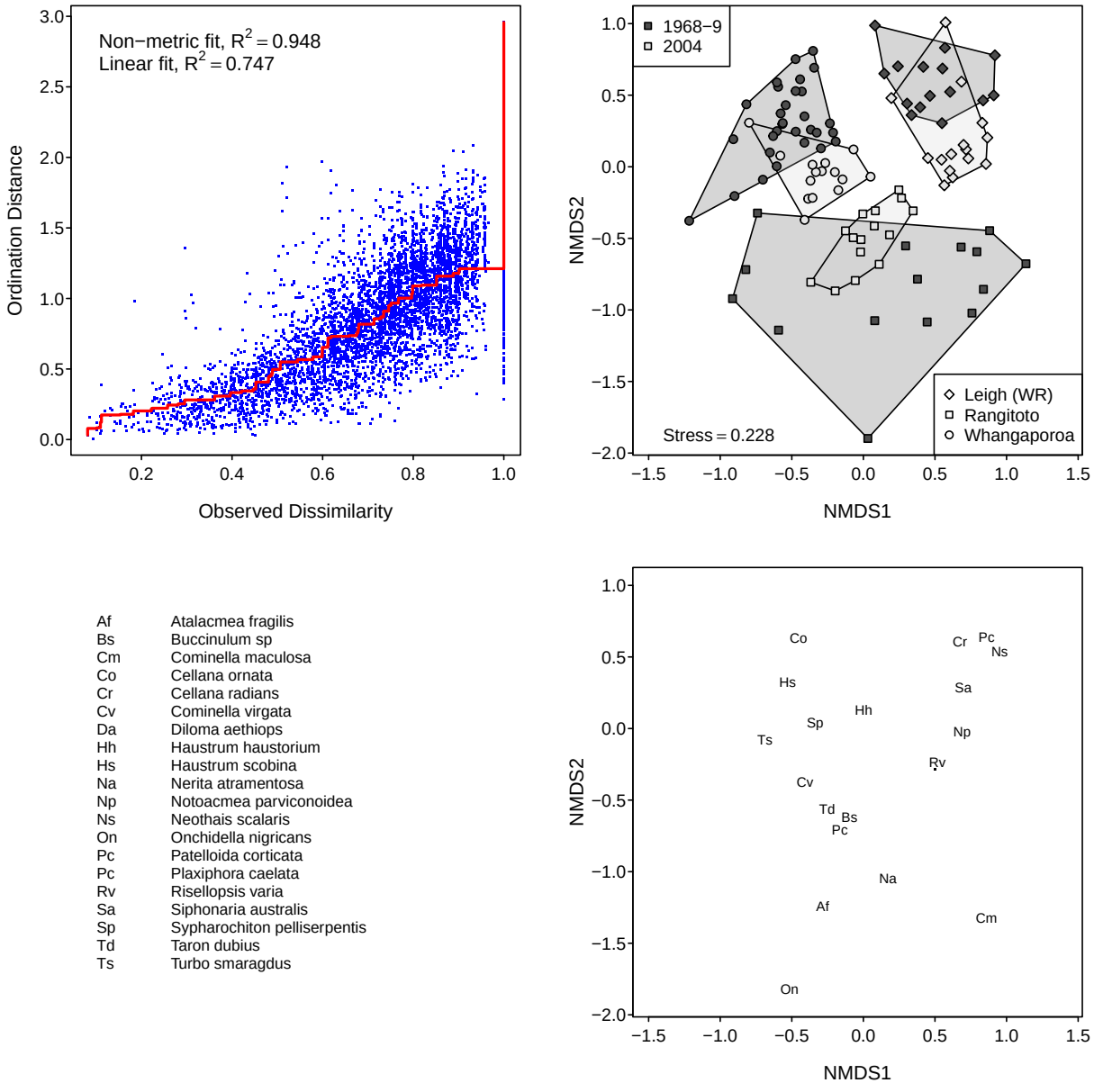

Figure S2: Non-metric multi-dimensional scaling using Bray-Curtis distances between quadrat-specific mobile species counts (including *H. haustorium*'s prey and other, non-prey species) at the three sites which Paine surveyed for species abundances in 1968–9 and which I resurveyed in 2004.

Section S1.6 Spurious versus non-spurious correlations of ratios

The difference between spurious and non-spurious interpretations of the correlation of ratios may be illustrated using variable permutations, as shown by the following `R` script (also available at `https://github.com/marknovak/NZPaineFrates/blob/main/code/RatioCorr.R`).

```
1  ################################################
2  ################################################
3  # Spurious versus non-spurious ratio correlations
4  ################################################
5  ################################################
6  library(MASS) # for mvrnorm
7  #~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
8  # Multivariate-normal random variables
9  # independent numerators
10 # but correlated denominators
11 #~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
12 S <- 100 # Sample size
13 xn <- rnorm(S, 10, 0.5) # first numerator
14 yn <- rnorm(S, 10, 0.5) # second numerator
15 cov <- 0.9 # Covariance between denominator variables
16 d <- data.frame(mvrnorm(n = S,
17 mu = c(xd = 10, yd = 10),
18 Sigma = rbind(c(1, cov), c(cov, 1))))
19 xd <- d$xd # first denominator
20 yd <- d$yd # second denominator
21
22 # Only the denominators are correlated
23 pairs(cbind(xn, yn, xd, yd))
24 cor(cbind(xn, yn, xd, yd))
25
26 # The ratios are correlated
27 cor.obs <- cor(xn/xd, yn/yd)
28
29 # Contrast spurious versus non-spurious inferences be permuting
     either
30 # just the numerators or both the numerators and denominators
31
32 num.sim <- 9999 # number of permutations
33
34 # It's a spurious correlation when drawing inference about the
     numerators
35 cor.spur <- replicate(num.sim, cor(sample(xn) / xd,
36 (yn) / yd))
37 # But *not* a spurious correlation when drawing inference about
     the ratios
38 cor.nonspur <- replicate(num.sim, cor(sample(xn/xd),
39 yn/yd))
```

```
40
41    cor.obs
42    mean(cor.spur)
43    mean(cor.nonspur)
44
45    # Inspect distributions of observed correlations
46    h1 <- hist(cor.nonspur, breaks = 200, xlim = c(-1,1),
47    main = '', xlab = 'Correlation')
48    abline(v = cor.obs, col = 'blue', lwd = 2)
49    abline(v = mean(cor.spur), col = 'red', lwd = 2)
50    h2 <- hist(cor.spur, breaks = 200, xlim = c(-1,1),
51    add = TRUE)
52    legend('topleft',
53    legend = c('Observed',"Mean (Expected)"),
54    lty = 1,
55    col = c('blue','red'),
56    bty = 'n')
57
58    # Conclusion: In the context of comparing feeding rates,
59    #  we are drawing inference about the correlation of the ratios
60    #  (not the numerator diet proportions).
61    # A correlation of zero,  mean(cor.nonspur),
62    #  is thus the appropriate null hypothesis.
63    # If we were drawing inference on the numerator diet proportions,
64    #  then the non-zero correlation, mean(cor.spur),
65    #  is the appropriate null hypothesis.
```

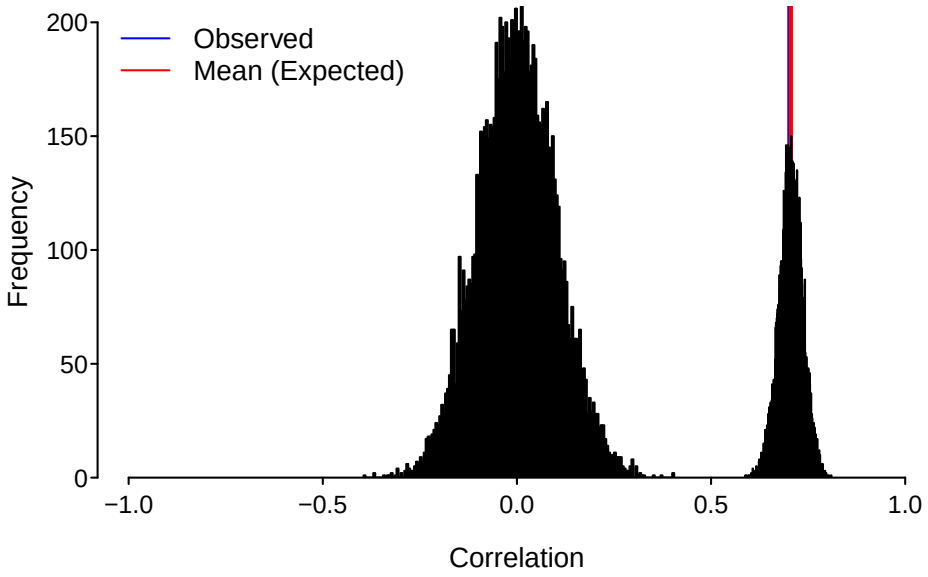

Figure S3: Frequency histograms for the correlation values when the numerators are permuted but the denominator variables remain correlated (right distribution) versus when the ratios themselves are permuted (left distribution). (Produced by above R code.)

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