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Research article

A spatial modeling approach for evaluating impacts of climate-driven species movement on biomass estimation methods

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Supplementary

Table S1. Settings for our two VAST models.

Parameter	Description	Settings A	Settings B
ObsModel	Link function and assumed distribution	c(10,2)	c(10,2)
FieldConfig	Specified spatial and/or spatio-temporal variation in predictors	c(Omega1=0, Epsilon1=0, Omega2=1, Epsilon2=1)	c(Omega1=0, Epsilon1=0, Omega2=1, Epsilon2=1)
RhoConfig	Specifying whether intercepts or spatio-temporal variation is structured among time intervals	c(Beta1=3, Beta2=0, Epsilon1=0, Epsilon2=4)	c(Beta1=3, Beta2=3, Epsilon1=0, Epsilon2=4)
X1_formula	Right-sided formula affecting the 1st linear predictor	N/A	X1_formula = ~ poly(Temp, degree=2)
X2_formula	Right-sided formula affecting the 2nd linear predictor	X2_formula = ~ poly(Temp, degree=2) + poly(Habitat, degree=2)	X2_formula = ~ poly(Temp, degree=2) + poly(Habitat, degree=2)

Table S2. yellowtail flounder biomass error results with full coverage survey sampling. Row colors correspond to the same settings applied in different seasons.

Temperature Scenario	Season	Covariate	Noise	VAST A	VAST B	Stratified Mean
Constant Population						
Repeating	spring	no cov	no	0.13	0.11	0.21
Repeating	spring	no cov	yes	0.14	0.16	0.25
Repeating	spring	w/ cov	no	0.07	0.07	n/a
Repeating	spring	w/ cov	yes	0.08	0.08	n/a
Repeating	fall	no cov	no	0.63	0.68	0.32
Repeating	fall	no cov	yes	0.80	0.77	0.31
Repeating	fall	w/ cov	no	0.14	0.08	n/a
Repeating	fall	w/ cov	yes	0.17	0.11	n/a
Increasing	spring	no cov	no	0.14	0.11	0.28
Increasing	spring	no cov	yes	0.18	0.15	0.28
Increasing	spring	w/ cov	no	0.05	0.06	n/a
Increasing	spring	w/ cov	yes	0.10	0.12	n/a
Increasing	fall	no cov	no	1.46	1.26	0.51
Increasing	fall	no cov	yes	1.40	1.38	0.5
Increasing	fall	w/ cov	no	0.21	0.23	n/a
Increasing	fall	w/ cov	yes	0.30	0.28	n/a
Decreasing Population						
Repeating	spring	no cov	no	0.11	0.08	0.23
Repeating	spring	no cov	yes	0.12	0.11	0.27
Repeating	spring	w/ cov	no	0.07	0.06	n/a
Repeating	spring	w/ cov	yes	0.11	0.07	n/a
Repeating	fall	no cov	no	0.97	0.81	0.41
Repeating	fall	no cov	yes	0.99	1.09	0.37
Repeating	fall	w/ cov	no	0.16	0.08	n/a
Repeating	fall	w/ cov	yes	0.29	0.18	n/a
Increasing	spring	no cov	no	0.17	0.15	0.22
Increasing	spring	no cov	yes	0.15	0.17	0.26
Increasing	spring	w/ cov	no	0.08	0.07	n/a
Increasing	spring	w/ cov	yes	0.16	0.10	n/a
Increasing	fall	no cov	no	1.17	1.06	0.28
Increasing	fall	no cov	yes	1.14	1.10	0.25
Increasing	fall	w/ cov	no	0.40	0.15	n/a
Increasing	fall	w/ cov	yes	0.40	0.20	n/a
Increasing Population						
Repeating	spring	no cov	no	0.46	0.13	0.16
Repeating	spring	no cov	yes	0.43	0.21	0.22
Repeating	spring	w/ cov	no	0.06	0.06	n/a
Repeating	spring	w/ cov	yes	0.08	0.07	n/a
Repeating	fall	no cov	no	0.40	0.36	0.34
Repeating	fall	no cov	yes	0.38	0.44	0.46
Repeating	fall	w/ cov	no	0.11	0.08	n/a
Repeating	fall	w/ cov	yes	0.24	0.17	n/a
Increasing	spring	no cov	no	0.16	0.13	0.32
Increasing	spring	no cov	yes	0.21	0.16	0.32
Increasing	spring	w/ cov	no	0.06	0.07	n/a
Increasing	spring	w/ cov	yes	0.12	0.10	n/a
Increasing	fall	no cov	no	0.71	0.66	0.3
Increasing	fall	no cov	yes	1.03	0.71	0.39
Increasing	fall	w/ cov	no	0.43	0.21	n/a
Increasing	fall	w/ cov	yes	0.51	0.37	n/a

Table S3. yellowtail flounder biomass error results with reduced coverage survey sampling. Row colors correspond to the same settings applied in different seasons.

Temperature Scenario	Season	Covariate	Noise	VAST A	VAST B	Stratified Mean
Constant Population						
Repeating	spring	no cov	no	0.24	0.19	0.27
Repeating	spring	no cov	yes	0.16	0.15	0.22
Repeating	spring	w/ cov	no	0.19	0.19	n/a
Repeating	spring	w/ cov	yes	0.12	0.14	n/a
Repeating	fall	no cov	no	0.30	0.25	0.47
Repeating	fall	no cov	yes	0.78	0.36	0.44
Repeating	fall	w/ cov	no	0.22	0.19	n/a
Repeating	fall	w/ cov	yes	0.24	0.17	n/a
Increasing	spring	no cov	no	0.23	0.17	0.31
Increasing	spring	no cov	yes	0.25	0.19	0.29
Increasing	spring	w/ cov	no	0.17	0.17	n/a
Increasing	spring	w/ cov	yes	0.62	0.15	n/a
Increasing	fall	no cov	no	2.22	0.75	0.64
Increasing	fall	no cov	yes	1.75	0.89	0.59
Increasing	fall	w/ cov	no	0.24	0.20	n/a
Increasing	fall	w/ cov	yes	0.59	0.13	n/a
Decreasing Population						
Repeating	spring	no cov	no	0.31	0.19	0.25
Repeating	spring	no cov	yes	0.27	0.16	0.27
Repeating	spring	w/ cov	no	0.19	0.19	n/a
Repeating	spring	w/ cov	yes	0.15	0.16	n/a
Repeating	fall	no cov	no	0.53	0.24	0.55
Repeating	fall	no cov	yes	0.53	0.36	0.53
Repeating	fall	w/ cov	no	0.18	0.23	n/a
Repeating	fall	w/ cov	yes	0.16	0.24	n/a
Increasing	spring	no cov	no	0.18	0.14	0.32
Increasing	spring	no cov	yes	0.37	0.15	0.29
Increasing	spring	w/ cov	no	0.21	0.22	n/a
Increasing	spring	w/ cov	yes	0.16	0.21	n/a
Increasing	fall	no cov	no	0.90	0.60	0.54
Increasing	fall	no cov	yes	0.84	0.62	0.48
Increasing	fall	w/ cov	no	0.32	0.31	n/a
Increasing	fall	w/ cov	yes	0.36	0.32	n/a
Increasing Population						
Repeating	spring	no cov	no	0.22	0.15	0.2
Repeating	spring	no cov	yes	0.19	0.11	0.22
Repeating	spring	w/ cov	no	0.17	0.17	n/a
Repeating	spring	w/ cov	yes	0.11	0.13	n/a
Repeating	fall	no cov	no	0.19	0.11	0.41
Repeating	fall	no cov	yes	0.26	0.21	0.46
Repeating	fall	w/ cov	no	0.21	0.22	n/a
Repeating	fall	w/ cov	yes	0.17	0.19	n/a
Increasing	spring	no cov	no	0.31	0.33	0.4
Increasing	spring	no cov	yes	0.30	0.26	0.38
Increasing	spring	w/ cov	no	0.30	0.30	n/a
Increasing	spring	w/ cov	yes	0.31	0.25	n/a
Increasing	fall	no cov	no	0.56	0.49	0.7
Increasing	fall	no cov	yes	0.58	0.48	0.69
Increasing	fall	w/ cov	no	0.48	0.53	n/a
Increasing	fall	w/ cov	yes	0.47	0.50	n/a

Table S4. yellowtail flounder trend error results with full coverage survey sampling. Row colors correspond to the same settings applied in different seasons.

Temperature Scenario	Season	Covariate	Noise	VAST A	VAST B	Stratified Mean
Constant Population						
Repeating	spring	no cov	no	0.014	0.010	0.03
Repeating	fall	no cov	no	0.025	0.019	0.05
Repeating	spring	no cov	yes	0.014	0.013	0.03
Repeating	fall	no cov	yes	0.024	0.022	0.05
Repeating	spring	w/ cov	no	0.005	0.007	n/a
Repeating	fall	w/ cov	no	0.013	0.008	n/a
Repeating	spring	w/ cov	yes	0.008	0.008	n/a
Repeating	fall	w/ cov	yes	0.011	0.010	n/a
Increasing	spring	no cov	no	0.015	0.012	0.03
Increasing	fall	no cov	no	0.036	0.032	0.08
Increasing	spring	no cov	yes	0.019	0.015	0.03
Increasing	fall	no cov	yes	0.039	0.035	0.09
Increasing	spring	w/ cov	no	0.006	0.006	n/a
Increasing	fall	w/ cov	no	0.013	0.012	n/a
Increasing	spring	w/ cov	yes	0.010	0.012	n/a
Increasing	fall	w/ cov	yes	0.016	0.010	n/a
Increasing Population						
Repeating	spring	no cov	no	0.017	0.012	0.02
Repeating	fall	no cov	no	0.017	0.014	0.04
Repeating	spring	no cov	yes	0.019	0.019	0.03
Repeating	fall	no cov	yes	0.023	0.016	0.05
Repeating	spring	w/ cov	no	0.005	0.004	n/a
Repeating	fall	w/ cov	no	0.007	0.004	n/a
Repeating	spring	w/ cov	yes	0.008	0.009	n/a
Repeating	fall	w/ cov	yes	0.016	0.010	n/a
Increasing	spring	no cov	no	0.014	0.012	0.03
Increasing	fall	no cov	no	0.030	0.023	0.04
Increasing	spring	no cov	yes	0.016	0.014	0.04
Increasing	fall	no cov	yes	0.032	0.023	0.04
Increasing	spring	w/ cov	no	0.006	0.006	n/a
Increasing	fall	w/ cov	no	0.013	0.007	n/a
Increasing	spring	w/ cov	yes	0.009	0.008	n/a
Increasing	fall	w/ cov	yes	0.015	0.009	n/a
Decreasing Population						
Repeating	spring	no cov	no	0.018	0.012	0.05
Repeating	fall	no cov	no	0.025	0.014	0.08
Repeating	spring	no cov	yes	0.018	0.015	0.05
Repeating	fall	no cov	yes	0.025	0.017	0.07
Repeating	spring	w/ cov	no	0.007	0.006	n/a
Repeating	fall	w/ cov	no	0.012	0.008	n/a
Repeating	spring	w/ cov	yes	0.010	0.010	n/a
Repeating	fall	w/ cov	yes	0.016	0.011	n/a
Increasing	spring	no cov	no	0.016	0.012	0.05
Increasing	fall	no cov	no	0.032	0.019	0.04
Increasing	spring	no cov	yes	0.018	0.014	0.05
Increasing	fall	no cov	yes	0.030	0.019	0.05
Increasing	spring	w/ cov	no	0.009	0.008	n/a
Increasing	fall	w/ cov	no	0.015	0.010	n/a
Increasing	spring	w/ cov	yes	0.014	0.014	n/a
Increasing	fall	w/ cov	yes	0.019	0.013	n/a

Table S5. yellowtail flounder trend error results with reduced coverage survey sampling. Row colors correspond to the same settings applied in different seasons.

Temperature Scenario	Season	Covariate	Noise	VAST A	VAST B	Stratified Mean
Constant Population						
Repeating	spring	no cov	no	0.018	0.013	0.03
Repeating	fall	no cov	no	0.029	0.026	0.07
Repeating	spring	no cov	yes	0.020	0.016	0.04
Repeating	fall	no cov	yes	0.026	0.031	0.07
Repeating	spring	w/ cov	no	0.005	0.004	n/a
Repeating	fall	w/ cov	no	0.012	0.009	n/a
Repeating	spring	w/ cov	yes	0.009	0.012	n/a
Repeating	fall	w/ cov	yes	0.018	0.018	n/a
Increasing	spring	no cov	no	0.020	0.016	0.03
Increasing	fall	no cov	no	0.115	0.071	0.14
Increasing	spring	no cov	yes	0.023	0.019	0.04
Increasing	fall	no cov	yes	0.088	0.078	0.13
Increasing	spring	w/ cov	no	0.004	0.005	n/a
Increasing	fall	w/ cov	no	0.021	0.012	n/a
Increasing	spring	w/ cov	yes	0.059	0.012	n/a
Increasing	fall	w/ cov	yes	0.064	0.015	n/a
Increasing Population						
Repeating	spring	no cov	no	0.026	0.011	0.03
Repeating	fall	no cov	no	0.024	0.012	0.06
Repeating	spring	no cov	yes	0.021	0.012	0.03
Repeating	fall	no cov	yes	0.028	0.012	0.07
Repeating	spring	w/ cov	no	0.005	0.005	n/a
Repeating	fall	w/ cov	no	0.014	0.009	n/a
Repeating	spring	w/ cov	yes	0.008	0.009	n/a
Repeating	fall	w/ cov	yes	0.015	0.011	n/a
Increasing	spring	no cov	no	0.013	0.016	0.03
Increasing	fall	no cov	no	0.059	0.040	0.13
Increasing	spring	no cov	yes	0.015	0.016	0.04
Increasing	fall	no cov	yes	0.059	0.044	0.12
Increasing	spring	w/ cov	no	0.010	0.009	n/a
Increasing	fall	w/ cov	no	0.029	0.029	n/a
Increasing	spring	w/ cov	yes	0.016	0.014	n/a
Increasing	fall	w/ cov	yes	0.036	0.024	n/a
Decreasing Population						
Repeating	spring	no cov	no	0.026	0.013	0.05
Repeating	fall	no cov	no	0.028	0.011	0.1
Repeating	spring	no cov	yes	0.027	0.015	0.05
Repeating	fall	no cov	yes	0.028	0.015	0.09
Repeating	spring	w/ cov	no	0.008	0.007	n/a
Repeating	fall	w/ cov	no	0.013	0.009	n/a
Repeating	spring	w/ cov	yes	0.018	0.011	n/a
Repeating	fall	w/ cov	yes	0.018	0.011	n/a
Increasing	spring	no cov	no	0.020	0.014	0.06
Increasing	fall	no cov	no	0.075	0.069	0.31
Increasing	spring	no cov	yes	0.046	0.022	0.07
Increasing	fall	no cov	yes	0.070	0.065	0.26
Increasing	spring	w/ cov	no	0.017	0.016	n/a
Increasing	fall	w/ cov	no	0.079	0.075	n/a
Increasing	spring	w/ cov	yes	0.018	0.025	n/a
Increasing	fall	w/ cov	yes	0.080	0.064	n/a

Table S6. Cod biomass error results.

Sampling Coverage	Noise	Season	VAST NC A	VAST NC B	VAST WC A	VAST WC B	Stratified Mean
Repeating Temp.							
full	no	spring	0.12	0.12	0.16	0.15	0.25
full	yes	spring	0.16	0.19	0.23	0.19	0.27
full	no	fall	0.86	0.76	0.47	0.13	0.45
full	yes	fall	1.13	0.89	0.55	0.33	0.44
reduced	no	spring	0.29	0.26	0.22	0.21	0.34
reduced	yes	spring	0.32	0.19	0.19	0.11	0.33
reduced	no	fall	1.41	0.79	0.37	0.26	0.62
reduced	yes	fall	2.09	1.37	0.40	0.26	0.57
Increasing Temp.							
full	no	spring	0.11	0.11	0.13	0.12	0.36
full	yes	spring	0.14	0.12	0.09	0.15	0.35
full	no	fall	0.23	0.19	0.09	0.05	0.49
full	yes	fall	0.34	0.30	0.20	0.23	0.41
reduced	no	spring	0.25	0.17	0.22	0.24	0.41
reduced	yes	spring	0.25	0.20	0.14	0.23	0.46
reduced	no	fall	0.16	0.21	0.26	0.33	0.60
reduced	yes	fall	0.16	0.18	0.26	0.31	0.58

Table S7. Cod trend error results.

Survey Coverage	Noise	Season	VAST NC A	VAST NC B	VAST WC A	VAST WC B	Stratified Mean
Repeating Temp.							
full	no	spring	0.013	0.016	0.010	0.009	0.03
full	yes	spring	0.013	0.017	0.012	0.010	0.03
full	no	fall	0.025	0.014	0.020	0.014	0.05
full	yes	fall	0.028	0.014	0.018	0.020	0.06
reduced	no	spring	0.019	0.023	0.013	0.012	0.04
reduced	yes	spring	0.031	0.020	0.017	0.012	0.05
reduced	no	fall	0.057	0.037	0.038	0.015	0.08
reduced	yes	fall	0.056	0.040	0.037	0.022	0.09
Increasing Temp.							
full	no	spring	0.020	0.018	0.009	0.008	0.04
full	yes	spring	0.021	0.021	0.012	0.012	0.05
full	no	fall	0.014	0.009	0.011	0.006	0.06
full	yes	fall	0.016	0.010	0.017	0.007	0.06
reduced	no	spring	0.034	0.027	0.015	0.011	0.05
reduced	yes	spring	0.034	0.017	0.014	0.012	0.05
reduced	no	fall	0.018	0.012	0.016	0.009	0.07
reduced	yes	fall	0.019	0.010	0.016	0.013	0.08

Table S8. Haddock biomass error results.

Sampling Coverage	Noise	Season	VAST NC A	VAST NC B	VAST WC A	VAST WC B	Stratified Mean
Repeating Temp.							
full	no	spring	0.28	0.25	0.11	0.05	0.26
full	yes	spring	0.35	0.30	0.11	0.06	0.31
full	no	fall	0.82	0.89	0.23	0.23	0.40
full	yes	fall	1.01	1.04	0.29	0.35	0.39
reduced	no	spring	0.35	0.32	0.41	0.40	0.44
reduced	yes	spring	0.33	0.38	0.39	0.37	0.36
reduced	no	fall	0.48	0.44	0.61	0.64	0.72
reduced	yes	fall	0.49	0.42	0.60	0.62	0.70
Increasing Temp.							
full	no	spring	0.45	0.49	0.13	0.18	0.18
full	yes	spring	0.55	0.73	0.18	0.43	0.14
full	no	fall	0.31	0.28	0.05	0.05	0.26
full	yes	fall	0.45	0.41	0.15	0.06	0.27
reduced	no	spring	0.34	0.34	0.30	0.35	0.45
reduced	yes	spring	0.31	0.30	0.45	0.33	0.44
reduced	no	fall	0.34	0.36	0.46	0.48	0.54
reduced	yes	fall	0.29	0.33	0.41	0.46	0.50

Table S9. Haddock trend error results.

Survey Coverage	Noise	Season	VAST NC A	VAST NC B	VAST WC A	VAST WC B	Stratified Mean
Repeating Temp.							
full	no	spring	0.018	0.017	0.009	0.004	0.02
full	yes	spring	0.020	0.016	0.008	0.004	0.02
full	no	fall	0.023	0.013	0.010	0.004	0.04
full	yes	fall	0.024	0.011	0.012	0.004	0.03
reduced	no	spring	0.022	0.016	0.011	0.004	0.03
reduced	yes	spring	0.023	0.024	0.014	0.009	0.03
reduced	no	fall	0.035	0.028	0.023	0.017	0.02
reduced	yes	fall	0.036	0.028	0.026	0.016	0.03
Increasing Temp.							
full	no	spring	0.022	0.013	0.008	0.009	0.02
full	yes	spring	0.022	0.012	0.009	0.012	0.02
full	no	fall	0.014	0.015	0.005	0.004	0.02
full	yes	fall	0.014	0.007	0.007	0.004	0.02
reduced	no	spring	0.020	0.015	0.007	0.006	0.02
reduced	yes	spring	0.022	0.019	0.009	0.008	0.02
reduced	no	fall	0.017	0.008	0.005	0.004	0.02
reduced	yes	fall	0.018	0.009	0.008	0.005	0.02

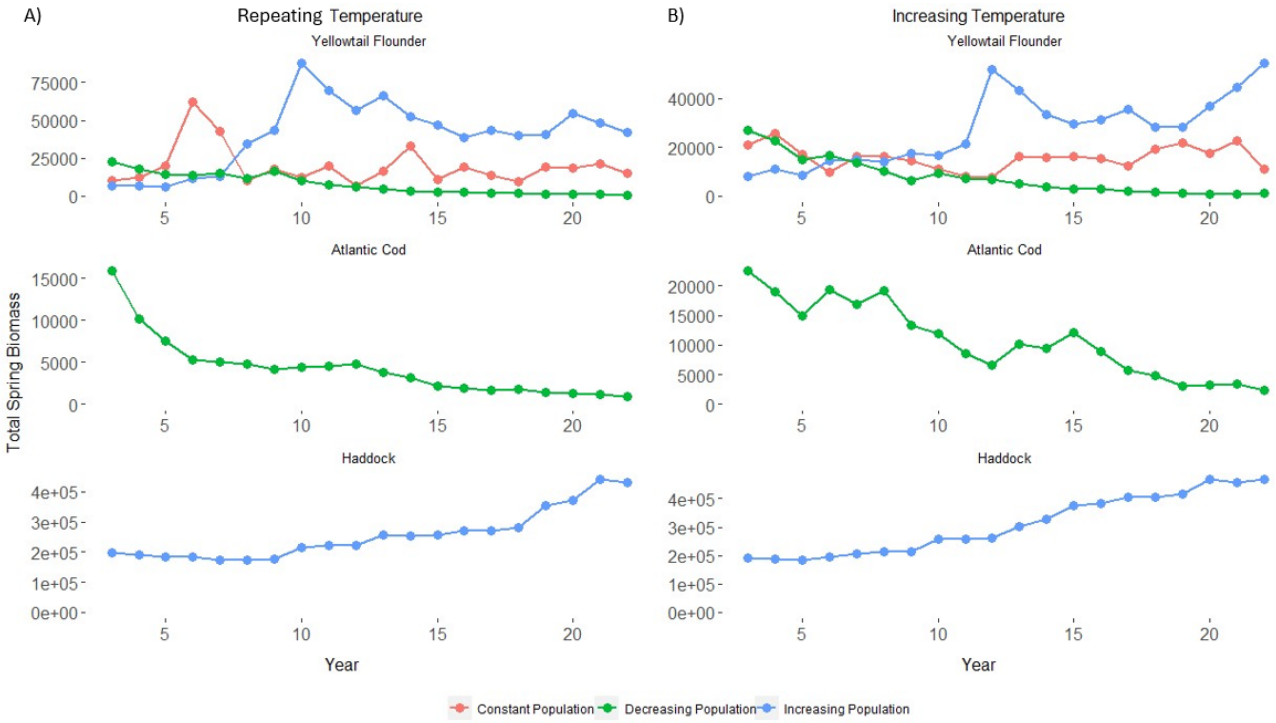

Figure S1. True population trends used in index analyses from scenarios that used an repeating temperature gradient (plot A) and increasing temperature (plot B) gradient. Spring biomass plots are shown. The fall values are very similar.

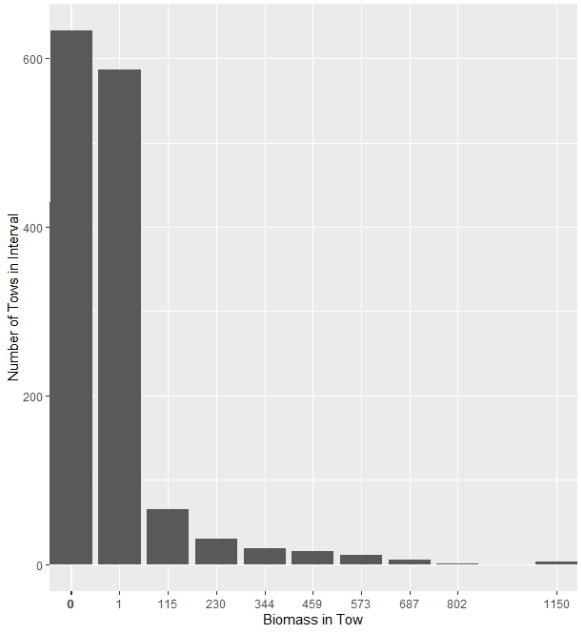

Figure S2. Histogram of spring haddock simulated biomass tows from the repeating temperature and increasing population scenario. The values on the x-axis represent the upper bound of the given interval. Similar to the real survey, there are a large number of 0 values in the tows.

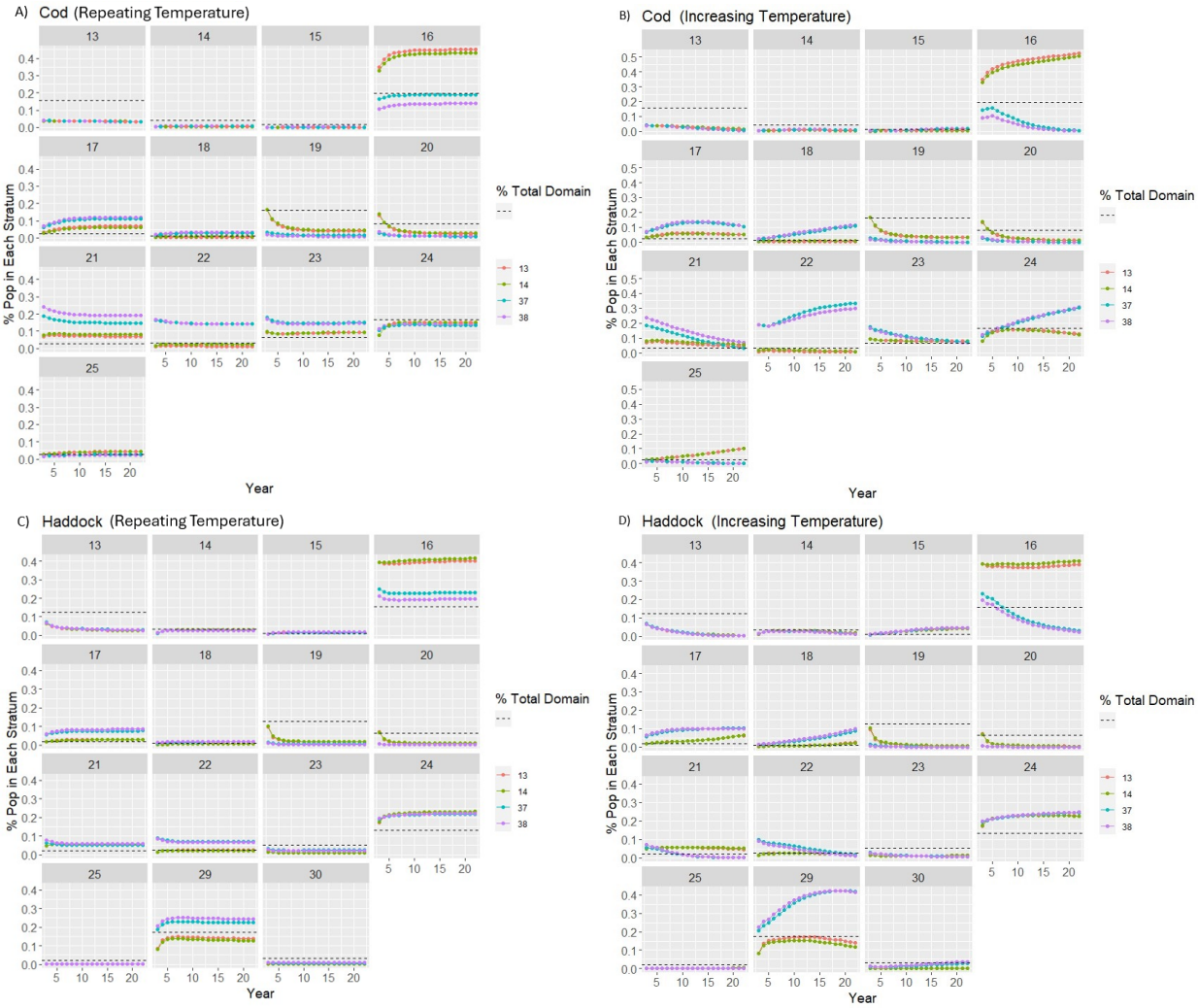

Figure S3. Percent of cod and haddock in each stratum during survey weeks (13, 14 in spring, 37, 38 in fall) in our spatial simulations. All repeating temperature scenarios follow the patterns in plots A and C while increasing temperature scenarios follow the patterns in plots B and D. See Figure 1 for a spatial reference of the Georges Bank strata. The black dotted line represents the percent of the entire domain that the given stratum covers, which also approximately corresponds to the allocation of tows to each stratum.

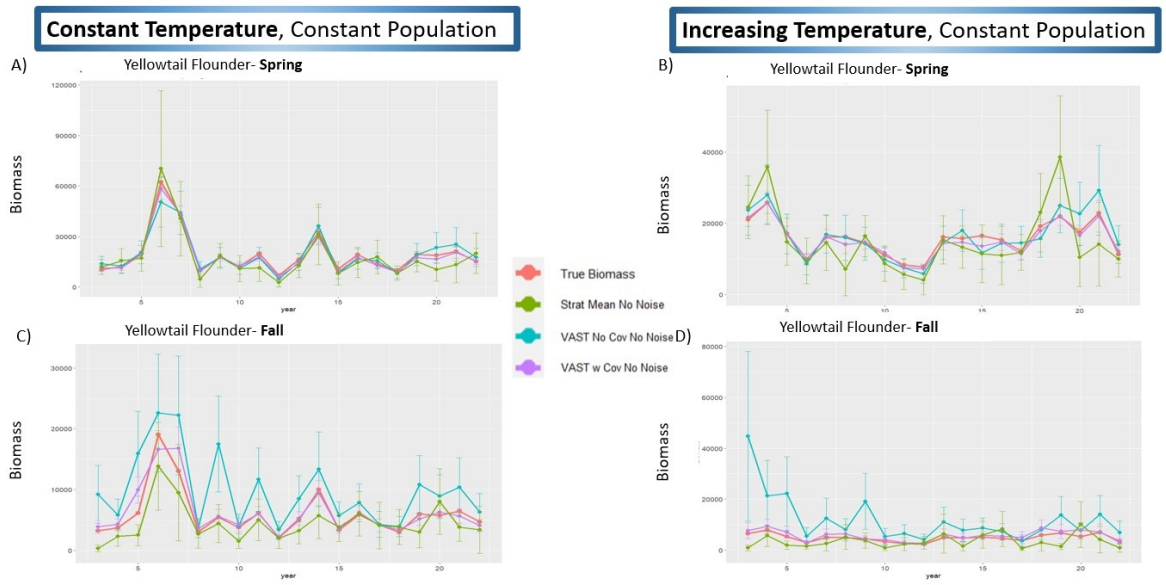

Figure S4. Representative example of biomass estimate trend for yellowtail with 95 percent confident interval for each year. Both scenarios have a relatively constant population with all strata being surveyed. The main difference is plots A and C have a repeating temperature gradient while plots B and D have an increasing average temperature. Biomass is measured in metric tons.

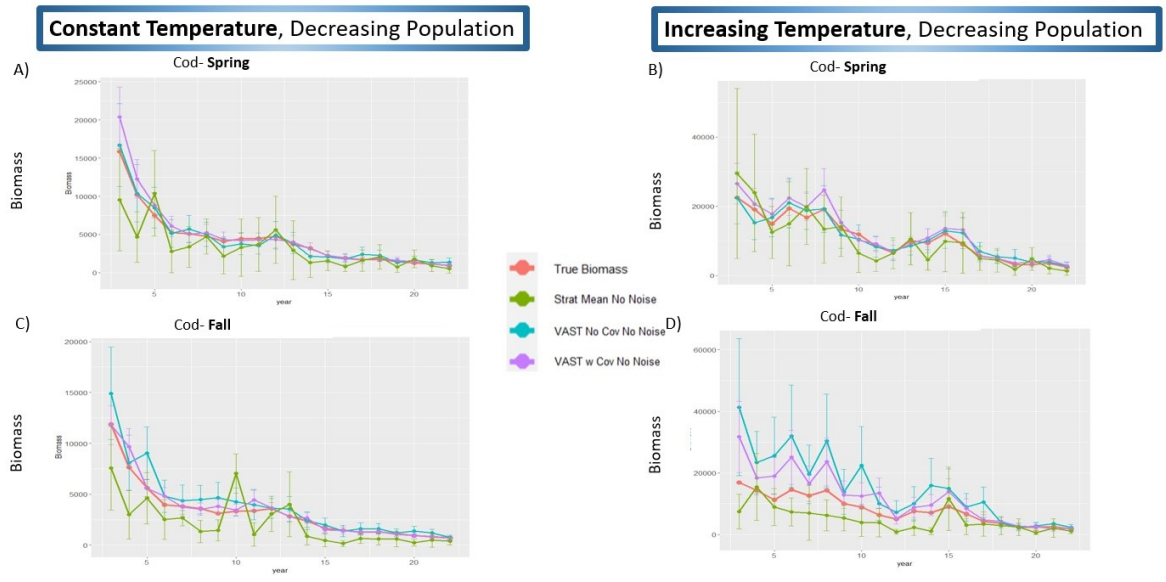

Figure S5. Representative example of biomass estimate trend for Atlantic cod with 95 percent confident interval for each year. Both scenarios have a decreasing population trend with all strata being surveyed. The main difference is plots A and C have a repeating temperature gradient while plots B and D have an increasing average temperature. Biomass is measured in metric tons.

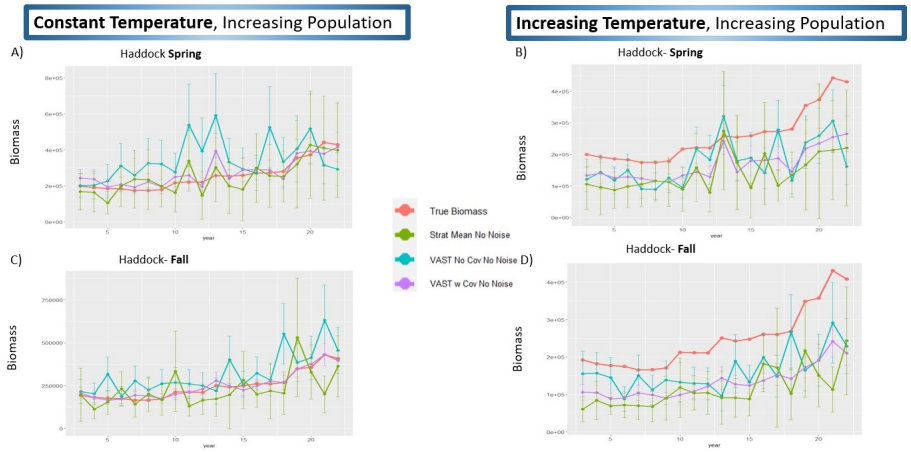

Figure S6. Representative example of biomass estimate trend for haddock with 95 percent confident interval for each year. Both scenarios have an increasing population trend and a repeating temperature gradient. The main difference is plots A and C have all strata being surveyed while plots B and D were derived from samples taken from a subset of strata. Biomass is measured in metric tons.

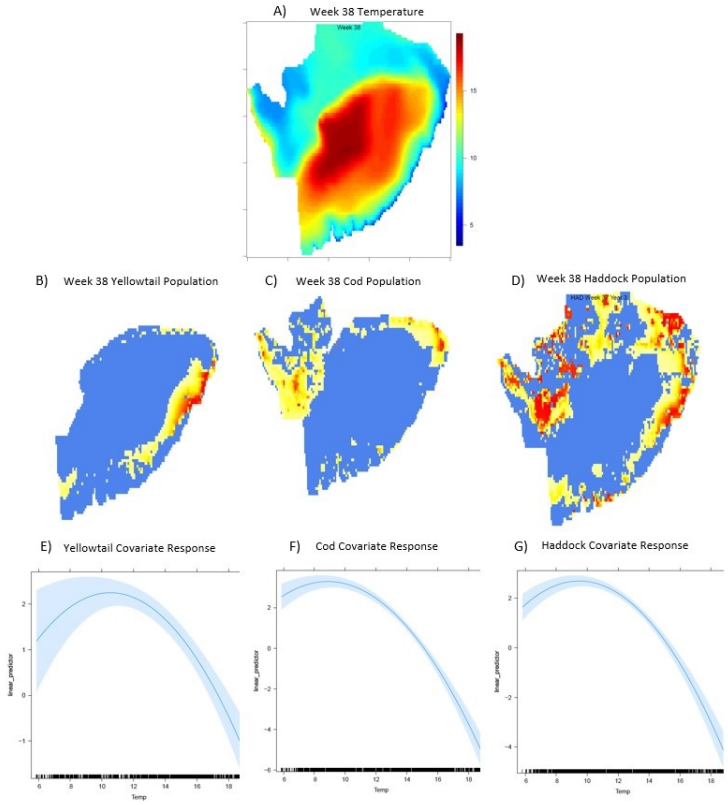

Figure S7. By surveying a large range of temperature values (plot A) for each species shown in plots B, C, and D, VAST can produce covariate response plots that reflect the true normally distributed temperature preferences used to drive MixFishSim movement for each species (plots E, F, and G).

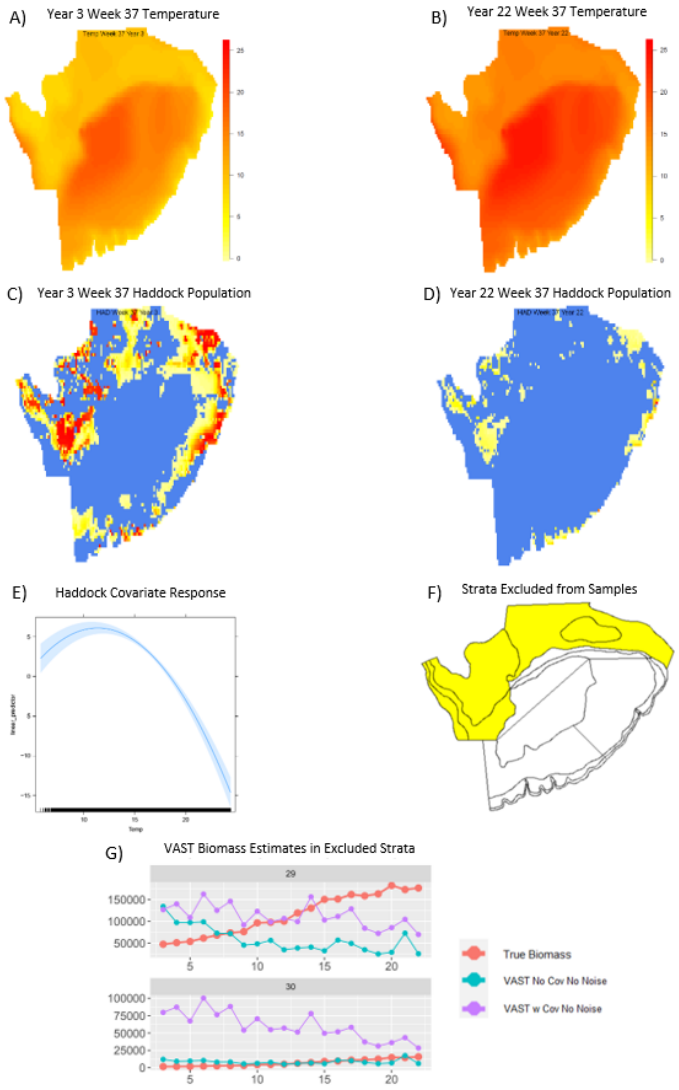

Figure S8. Temperature distribution (plots A and B), population distribution (plots C and D), temperature covariate response (plot D) and resulting population estimate for haddock (plot G) when the population was increasing over time, the average temperature was increasing, and certain strata shown were excluded from sampling (plot F). Since we are not sampling in the coldest part of haddock's domain, the covariate response is incomplete and the resulting estimate in that region provides the wrong trend.