The integrated assessment of critical ecosystem dynamics in a marine fishery

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Session 5: Multi-scale, ecosystem-based, Arctic marine resource management

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Presentation Contents

1 Biological General Equilibrium Model – Construction: Problem statement

- **Question:** Can an ecosystem be modeled within the complementarity format of the computed general equilibrium (CGE) framework?
- **Challenge:** complex problem with very limited precedent

  > "after 40 years of development, there are precious few advances towards truly synthesizing the connections between individuals, populations and large interconnected food webs" (Beckerman et al., 2010, p. 1)

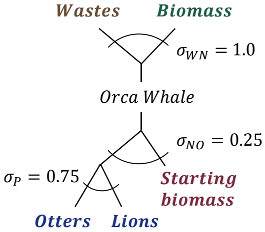
- **Approaches:** two closest approaches are
  – *GEEM*: micro-behavioral, bioenergetic, *but* fixed marginal benefits, ltd. adaptive responses, under-determined scarcities (Tschirhart et al.)
  – *Ecosim*: highly-parametric behavior, not micro-behavioral
- **Solution:** abstract economic GE structure & adapt to biology
- **Novelty:** synthesizes *adaptive behavior* driven by *endogenous scarcity* constrained by *energy budgets* generating *inter-period dynamics*

1.1 Optimal foraging: Scarcity & adaptive behavior

- **Premise:** species face *decisions* made subject to *constraints* that can be evaluated by a *currency*, Stephens and Krebs (1986)
- **Decisions:** competition drives species → optimal behavior
  - System rests when behavior stops changing - species can't do better
  - First-order condition PDEs define intra-period activity
- **Constraints:** scarcity & starting biomass exogenous to individuals
  - Scarcity a fcn. of initial stocks (set in prior periods) & competition
  - Prey consumption added to existing biomass w. diminishing returns
- **Currency:** energy gains & expenditures determine survival
  - Scarcer prey incur higher search costs but deliver equal benefit
  - Competitive pressure favors "switching" toward abundant prey
  - Individuals who make energetically "profitable" choices proliferate

1.1 Optimal foraging: Modeling adaptive behavior

- **Period activity:** choosing how much & who to eat
  - *How much* I eat depends on my size & aggregate prey scarcity
  - *Who* I eat depends on my preferences & *relative* prey scarcity



$$\left(\alpha_W \mathbf{w_i}^{1-\sigma_{WN}} + \alpha_B \mathbf{b_i}^{1-\sigma_{WN}}\right)^{\frac{1}{1-\sigma_{WN}}}$$

$$= \text{Total Output} =$$

$$\tau_i \left(\alpha_X \left(\sum_j \alpha_{ji} \mathbf{x_{ji}}^{1-\sigma_P}\right)^{\frac{1-\sigma_{NO}}{1-\sigma_P}} + \alpha_M \mathbf{m_i}^{1-\sigma_{NO}}\right)^{\frac{\eta_g}{1-\sigma_{NO}}}$$

- **Key parameters:** elasticities of substitution (σ's) relate relative changes in scarcities & quantities
- **Outputs**
  - wastes $\propto$ energy expenditures $\propto$ prey scarcity
  - Decisions made on *intensive vars* via marginal cost-benefit trade-offs
  - Intra-period activity give rise to *inter*-period dynamics

1.2 System dynamics: Biological Accounting Matrix

Biological Accounting Matrix (BAM) of Energy Flows, Aleutian Islands Marine Ecosystem (Ecosim data)

Species		WHL	MML	BRD	BGF	LGF	HVF	MDF	SMF	BTM	Net Migr.	Ending Biomass	Wastes	Total Output
Whales	WHL	❷ 4	0	0	2	0	0	0	0	0	❸ -12	395	1,396	1,785
Mammals	MML	344	0	0	3	0	0	0	0	0	6	123	4,080	4,556
Birds	BRD	3	0	0	0	0	0	0	0	0	0	0	0	3
Big fish	BGF	0	39	0	21	0	0	0	0	0	206	4,141	1,461	5,868
Large fish	LGF	438	1,929	2	161	166	1,505	335	136	866	815	18,929	10,406	35,688
Harvest fish	HVF	146	1,056	1	404	1,718	313	141	96	0	-246	9,643	12,149	25,421
Med. Fish	MDF	2	210	0	190	0	25	10	0	0	67	2,917	2,634	6,054
Small fish	SMF	34	836	0	141	197	2,126	490	154	177	-57	1,622	301	6,022
Bot. feeders	BTM	411	363	1	776	14,564	10,531	2,123	3,902	14,394	48	2,616	2,624	52,353
Primary producers		❶ 0	0	0	0	101	1,142	0	104	21,621		↓		
Detritus		0	0	0	30	14	204	4	8	12,678	→	=	❹	
Starting Biomass		402	124	0	4,141	18,929	9,576	2,952	1,622	2,616				
Total Energy Input:		1,785	4,556	3	5,868	35,688	25,421	6,054	6,022	52,353				

Data: Must assemble BAM from algorithmically-revised Ecosim data

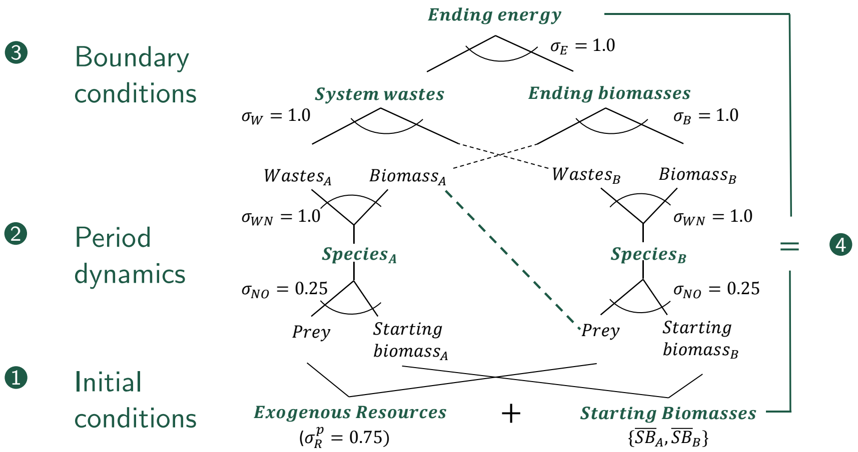
❶ Initial conditions: start period with *exogenous resources & biomass*

❷ Period dynamics: stocks revised by *PDE-defined trophic exchanges*

❸ Boundary cond: revised stocks allocated to *final biomasses & wastes*

❹ System cond: accounting ensures *energy-in = energy-out*

1.2 System dynamics: Ecosystem schematic



- Scarcity = f(initial stocks, competition)
- Diet composition = f(relative prey scarcity)
- Total cons. = f(start biomass, agg. prey scarcity)

1.2 System dynamics: Boundary conditions

Why do we need boundary conditions?

"Close" the model: relate intra-period dynamics to final quantities

- Without specifying final demands, scarcity values would fall to zero
  - we cannot leave wastes or ending biomasses as a remainder
  - me must specify how final quantities respond to scarcity
- Substitution elasticities across species' wastes & ending biomasses $= 1$
  - Final quantities move percent-for-percent against scarcities
  - Final Qs', predators', harvesters' scarcity responses may differ
- Accounting: sum of final quantities $=$ starting quantities

Set inter- temporal & spatial dynamics: depend on final quantities

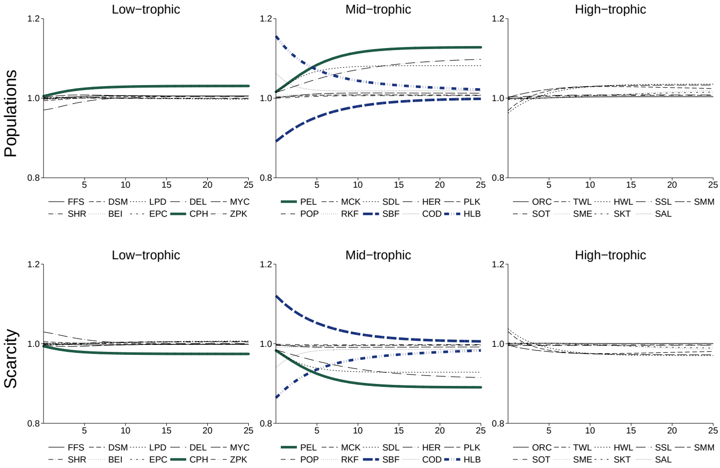
- Temporal: Today's ending is tomorrow's starting biomass
- Spatial: Migration in & out of system

2 Biological General Equilibrium Model – Applications: Problem statement

- **Question:** What are the ecosystem-wide consequences of harvesting shocks, invasive species, & stochastic shocks?
- **Approaches:** three ways to examine BGE model results
  – Simulate observed ecosystem phenomena: harvesting shocks, invasive species
  – Numerical experiments with stochastic perturbations verified against theory & intuition
  – Monte carlo analysis to test robustness of scenario results
- **Novelty:** BGE model's micro-foundation helps reveal causal chains; micro-foundation facilitates specification of observed shocks; minimal parameterization facilitates MC analysis
- **Experiments:** experiments simulated over 25-year horizon
  – ending biomasses seed following period's starting biomasses
  – Model run sequentially for 25 periods (yrs), stopped for extinctions

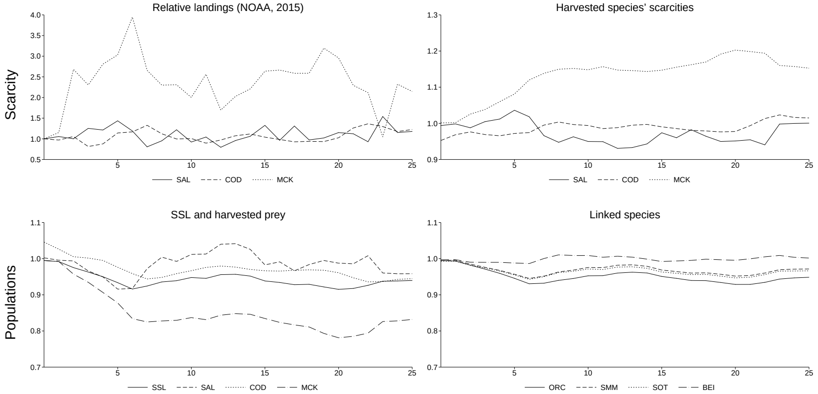
2.1 Conservation applications: Invasive species

- Invasive species, Kurle et al. (2008): Norway rats eat bird eggs →↑ CPH & PEL



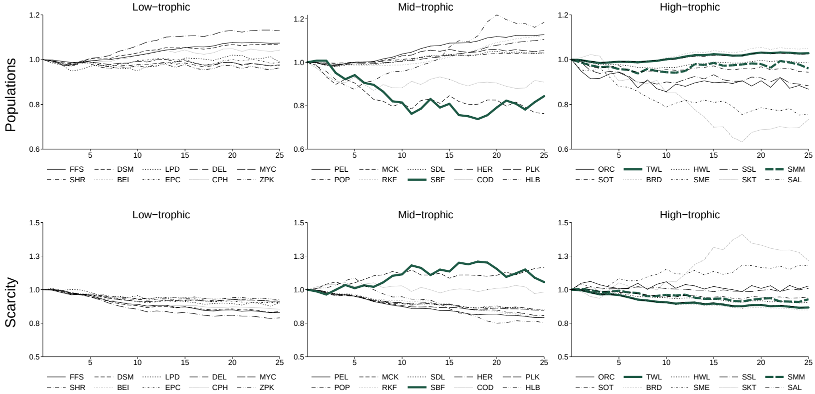
2.1 Conservation applications: Trophic cascade

- Harvest-induced trophic cascade, Estes et al. (1998): increased harvesting sets off long-chain ripple effect: ■ harvesting → ↓ fish stocks → ↓ sea lions → Orca switching (sea lions → otter) ↛ ↑ sea urchins ↛ ↓ kelp



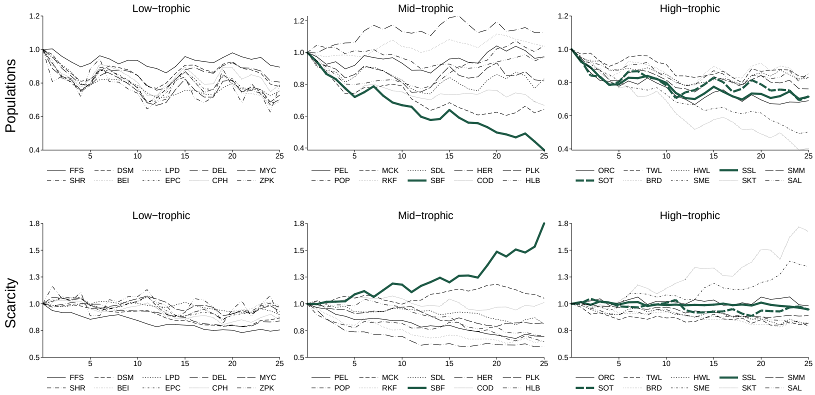
2.2 Simulation exercises: Stochastic harvesting

	Mid-Trophic					High-Trophic						
Measure	PLK	POP	SBF	COD	RWT	TWL	HWL	SSL	SMM	SOT	SME	SKT
Biomass (t Km^{-2})	3.38	1.11	1.80	2.40	0.50	0.01	0.14	0.04	0.02	0.00	0.05	2.60
Baseline harvest	0.40%	2.80%	0.60%	0.40%	0.40%	4.20%	4.60%	0.60%	1.70%	0.20%	0.40%	0.60%
Shocks relative to baseline												
Min	61%	52%	72%	45%	53%	70%	63%	50%	49%	46%	69%	55%
Mean	194%	195%	238%	201%	214%	249%	205%	212%	253%	226%	222%	207%
Max	356%	393%	405%	425%	404%	399%	387%	397%	404%	407%	379%	375%



2.2 Simulation exercises: Systemic stochastic perturbations

	Mid-Trophic					High-Trophic						
Measure	PLK	POP	SBF	COD	RWT	TWL	HWL	SSL	SMM	SOT	SME	SKT
Biomass (t Km^{-2})	3.38	1.11	1.80	2.40	0.50	0.01	0.14	0.04	0.02	0.00	0.05	2.60
Baseline harvest	0.40%	2.80%	0.60%	0.40%	0.40%	4.20%	4.60%	0.60%	1.70%	0.20%	0.40%	0.60%
Shocks relative to baseline												
Min	63%	67%	52%	50%	54%	57%	57%	53%	59%	72%	52%	56%
Mean	180%	181%	193%	184%	145%	168%	169%	189%	150%	208%	165%	164%
Max	273%	284%	314%	314%	301%	294%	296%	298%	285%	309%	260%	280%



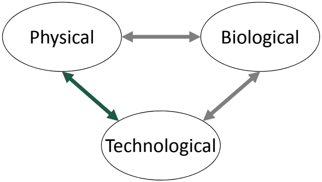
2.2 Simulation exercises: Systemic stochastic perturbations

	ORC	TWL	HWL	SSL	SMM	SOT	BRD	SME	SKT	SAL	PEL	MCK	SDL	HER	PLK	POP	RKF	SBF	COD	HLB	RWT	FFS	DSM	LPD	DEL	MYC	SHR	BEI	EPC	CPH	ZPK	EB	EW	EX
ORC																																-0.04	-0.04	0.00
TWL								-0.03																								-0.06	-0.06	0.00
HWL	-0.04							-0.03																								-0.06	-0.06	0.00
SSL	-0.04							-0.02																								-0.05	-0.05	0.00
SMM	-0.05							-0.03																								-0.06	-0.06	0.00
SOT	-0.09																															-0.12	-0.11	0.00
BRD	-0.06							-0.04																								-0.08	-0.07	0.00
SME								0.01																								-0.01	-0.01	0.00
SKT		-0.02		-0.02				0.01	0.03																							-0.01	-0.01	0.00
SAL		-0.06	-0.05	-0.06	-0.06		-0.05	-0.04	-0.02		-0.02																					-0.07	-0.07	0.00
PEL		-0.05	-0.04		-0.05		-0.05	-0.02	-0.01		-0.01								-0.02	0.00	-0.03		-0.02							-0.01		-0.06	-0.05	0.00
MCK		-0.04	-0.03	-0.04	-0.04	-0.06	-0.03		0.00						-0.02				0.00	0.01	-0.02	-0.01		0.00								-0.04	-0.03	0.00
SDL			-0.07	-0.08	-0.07	-0.10	-0.07		-0.03		-0.03						-0.02		-0.04	-0.02		-0.04								-0.03		-0.08	-0.07	0.00
HER		-0.04	-0.03		-0.04		-0.03	0.00	0.01		0.01										-0.01		0.00									-0.03	-0.03	0.00
PLK		-0.06	-0.06	-0.07	-0.07		-0.06	-0.03	-0.02		-0.02	-0.02			-0.04		-0.01		-0.03	-0.01	-0.04	-0.03	-0.03	-0.03								-0.07	-0.06	0.00
POP							-0.02	0.01											0.01			0.01										-0.02	-0.02	0.00
RKF		-0.03	-0.02	-0.03	-0.03		-0.02	0.00	0.01																							-0.03	-0.03	0.00
SBF		-0.05			-0.05			-0.02	-0.01										-0.01	0.00	-0.03											-0.05	-0.05	0.00
COD		-0.03	-0.02	-0.03	-0.03		-0.02	0.01	0.02										0.01	0.03	0.00											-0.02	-0.02	0.00
HLB								0.01	0.02																							-0.01	-0.01	0.00
RWT				-0.04				-0.01	0.00																							-0.04	-0.03	0.00
FFS				-0.04	-0.03			0.00	0.02										0.01	0.03												-0.05	-0.04	0.00
DSM		-0.05	-0.03	-0.06	-0.06	-0.08		-0.03	-0.01			0.00			-0.02		0.00		-0.02	0.00	-0.03	-0.02	-0.01	-0.01								-0.08	-0.07	0.00
LPD				-0.05				-0.01	0.00		0.02								-0.01	0.01	-0.02		0.00	0.01								-0.07	-0.05	0.00
DEL								-0.02	-0.01							0.03			-0.01	0.00	-0.03	-0.01										-0.08	-0.06	0.00
MYC		-0.09		-0.09	-0.09		-0.08	-0.06	-0.04		-0.03	-0.03			-0.05	-0.01	-0.03		-0.05	-0.04	-0.06	-0.05	-0.05	-0.04	-0.04	-0.03				-0.04		-0.12	-0.09	0.00
SHR					-0.11			-0.08	-0.07		-0.06	-0.05			-0.07	-0.04	-0.05		-0.08	-0.06	-0.09	-0.07	-0.07	-0.07	-0.06				-0.06	-0.06		-0.15	-0.12	0.00
BEI		-0.12			-0.12	-0.14	-0.11	-0.09	-0.07		-0.06	-0.06			-0.08	-0.04	-0.06	-0.06	-0.08	-0.07	-0.09	-0.08	-0.08	-0.07	-0.07	-0.06	-0.08	-0.08	-0.07	-0.07		-0.16	-0.12	0.00
EPC					-0.10	-0.12		-0.06	-0.05			-0.04			-0.05		-0.04		-0.06	-0.04		-0.06	-0.05	-0.05					-0.04	-0.04		-0.13	-0.10	0.00
CPH		-0.08	-0.06	-0.09	-0.09		-0.08	-0.05	-0.04	-0.04	-0.03	-0.03			-0.04	-0.01	-0.03	-0.03	-0.05	-0.03	-0.06	-0.05	-0.04	-0.04	-0.04							-0.12	-0.08	0.00
ZPK		-0.14	-0.12		-0.14		-0.13		-0.10	-0.10	-0.09	-0.08	-0.09	-0.06	-0.10	-0.07	-0.08	-0.09	-0.10		-0.11	-0.10	-0.10	-0.09		-0.09	-0.10		-0.09	-0.09	-0.09	-0.19	-0.14	0.00
PHY																															-0.10	Pd. 1		
MPH										-0.10	-0.08		-0.09													-0.09		-0.09	-0.08	-0.08				
DET								-0.09	-0.08			-0.08			-0.10		-0.08		-0.09	-0.07	-0.10			-0.09			-0.10	-0.09	-0.09		-0.10			
SB	0.00	-0.02	-0.02	0.00	-0.01	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		-0.02	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			

- **Pds.** 1 – 5**:** Primary production & other resources ↓ 20%
- **Pds.** 10 – 15**:** Harvesting rates tripled
- **Pds.** 20 – 25**:** All species 20% less productive (more wastes)

3 Discussion: Way forward

- **Science & policy applications**: additional Ecosim data; terrestrial ecosystems; validation exercises; climate shocks; spatial features
- **Inter-model comparisons**: mimic Ecosim & L-V models
- **Integrated assessment**: Enhanced biological modeling helps complete the integrated assessment triad



  - Advanced models of P & T systems have enabled extensive P$\leftrightarrow$T IA
  - The BGE model enhances weakest node of IA triad
  - Common GE framework may enable BGE-CGE *model* integration

THANK YOU!

. . . Q & A . . .

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Ecosim species

Ecosim Species Mapping

No.	Code	Description	No.	Code	Description	No.	Code	Description
Whales (WHL)			*Large fish (LGF)*			*Small fish (SMF)*		
1.	ORC	Transient orca	11.	PEL	Lg. pelagics	23.	DSM	Sm. demersals
2.	TWL	Toothed whales	12.	MCK	Atka mackerel	24.	LPD	Lg. demersals
3.	HWL	Baleen whales	13.	SDL	Sandlance	25.	DEL	Lg. deep water
						26.	MYC	Myctophids
Other mammals (MML)			*Harvested fish (HVF)*					
4.	SSL	Stellar sea lion	10.	SAL	Salmon	*Bottom feeders (BTM)*		
5.	SMM	Sm. mammals	14.	HER	Herring	27.	SHR	Shrimps
6.	SOT	Sea otters	15.	PLK	Adult pollock	28.	BEI	Benthic inverts
			16.	POP	Pacific perch	29.	EPC	Epiben pred.
Birds (BRD)			19.	COD	Pacific cod	30.	CPH	Cephalopods
7.	BRD	Birds	20.	HLB	Halibut	31.	ZPK	Lg. zooplankton
Big fish (BGF)			*Medium fish (MDF)*					
8.	SME	Shark mml. pred.	17.	RKF	Rockfish			
9.	SKT	Shark & skates	18.	SBF	Sablefish			
			21.	RWT	Arrowtooth			
			22.	FFS	Flatfish			

Ecosim system metrics

System metrics by scenario								
		Baseline	Post Scenario					
Metric	Units	BLG	STS		SSH		SPS	
Aggregate System Metrics								
Total system throughput (energy)	Bn. Kcal	135,267	100,554	-25.7%	136,358	0.8%	103,116	-23.8%
Total system throughput	MMT	252.3	187.5	-25.7%	254.4	0.9%	192.2	-23.8%
Total biomass		36.2	26.9	-25.7%	36.6	1.0%	27.6	-23.8%
Primary production		60.2	44.8	-25.6%	60.9	1.1%	45.7	-24.2%
Ascendancy	None	1.28	1.28	-0.2%	1.26	-1.0%	1.27	-0.6%
Intra-Period Flows								
Respiratory flows	Bn. Kcal	20,678	15,317	-25.9%	20,618	-0.3%	15,703	-24.1%
Consumption	MMT	91.0	67.7	-25.7%	91.9	1.0%	69.5	-23.6%
Detrital flows		43.5	32.4	-25.5%	44.1	1.2%	33.3	-23.5%
System Exports								
Net exports	MMT	0.352	0.255	-27.4%	0.555	57.8%	0.367	4.2%
Total catch		0.836	0.619	-25.9%	0.834	-0.2%	0.638	-23.8%
Mean trophic sequency of catch	None	14.1	14.1	-0.1%	14.2	0.6%	14.1	-0.3%

Ecosim system metrics (cont.)

System metrics by scenario							
		Baseline		Scenario			
Metric	Units	BLG	IVS	IVS		EXT	
Aggregate System Metrics							
Total system throughput (energy)	Bn. Kcal	135,267	140,280	140,918	0.5%	135,360	0.1%
Total system throughput	MMT	252.3	264.5	265.8	0.5%	253.0	0.3%
Total biomass		36.2	36.6	36.8	0.5%	36.4	0.5%
Primary production		60.2	62.3	62.6	0.5%	60.5	0.5%
Ascendancy	None	1.28	1.32	1.32	-0.4%	1.27	-0.5%
Intra-Period Flows							
Respiratory flows	Bn. Kcal	20,678	22,776	22,823	0.2%	20,699	0.1%
Consumption	MMT	91.0	94.1	94.5	0.4%	91.0	-0.1%
Detrital flows		43.5	45.3	45.7	0.8%	43.8	0.7%
System Exports							
Net exports	MMT	0.352	-0.753	-0.755	0.2%	0.351	-0.2%
Total catch		0.836	0.470	0.472	0.5%	0.837	0.1%
Mean trophic sequency of catch	None	14.1	17.4	17.4	-0.1%	14.1	0.1%

Appendix: Monte-carlo analysis description

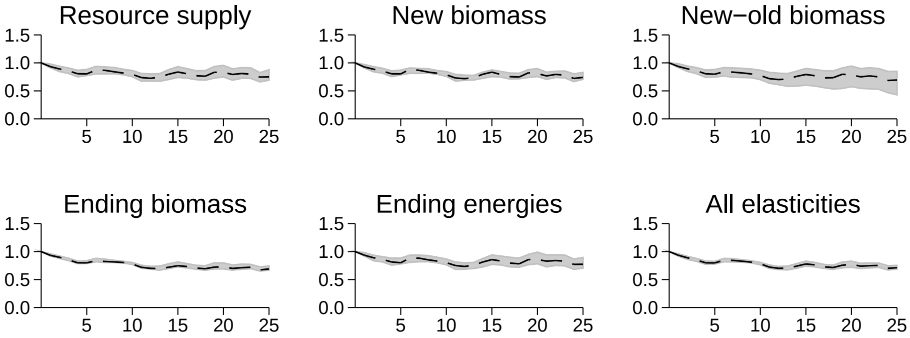
Overview:

- Take random draw from the parameter range & run 25-period horizon
- Take 25 draws for each parameter
- Take 125 all-at-once "buckshot" draws

	Symbol	Description	Benchmark	Monte Carlo Distribution
1.	σ_R^p	Resource supply	0.75	$0.5 - 2.0$
2.	σ_P	New prey	0.75	$0.5 - 2.0$
3.	σ_{NO}	New-old biomass	0.25	$0.0 - 0.5$
4.	σ_{EB}	Ending biomass	1.00	$0.0 - 1.0$
5.	σ_{EE}	Ending energies	1.00	$0.0 - 1.0$

Appendix: Monte-carlo analysis SPS results

Median & $20-80^{th}$ percentile range of population outcomes



- Median population outcomes are very stable
- New-old biomass parameter generates most outcome variance

  $\rightarrow$ *Key parameter* sets diminishing marginal product of consumption