US Caribbean Application of Alternate Assessment Methods
An integrated trophic frontier framework for managing U.S. Caribbean fisheries

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SEDAR 103: US Caribbean Application of Alternate Assessment Methods
An integrated trophic frontier framework for managing U.S. Caribbean fisheries

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I. Introduction

Maintaining sustainable fisheries in the U.S. Caribbean region is a function of both ecological and economic limitations, ensuring that stocks are not overfished and not undergoing overfishing while also ensuring that the fishing industry is economically viable. U.S. Caribbean fisheries occur around small islands, with a discrete shelf area and finite productivity levels, with limited ability to expand. Fisheries are largely prosecuted by trap gear and divers, which are constrained to certain areas due to limitations of human physiology and bottom depth. While biological productivity limits dictate sustainable extraction levels (e.g., annual catch limits; maximum sustainable yields), realized landings are heavily modulated by complex market dynamics, infrastructural constraints, and shifts in resource availability. Catch is sold almost exclusively to local markets, and market demand varies throughout the year with various culturally significant holidays or seasons and tourist demand. Limitations on refrigeration (particularly with respect to power outages), tolerance of different species to freezing, and opportunities to market their catch also constrain fishing effort. Further, many fishermen participate in the industry as a part-time venture, providing additional capacity limitations. Critically, market demand, harvest capacity, and profitability for a particular species or complex fluctuates and is driven by factors that cannot be quantified from a single survey. A successful management strategy for the region must account for the ecological, economic and social limitations with consideration for sustainable populations and profitable fishing industries.

The prevailing paradigm of single-species annual catch limits (ACLs) is suboptimal for the U.S. Caribbean, primarily due to the lack of quantitative stock assessments for informing catch limits. The region has highly diverse, multi-species fisheries, leaving management controls over individual catch limits ineffective. A single-species management framework is further compromised by significant uncertainty in self-reported commercial landings data, which undermines the reliability of historical reference points and real-time quota tracking. Current data suggests a significant difference between reported and actual catch, as evidenced by the expansion factors required to align logbook data with estimated effort (approximated at 2.0x in Puerto Rico and unquantified for the U.S. Virgin Islands). Recreational management efforts have similarly been hampered by highly uncertain and incomplete data. Enforcing individual species regulations across island-specific management plans and data collection efforts for tracking annual progress towards quotas is highly resource intensive.

A more fitting method for managing fisheries in the U.S. Caribbean would be: 1) dependent on easily gathered data sources with reasonably low uncertainty, 2) robust to data limitations, 3) applicable at a species complex level, 4) cost-effective with respect to data collection, management, and enforcement, and 5) responsive to not only biological but also social and economic goals for the fisheries. Ideally, the management controls would occur at the gear-specific level (e.g., diving, traps), as managing output controls at the single-species level is not practical given the way that fisheries operate. For example, in St. Thomas and St. John, over three-quarters of the fishing effort is composed of trap fisheries which catch dozens of species, making it challenging to execute adjustments to catch limits on a species-by-species basis (Southeast IEA, 2025; Fig. 1). Because of the multi-species nature of the fisheries, input controls at the gear-specific level can offer a more pragmatic path forward. By regulating the method and intensity of fishing (e.g., gear limits, closed seasons, and entry permits) rather than the ACLs of dozens of individual species, the region can leverage cost-effective methodologies (e.g., multi-species assessment frameworks, community-scale fisheries independent surveys), relative to contemporary methods, to strengthen the U.S. Caribbean fishing industry without sacrificing conservation goals.

The proposed bio-economic management approach operates in four sequential phases that connect ecological limits and fishing behavior with specific management reference points. First, we establish biological ecosystem caps by integrating primary productivity estimates with a static trophic transfer model to define multi-species maximum sustainable yield (MMSY) limits for all species guilds in the fishery management plans. Second, we define operational gear frontiers by running commercial trip-ticket data through a Stochastic Production Frontier (SPF) model, which reveals the present operating efficiency of different gears and quantifies how much effort could harvest the MMSY at maximum efficiency. Third, we merge these estimates into a management decision framework, mapping guild catch totals against gear efficiencies to trigger proactive regulations based upon input controls. Finally, to rigorously evaluate the efficacy, distributional impacts, and responsiveness of the proposed management procedures prior to real-world implementation, the entire framework can undergo closed-loop testing via a Management Strategy Evaluation (MSE). Such an evaluation would simulate increases in gear efficiency and environmental shocks, with observation error in data reporting, to determine whether the approach maximizes both ecological resilience and fleet profitability under realistic data scenarios. The approach fulfills the Magnuson-Stevens Act mandate to base management decisions on the best available science, as well as being responsive to national standards regarding achieving optimum yield and considering the participation of fishing communities, while addressing the executive mandate to strengthen American seafood opportunities for U.S.-based fisheries in the Caribbean.

II. Method Description

The management approach has four phases: 1) establishing biomass caps, 2) estimating production frontiers, 3) creating the management framework, and 4) simulation testing. The first two steps are analysis steps and we describe the data inputs, analyses and outputs in the *Data Inputs* and *Analyses* sections below. Step three combines the outputs from the first two steps into a management framework, and step four describes a simulation testing framework for testing the methods prior to implementation; these steps are outlined in the *Implications for Management* section.

A. Data Inputs

The first step of the approach involves a trophic transfer model (TTM) to estimate reference points for multi-species guilds. This model requires as inputs estimates of benthic primary production (derived from habitat mapping and literature-based areal productivity rates) and pelagic primary production (sourced from satellite-based models; see Appendix A). The primary productivity estimates are then partitioned by a simplified diet matrix to determine trophic levels and energy pathways that are defined using data inputs from literature and other published estimates. The second step of the approach involves a stochastic production frontier (SPF) model which uses commercial trip-ticket data to analyze the trip-level inputs (gear types, numbers of traps, soak time, dive hours, etc.) and their associated outputs (catch or revenue by species).

B. Analyses

Establishing biomass caps

To define sustainable extraction limits for the U.S. Caribbean, this framework establishes island-based biological ecosystem caps by integrating broad ecological boundaries with targeted guild-level modeling. This process relies on a combination of area-based productivity estimates and a quantitative trophic transfer model tailored for data-limited environments.

Estimating Ecosystem-Level Productivity Limits: The initial step is to estimate the ecosystem-scale multispecies maximum sustainable yield (MMSY) on an island basis by assessing both benthic and pelagic productivity. For benthic productivity, we aim to leverage published estimates of coral reef multispecies MSY per area to define an upper biological threshold. Applying these area-based limits provides a macro-level reference point for total sustainable reef extraction. Satellite-derived estimates of pelagic net primary productivity (NPP) provide spatially and temporally resolved measures of the energy entering pelagic food webs across each island ecosystem. To reduce potential regional biases, these estimates are derived from an ensemble of established NPP models rather than any single algorithm. Together, these benthic and pelagic limits represent the total basal energy available across each island ecosystem (see Appendix A).

Defining Guild-Specific Caps: A multi-species Trophic Transfer Model (TTM) can delineate the benthic and pelagic productivity MMSY estimates among species complexes defined in each island's respective fisheries management plan (FMP). Each complex can be assigned a guild based on trophic (e.g., piscivore, planktivore) and habitat-based (e.g., pelagic, benthic/demersal) characteristics to determine the approximate trophic level and productivity pathway. The TTM operates as a static food web model that demands less complexity and data than traditional end-to-end ecosystem models (e.g., Ecospace, Atlantis) but incorporates key ecological drivers. The model relies on specific empirical inputs: benthic and pelagic primary production (*P1; see primary production limits section*) and a simplified diet matrix to determine a species' trophic level and relative contribution of the benthic and pelagic pathway to the complex's energy reliance. Energy is transferred stepwise up the food web to higher trophic levels using a baseline habitat-specific Trophic Transfer Efficiency ($TTE_{habitat}$; e.g., $P2 = P1 * TTE_{habitat}$; $P3 = P2 * TTE_{habitat}$). The $TTE_{habitat}$ can be set based on literature values, with a default of 15%. Sensitivity testing can be conducted to test a range of $TTE_{habitat}$ values (10% - 20%). By quantifying the simulated harvest biomass against the total available biomass, the model outputs an operational Energy Utilization Ratio. This metric directly communicates the risk of ecosystem overfishing per complex and could be utilized as a separate, ecosystem-based management lever.

Deriving Species-Specific Limits within the Ecosystem Framework: While the prevailing single-species paradigm is suboptimal for managing the entirety of the region's diverse multi-species catch, species-specific management limits may be required for certain primary target species (e.g., queen conch and spiny lobster). Species-specific MSYs for these key species can be derived from the TTM. By explicitly partitioning these highly targeted species within the model, the framework generates species-specific limits that are dynamically bounded by the energetic constraints of the ecosystem, ensuring that their harvest does not compromise the energetic needs of higher trophic level piscivores. Alternatively, if a single-species assessment exists for a species, and is deemed to be more robust by a Council, it could be implemented into the MSE framework described below to provide an MSY.

Scenario Testing and Environmental Forecasting: The TTM is also designed to accommodate scenario testing to predict how MMSY fluctuates amidst changing non-trophic conditions. By incorporating functional group-specific environmental sensitivities, variable production-to-biomass (P/B) ratios, and gear-specific fishing effort multipliers, the model simulates a range of environmental and economic drivers. Examples may include thermal anomalies that lead to coral bleaching events, unmanaged fishing effort surges, and market-driven fishing effort shifts. This capability ensures the management framework can identify potential harvest opportunities, respond to environmental fluctuations, and remain biologically robust beyond the immediate SEDAR103 assessment cycle.

Estimating stochastic production frontiers

Fisher behavior is shaped by two fundamental constraints: what is physically possible and what is economically viable. Using trip-ticket records and economic information, we can estimate the feasible range of achievable catch for each gear type over a given time period. On the upper bound, fishers face clear biophysical and operational limits. Trap fishers can deploy only a finite number of traps, soak them for limited durations, and expect a predictable harvest per trap. Divers are constrained by depth, bottom time, air supply, and weather. These factors jointly determine the maximum attainable catch for a given set of inputs. On the lower bound, fishers must generate enough revenue to cover variable costs (e.g., fuel, bait, air, maintenance, etc.). When catch consistently falls below this minimum viable threshold, fishing becomes unprofitable and effort exits the fishery.

A stochastic production frontier (SPF) provides a rigorous, data-driven way to quantify these bounds. Each fisher or trip is modeled as a production unit, with catch (or revenue) explained by observable inputs such as gear deployment, soak time, dive hours, labor, and environmental conditions. This method can also be adapted to multi-output settings depending on the characteristics of specific fisheries. An analysis of trip ticket data using multivariate methods (e.g., non-metric multidimensional scaling of species composition at the trip level) can be used in order to define species guilds into groupings and or metiers (groups of fishermen targeting similar species assemblages with the same gear), for which individual stochastic production frontiers would be estimated. The SPF accounts for variation in observed catch by separating it into two components: (1) random noise, representing unpredictable variation outside the fisher's control (weather, habitat patchiness, gear fouling, short-term stock fluctuations), and (2) technical inefficiency, capturing persistent differences in performance due to skill, experience, gear condition, search behavior, or decision-making. By separating these components, the SPF identifies the frontier, which represents the maximum feasible output for a given combination of inputs under prevailing ecological and technological conditions (Fig. 2). Observed catch almost always lies below this frontier because fishers face both stochastic shocks and varying levels of efficiency.

From an ecological perspective, the frontier reflects not only technology and effort but also ecosystem constraints—stock abundance, habitat quality, species composition, and environmental conditions. Deviations from the frontier therefore capture both fisher performance and ecological heterogeneity. In this sense, the frontier serves as a proxy for fleet capacity, while inefficiency measures reveal how human behavior interacts with ecological limits. SPF results can be used to define realistic operating ranges for each gear type—for example, by deriving percentile-based upper and lower bounds. Linking predicted catch or revenue to input levels also allows identification of minimum viable production thresholds required for profitability. Because SPF models can be estimated separately or hierarchically across islands and gears, they naturally incorporate differences in technology, habitat, and fishing practices.

In addition, the SPF framework produces several management-relevant metrics that are straightforward to interpret:

a) Capacity, which represents the maximum catch the fleet could produce if all fishers operated as efficiently as possible under current ecological conditions.
b) Overcapacity (i.e., permanent excess capital and labor in the fishery) which compares a fleet's potential output to the ecosystem's sustainable production level. For example, a

capacity of 1,200 t relative to an MSY of 900 t indicates that over the long term, the fleet's harvesting power exceeds ecosystem productivity.

c) Excess capacity, which compares short-term potential output to management limits such as an ACL or TAC. For instance, if capacity is 1,200 t but the ACL is 700 t, the fleet has 500 t of excess capacity—indicating that even if the ecosystem could support more harvest, current management rules intentionally restrict it.

When combined with the ecosystem-level MSY constraints from the previous step, SPF results translate broad sustainability targets into gear-specific effort ceilings and floors that are both biologically defensible and economically realistic (see *Implications for Management*).

C. Implications for Management

Aligning ecological caps with the stochastic production frontier in a management framework

The complex-specific MMSYs and available biomass estimates generated by the TTM establish the absolute biological constraints in the fishery. While the TTM defines how much biomass the ecosystem can sustainably produce, the SPF model evaluates how efficiently the fleet could harvest those resources under optimal conditions – and these two pieces of information can be combined to define effort limits that are feasible to sustainably harvest the biomass. If a fleet's estimated production capacity exceeds the TTM's guild-specific cap, it indicates the fleet possesses excess capacity relative to the ecosystem's limits, integrating biological sustainability with economic viability.

The combination of the MMSY from the TTM, and the capacity limits from the SPF can therefore be used to estimate management reference points. The MMSY is not known with certainty, and has some level of scientific uncertainty associated with it, as is true for all estimates of MSY. Allowing the fleet to operate at a level of effort where the maximum capacity is equated to the estimated MMSY can serve as a limit reference point akin to the overfishing limit (OFL), where the probability of overfishing at that effort is 50%. A target reference point could be developed based on the level of risk that the Council wishes to take, e.g., what percent change of overfishing is acceptable for management. For example, if the Council wished to maintain no more than a 40% chance of overfishing, then the target reference point could be equated to the fleet capacity required to harvest the catch associated with the 40th percentile of the MMSY probability distribution.

The description above represents management reference points for a single complex MMSY and a single fleet. To implement this method for an entire island platform or fishery, however, there would be multiple complexes with different MMSYs and multiple fleets with different capacities to harvest that MMSY. The effort dimension above would thus be composed of contributions of multiple fleets that sum together to harvest the biomass, and there would be multiple estimates of MMSY (one per species complex) against which effort levels would need to be tracked.

Another way that the TTM and SDF models could be combined to provide management advice would be to use an optimization routine to maximize economic or social benefits while staying within biological limits. By combining market prices, catch composition data by fleet, and fleet efficiency metrics, an optimization routine can be tailored to support different management priorities. For example, if the goal is to maximize total fleet profit, an optimization algorithm could calculate the exact amount of fishing effort allowed for each gear type to get the highest financial return. Because gears like traps or nets are often non-selective and catch multiple species at once, the routine should automatically signal a shutdown or slow down effort the moment the most vulnerable group hits its ecosystem limit—identifying it as the choke species. Alternatively, if the priority is protecting fishers' livelihoods and community stability, optimization could be adjusted to maximize active participation across all gear types instead of pure profit. This would prevent higher-cost or lower-value traditional fishing sectors from being completely phased out by the model. Ultimately, combining the information in such a routine allows managers to identify species complexes that act as choke species as well as MMSY for complexes that are underutilized.

An initial trophic transfer model and set of stochastic production frontiers can be used to estimate extractable biomass and fleet capacity under current conditions. However, as stock biomasses shift, both MMSYs and fleet operating capacity would be expected to shift, as the productivity of a given complex may be dependent on predator-prey abundances and/or prevailing environmental conditions, and fleet efficiency will increase as stock abundances increase. Therefore, an initial estimation would guide fishery managers in terms of which complexes are currently underutilized and overutilized, and where effort needs to be scaled back to avoid overfishing, based on the comparison of fleet capacity to MMSY.

The framework would then need to be updated to account for changing conditions (e.g. prevailing environmental conditions, stock abundances, technological advances). For actual implementation, a series of indicators can be tracked which, when they exceed certain rates of change, would trigger a reevaluation. These triggers could indicate that there was some unforeseen or extreme event that changes the dynamics of the system and can thus threaten sustainability of one or more stocks. Ecosystem-level indicators could include measures of primary productivity, pelagic-to-demersal ratio in the catch, average trophic level of the catch, or density of commercially fished species in fishery-independent surveys, among others. Relative abundances of individual species can also be tracked by fishery-independent surveys to ensure that there are no concerning trends for any individual species. A significant change in an ecosystem indicator may convey the need to reevaluate the management framework (e.g., reconsider the suite of species defining each gear-specific stochastic production frontier). A significant decline in relative abundance of an individual species may convey an issue with the management framework failing to adequately protect all species within a guild.

A predefined change in any of these indicators (e.g., a drop of 25% or more in any individual species) would trigger an updated estimation of reference points, to ensure that overall management remains robust. The specific frequency at which the models should be rerun can be determined in a simulation phase (see *Simulation testing* section) by simulating shocks of different magnitudes. For example, we can simulate increases in fishing efficiency of different magnitudes (10%, 20%, 30%) and look at under which scenarios the changes render the reference points unsuitable. Similarly, we can simulate shifts in fishing behavior that manifest as changes in average trophic level of the catch or changes in pelagic-to-demersal ratios, and determine at what magnitude the changes are sufficient to warrant updated model estimations.

Simulation testing

To evaluate the efficacy, distributional impacts, and responsiveness of the proposed management procedures prior to real-world implementation, the framework can undergo closed-loop simulation testing via a Management Strategy Evaluation (MSE). This approach dynamically links the biological (TTM) and economic (SPF) models to simulate fishery performance over a multi-decadal timeline. The simulation operates on an annual time step, aligning with the region's trip-ticket data aggregation and the CFMC's standard management cycle. Simulated catch is extracted based on current fleet effort, with applied stochasticity to mimic the observation error and reporting noise inherent in U.S. Caribbean commercial trip-ticket data. The simulated management framework evaluates this data to dictate allowable fishing effort in the subsequent year, creating a continuous feedback loop that provides ongoing management advice.

By running this continuous loop, we can stress-test proposed management rules by introducing simulated shocks to the system under different scenarios. First, to simulate an increase in technological efficiency (e.g., fishers adopting novel hyper-efficient technology) we can artificially force an upward trend in a single fleet's catchability. The simulation can test whether the SPF module can successfully detect this shrinking inefficiency ($u_k \rightarrow 0$) and trigger proactive, gear-specific restrictions before the overall guild cap is breached.

Second, we can simulate environmental change and extreme weather events. Because the biological and economic models operate on an annual scale, acute sub annual disturbances are translated into annualized parameter shocks. For example, a major hurricane can be represented biologically by forcing an immediate drop in benthic primary productivity (*P1*) and temporarily depressing the production to biomass ratios of habitat-dependent complexes. These impacts can be carried forward using multiyear decay and recovery curves to simulate natural habitat regeneration over time. Operationally, the potential physical destruction of vessels, gear, and port infrastructure can be captured by applying an annualized constraint on fleet effort capacity or forcing an outward shift in the frontier inefficiency parameter for that year. Similarly, severe coral bleaching events can be simulated utilizing the functional group specific thermal stressor responses built into the TTM. The simulation uses these annualized shock profiles to test whether the harvest control rules are robust enough to protect recovering stocks and sustain fleets under severe, unpredictable disruptions.

By tracking long term performance indicators across these different stress test scenarios, specifically focusing on fleet profitability, catch stability, and overall guild biomass health, this MSE quantifies the tradeoffs between biological constraints and economic goals. The primary purpose of this simulation is to deliver robust management advice by identifying which decision rules perform best across a wide range of uncertainties. Relying on the dynamic interaction between the TTM and SPF models ensures that the framework can adapt to unforeseen changes, ultimately equipping the Council and stakeholders with a scientifically defensible, resilient strategy for ecosystem protection and socioeconomic stability.

D. Caveats

As is the case for any analytical method, the inputs to the methods here are associated with various forms of uncertainty. Inputs to the trophic transfer model depend largely on values from published literature, which are subject to the uncertainty associated with the various studies from which these values are derived. The TTM can be scaled in complexity to available data, to avoid reliance on uninformed inputs; however, simpler models will be influenced to a higher degree by the underlying assumptions. The stochastic production frontier model is reliant on self-reported trip tickets which adds uncertainty to this analysis; however, it avoids major uncertainties inherent in estimation of the extent of underreporting that are assumed in the total landings. Options for reducing uncertainty from self-reported trip tickets are to use subsets of the trip ticket data that show indications of more robust reporting, or trip data that have been validated by observers (e.g., via the MER Consultants Sampling and Catch Validation Project). Finally, management strategy evaluation can be used to test performance of the methods in light of known uncertainties and suspected biases, by simulating a range of input values and evaluating how robust management performance is to these changes.

III. Applications of the Method

While the underlying models are relatively simplistic, the management framework could quickly become complex when trying to manage for multiple areas and gear types. An initial way forward to pilot the feasibility of this approach could be to focus on a single area with low gear diversity. For example, in St. Thomas, the fisheries are largely composed of trap fisheries targeting a diverse suite of species. A pilot study could consider developing a few different SPFs based on different types of trap fisheries, linked with MMSYs developed from a trophic model for several species guilds. This would keep the dimensionality of the outputs low and allow for a relatively straightforward calculation of reference points. Furthermore, traps are carefully tracked and identified in St. Thomas, and management has implemented a trap reduction program with the goal of reducing pressure on reef fish, so there is some precedent for managing input controls to reach conservation goals. Another example of input controls in the region is the limited entry program that was considered for deepwater snappers in federal waters of Puerto Rico (CFMC, 2016). The methods proposed here could be used to evaluate the appropriate level of effort to ensure sustainable harvest of these species in such a framework.

IV. Discussion

This method represents a novel yet straightforward approach for management of large suites of species in the U.S. Caribbean, using readily available data and sound ecological theory. By combining a data-limited trophic transfer model with stochastic production frontiers, we create a decision framework that can be used to track current energy utilization in the fisheries and inform appropriate levels of fishing effort to prevent overfishing. A strength of the method is that it moves away from reliance solely on single-species annual catch limits, which are impractical to implement and enforce, to effort-based controls that are more appropriate given the multi-species nature of the fisheries and the challenges with tracking individual species catch limits. The method includes a management strategy evaluation process to test the framework against known uncertainties and environmental shocks, prior to implementation. Overall, the approach offers a scientifically defensible method for meeting legal mandates to prevent overfishing while also informing social and economic constraints and contributing to ecosystem-based fishery management objectives.

V. References

Caribbean Fishery Management Council. (2016). Puerto Rico Commercial Snapper Unit 2 Federal Permit Program: Scoping document. National Marine Fisheries Service.

Southeast Integrated Ecosystem Assessment Program. (2025). Caribbean Ecosystem Status Report. NOAA Tech. Memo. NMFS-792 61 p.

VI. Tables and Figures

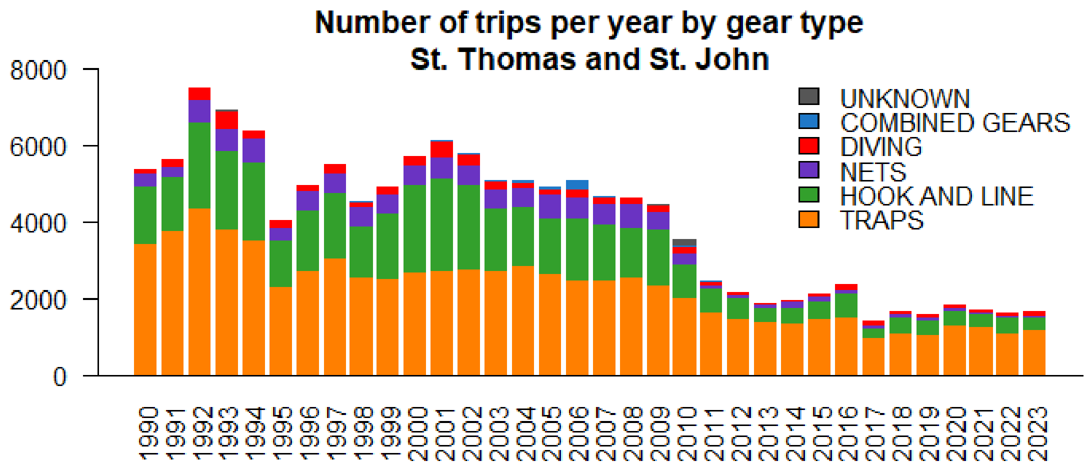

Figure 1. Total number of commercial fishing trips by gear type in St. Thomas and St. John, separated by primary gear used on the trip. Note that the years are fishing years (July 1st to June 30th of the following year). Reproduced from Caribbean Ecosystem Status Report (Southeast IEA, 2025).

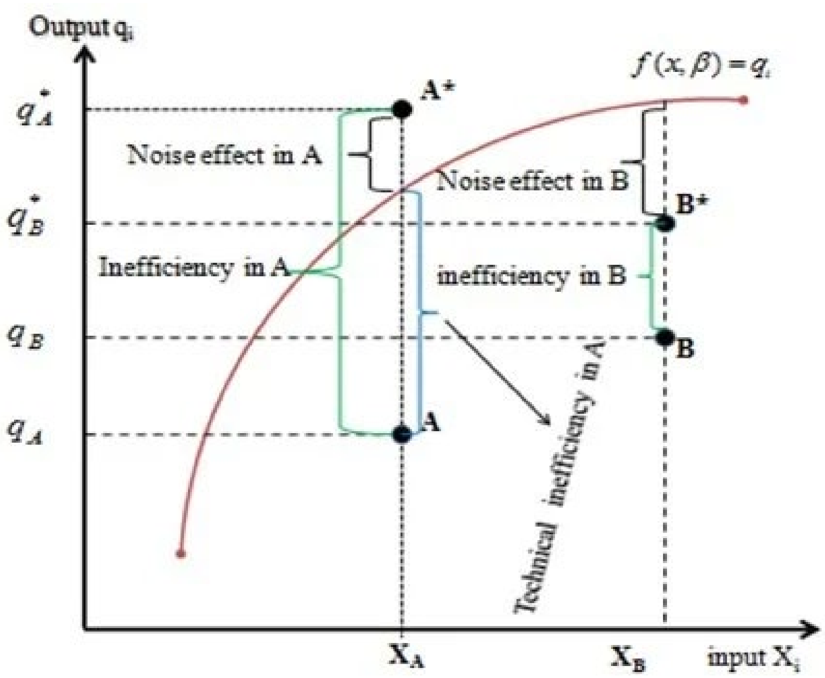

Figure 2. The SPF model, which separates observed output into two components: random noise and technical inefficiency. The curved line labeled $f(x,\beta) = q_i^*$ represents the frontier (maximum possible output) for a given level of input X. Points such as A and B lie below this frontier, indicating that the firms are not fully efficient. The vertical distance between each

observed point (A or B) and the frontier is decomposed into two parts. The first part, shown between A and A* (or B and B*), represents inefficiency, meaning the shortfall in output due to poor performance relative to the best possible level. The second part, between A* and the frontier (and similarly for B*), captures the noise effect, which reflects random shocks beyond the firm's control, such as measurement errors or external factors. Thus, the total deviation from the frontier is split into inefficiency and noise, allowing the model to distinguish between controllable inefficiency and unavoidable randomness in production.

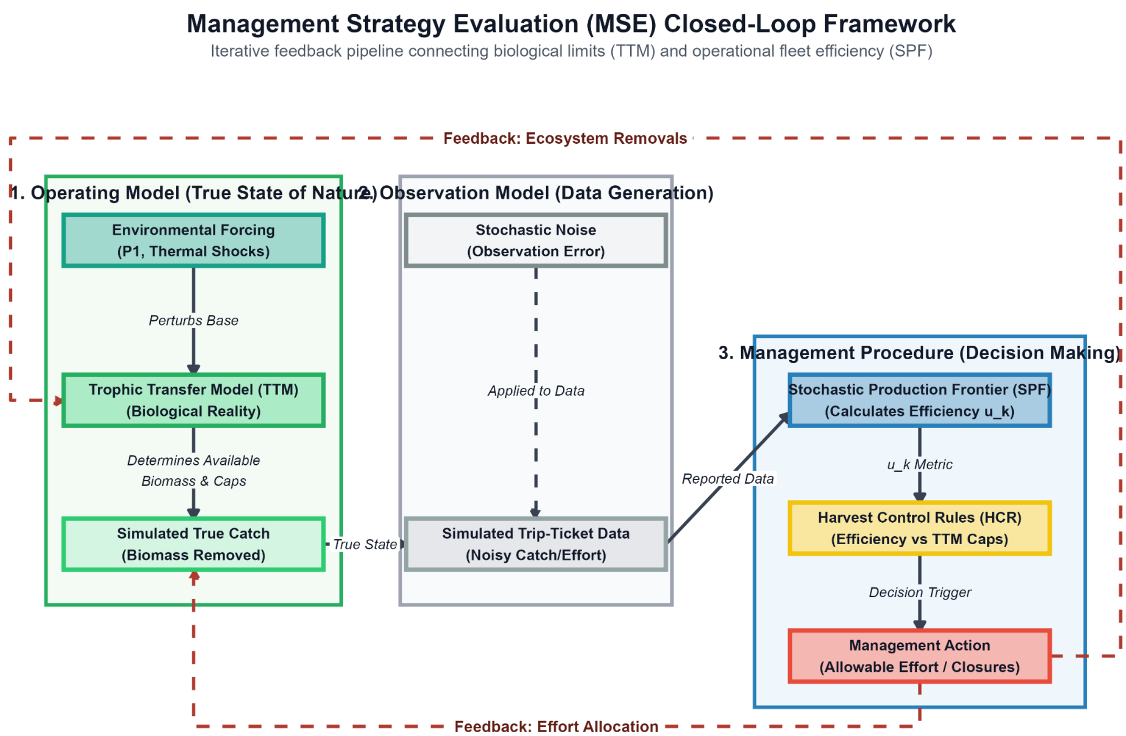

Figure 3. A schematic representation of a closed-loop management strategy evaluation framework linking ecological and economic models, used to test the management procedures described prior to implementation.

Appendix A – Primary Productivity Estimates

Pelagic Primary Production Estimates

Net primary production (NPP) is the rate at which phytoplankton convert sunlight and dissolved carbon dioxide into new organic matter through photosynthesis. Because this organic matter provides the energy that ultimately supports zooplankton, fish, marine mammals, and other higher trophic levels, NPP is a useful measure of the amount of trophic energy available to an ecosystem. Unlike chlorophyll concentration, which indicates how much phytoplankton is present at a given time, NPP describes how rapidly new biomass is being produced and is therefore expressed as a rate (e.g., mg C m^{-2} day^{-1}).

Satellites cannot measure primary production directly. Instead, they observe subtle differences in the color of the ocean, from which quantities such as chlorophyll concentration, phytoplankton light absorption, particulate backscatter, and water clarity can be estimated. These optical measurements are combined with environmental information, including sea surface temperature and available sunlight (photosynthetically available radiation; PAR), within bio-optical models that estimate the rate at which phytoplankton convert light into organic carbon. Collectively, these observations provide a spatially continuous and temporally consistent view of phytoplankton productivity across large marine ecosystems that would be impractical to obtain using ship-based observations alone.

A variety of satellite NPP models have been developed over the past three decades. While they all estimate the same quantity, they differ in how they represent phytoplankton physiology and the environmental processes that regulate growth. Some models estimate productivity primarily from chlorophyll concentration, others estimate phytoplankton carbon biomass from optical scattering properties, and newer approaches explicitly represent the absorption of light by phytoplankton. Each approach emphasizes different aspects of phytoplankton ecology and consequently performs better under some environmental conditions than others. Rather than selecting a single "best" algorithm, this assessment adopts an ensemble approach that combines multiple well-established NPP models. This strategy reduces dependence on any one set of assumptions while providing a more robust estimate of ecosystem productivity and a useful measure of uncertainty for ecosystem-based management.

The ensemble used in this assessment follows Ryan-Keogh et al. (2023), who applied four widely used satellite NPP algorithms to a harmonized ocean color record (Behrenfeld et al. 1997, Westberry et al. 2008, Silsbe et al. 2016). The resulting dataset is distributed as 8-day composites at approximately 25-km spatial resolution and incorporates satellite-derived chlorophyll concentration, particulate backscatter, phytoplankton absorption, diffuse attenuation (Kd490), photosynthetically available radiation (PAR), sea surface temperature, mixed-layer depth, and nutricline depth. Together, these variables constrain estimates of phytoplankton biomass, light availability, and growth across the different modeling approaches.

The four algorithms included in the ensemble represent complementary views of phytoplankton productivity:

Model	What makes it unique	Considerations
VGPM	Estimates NPP primarily from chlorophyll, light, and sea surface temperature using one of the most widely applied global productivity models.	Performs well across many regions but assumes that very warm waters are increasingly nutrient-limited, which may not capture all ocean conditions.
VGPM-Eppley	Uses the same framework as VGPM but applies an alternative temperature response that emphasizes phytoplankton growth under warmer, high-light conditions.	Tends to represent warm-water productivity differently than VGPM because it places less emphasis on nutrient limitation at high temperatures.
CbPM	Estimates phytoplankton carbon biomass from satellite backscatter and derives growth rates from changes in the chlorophyll-to-carbon ratio, providing a more physiological representation of productivity.	Relies on additional satellite-derived optical properties and assumptions about how phytoplankton adjust their pigment content under changing environmental conditions.
CAFE	Estimates productivity from the amount of light absorbed by phytoplankton and the efficiency with which that energy is converted into biomass, using spectrally resolved optical properties.	Better represents diverse optical environments but requires additional optical inputs and a more complex representation of underwater light fields.

Although each model differs in its representation of phytoplankton physiology and environmental controls, they are all designed to estimate the same ecological quantity: the rate at which carbon is fixed into new biomass through photosynthesis. Combining these complementary approaches produces a more balanced estimate than relying on any single model and allows the spread among models to be used as an indicator of structural uncertainty.

To derive ecosystem-scale productivity estimates, the 8-day composite NPP fields were converted to daily values and multiplied by the area represented by each satellite grid cell to estimate total daily carbon production. A region-specific management polygon was then applied to aggregate production across all pixels within the Caribbean ecosystem. Daily totals were summed over each calendar year to produce annual pelagic NPP estimates (g C yr^{-1}) for the

Caribbean management region (Figure A1). This processing workflow preserves the spatial variability observed by satellites while generating annual ecosystem-scale productivity estimates that are directly comparable among regions and years. By combining multiple physiologically distinct productivity models within a consistent processing framework, this ensemble provides a transparent, repeatable, and scientifically defensible estimate of the energy entering marine ecosystems for use in ecosystem-based fisheries assessments.

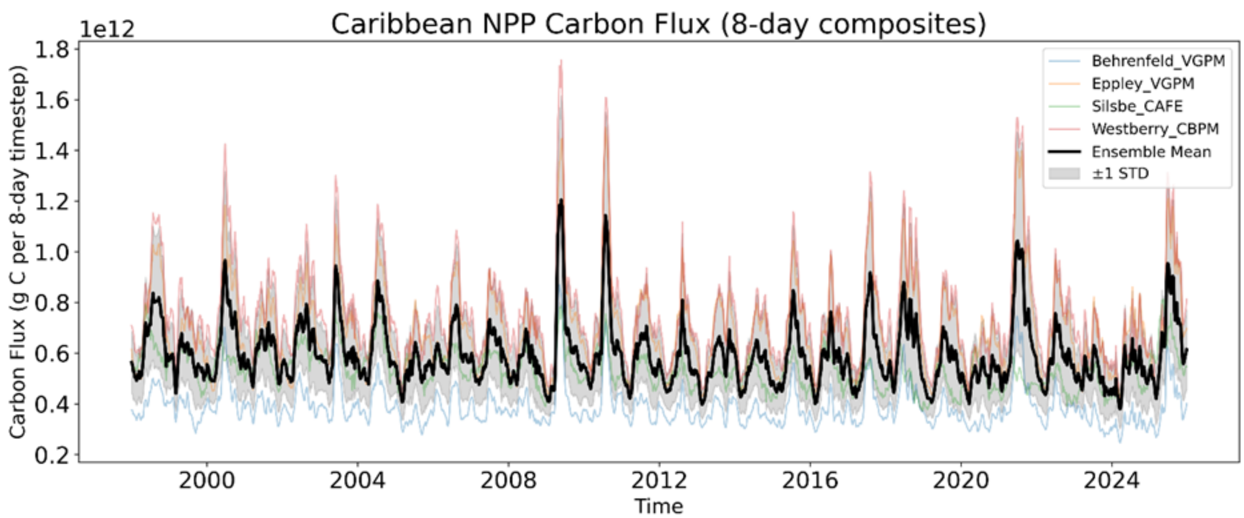

Figure A1. Time series of regional pelagic primary production derived from the satellite NPP ensemble. The figure shows the total pelagic carbon fixation integrated across the Caribbean management region for each 8-day composite interval from the multi-model satellite NPP dataset. Colored lines represent the individual productivity models included in the ensemble (VGPM, Eppley-VGPM, CbPM-Westberry, and CAFE), while the black line indicates the ensemble mean. The shaded envelope represents ±1 standard deviation among models, providing a measure of structural uncertainty arising from differences in model formulation. Regional values were calculated by integrating gridded satellite NPP over the Caribbean management polygon, preserving the temporal variability in pelagic primary production prior to aggregation into annual ecosystem-scale estimates.

Benthic Primary Production Estimates

Satellite-derived NPP provides an estimate of productivity within the pelagic (water-column) ecosystem but does not resolve the high rates of primary production that occur within shallow benthic habitats such as seagrass meadows and coral reefs. To provide a more complete characterization of ecosystem energy inputs, independent estimates of benthic primary production were developed for these habitats using published literature values.

Mapped benthic habitat polygons for Puerto Rico, St. Croix, and St. Thomas/St. John (Figure A2) were compiled to estimate the total areal extent of seagrass and coral reef habitats within the study region. Habitat areas were calculated in an equal-area projected coordinate system to ensure accurate estimates of surface area. Published estimates of areal primary production were then extrapolated across the mapped habitat extent to estimate total annual benthic production for each habitat type.

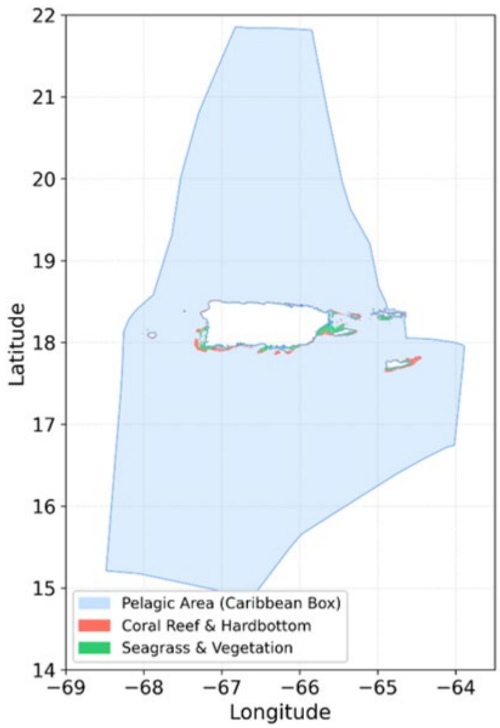

Figure A2. Delineation of pelagic and benthic primary production domains used in this assessment. The light blue polygon represents the Caribbean pelagic management region over which satellite-derived net primary production (NPP) was integrated. Mapped benthic habitats used to estimate benthic primary production are overlaid, with coral reef and hardbottom habitats shown in red and seagrass and vegetated habitats shown in green. Benthic habitat maps for Puerto Rico, St. Croix, and St. Thomas/St. John were used to calculate the total area of each habitat type, which was subsequently combined with literature-derived areal productivity estimates to estimate total annual benthic primary production.

For coral reef and hardbottom habitats, annual production was based on the synthesis of Douglas (2001), which reports reef primary production spanning approximately 1–15 g C m^{-2} day^{-1}, reflecting the broad range of productivity observed across reef environments. These values were converted to equivalent annual areal production (3,600–49,500 metric tons km^{-2} yr^{-1}) and used to define the range of plausible regional coral reef productivity. Seagrass productivity was estimated using the global synthesis of Gomis et al. (2025), which reported mean annual production of 5,833 ± 557 kg C ha^{-1} yr^{-1}. These values were converted to 5,250 ± 501 metric tons km^{-2} yr^{-1} and extrapolated across the mapped seagrass habitat.

Pelagic and benthic productivity estimates were intentionally derived using independent approaches. Pelagic production was estimated from satellite observations integrated across the open-water ecosystem, whereas benthic production was estimated by combining mapped habitat extent with literature-derived areal productivity. This separation avoids double-counting while allowing each ecosystem component to be represented using the methodology best suited to its characteristics. The resulting estimates provide complementary measures of energy supplied by pelagic and benthic primary producers and together offer a more complete depiction of ecosystem-scale primary production (Figure A3).

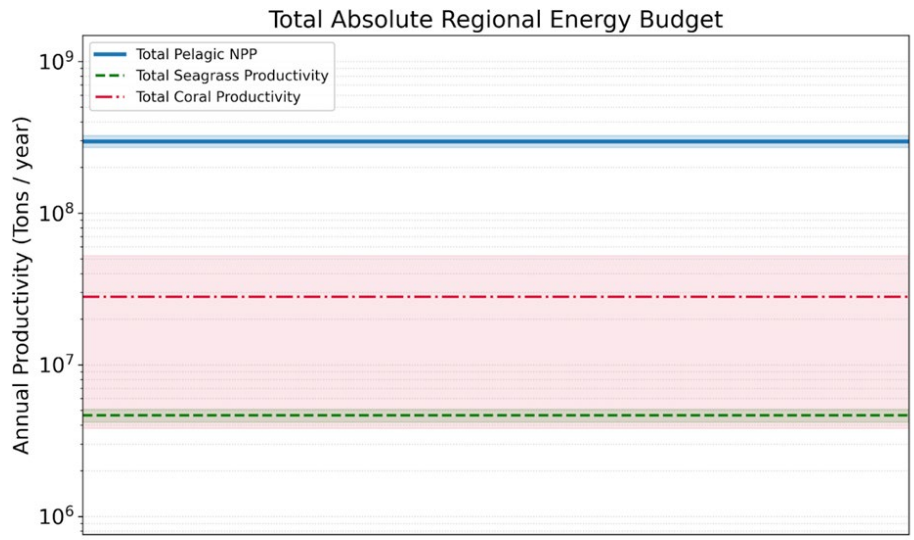

Figure A3. Comparison of estimated annual primary production from pelagic and benthic ecosystem components. Horizontal lines represent the mean annual regional primary production estimated for the pelagic ecosystem (blue), seagrass habitats (green), and coral reef/hardbottom habitats (red). Shaded regions indicate the associated uncertainty or range of reported productivity values used in each estimate. Pelagic productivity was derived from the satellite-based multi-model NPP ensemble, whereas benthic productivity was estimated by extrapolating published areal production rates across the mapped extent of seagrass and coral reef habitats.

References

Behrenfeld, M. J. and Falkowski, P. G. (1997). Photosynthetic rates derived from satellite-based chlorophyll concentration, Limnol. Oceanogr., 42, 1–20.

Douglas, A. E. (2001). The productivity of corals. In Oceanography (Vol. II). Encyclopedia of Life Support Systems (EOLSS). EOLSS Publishers.

Gomis, E., Strydom, S., Foster, N. R., Montemayor, D., Mateo, M. A., Serrano, E., ... & Serrano, O. (2025). Global estimates of seagrass blue carbon stocks in biomass and net primary production. Nature Communications, 16(1), 9530.

Ryan-Keogh, T. J., Thomalla, S. J., Chang, N., & Moalusi, T. (2023). A new global oceanic multi-model net primary productivity data product. Earth System Science Data, 15(11), 4829-4848.

Silsbe, G. M., Behrenfeld, M. J., Halsey, K. H., Milligan, A. J., and Westberry, T. K. (2016). The CAFE model: A net production model for global ocean phytoplankton, Global Biogeochem. Cy., 30, 1756–1777.

Westberry, T., Behrenfeld, M. J., Siegel, D. A., and Boss, E. (2008). Carbon-based primary productivity modeling with vertically resolved photoacclimation, Global Biogeochem. Cy., 22, GB2024.