An integrated trophic frontier framework for managing U.S. Caribbean fisheries

Mandy Karnauskas[1], Matt Woodstock[2], Juan Agar[1], Daniel Solis[3], Ryan Vandermeulen[4]

[1]Southeast Fisheries Science Center, [2]University of Miami, [3]Florida A&M University, [4]Office of Science and Technology

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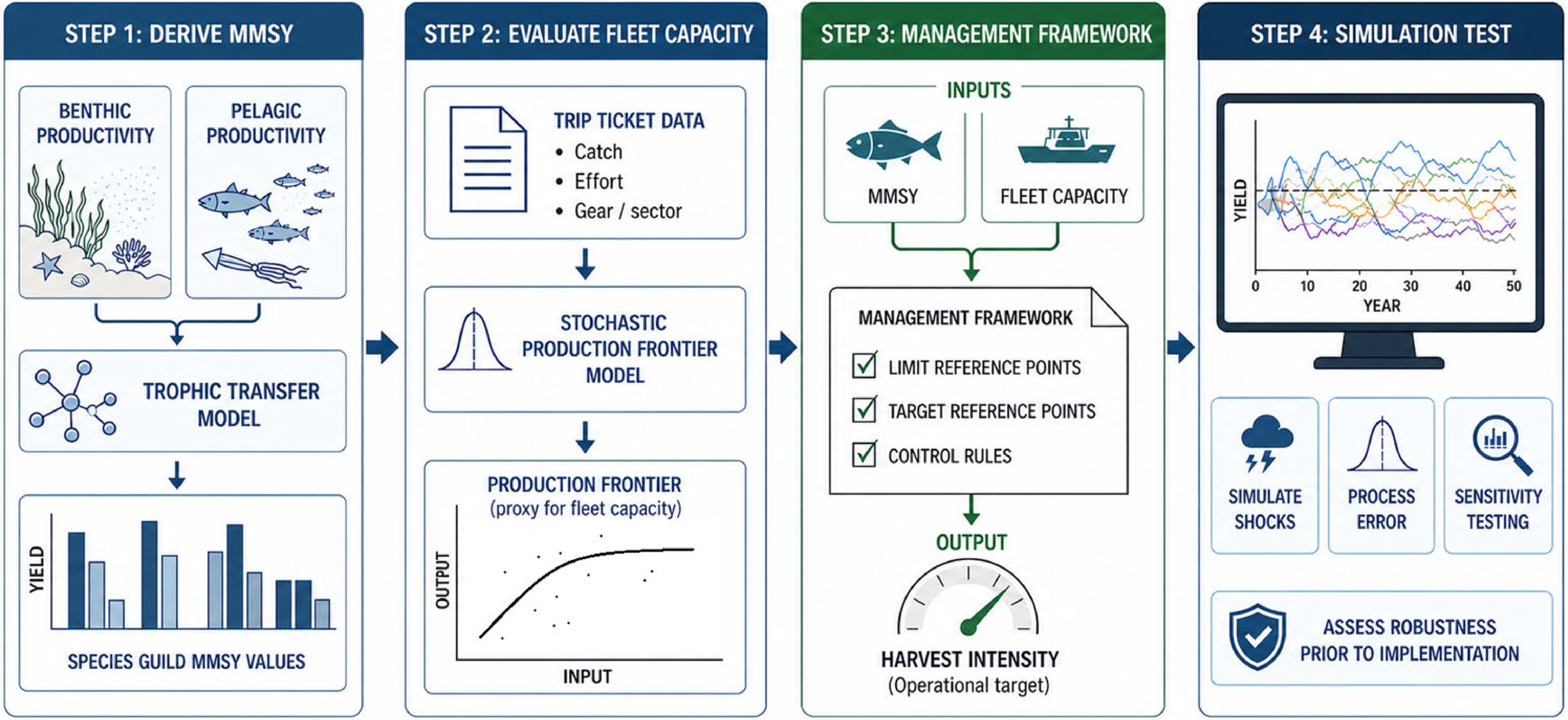
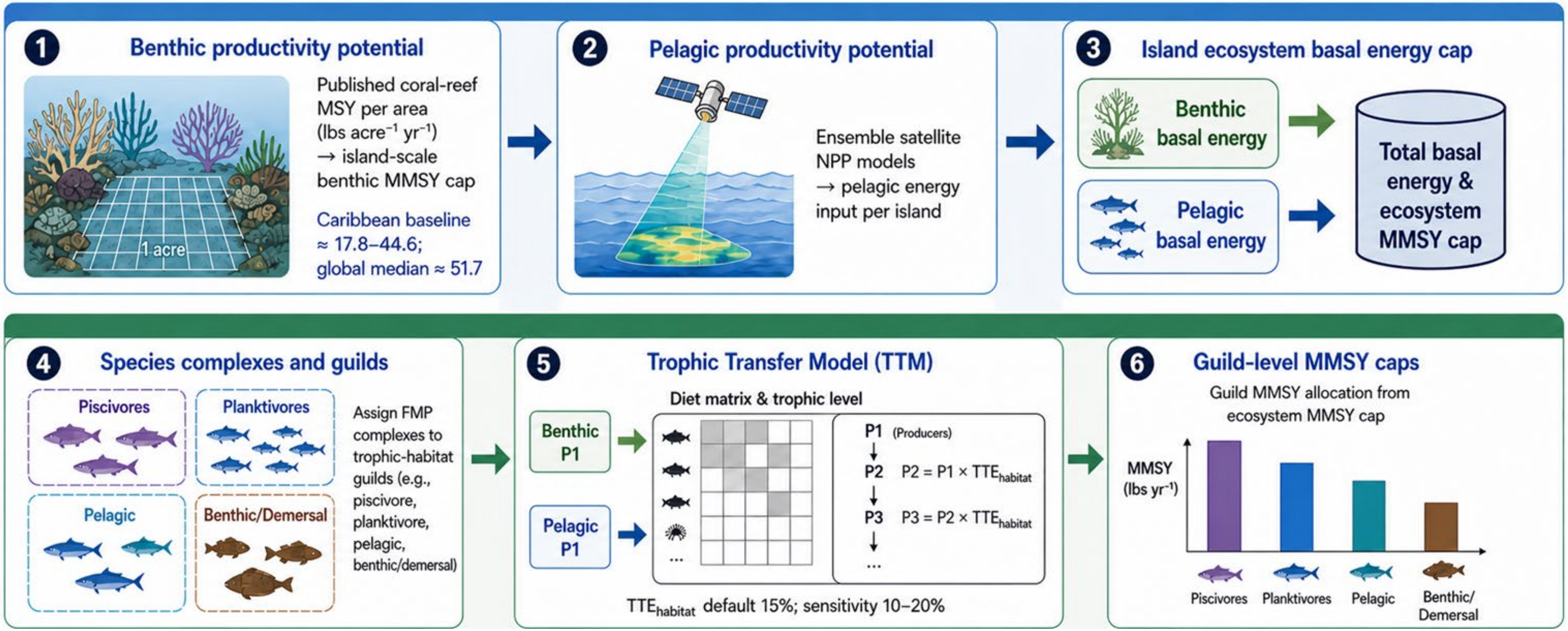
Challenges this method is designed to address:

- U.S. Caribbean fisheries have constraints with respect to physical (limited fishing area), biological (finite productivity), economic (limited market opportunities) and social (high dependence) environment
- High prevalence of gears targeting multiple species $\longrightarrow$ single-spp controls challenging to execute
- Severe data limitations including severely underreported / unknown landings
- Limited budget for monitoring and enforcement

Management approach has four steps



Step 1: Deriving ecosystem- and guild-level MMSYs



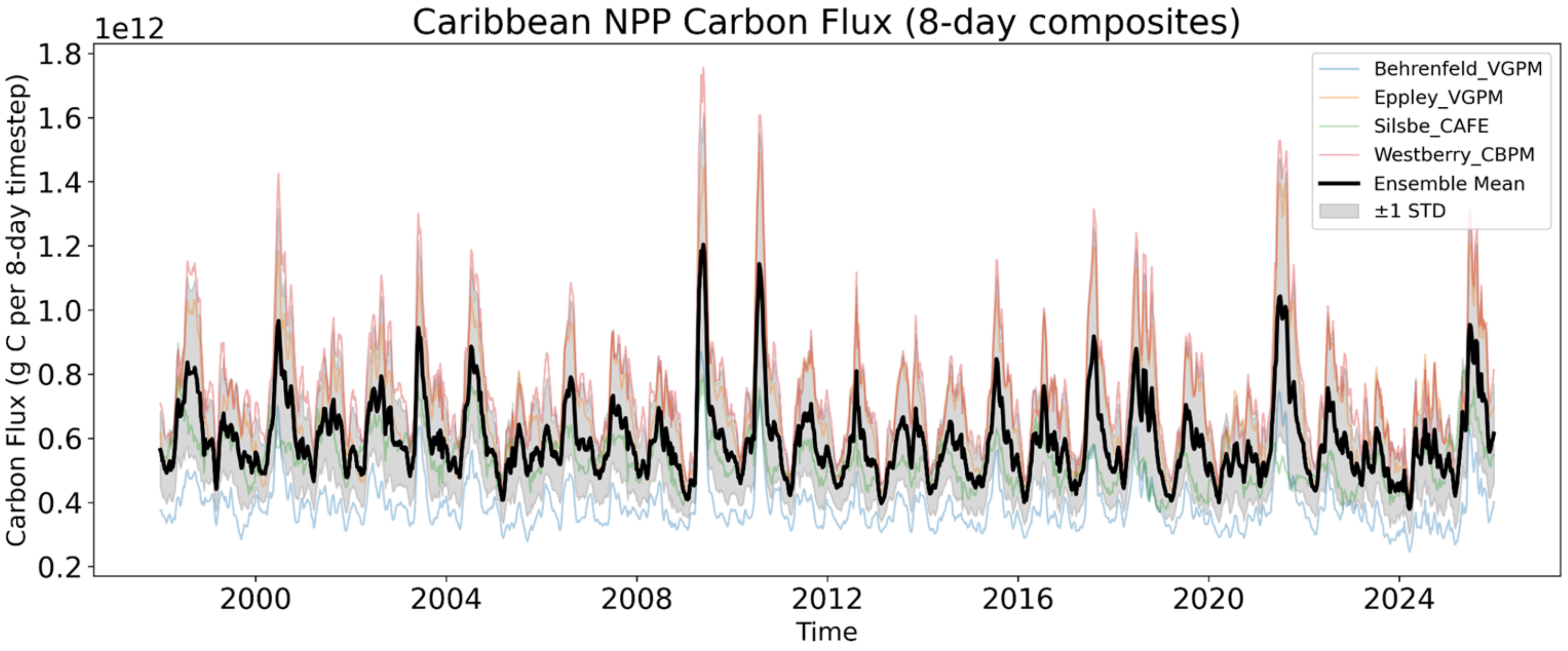
Inputs: Satellite data, published information, trophic information

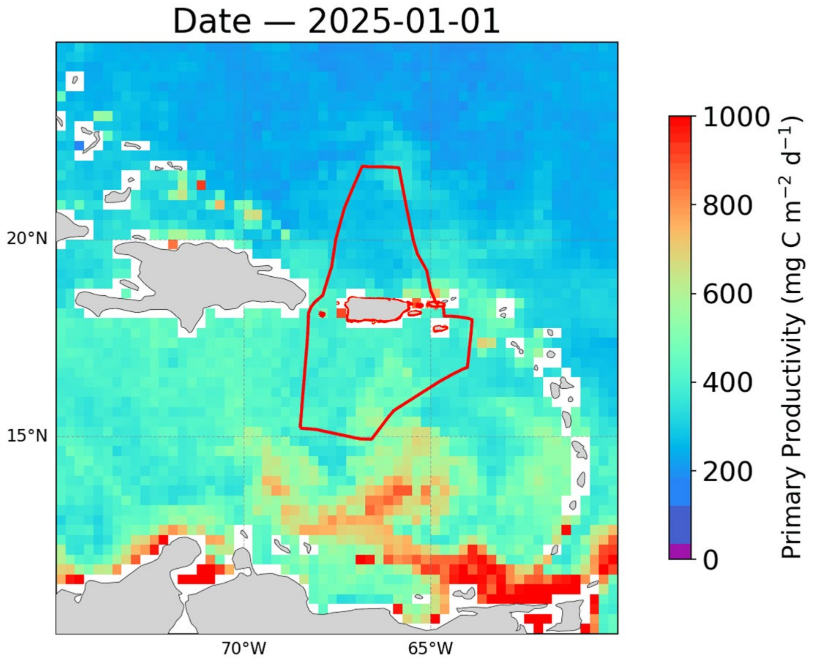
Method: Estimate benthic + pelagic productivity → partition into species and guilds

Outputs: Species- or guild-specific MSY, Ecosystem-based MSY (per island)

Pelagic Productivity - “Weather”-like ensemble approach

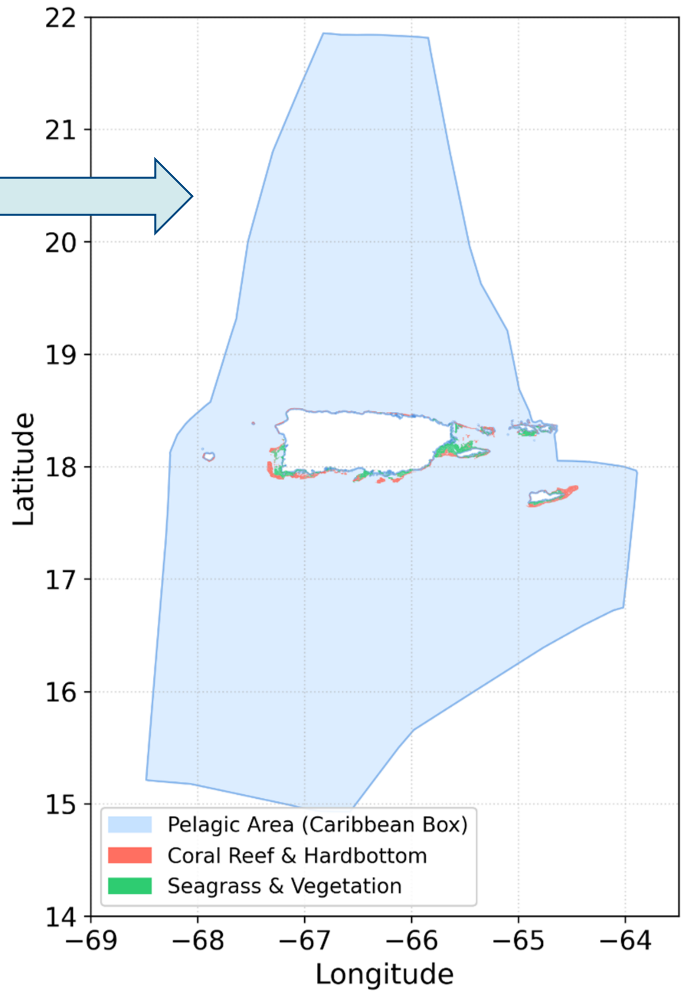
- Net Primary Productivity (NPP) measures energy entering the pelagic food web
- Satellite observations provide continuous ecosystem monitoring over 28 years
- Ensemble of multiple (independent) models improves robustness
- Productivity is dynamic and crosses management boundaries





Benthic Productivity - Literature-Based Spatial Integration

- *Seagrass*: 5,250 ± 501 t C km^{-2} yr^{-1} (Gomis et al., 2025)
- *Coral reefs*: 3,600–49,500 t C km^{-2} yr^{-1} (Douglas, 2001)
- Literature values applied to mapped habitat extent
- Combined with pelagic NPP → ecosystem productivity



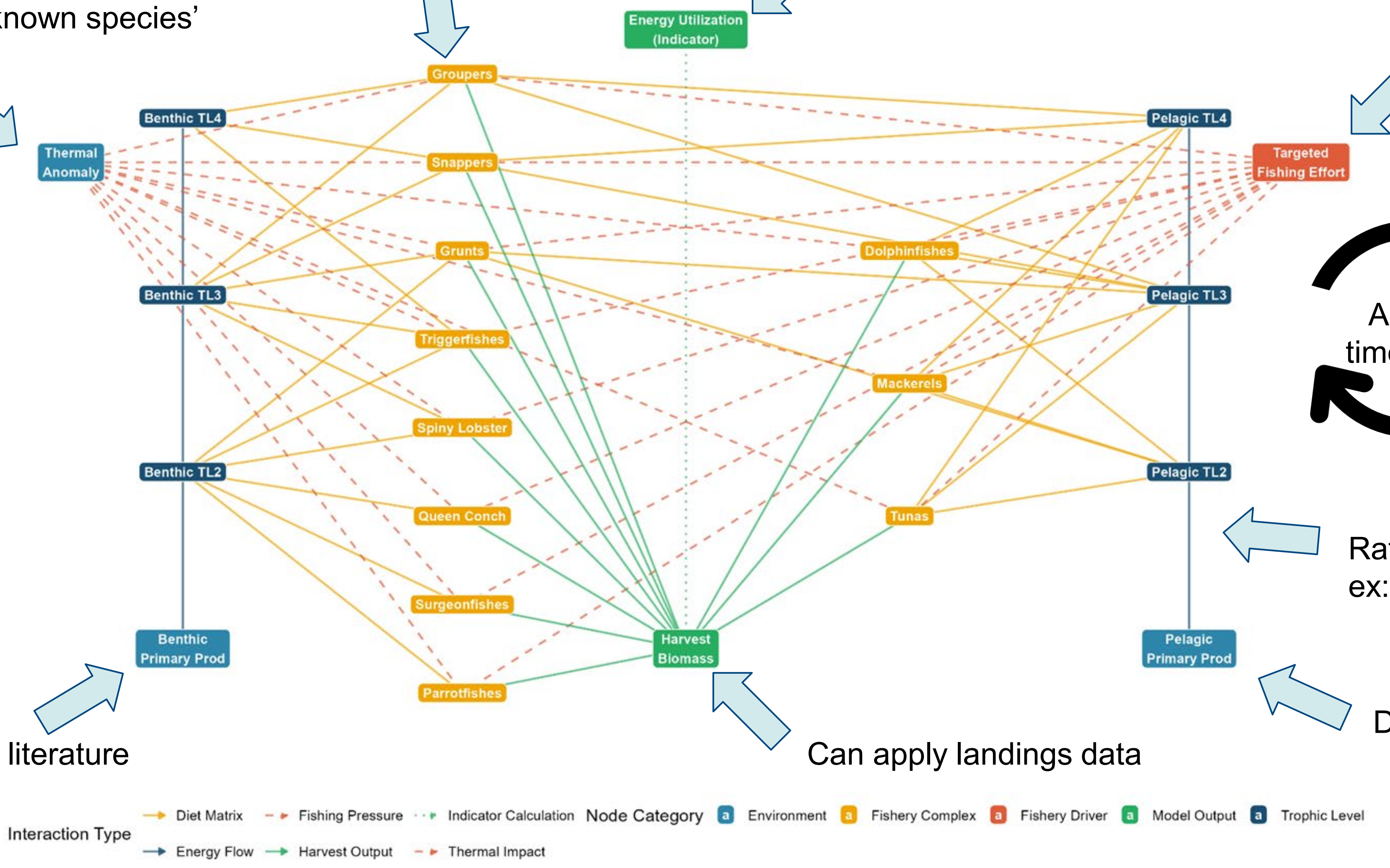
TTM Further Explained

Could be any environmental stressor (or multiple) w/ known species' thresholds

Each group = FMP stock complex

Static value of exploitation for each group

Can also split to multiple gears per group and change effort over time



Annual time steps

Empirically estimated P/B ratios allow this to be time-dynamic & not reliant on an assumed equilibrium/steady state

Rate = *f*(Transfer Efficiency Parameter); ex: 15% +- 5%

Derived from literature

Can apply landings data

Derived from satellite data

Functional Group Definition

Family	Stock or stock complex and species composition
Angelfishes	Angelfish—French angelfish, gray angelfish, queen angelfish
Groupers	Grouper 3—coney,[1] graysby
	Grouper 4—black grouper, red grouper, tiger grouper, yellowfin grouper, yellowmouth grouper
	Grouper 5—misty grouper, yellowedge grouper
	Grouper 6—red hind,[1] rock hind
Grunts	Grunts—white grunt
Jacks	Jacks 1—crevalle jack
	Jacks 2—African pompano
	Jacks 3—rainbow runner
Parrotfishes	Parrotfish 2—princess parrotfish, queen parrotfish, redband parrotfish, redtail parrotfish, stoplight parrotfish, striped parrotfish
Snappers	Snapper 1—black snapper, blackfin snapper, silk snapper,[1] vermilion snapper, wenchman
	Snapper 2—cardinal snapper, queen snapper [1]
	Snapper 3—lane snapper
	Snapper 4—dog snapper, mutton snapper,[1] schoolmaster
	Snapper 5—yellowtail snapper
	Snapper 6—cubera snapper
Surgeonfishes	Surgeonfish—blue tang, doctorfish, ocean surgeonfish
Triggerfishes	Triggerfish—gray triggerfish, ocean triggerfish, queen triggerfish [1]
Wrasses	Wrasses 1—hogfish
	Wrasses 2—puddingwife, Spanish hogfish

- Each functional group is designed to be the species complex managed at the Council level
- Can include single species & aggregate functional groups
- Can also aggregate further based on data availability (i.e., balance model complexity and efficacy)

Converting trophic level biomass to group biomass

(also open to ideas)

- **Total biomass from benchmark assessment or surveys** — Ex: Spiny Lobster, Queen Conch, NCRMP/DCRMP
- **Estimated as % catch, relative to other, same trophic level species in non-selective gear (e.g., traps)**
- **Estimated as % reported landings among other, same trophic level species**
- **Assumed to be uniform among other, same trophic level species, possibly weighted by empirically derived biological turnover rates (i.e., P/B)**

*Can mix and match methods among functional groups to sum to the total trophic level biomass (primary production & transfer efficiency-derived)

Diet Information - Literature derived

- **Local studies that identify particular predator-prey relationships**
- **Studies from the Caribbean that identify *general* feeding relationships (e.g., species is a secondary consumer)**
- **Studies from any reef ecosystem that identify trophic level feeding**
- **Assumed based on trophic level in trait databases (e.g., FishBase) or expert opinion**

* Given the TTM only needs to identify trophic level-specific feeding (i.e., does not need direct predator-prey relationship data), the bar to parameterize feeding relationships is relatively low compared to other foodweb models.

Key Model Outputs

Available Biomass per Guild

Group-Level MMSY
(MMSY = Available Biomass * P/B)

Energy Utilization Ratio (EU)
(EU = Energy Caught / Energy Available)

*requires energy content (kJ / g)

Data Inputs:

- Group MMSYs from TTM
- Trip-ticket species mix by gear (% composition, not totals)
- Trips per gear type per year (effort calculations)

Relevant Gears

Groups Defined Previously

	Traps	Diving	H & L	Nets
Lobster	0.34	0.55	0.00	0.00
Conch	0.00	0.38	0.00	0.00
Snappers	0.39	0.04	0.38	0.22
Groupers	0.27	0.03	0.32	0.14
Pelagics	0.00	0.00	0.30	0.64

$W_{gear,group}$ = % composition

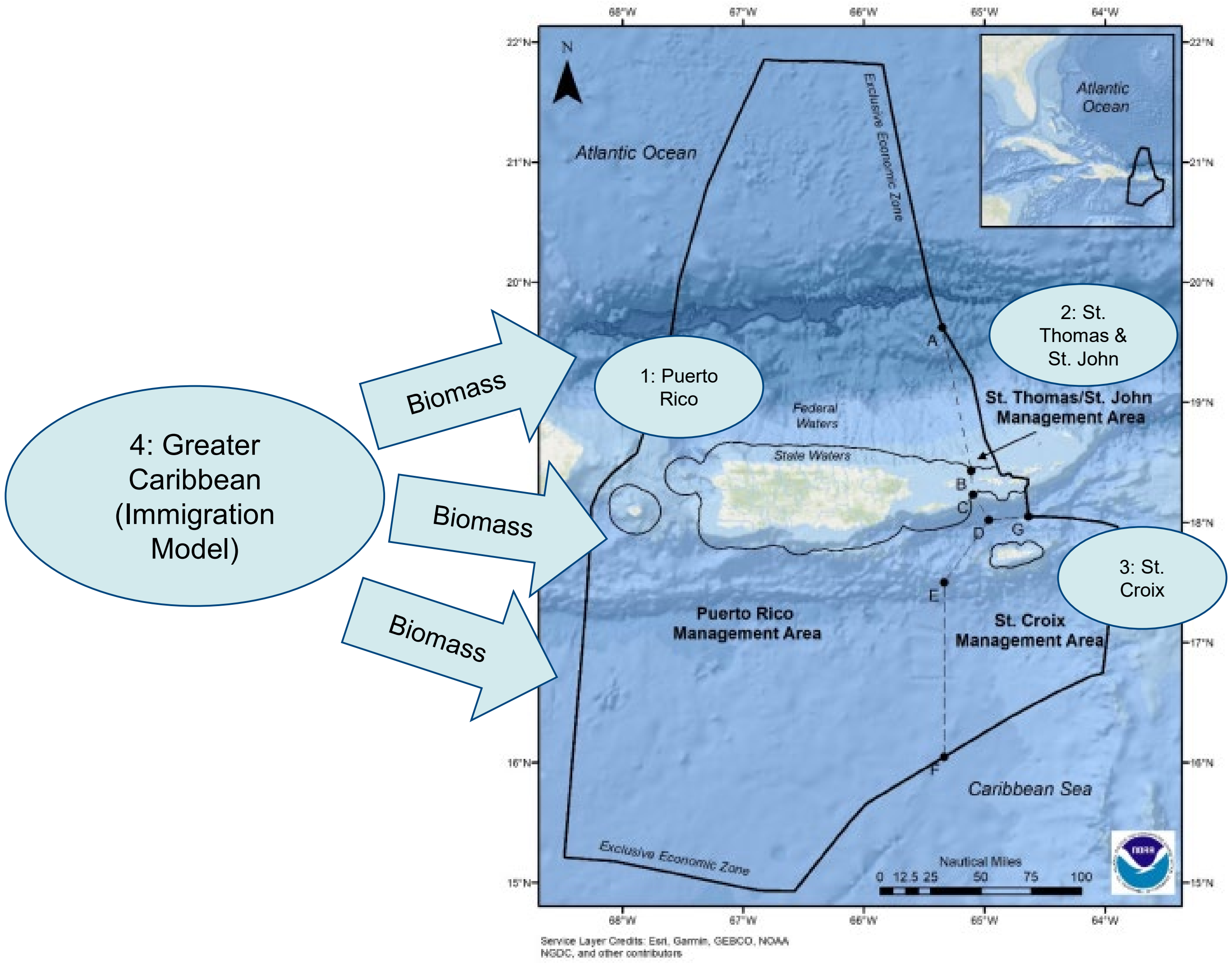
Key Outputs:

- Gear-specific MMSYs
- Identification of choke groups per gear
- Recognition of major gear types

$$MMSY_{gear,group} = MMSY_{group} * W_{gear,group} * Effort_{gear} / sum(Effort)$$

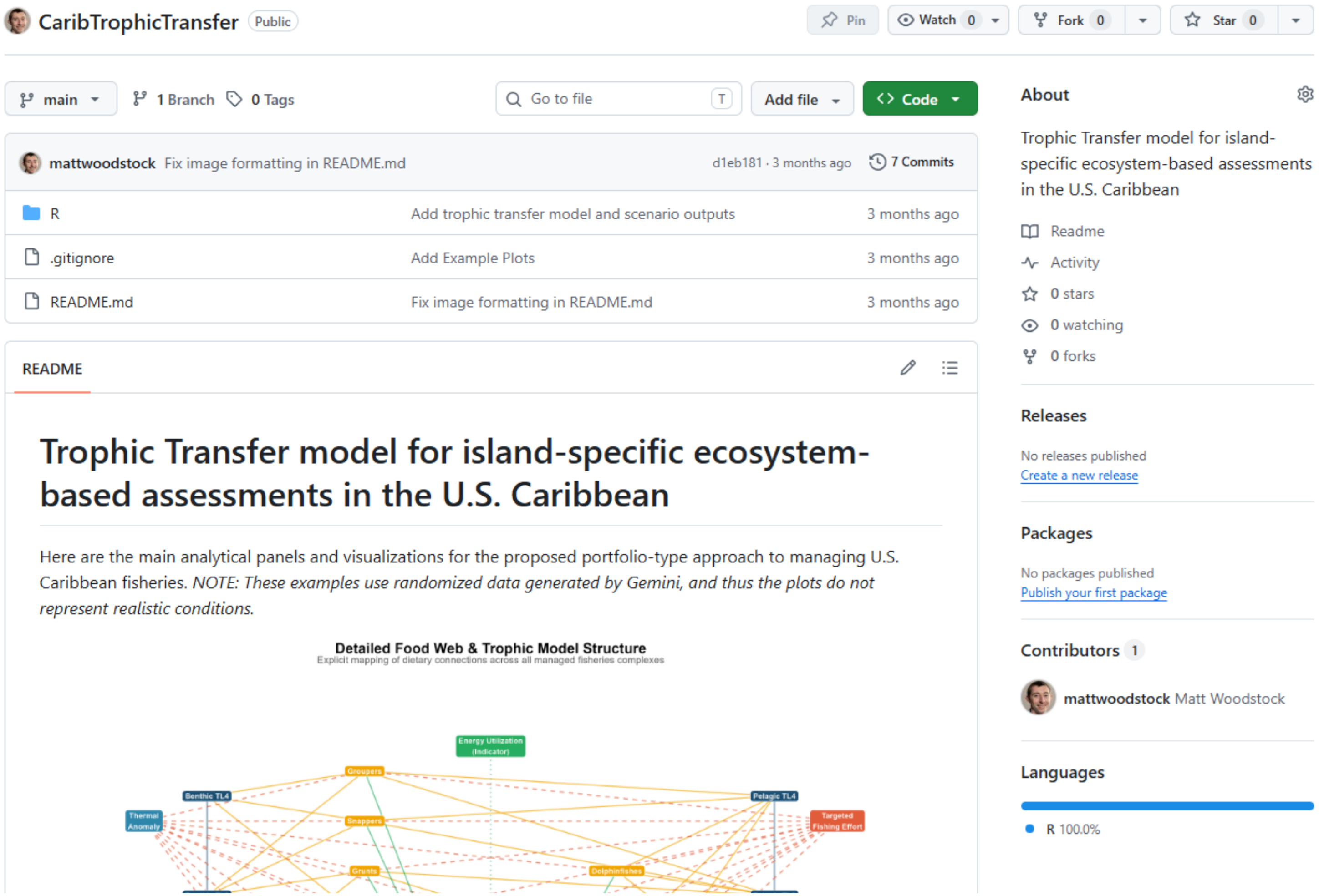
Gear Type-Specific MMSYs
to convert biological productivity potential for effort-based analyses and management interventions

Island-Specific TTMs (plus 1)



- Different model for each FMP region
- Connectivity to broader Caribbean (and beyond) handled as best as possible through a fourth model
- Connectivity (lbs or ind. yr^{-1}) can be informed through larval connectivity models, assumed, used as a sensitivity, or assumed to be 0

Is this built yet? Yes, but…



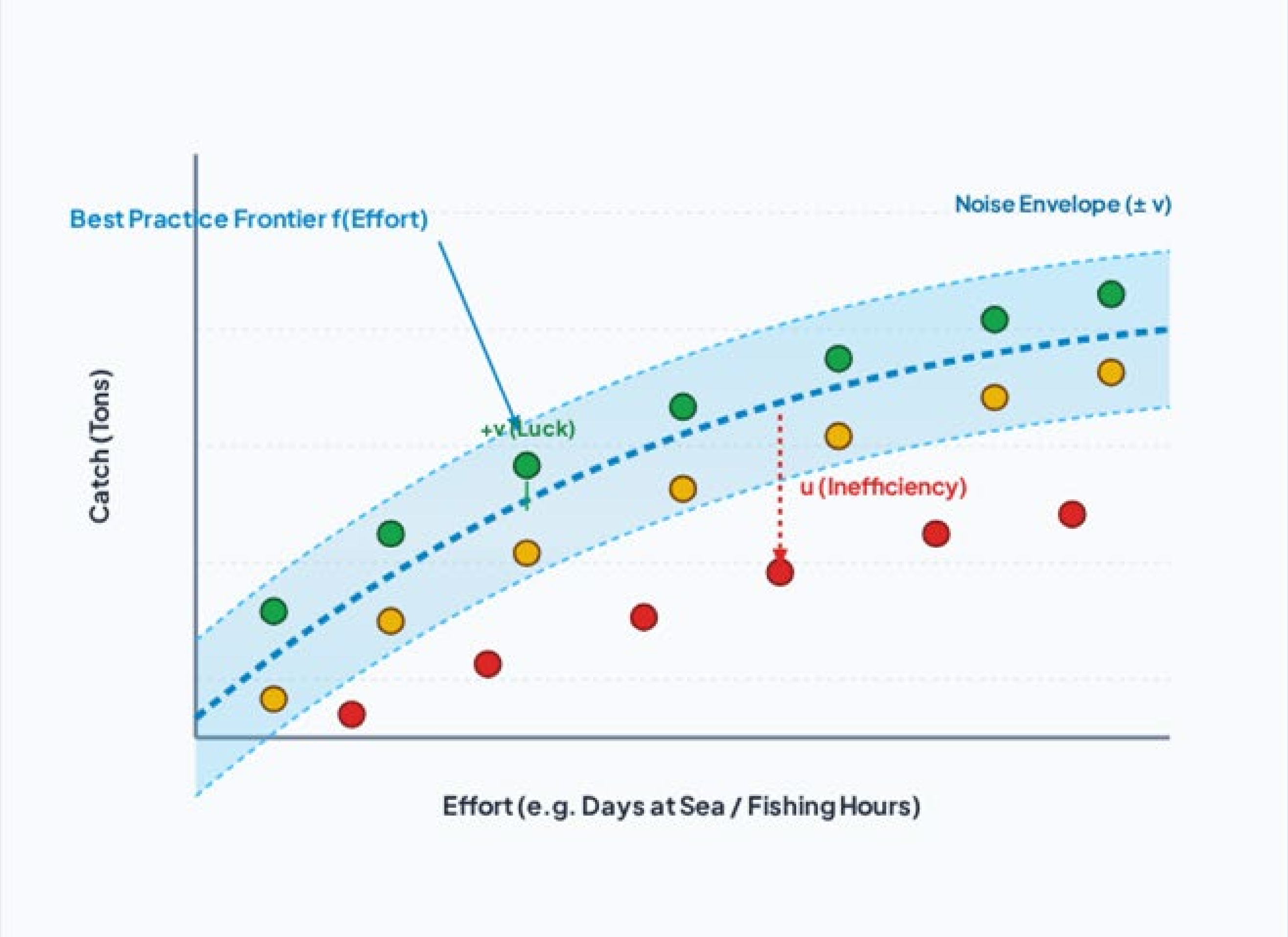
https://github.com/mattwoodstock/CaribTrophicTransfer

- Example code base on Github, but has not been applied to a real situation
- Based on sound ecological theory (e.g., foodweb dynamics; bioenergetics) and similar to other foodweb models
- Specific goal of managing model complexity based on data availability & management need
- TTM can be both modular and connected to rest of methods presented here

Step 2: Stochastic Frontier

Catch = f(Effort) + v (luck/unlucky) − u (inefficiency)

Separating Random Environmental Noise (v) from Vessel Inefficiency (u)



Lucky Trips

`v > 0, u = 0`

Vessels operate with full efficiency and encounter exceptionally good fortune (calm seas, dense fish schools). They lie **above** the Best Practice Frontier curve.

Unlucky Trips

`v < 0, u = 0`

Vessels are fully efficient, but experience bad luck (gear snags, poor weather). They lie **below** the Best Practice Frontier curve, but remain inside the random noise envelope.

Inefficient Trips

`u > 0`

Vessels suffer from skill gaps, outdated technology, or poor operational choices. Catch falls **well below** the Best Practice Frontier due to actionable inefficiency (u).

Calculating TE for Green, Yellow, and Red Points

SFA Point-by-Point Analysis

Evaluating Technical Efficiency (TE) across lucky, unlucky, and inefficient trips

CORE SFA EFFICIENCY FORMULA TE_i = Observed Output (q_i) / Stochastic Target (q_i^*) = $\exp(-u_i)$ Where Stochastic Target $q_i^* = f(X_i, \beta) + v_i$

Green Points

$v > 0$, $u = 0$

Lucky & 100% Efficient

Baseline f(Xi): **100 Tons**

Random Noise (v): **+10 T (Good Luck)**

Target Catch (q*): **110 Tons**

Observed Catch (q): **110 Tons**

Inefficiency (u): **0.00 (u = 0)**

TE = 110 T / 110 T = exp(0)
TE = 1.00 (100%)

Interpretation: The vessel reaches its elevated 110-ton target completely. Catch is above average due to good luck, with **zero technical inefficiency**.

Yellow Points

$v < 0$, $u = 0$

Unlucky & 100% Efficient

Baseline f(Xi): **100 Tons**

Random Noise (v): **−10 T (Bad Luck)**

Target Catch (q*): **90 Tons**

Observed Catch (q): **90 Tons**

Inefficiency (u): **0.00 (u = 0)**

TE = 90 T / 90 T = exp(0)
TE = 1.00 (100%)

Interpretation: Catch sits below the 100-ton baseline, but reaches the realistic 90-Ton target. The trip is **100% efficient** because the shortfall is entirely bad luck (v < 0).

Red Points

$u > 0$

Technically Inefficient

Baseline f(Xi): **100 Tons**

Random Noise (v): **−10 T (Bad Luck)**

Target Catch (q*): **90 Tons**

Observed Catch (q): **63 Tons**

Inefficiency (u): **0.357 (u > 0)**

TE = 63 T / 90 T = exp(−0.357)
TE = 0.70 (70%)

Interpretation: Operating 27 Tons below its 90-ton target. The vessel achieves only 70% efficiency due to skipper skill or operational gaps (u = 0.357).

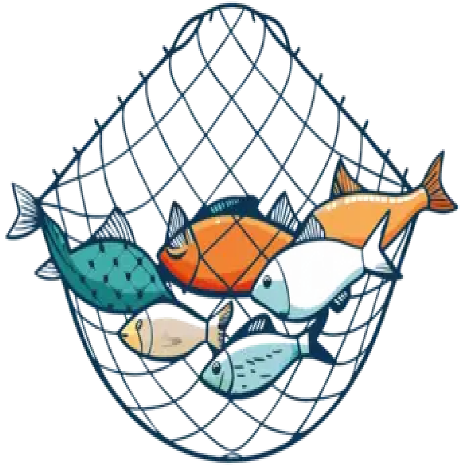
Key Econometric Advantage: Both Green AND Yellow trips have TE = 100% because both operate with zero technical inefficiency (u = 0).

SFA prevents unlucky vessels (Yellow) from being falsely penalized as inefficient!

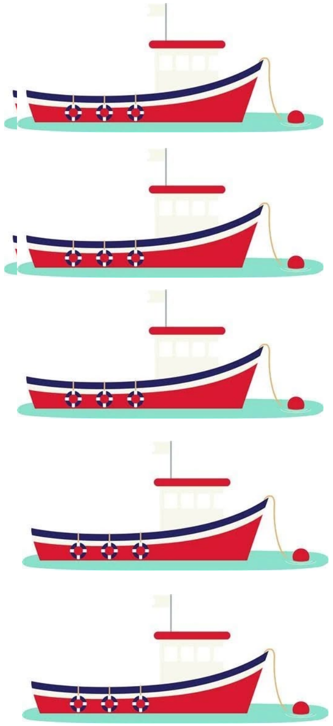
Aligning fleet size with resource productivity

Overcapacity (excess boats)

Excess capacity (inefficiency)



MS-MSY

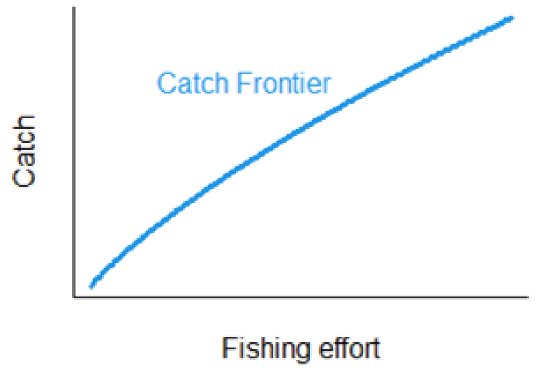


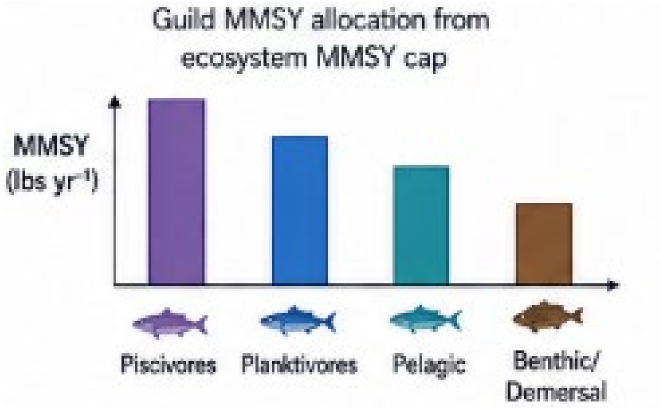
Observed Catch
C= f(X) + v – u
What did I actually land on this trip?

Full-efficiency Catch
C= f(X current) + v
What would I land at <u>max skill</u> at current 15 days at sea?

Maximum Full-Potential Catch (Capacity Output)
C= f(X max) + v
What would this vessel land at <u>max skill</u> & <u>max seasonal days</u> (30 days)?

Step 3: Aligning ecological caps with catch potential of the fleets in a management framework





Stochastic production frontier model

How much biomass the fleet could harvest under optimal conditions

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Trophic transfer model

How much biomass the ecosystem can sustainably produce (by species, guild)

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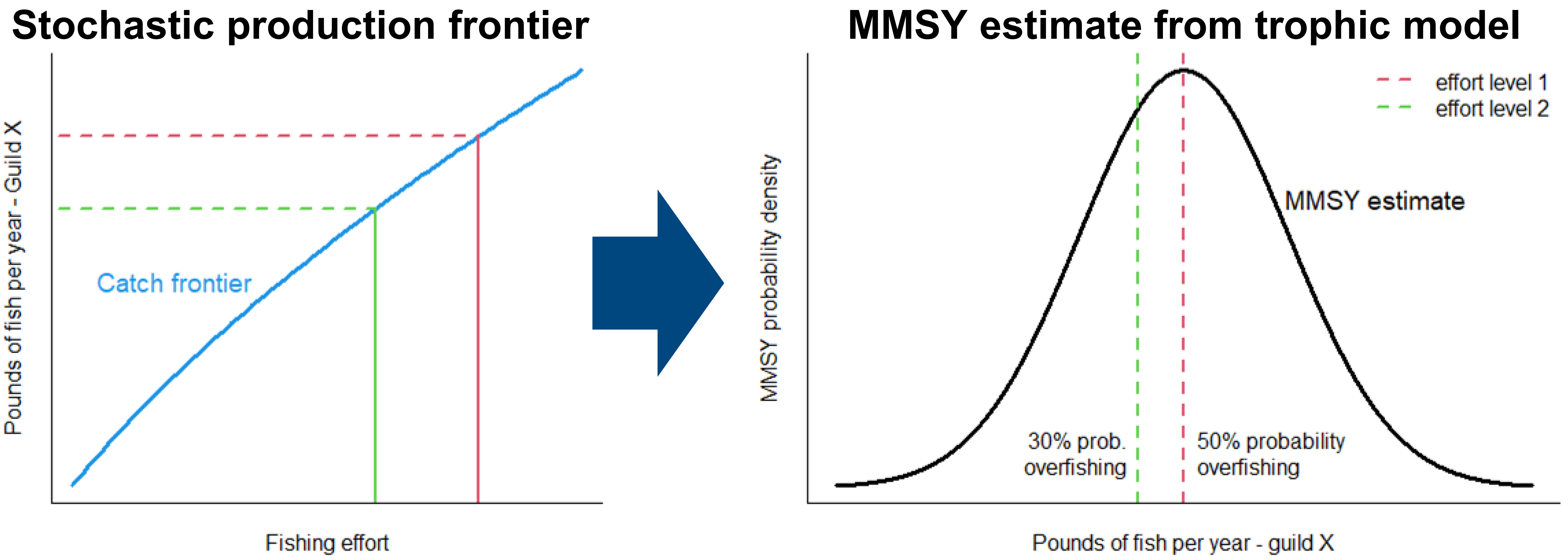
Sustainable effort
(with associated uncertainty)

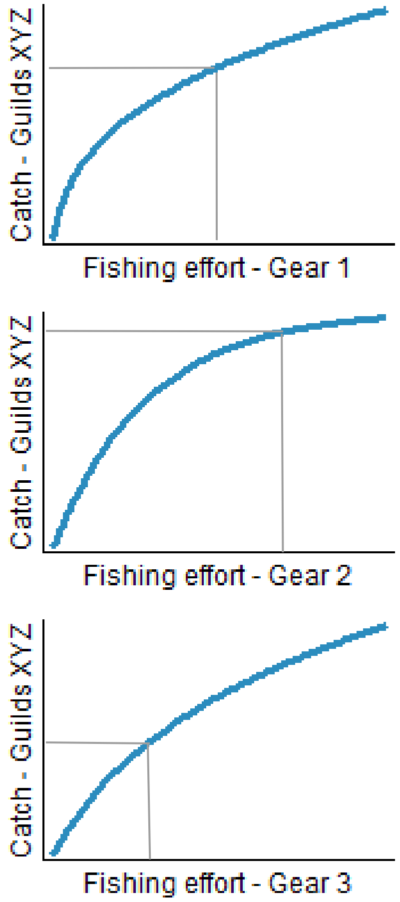
Single species framework



- Only a short-term concept because catch depends on current biomass levels
- Fishing effort would be linked to MMSY utilization through harvest control rule

Multi-species framework

Catch frontiers by gear



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Gear targeting matrix

	Gear 1	Gear 2	Gear 3
Guild X	0.43	0.42	0.48
Guild Y	0.44	0.32	0.09
Guild Z	0.13	0.26	0.43

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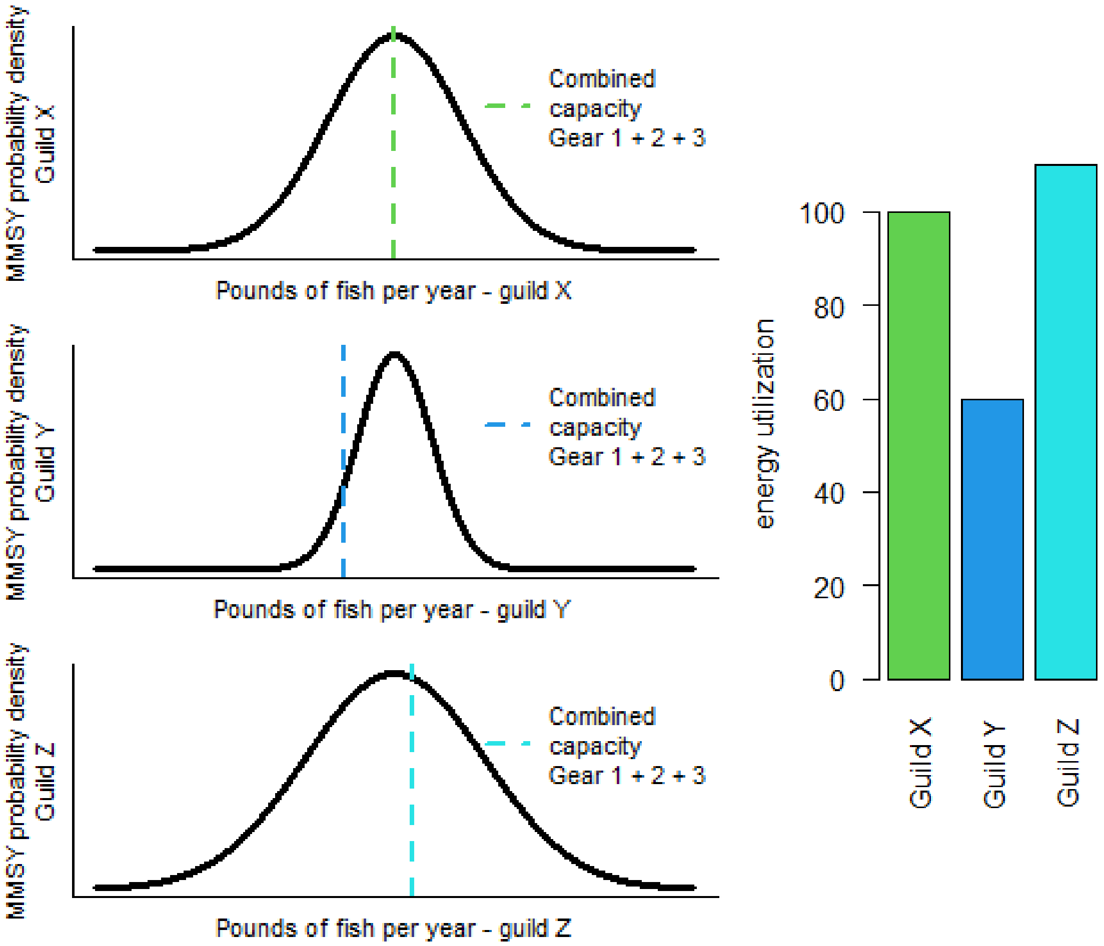
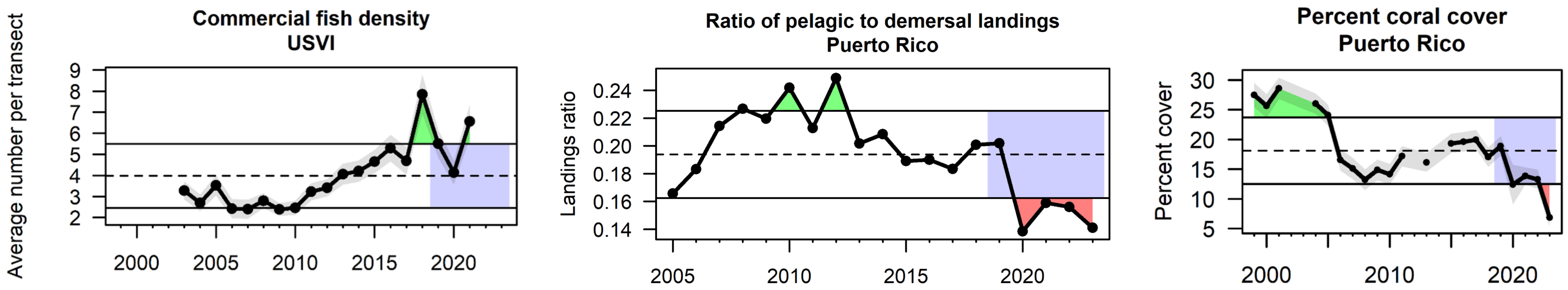
MMSY usage by guild



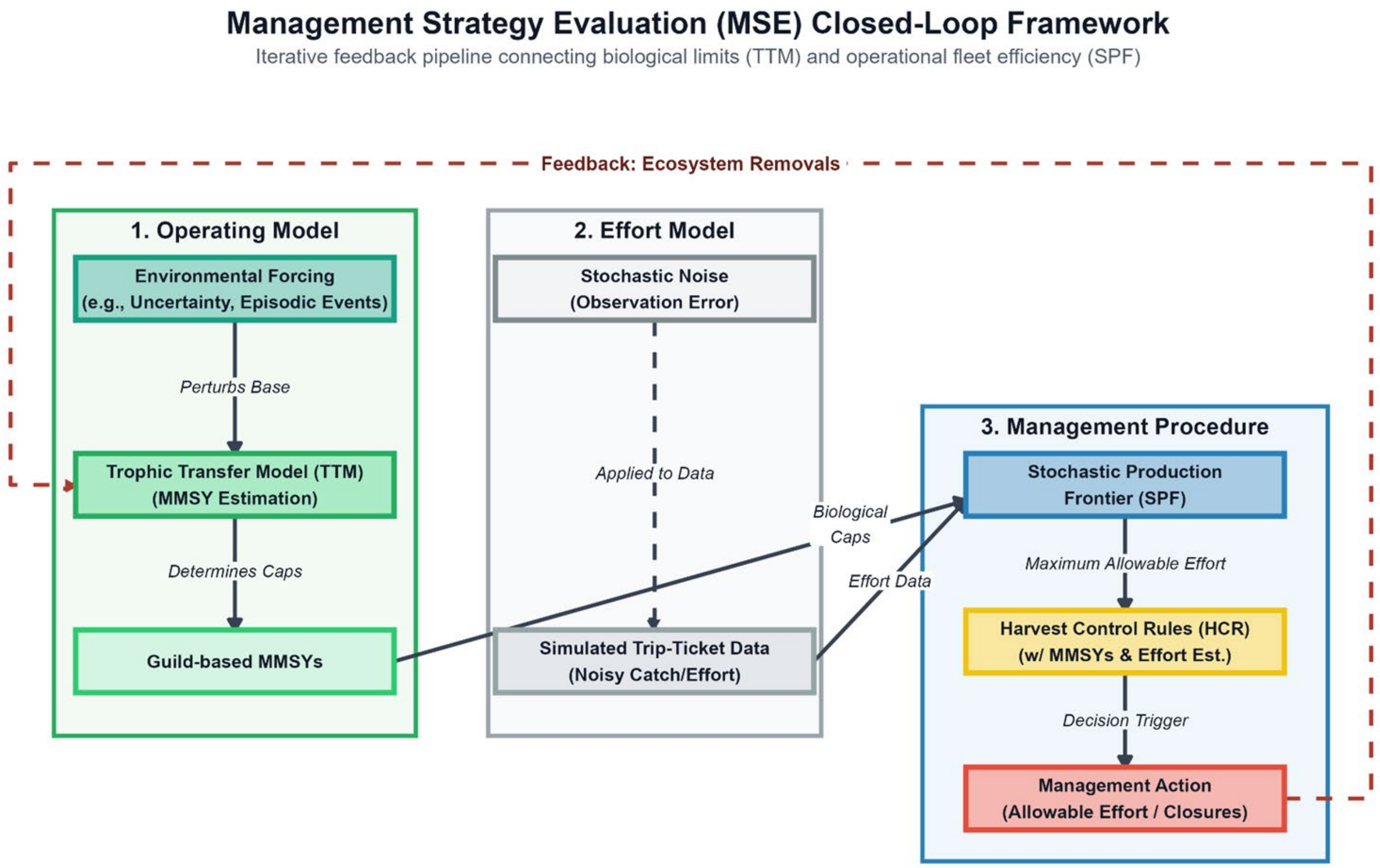
Updating the framework

- Catch frontier is short-term concept (depends on prevailing conditions for habitat, stock abundance, catchability) but MSY is long-term concept
- Framework would need to be updated for changing conditions
- Significant changes in fishery can be tracked through indicators (e.g., below)
- Appropriate triggers for re-evaluation would be determined through simulation



Step 4: Simulation testing

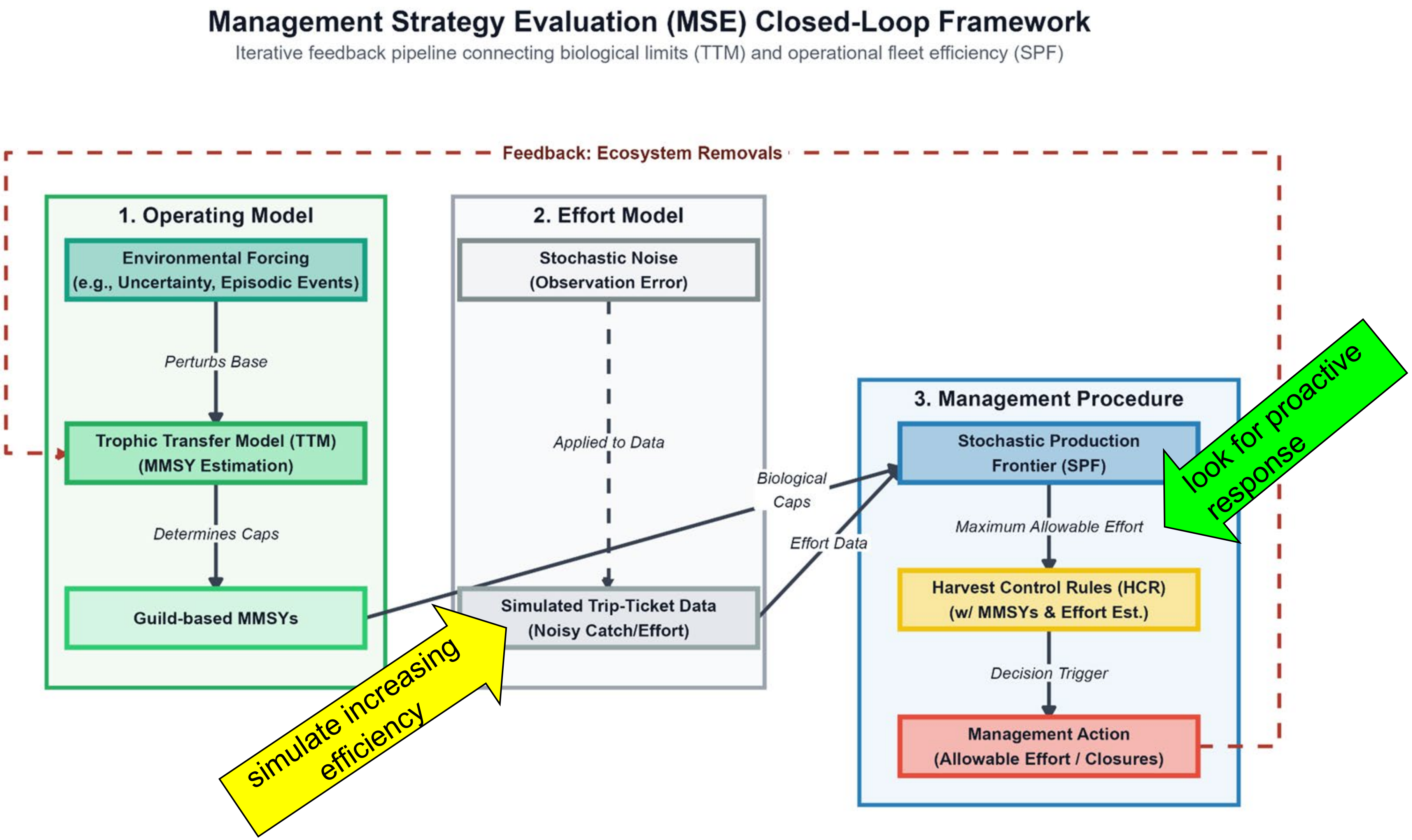
Framework can undergo full closed-loop simulation testing with dynamically linked biological and economic models to evaluate efficacy



Step 4: Simulation testing

Stress-test by introducing simulated shocks:

- an increase in technological efficiency
- environmental shock(e.g. hurricane) triggering immediate drop in productivity



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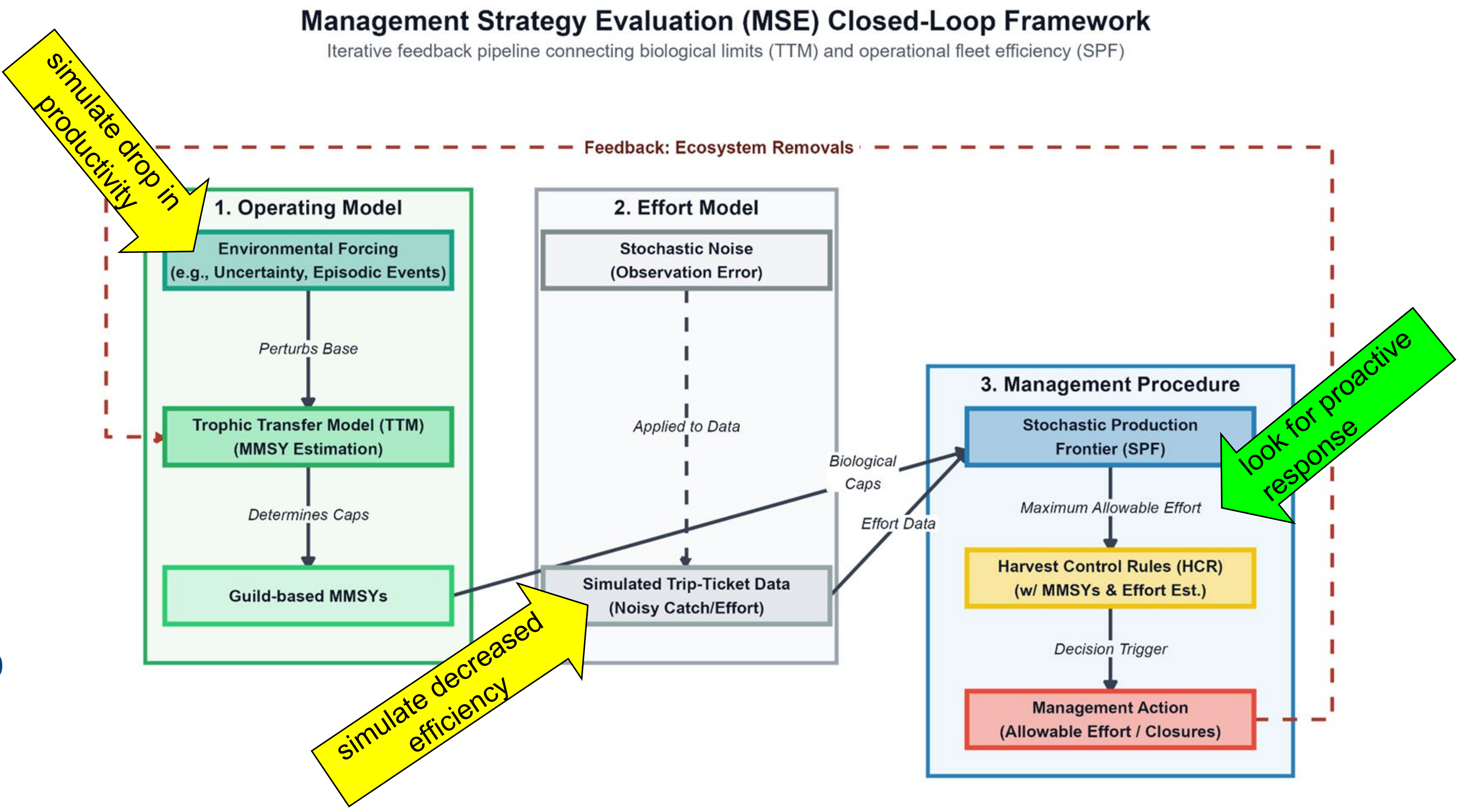


Minimum requirements and caveats

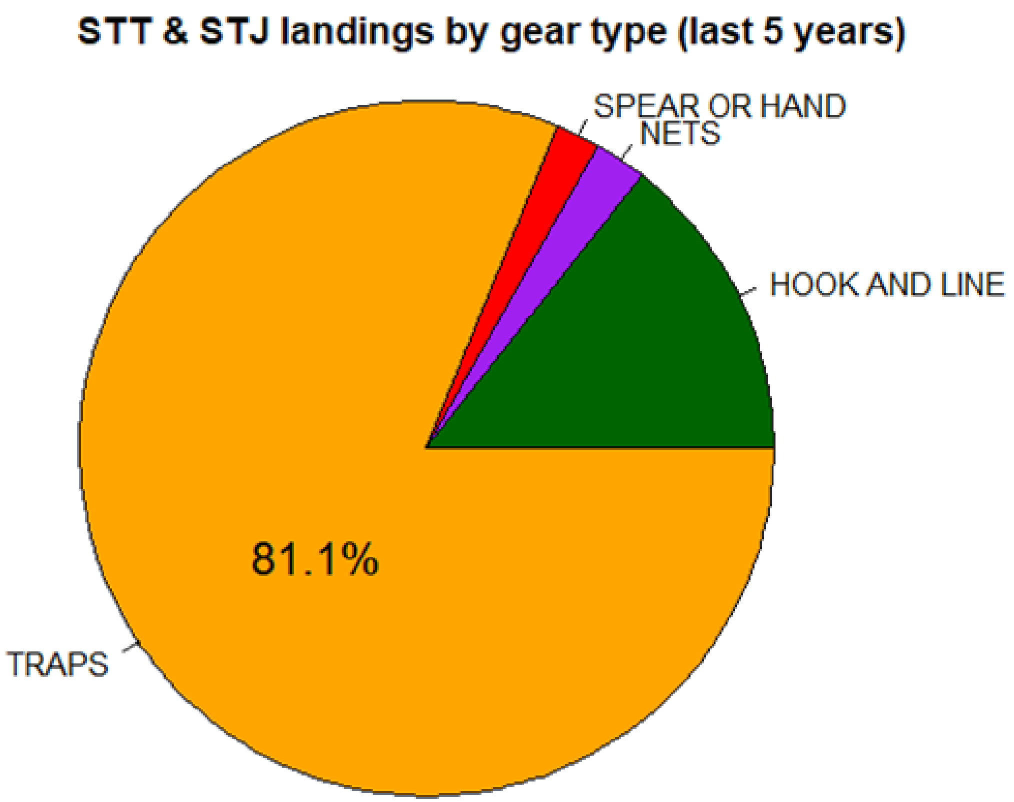
Are the required data currently available for some number of Caribbean species based on the data reviews provided in the Data Webinars?	Yes; some inputs are uncertain but we can bound with published knowledge and carry uncertainty through the analysis.
What species or species groups can the method currently be performed on?	All; single-species stock assessments, where available, can also be incorporated into framework
Does the time step (e.g., day, week, year) required for the method align with currently available data?	Yes; can be run at any time step, biological and temporal resolution of the TTM can be adapted to data availability
Can the method inform management now?	Yes; once underlying models are established they can be easily updated with new data

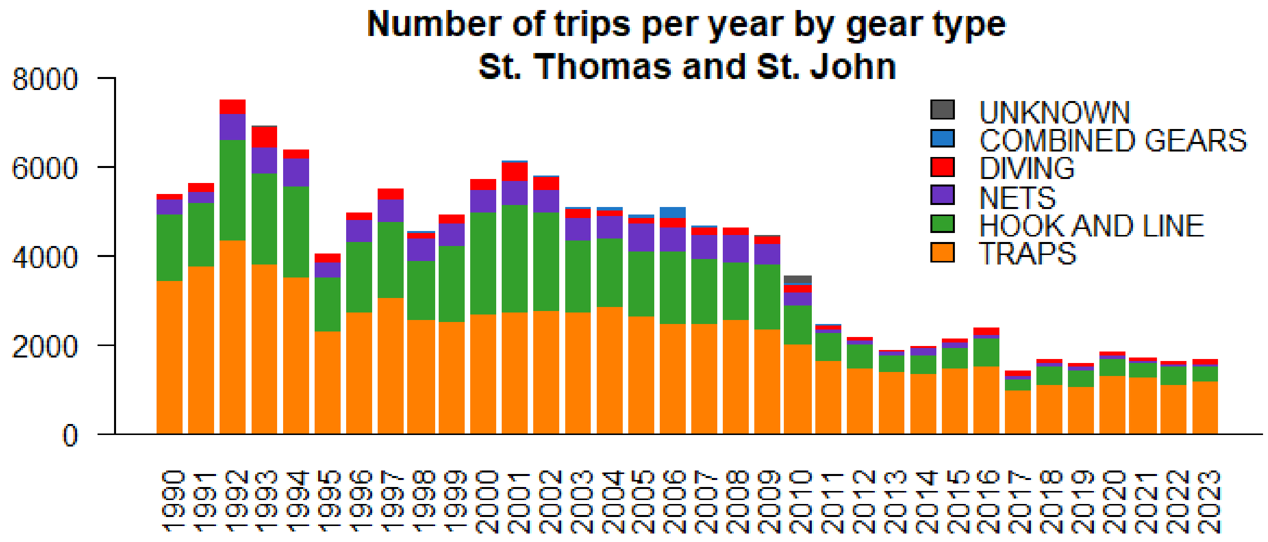
- Uncertainty in some inputs, but we can scale model complexity to data availability and test sensitivity to inputs in MSE framework
- Ideally pilot the method in a single area with low gear diversity

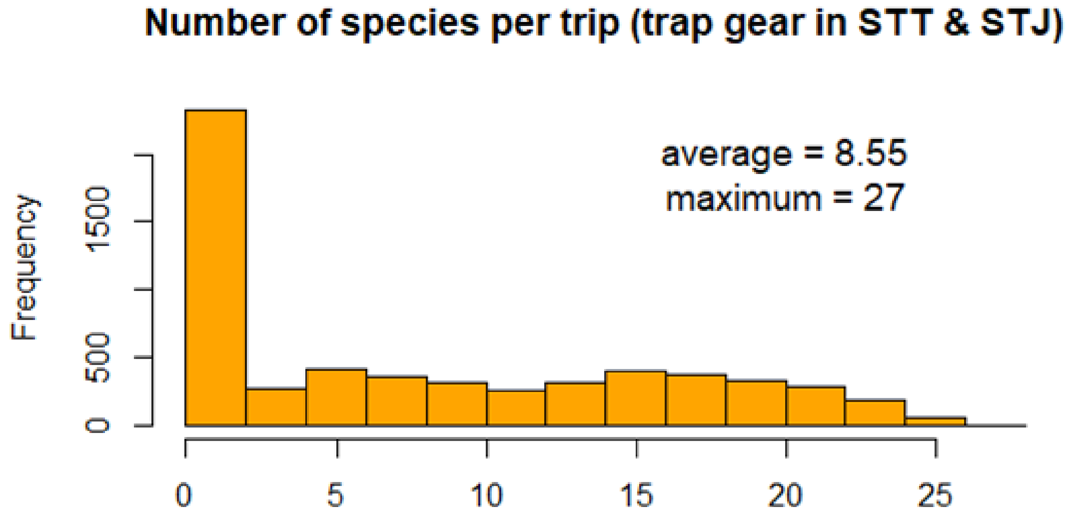
St. Thomas / St. John case study

>80% of landings caught by trap gear

Many species caught simultaneously

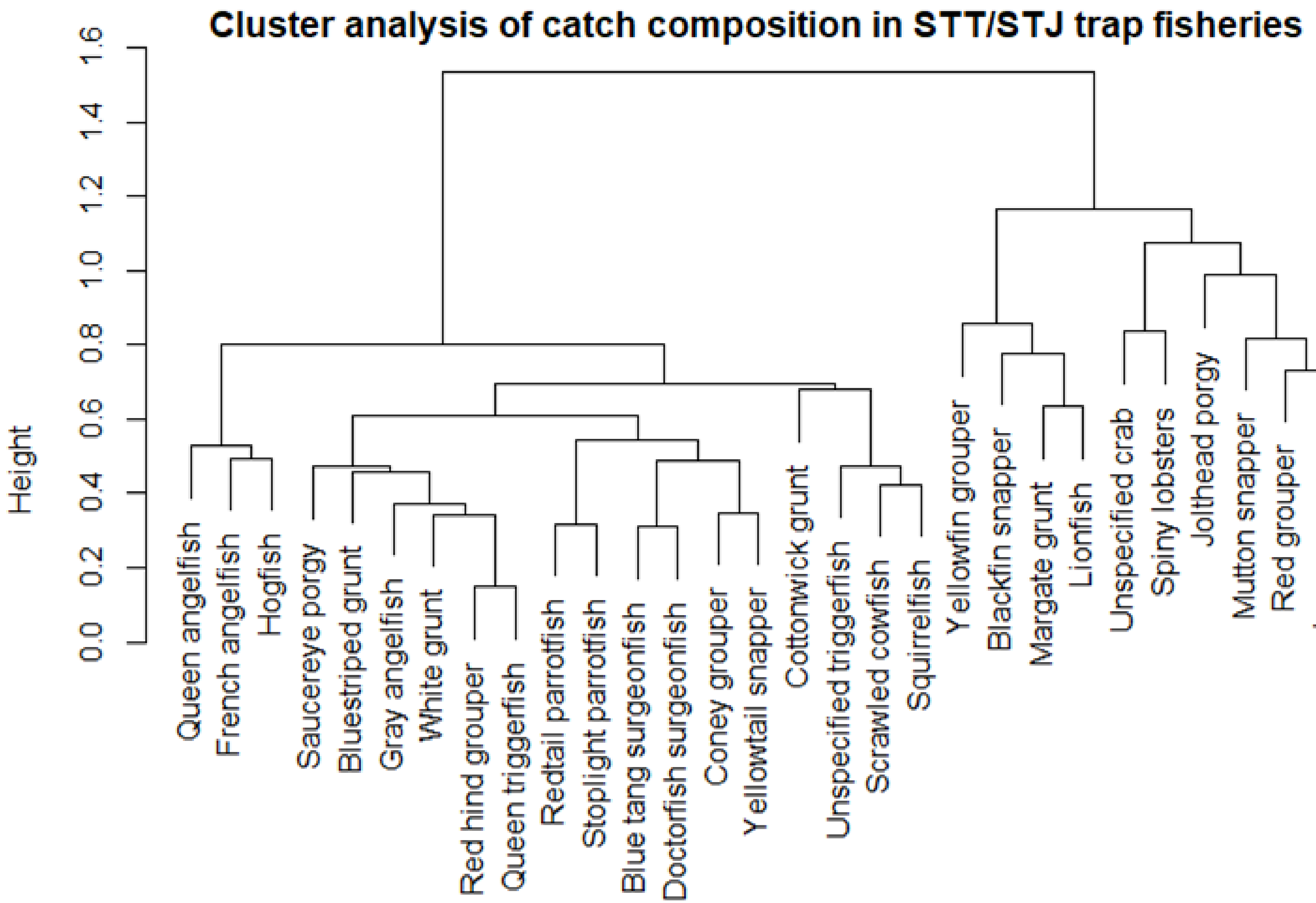






St. Thomas / St. John case study

- Cluster analysis can be used to define different types of trips within trip ticket data
- Cluster analysis based on presence-absence data at trip level
- Shows which species tend to be caught together
- Note: includes lobster traps and fish traps



Conclusions

- Straightforward and scientifically defensible approach for managing large species suites in the U.S. Caribbean using readily available data
- Addresses legal mandates to prevent overfishing while balancing social, economic, and ecosystem-based fishery management objectives
- Moves from impractical single-species annual catch limits toward more effective, effort-based controls tailored to multi-species fisheries
- MSE can stress-test the framework against uncertainties and environmental shocks prior to implementation
- First principles approach to inform information gaps (e.g., are increasing catches due to increased productivity, expanding fishery, or good recruitment?)

FishPath standardization

Assessment Category: Multiple Indicators, Population Dynamics Model, Risk analysis

Assessment Output: Fishing rate

Management Measure: Effort limits, gear management

Assessment Tier: Mid