U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Appendix E. Appendix to Chapter 7.2: Macroalgae

March 2024

Disclaimer

Availability

This report and supporting documentation, data, and analysis tools are available online:

Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources

Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

Suggested Citation

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Appendix E. Appendix to Chapter 7.2: Macroalgae

Appendix E.1: Production Cost Calculation Overview

The total production cost of growing and harvesting macroalgae and delivering it to shore is calculated as:

$$c_{prod} = \frac{(c_{cap})+(c_{op})+(c_{harv})+(c_{trans})}{s_{dw}} \tag{1}$$

where $\boldsymbol{c_{prod}}$ is total annual cost of macroalgae production (growth + harvesting + transport to shore), c_{cap} is as calculated in E.2, c_{op} is as calculated in E.3, c_{harv} is as calculated in E.4, $c_{eqtrans}$ is as calculated in E.5, and s_{dw} is the dry weight of macroalgae harvested annually per km^2.

Appendix E.2: Capital Cost Inputs and Calculations

Capital costs are calculated as:

$$c_{cap} = c_{capbase} + \left(c_{capbase} \times (k_d + k_w)\right) + c_{sl} \tag{2}$$

where c_{cap} is the total annualized capital costs per km^2, $c_{capbase}$ is the annualized capital cost per km^2 (e.g., cost of buoys, anchors, boats, structural rope) prior to applying depth and wave impacts, k_d and k_w are the impacts of depth and waviness on capital cost, respectively, each expressed as a multiplier that doubles capital costs in grid cells where depth >500 m and/or significant wave height >3 m, respectively, and c_{sl} is the total annual cost of seeded line calculated as:

$$c_{sl} = c_{slbase} \times p_{sline} \tag{3}$$

where c_{slbase} is the cost per meter of seeded line, and p_{sline} is the total length of line per km^2, based on the optimal macroalgae type grown in each grid cell.

Appendix E.3: Operating and Maintenance Cost Inputs and Calculations

Operating and maintenance costs are calculated as:

$$c_{op} = c_{ins} + c_{lic} + c_{lab} + c_{opbase} \quad (4)$$

where c_{op} is the total annualized operating and maintenance costs per km^2, c_{ins} is the annual insurance cost per km^2, c_{lic} is the annual cost of a macroalgae aquaculture license per km^2, c_{lab} is the annual cost of labor excluding harvest labor, and c_{opbase} is all other operating and maintenance costs.

Appendix E.4: Harvest Cost Inputs and Calculations

Harvest costs are calculated as:

$$c_{harv} = c_{harvbase} \times n_{harv} \quad (5)$$

where c_{harv} is the total annual costs associated with harvesting macroalgae per km^2, $c_{harvbase}$ is the cost per harvest per km^2 (including harvest labor but excluding harvest transport), and n_{harv} is the total number of harvests per year.

Appendix E.5: Transport Cost Inputs and Calculations

Costs associated with transporting equipment to the aquaculture farming location are calculated as:

$$c_{eqtrans} = c_{transbase} \times m_{eqsw} \times d_{port} \quad (6)$$

where $c_{eqtrans}$ is the annualized cost of transporting equipment to the farm, $c_{transbase}$ is the cost to transport 1 ton of material 1 km^{-1} on a barge, m_{eq} is the annualized equipment mass in tons, and d_{port} is the ocean distance to the nearest port in km^{-1}.

Costs associated with transporting harvested macroalgae and retired equipment back to port are calculated as:

$$c_{swtrans} = c_{transbase} \times \left(m_{eq} + m_{s_{ww}}\right) \times d_{port} \quad (7)$$

where $c_{swtrans}$ is annualized cost of transporting harvested macroalgae biomass and retired equipment to shore, $c_{transbase}$ is the cost to transport 1 ton of material 1 km^{-1} on a barge, m_{eq} is the annualized equipment mass in tons, s_{ww} is the wet weight macroalgae biomass, and d_{port} is the ocean distance to the nearest port in km^{-1}.

The total transport costs are therefore calculated as:

$$c_{trans} = c_{eqtrans} + c_{swtrans} \quad (8)$$

where $c_{eqtrans}$ and $c_{swtrans}$ are calculated as in Equations 6 and 7.

Appendix E.6: Cost Model Parameter Input Values

Table E-1. Techno-Economic Model Cost Inputs for Each Scenario

Cost Parameter	Unit	Scenario 1 (Low Yield, Low Cost)	Scenario 2 Representative Scenario (Medium Yield, Low Cost)	Scenario 3 (High Yield, High Cost, Optimized Seeding and Harvesting)
Capital (incl. nutrient system, if applicable)	$ km^{-2} yr^{-1}	342,185	383,594	2,056,746
Operating + maintenance	$ km^{-2} yr^{-1}	31,120	31,120	770,604
Harvest + seeding	$ km^{-2} harvest^{-1}	8,510	8,510	124,361
Transport	$ km^{-1} t^{-1}	0.23	0.23	0.23
Labor	$ km^{-2} yr^{-1}	67,933	67,933	80,567
License	$ km^{-2} yr^{-1}	1,250	1,250	1,250
Insurance	$ km^{-2} yr^{-1}	11,209	11,209	39,567
Cultivation line	$ m^{-1}	0.04	0.04	0.27
Nutrient system inclusion	N/A (yes or no)	No	Yes	Yes

Appendix E.7: Low-Yield, Low-Cost Scenario Results

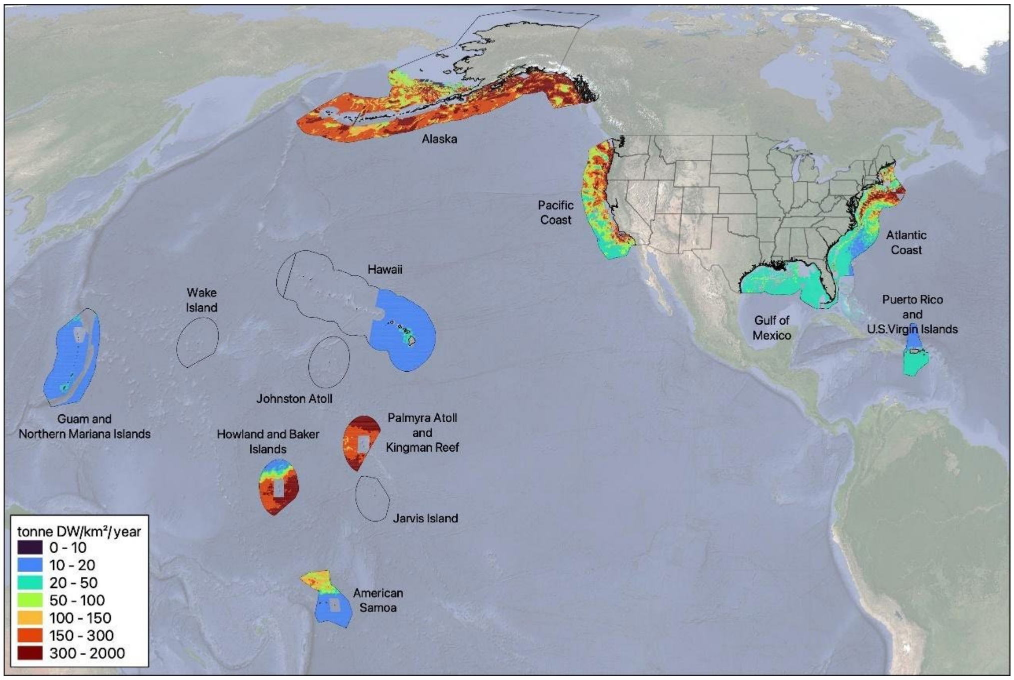

Figure E-1. Macroalgae biomass yield under the low-yield/low-cost scenario (Scenario 1) with marine area screening

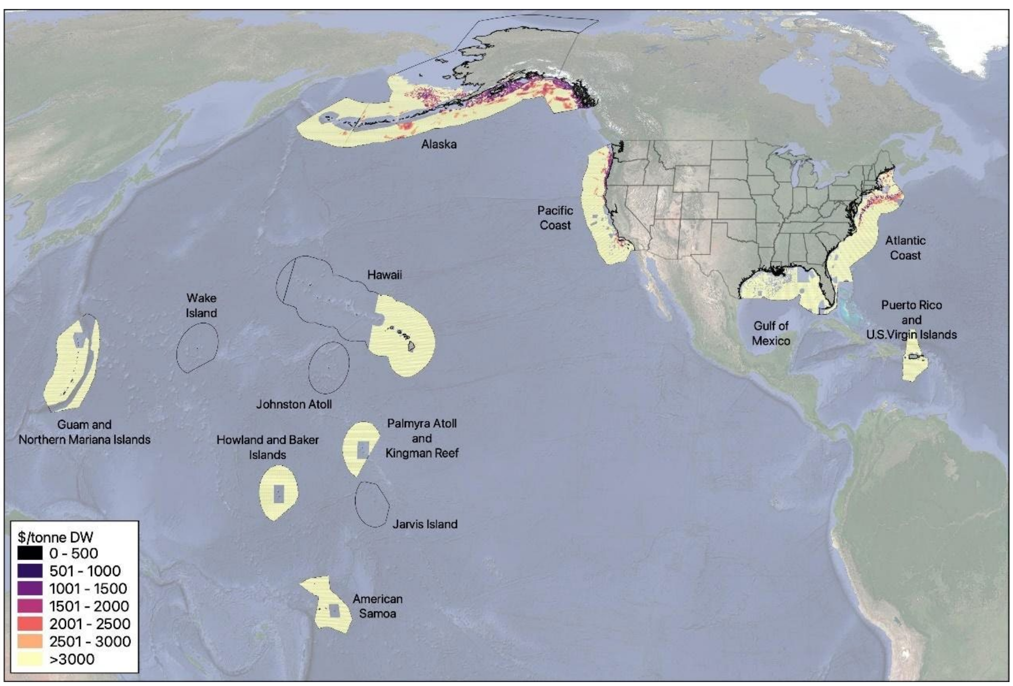

Figure E-2. Macroalgae cost under the low-yield/low-cost scenario (Scenario 1) with marine area screening

Appendix E.8: High-Yield, High-Cost Scenario Results

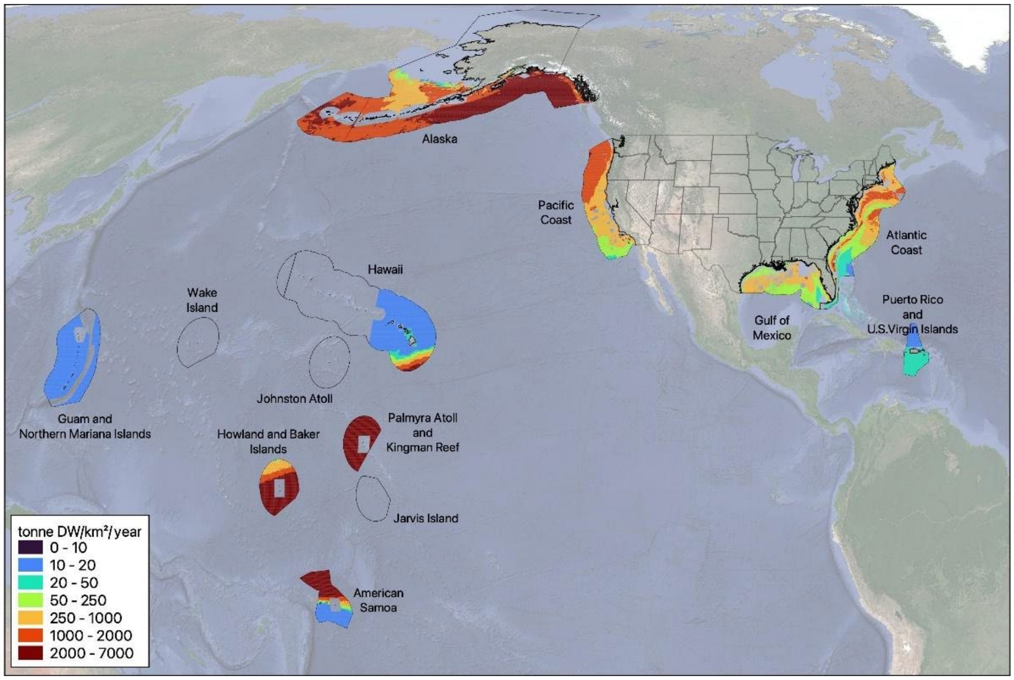

Figure E-3. Macroalgae biomass yield under the high-yield/high-cost scenario (Scenario 3) with marine area screening. Note the color scale differs from Figure E-1.

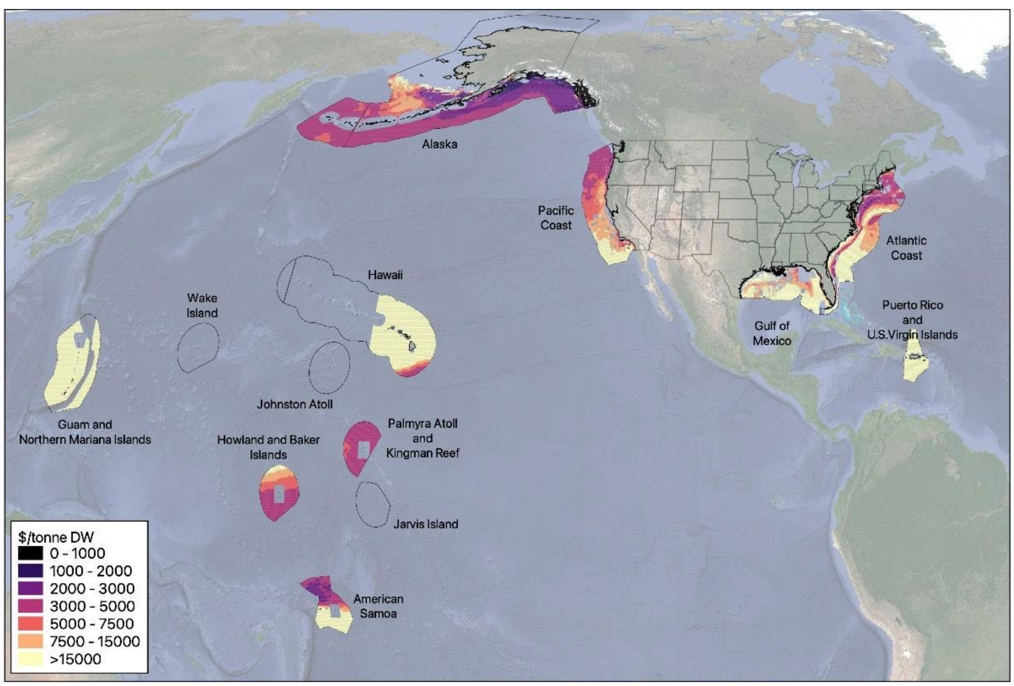

Figure E-4. Macroalgae cost under the high-yield/high-cost scenario (Scenario 3) with marine area screening. Note this color scale differs from Figure E-2.

Appendix E.9: Additional Methods, Limitations, Inventory of Marine Area Screening Data Layers, and Region-Specific Screening Area Results

The full set of data layers, buffer distances, and sources used in the marine area screening are presented in Table E-2. For each of the 13 defined regions in this study, the resulting screened-inclusive area are presented in Table E-3.

Supplemental Marine Area Screening Methods

- Datasets that were given a weight of 0 in the National Oceanic and Atmospheric Administration's (NOAA's) Aquaculture Opportunity Atlas, also referred to as constraints, were identified and downloaded from their respective sources.
- Datasets were projected to a common projection—the Equal Earth map projection (Šavrič, Patterson, and Jenny 2018[1]). Any point or line datasets were buffered by 500 m on all sides. The data were masked using the U.S. exclusive economic zone (EEZ) boundary, then converted to raster format with a 200-m resolution. Areas of the U.S. EEZ that had any of these layers intersect were screened exclusively (i.e., not included).

Marine Area Screening Limitations

- Ocean screening was qualitative based on the available data and screening decisions that were informed by NOAA and partnering agencies.
- Screened areas may change if a dataset is updated, or new considerations are included; we used the most complete and accurate datasets that are publicly available.
  This study only included uses and features that were certainly conflicting with macroalgae farming. There are numerous other possible conflicts that could be better reflected in a smaller-scale study. NOAA's Aquaculture Opportunity Area Atlas' are working examples of full site suitability analyses in the Southern California Bight and Gulf of Mexico.
- Screening is currently binary (inclusive/exclusive); the next phase would drive toward gradient-based suitability ranges.
- Due to the biomass productivity modeling scale (1/12°), bays and near-coastal areas were not assessed.
- Conflicting uses/features were often smaller than the grid resolution of the biophysical modeling.

[1] Šavrič, B., Patterson, T., and B. Jenny. 2019. "The Equal Earth map projection." *International Journal of Geographical Information Science* 33 (3): 454–465. https://doi.org/10.1080/13658816.2018.1504949.

Table E-2. Data Layers, General Category, Buffer Distance (If Applicable), and Data Source Used for the Marine Area Screening

Dataset	Category	Buffer	Data Source
State and Federal Waters	Boundaries		ftp.coast.noaa.gov/pub/MSP/ORT/FederalAndStateWaters.zip
Benthic Cover	Natural and Cultural Resources	500 m	ftp.coast.noaa.gov/pub/MSP/BenthicCover.zip
Rocky Reef HAPC	Natural and Cultural Resources		www.habitat.noaa.gov/protection/efh/newInv/data/nationwide/nationwide_hapc.zip
National Marine Sanctuaries	Natural and Cultural Resources		sanctuaries.noaa.gov/library/imast_gis.html
NOAA Marine Protected Area	Natural and Cultural Resources		marineprotectedareas.noaa.gov/media/data/NOAA_MPAI_2020_IUCN_gdb.zip
Artificial Reefs	Natural and Cultural Resources	500 m	ftp.coast.noaa.gov/pub/MSP/ArtificialReefs.zip
Deep Sea Coral and Sponge Observation	Natural and Cultural Resources	500 m	www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:145037
Protected Areas	Natural and Cultural Resources		ftp.coast.noaa.gov/pub/MSP/ORT/ProtectedAreas.zip
Aquaculture	Fishing and Aquaculture		ftp.coast.noaa.gov/pub/MSP/Aquaculture.zip
Unexploded Ordnance Locations	National Security	500 m	ftp.coast.noaa.gov/pub/MSP/ORT/UnexplodedOrdnance.zip
Unexploded Ordnance Areas	National Security		ftp.coast.noaa.gov/pub/MSP/ORT/UnexplodedOrdnance.zip
Danger Zones Restricted Areas	National Security		ftp.coast.noaa.gov/pub/MSP/DangerZonesAndRestrictedAreas.zip
Submarine Cable Areas	Industry Navigation Transportation		ftp.coast.noaa.gov/pub/MSP/ORT/SubmarineCableAreas.zip
Submarine Cable Lines	Industry Navigation Transportation	500 m	ftp.coast.noaa.gov/pub/MSP/ORT/SubmarineCables.zip
Pipeline Areas	Industry Navigation Transportation		ftp.coast.noaa.gov/pub/MSP/ORT/PipelineArea.zip
Pipeline Lines	Industry Navigation Transportation	500 m	ftp.coast.noaa.gov/pub/MSP/ORT/Pipelines.zip
Pilot Boarding Areas	Industry Navigation Transportation		ftp.coast.noaa.gov/pub/MSP/ORT/PilotBoarding.zip
Pilot Boarding Stations	Industry Navigation Transportation	500 m	ftp.coast.noaa.gov/pub/MSP/ORT/PilotBoarding.zip
Ocean Disposal Sites	Industry Navigation Transportation	500 m	ftp.coast.noaa.gov/pub/MSP/OceanDisposalSites.zip

Dataset	Category	Buffer	Data Source
Significant Sediment Sources	Industry Navigation Transportation		mmis.doi.gov/boemmmis/downloads/layers/GOMSigSedBlocks_shp.zip
Anchorage Areas	Industry Navigation Transportation		ftp.coast.noaa.gov/pub/MSP/AnchorageAreas.zip
BOEM Pacific Leases	Industry Navigation Transportation		www.boem.gov/Oil-and-Gas-Energy-Program/Mapping-and-Data/Pacific-files/pac_lease(3).aspx
Alaska Oil and Gas Leases	Industry Navigation Transportation		www.boem.gov/regions/alaska-ocs-region/leasing-and-plans/akhistoricalleaseszip
GOM Leases	Industry Navigation Transportation		www.data.boem.gov/Mapping/Files/actlease.zip
Shipping Lanes	Industry Navigation Transportation	500 m	encdirect.noaa.gov/theme_layers/data/shipping_lanes/shippinglanes.zip
ENC Danger Wrecks	Industry Navigation Transportation	500 m	www.nauticalcharts.noaa.gov/enconline/enconline.html
ENC Wrecks	Industry Navigation Transportation	500 m	wrecks.nauticalcharts.noaa.gov/downloads/ENC_Wrecks.zip
Oil and Gas Wells	Industry Navigation Transportation	500 m	ftp.coast.noaa.gov/pub/MSP/ORT/OilandGasWells.zip
Oil and Gas Platforms	Industry Navigation Transportation	500 m	ftp.coast.noaa.gov/pub/MSP/ORT/OilandGasPlatforms.zip
NDBC Sensors and Buoys	Industry Navigation Transportation	500 m	www.ndbc.noaa.gov/kml/marineobs_by_pgm.kml
Ferry Routes	Industry Navigation Transportation	500 m	stacks.stanford.edu/file/druid:gd729dg1947/data.zip
CalCOFI Stations	Industry Navigation Transportation	500 m	https://calcofi.org/files/maps/CalCOFI_113StationMap.kml
BOEM Pacific Pipelines	Industry Navigation Transportation	500 m	www.boem.gov/Oil-and-Gas-Energy-Program/Mapping-and-Data/Pacific-files/pc_pipe(2).aspx
AWOIS Wrecks	Industry Navigation Transportation	500 m	wrecks.nauticalcharts.noaa.gov/downloads/AWOIS_Wrecks.zip
AWOIS Obstructions	Industry Navigation Transportation	500 m	wrecks.nauticalcharts.noaa.gov/downloads/AWOIS_Obstructions.zip
Aids to Navigation	Industry Navigation Transportation	500 m	ftp.coast.noaa.gov/pub/MSP/AidsToNavigation.zip

Table E-3. Total EEZ Area and Resulting Screened-Inclusive Area for Each of the 13 Defined Regions

Region	Total Area (km^2)	Screened Area (km^2)	Percent Area Screened-Inclusive
Puerto Rico Virgin Islands	211,120	199,795	94.6%
Howland and Baker islands	434,884	384,265	88.4%
Johnston Atoll	442,446	0	0%
Jarvis Island	315,079	0	0%
Palmyra Atoll and Kingman Reef	351,385	299,203	85.1%
American Samoa	406,018	369,061	90.9%
Atlantic Coast	933,201	781,497	83.7%
Alaska	3,711,762	2,220,074	59.8%
Pacific Coast	823,753	732,849	89.0%
Guam Northern Mariana Islands	970,396	720,270	74.2%
Wake Island	407,765	0	0%
Hawaii	2,474,750	948,854	38.3%
Gulf of Mexico	698,981	472,143	67.5%

Appendix E.10: Region-Specific Biomass and Techno-Economic Mapping Results for the Medium-Yield/Low-Cost Representative Scenario (Scenario 2)

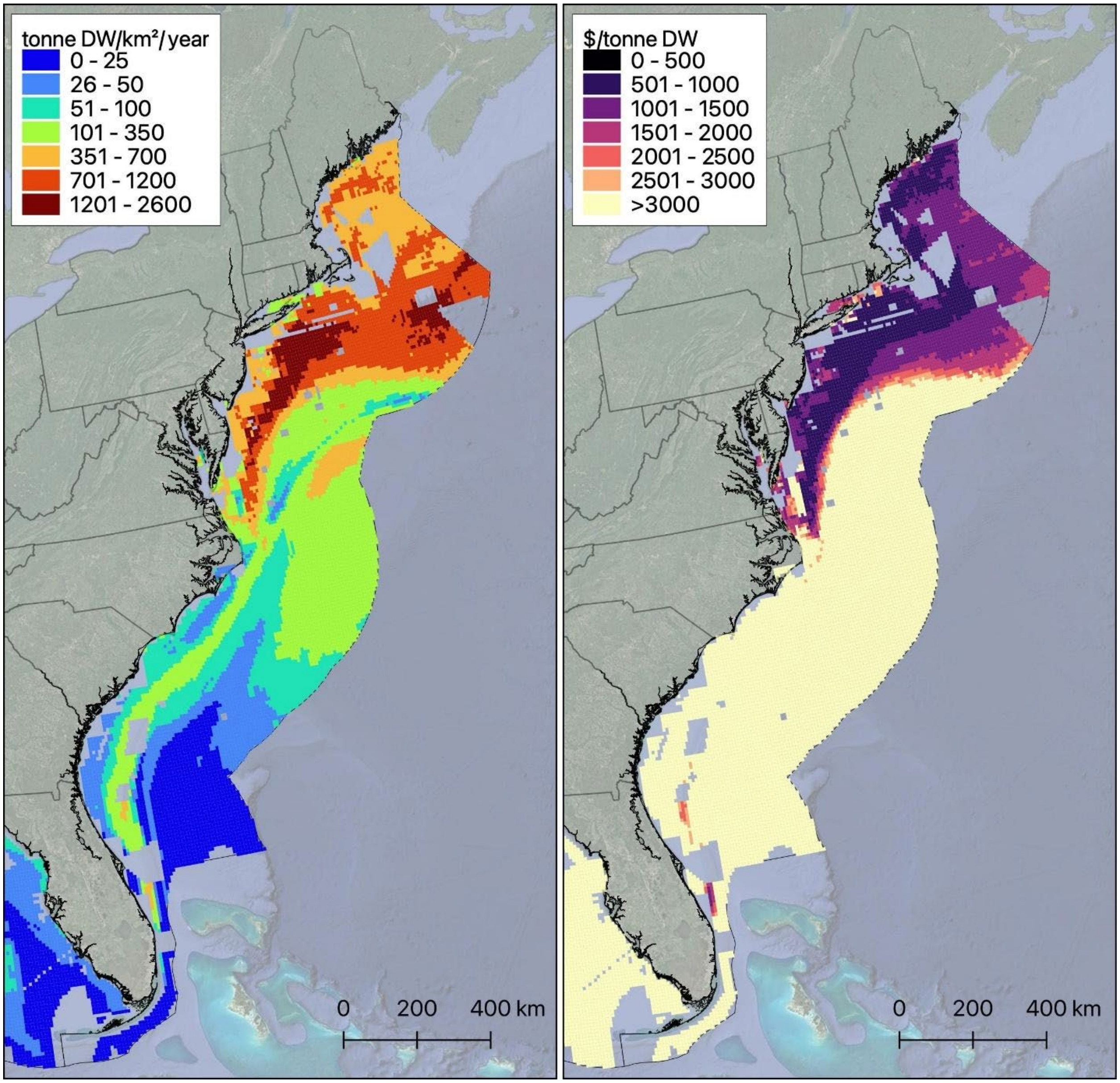

Figure E-5. Atlantic coastal region biomass productivity (left) and techno-economic result (right) with marine area screening

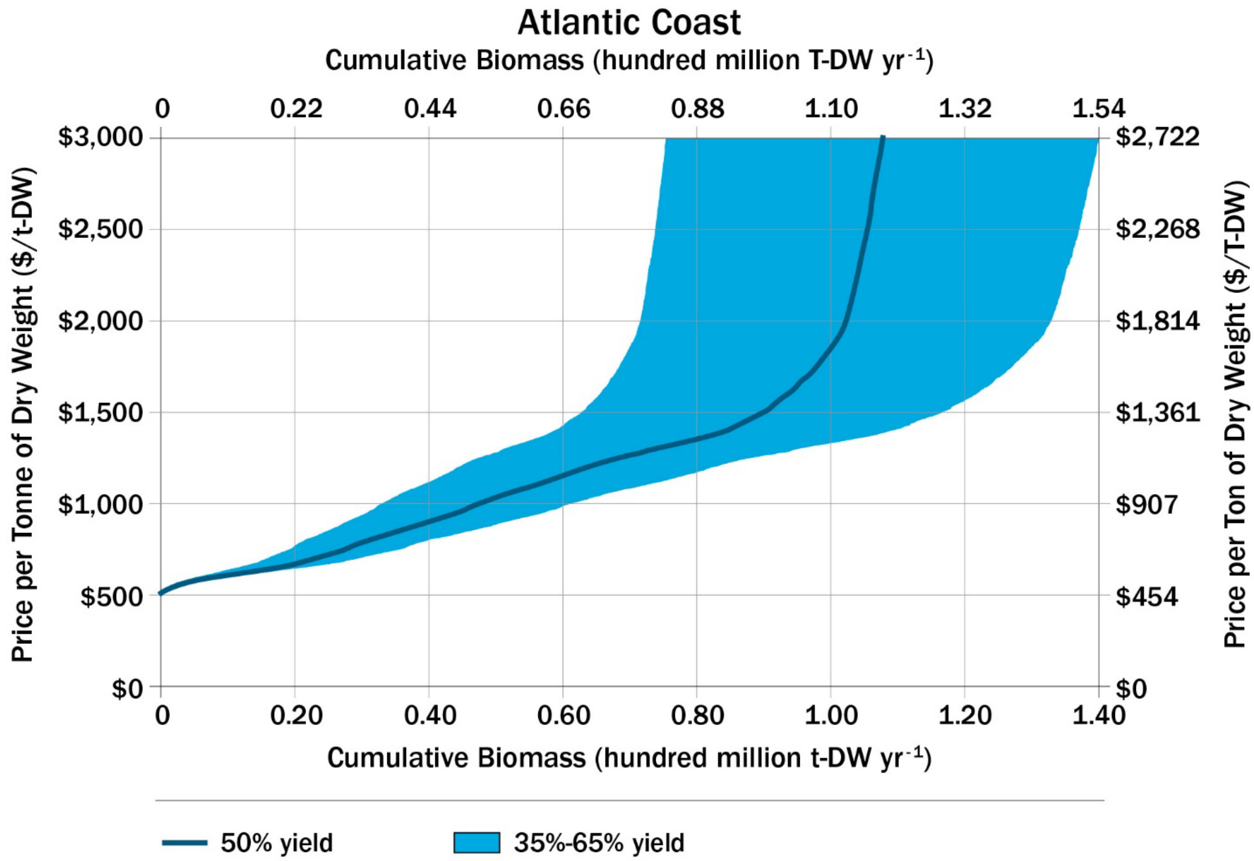

Figure E-6. Cost-supply curve of the Atlantic Coast EEZ region for the representative scenario at 35%, 50%, and 65% area coverage

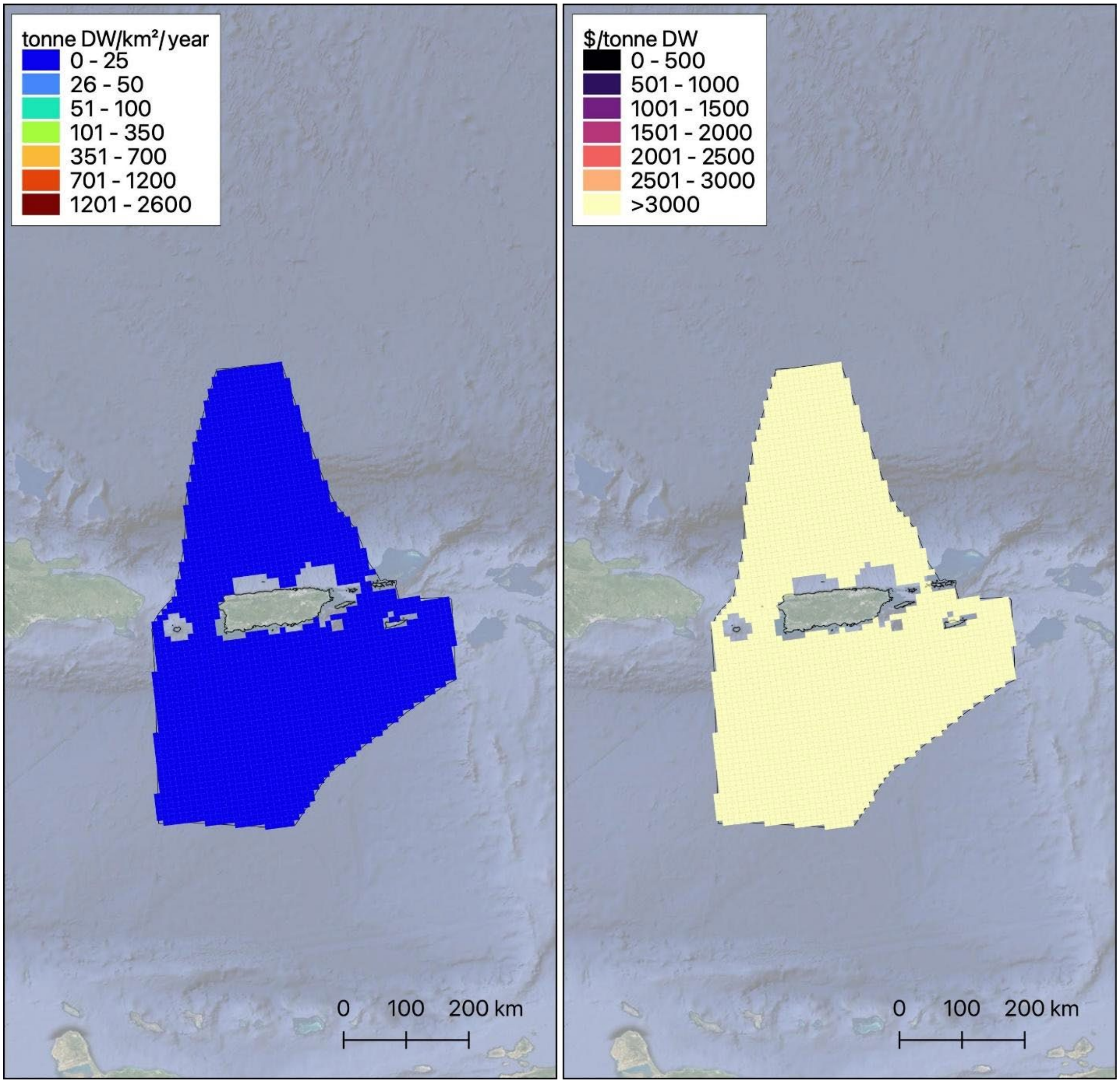

Figure E-7. Puerto Rico and the U.S. Virgin Islands coastal region biomass productivity (left) and techno-economic result (right) with marine area screening

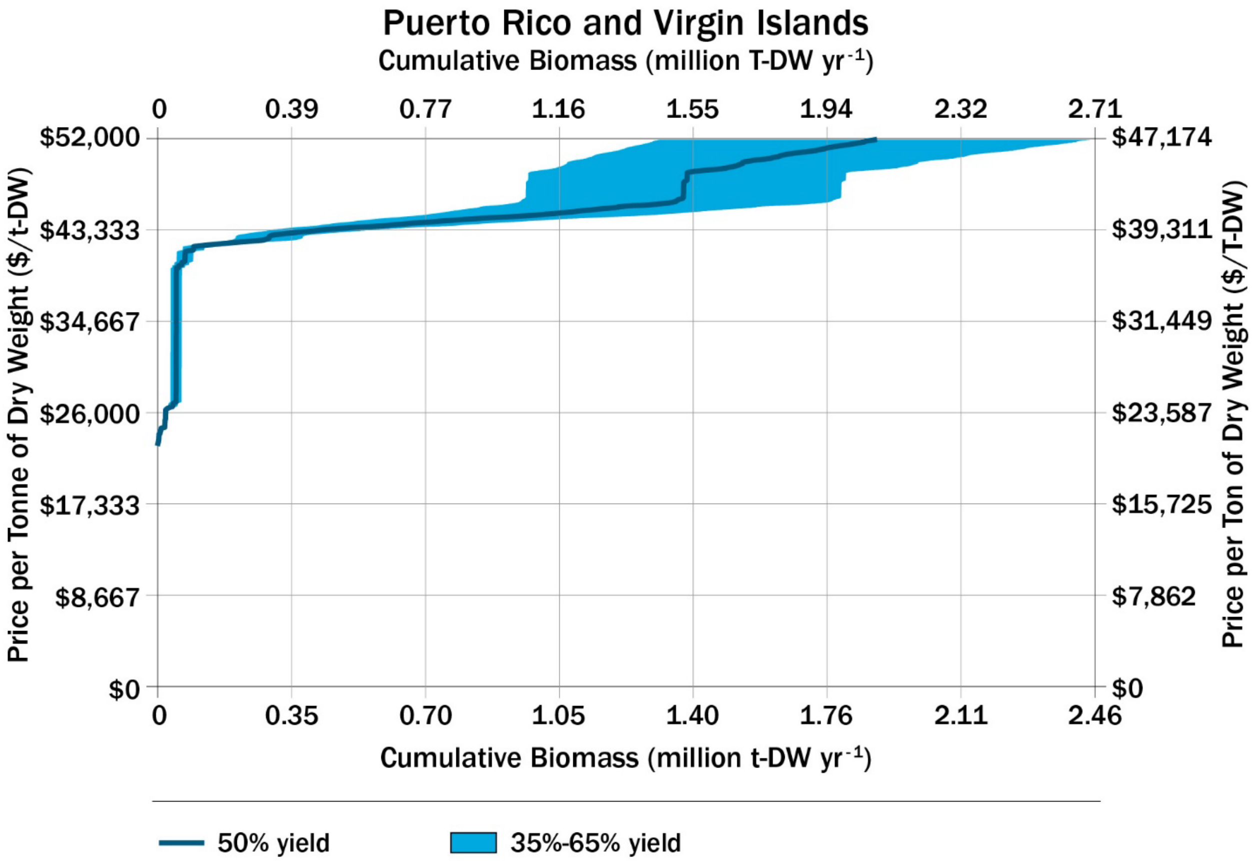

Figure E-8. Cost-supply curve of the Puerto Rico/U.S. Virgin Islands EEZ region for the representative scenario at 35%, 50%, and 65% area coverage

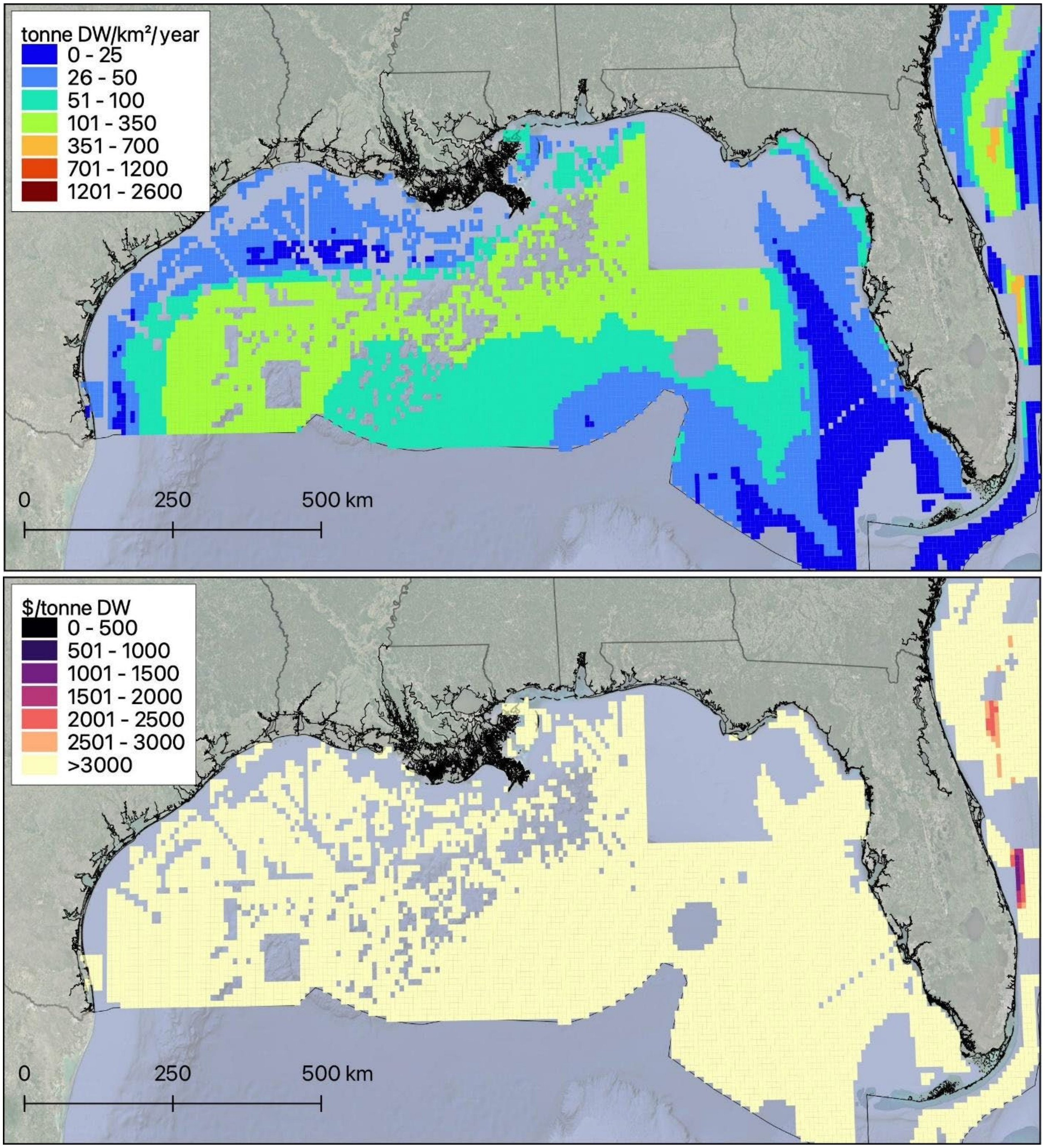

Figure E-9. Gulf of Mexico coastal region biomass productivity (top) and techno-economic result (bottom) with marine area screening

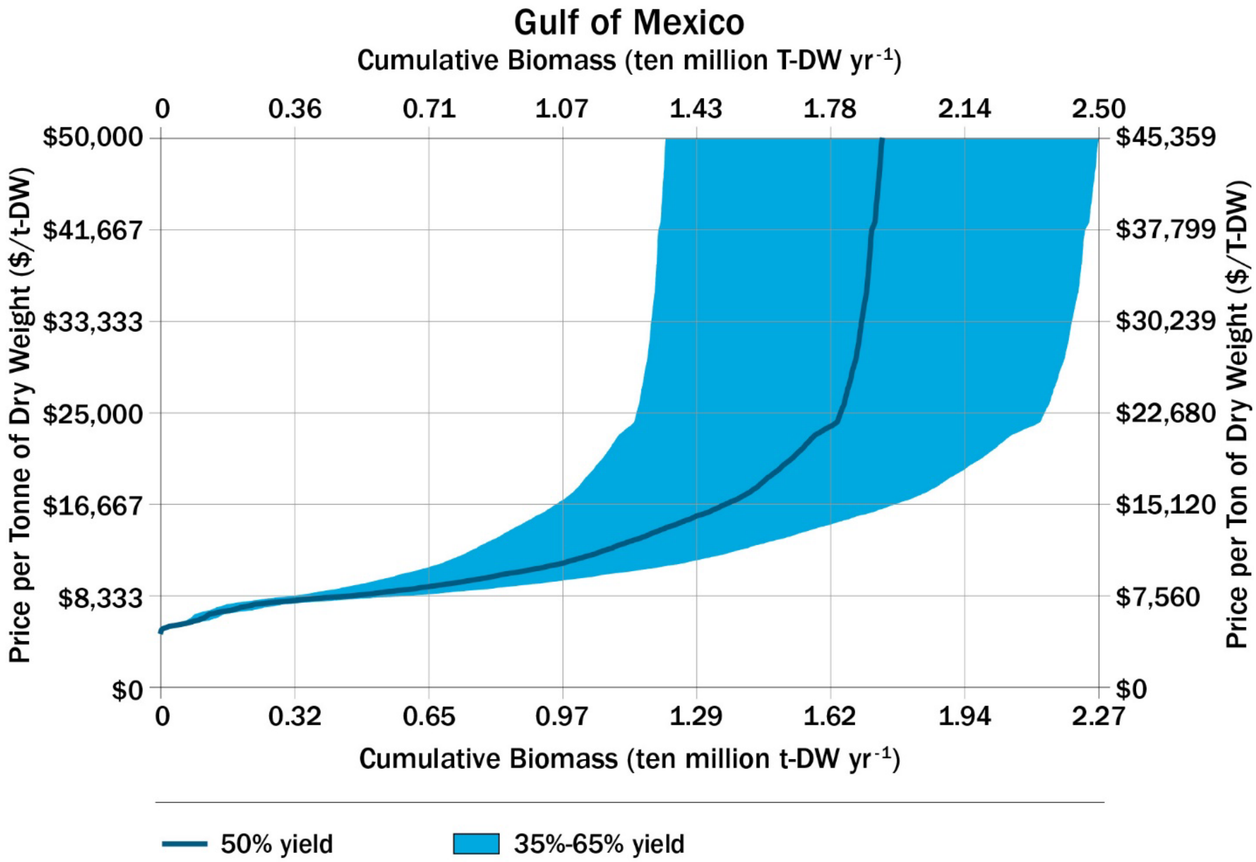

Figure E-10. Cost-supply curve of the Gulf of Mexico EEZ region for the representative scenario at 35%, 50%, and 65% area coverage

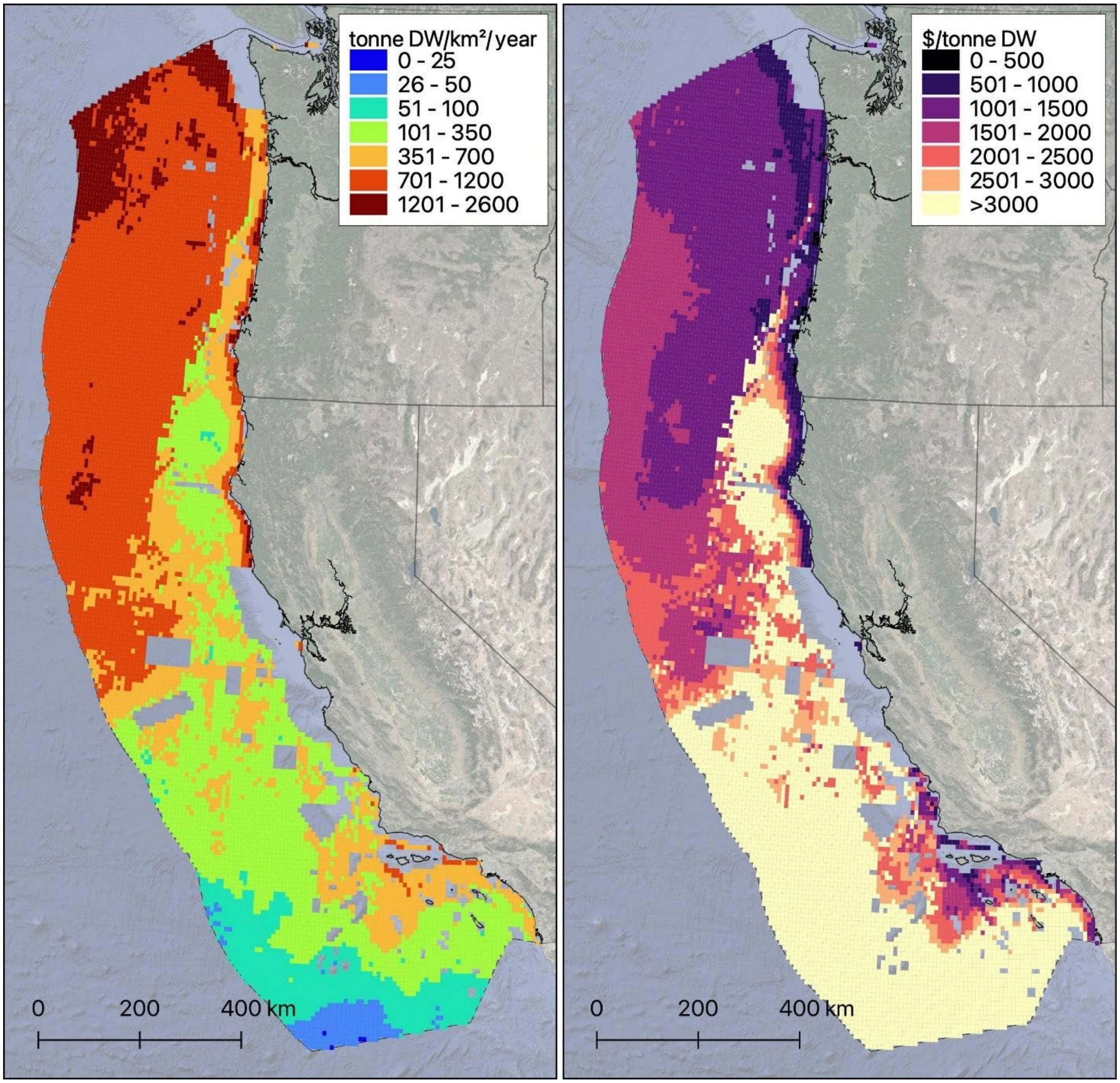

Figure E-11. Pacific coastal region biomass productivity (left) and techno-economic result (right) with marine area screening

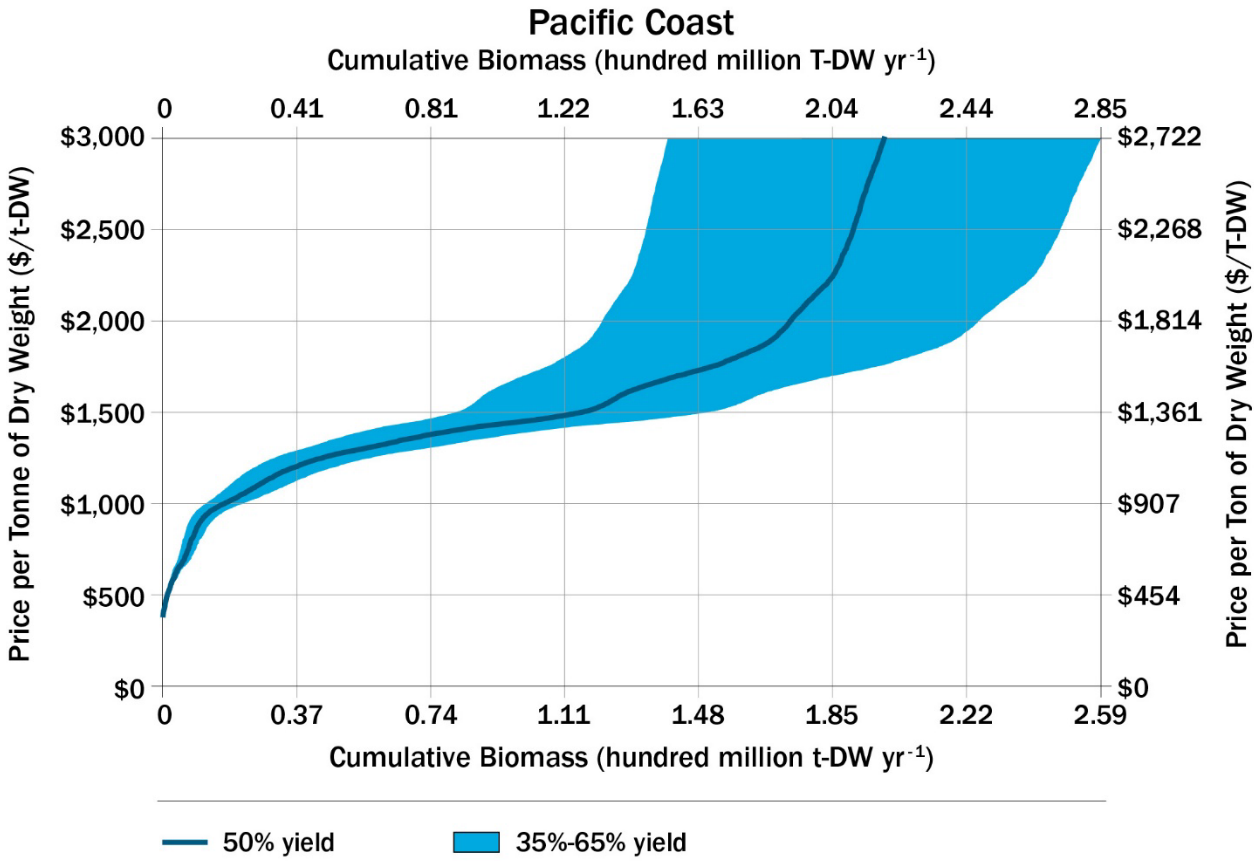

Figure E-12. Cost-supply curve of the Pacific Coast EEZ region for the representative scenario at 35%, 50%, and 65% area coverage

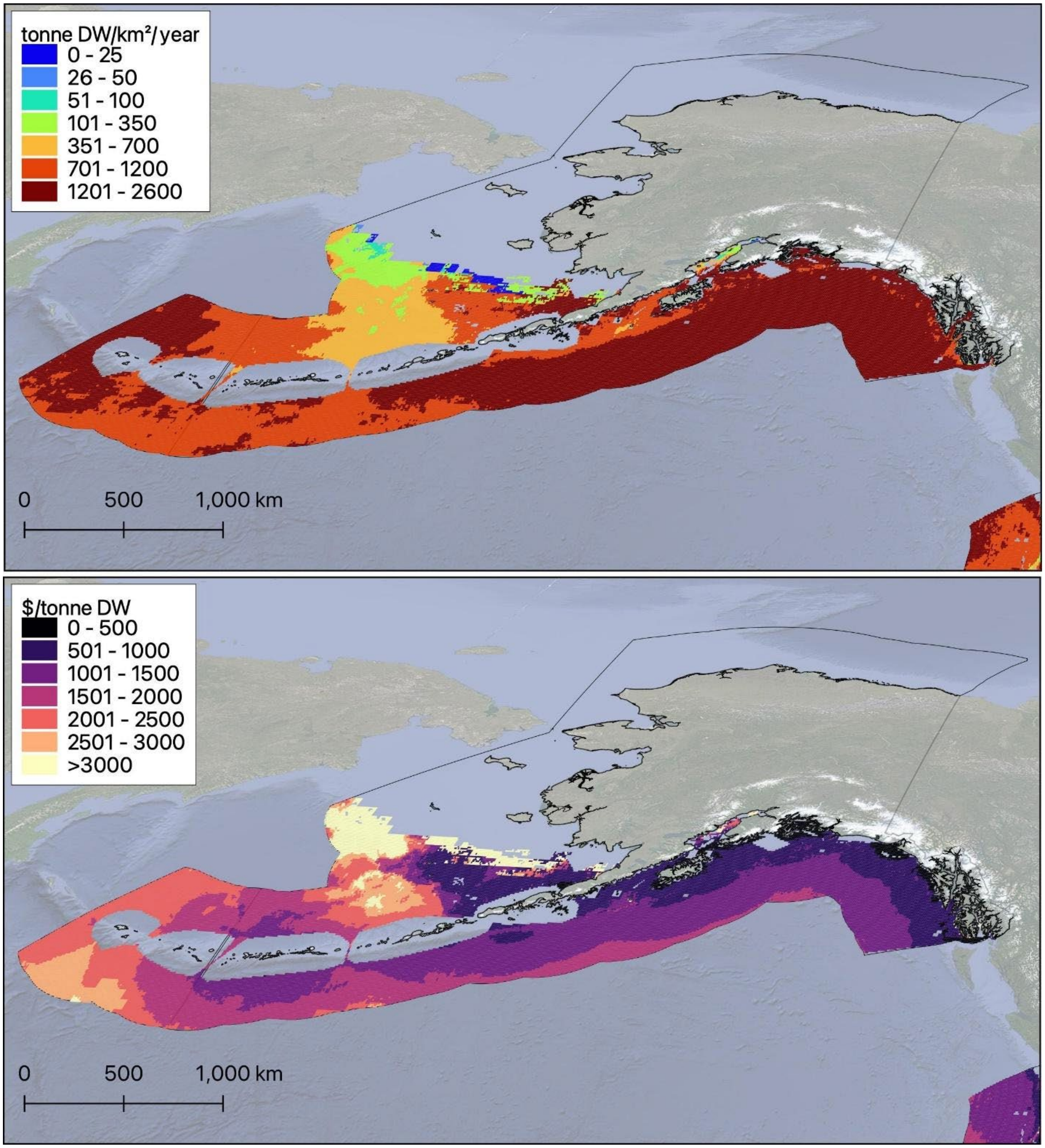

Figure E-13. Alaska coastal region biomass productivity (top) and techno-economic result (bottom) with marine area screening

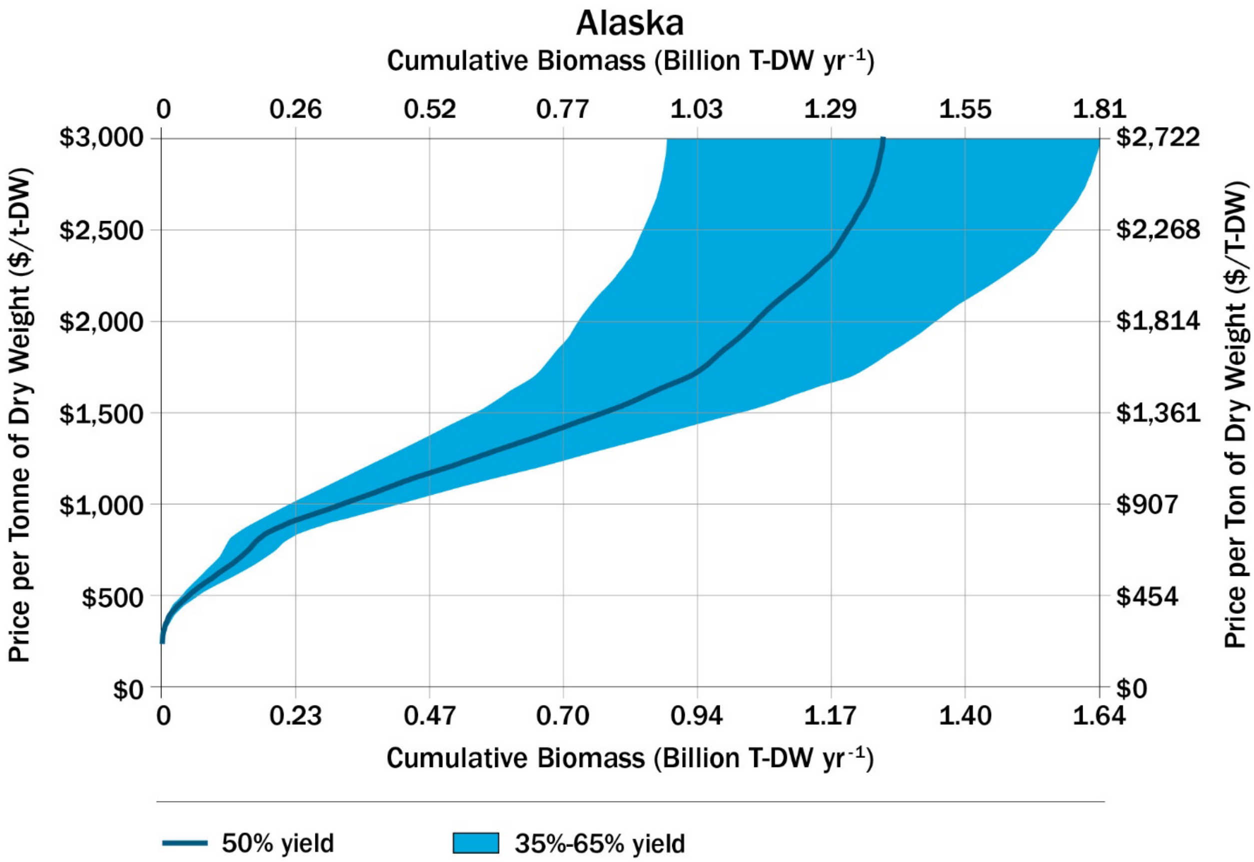

Figure E-14. Cost-supply curve of the Alaska EEZ region for the representative scenario at 35%, 50%, and 65% area coverage

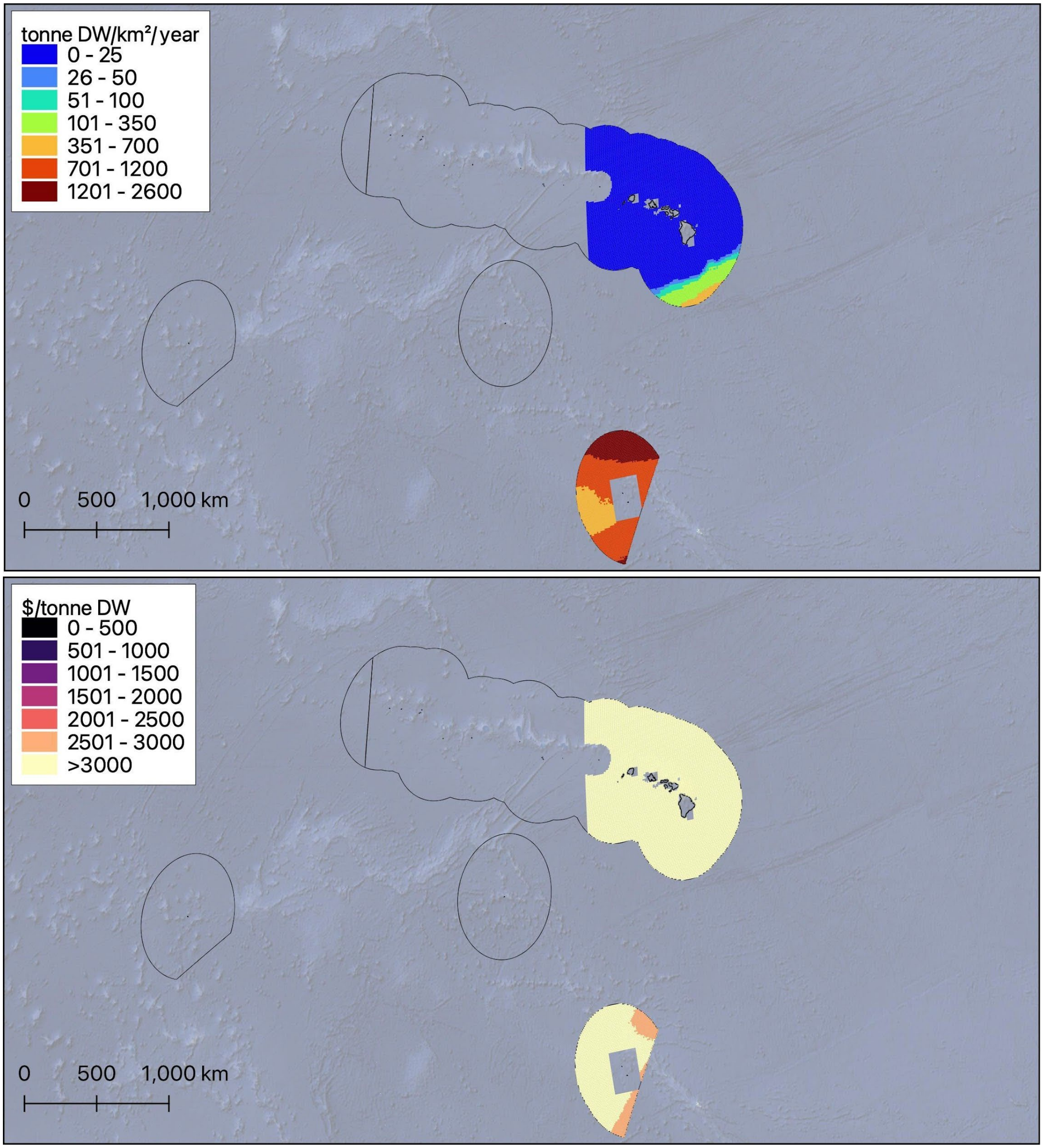

Figure E-15. Hawaiian Islands, Johnston Atoll, Wake Island, Palmyra Atoll, and Kingman Reef coastal region biomass productivity (top) and techno-economic result (bottom) with marine area screening

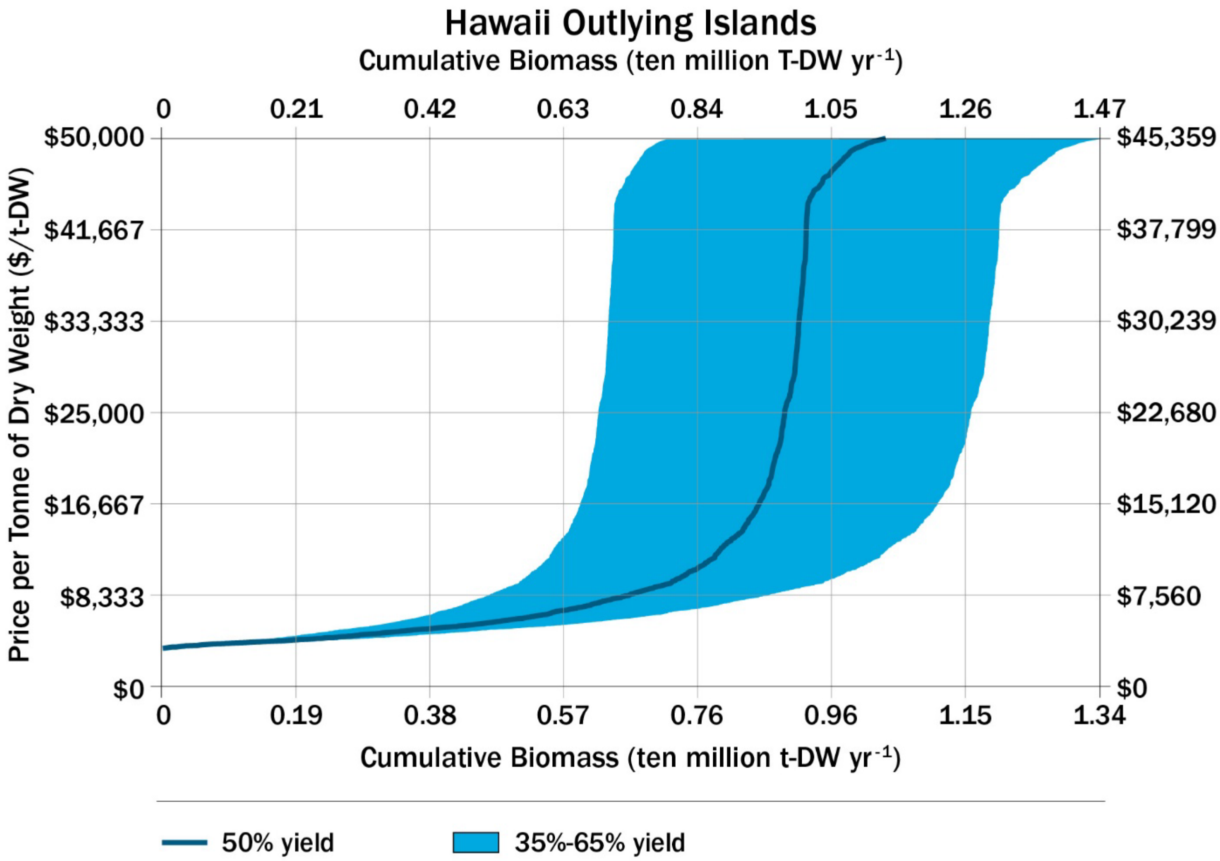

Figure E-16. Cost-supply curve of the Hawaii and outlying islands EEZ region for the representative scenario at 35%, 50%, and 65% area coverage

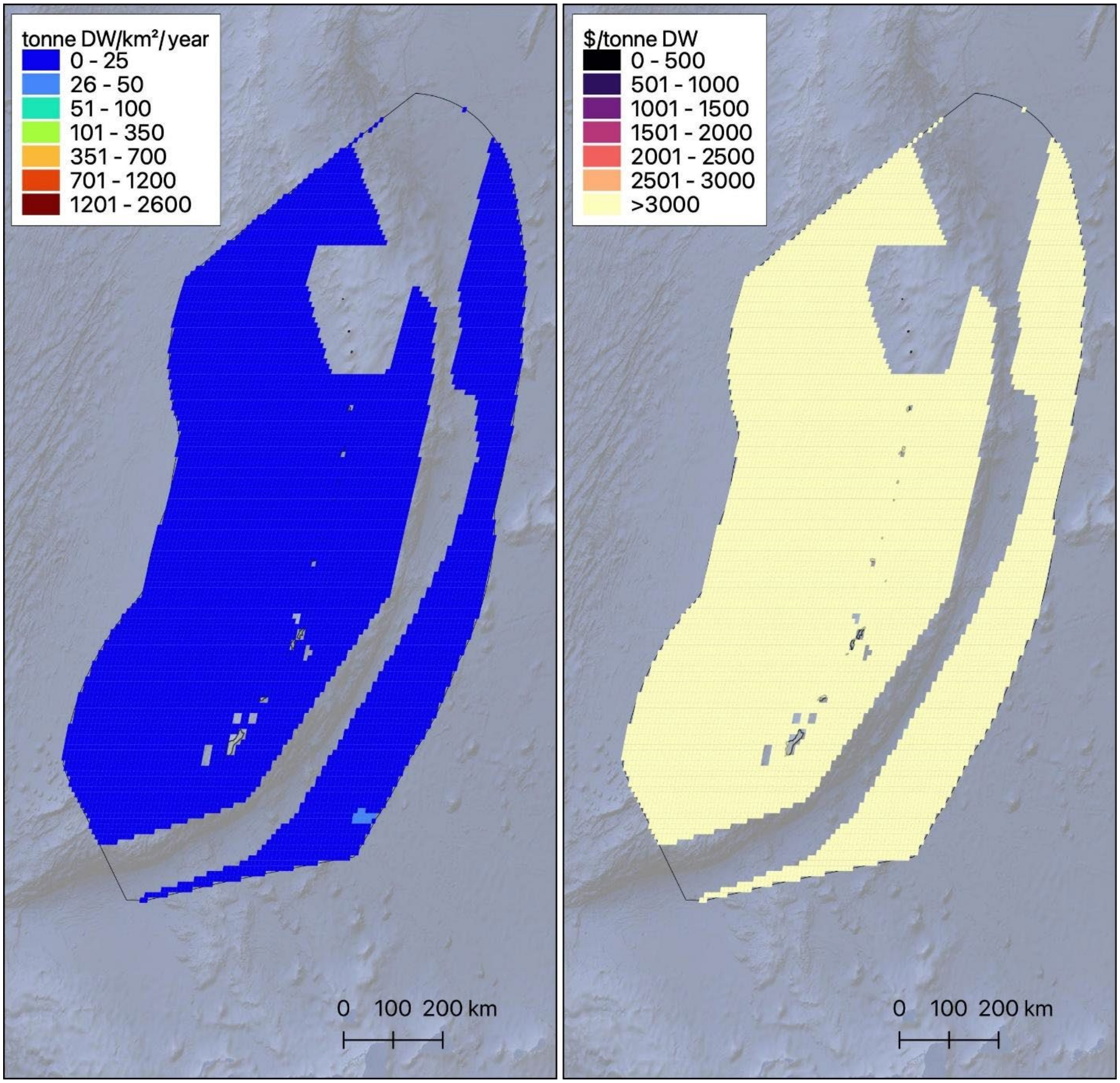

Figure E-17. Guam and the Northern Mariana Islands coastal region biomass productivity (left) and techno-economic result (right) with marine area screening

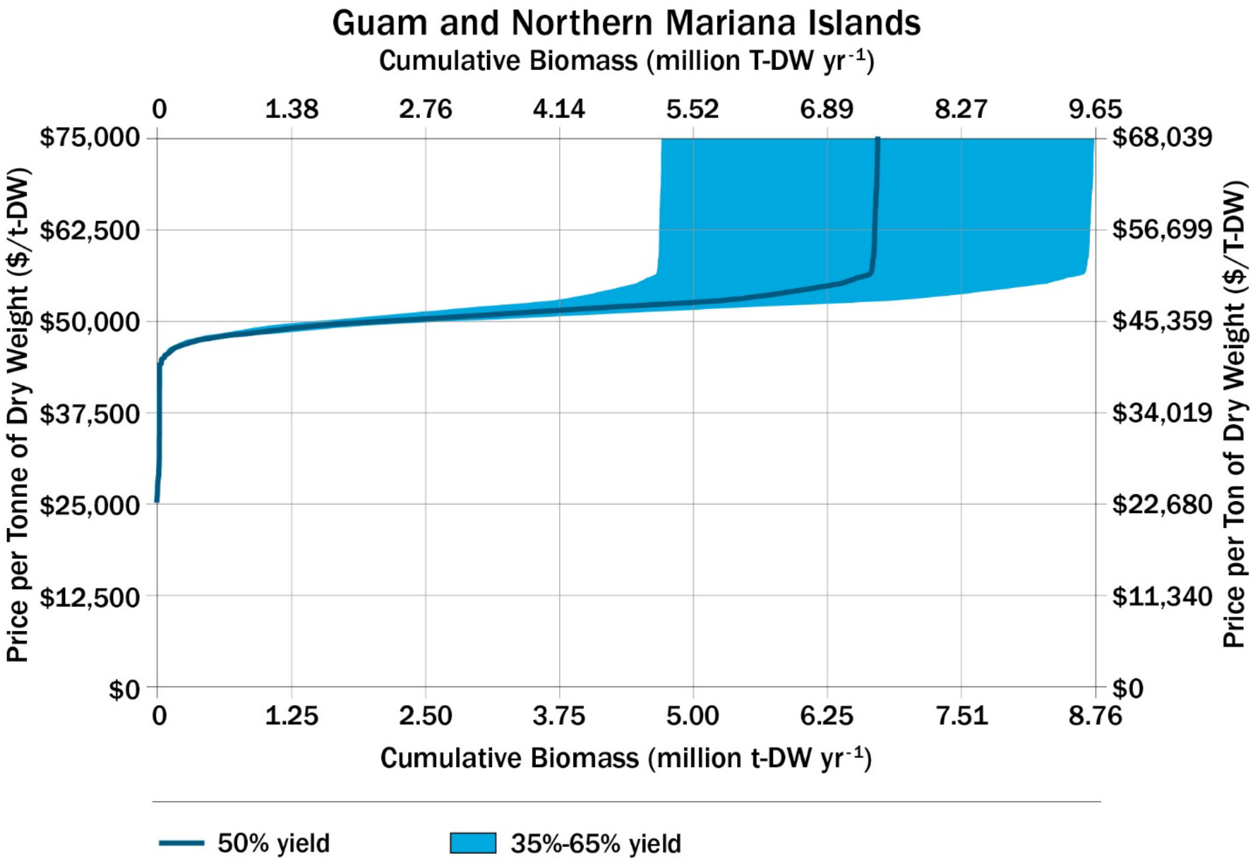

Figure E-18. Cost-supply curve of the Guam and Northern Mariana Islands EEZ region for the representative scenario at 35%, 50%, and 65% area coverage

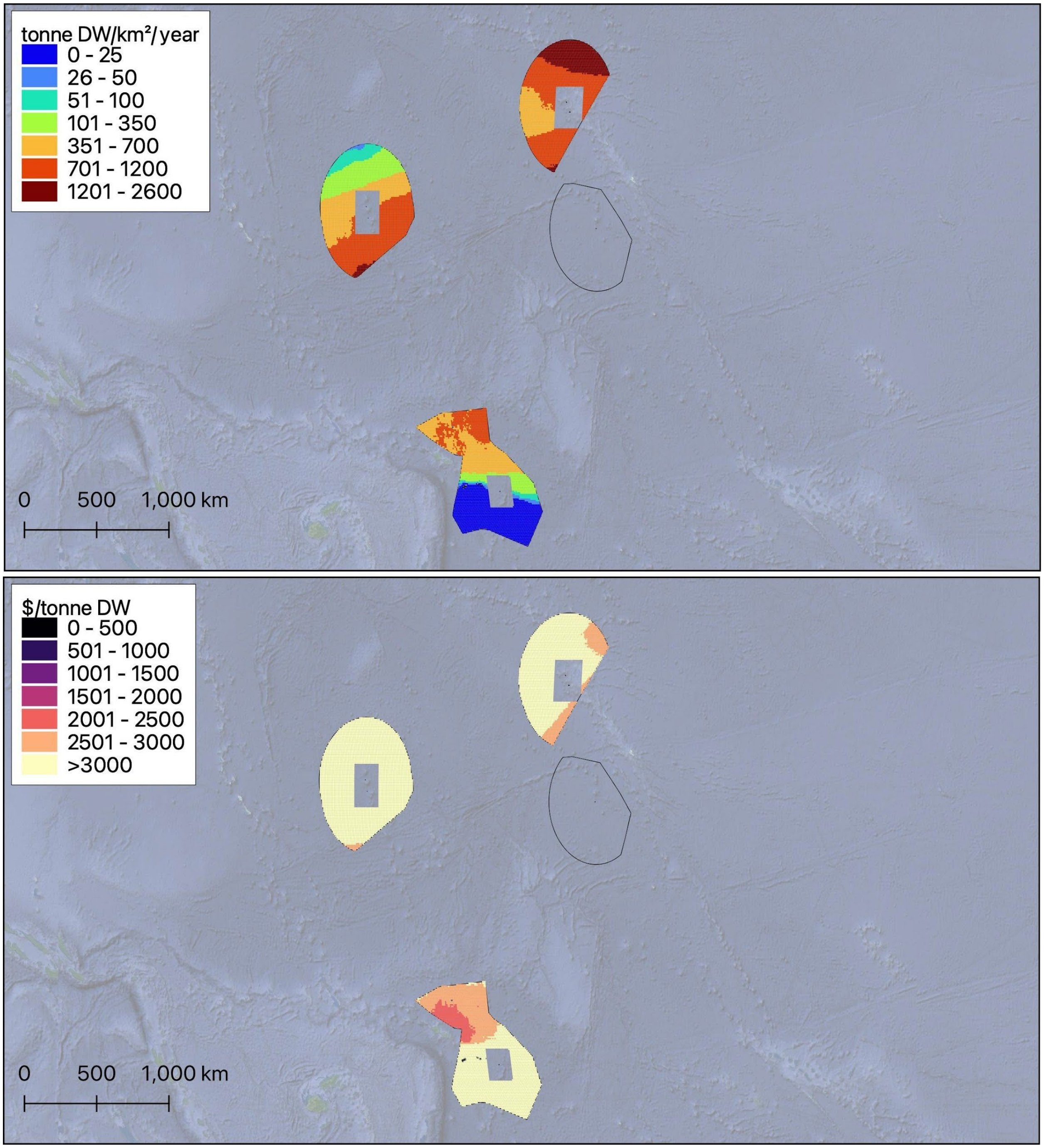

Figure E-19. Howland and Baker islands, Palmyra Atoll, Kingman Reef, Jarvis Island, and American Samoa coastal region biomass productivity (top) and techno-economic result (bottom) with marine area screening

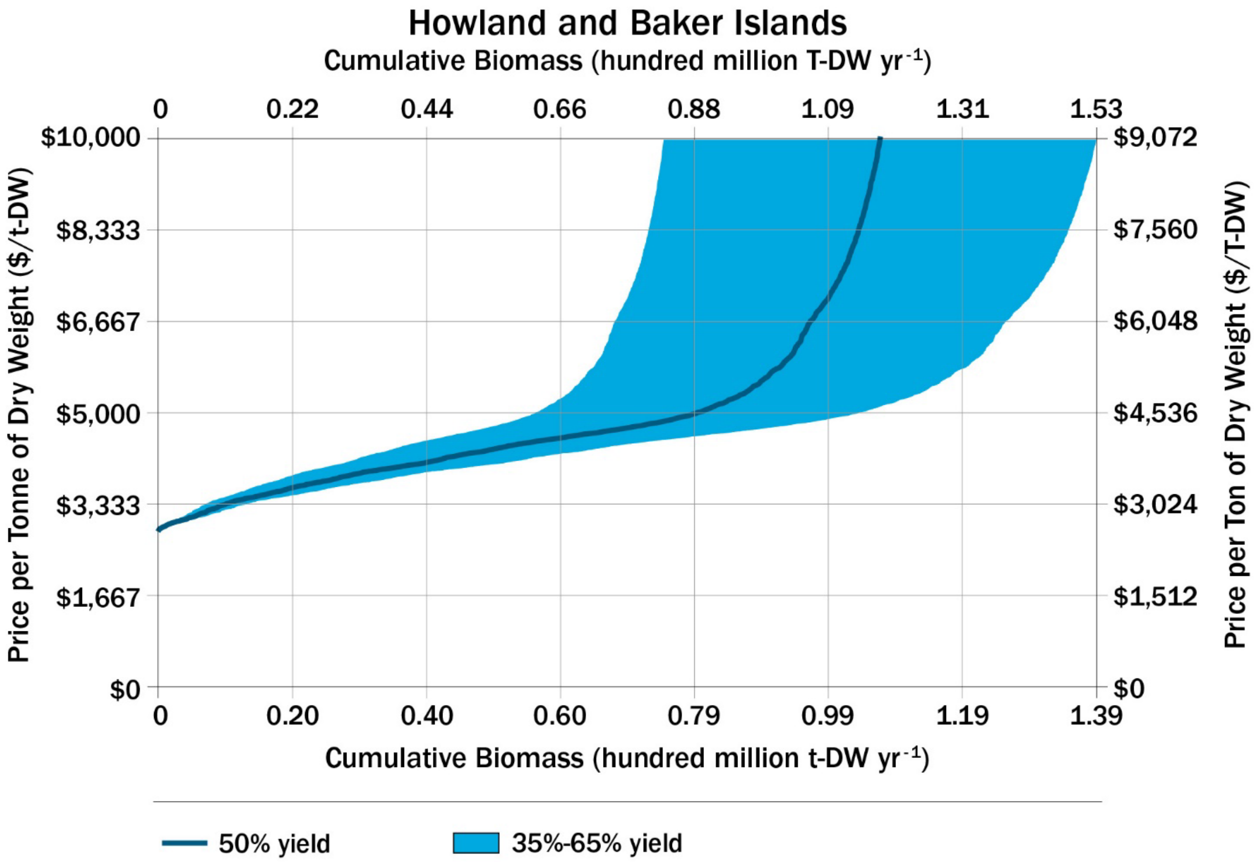

Figure E-20. Cost-supply curve of the Howland and Baker islands EEZ region for the representative scenario at 35%, 50%, and 65% area coverage

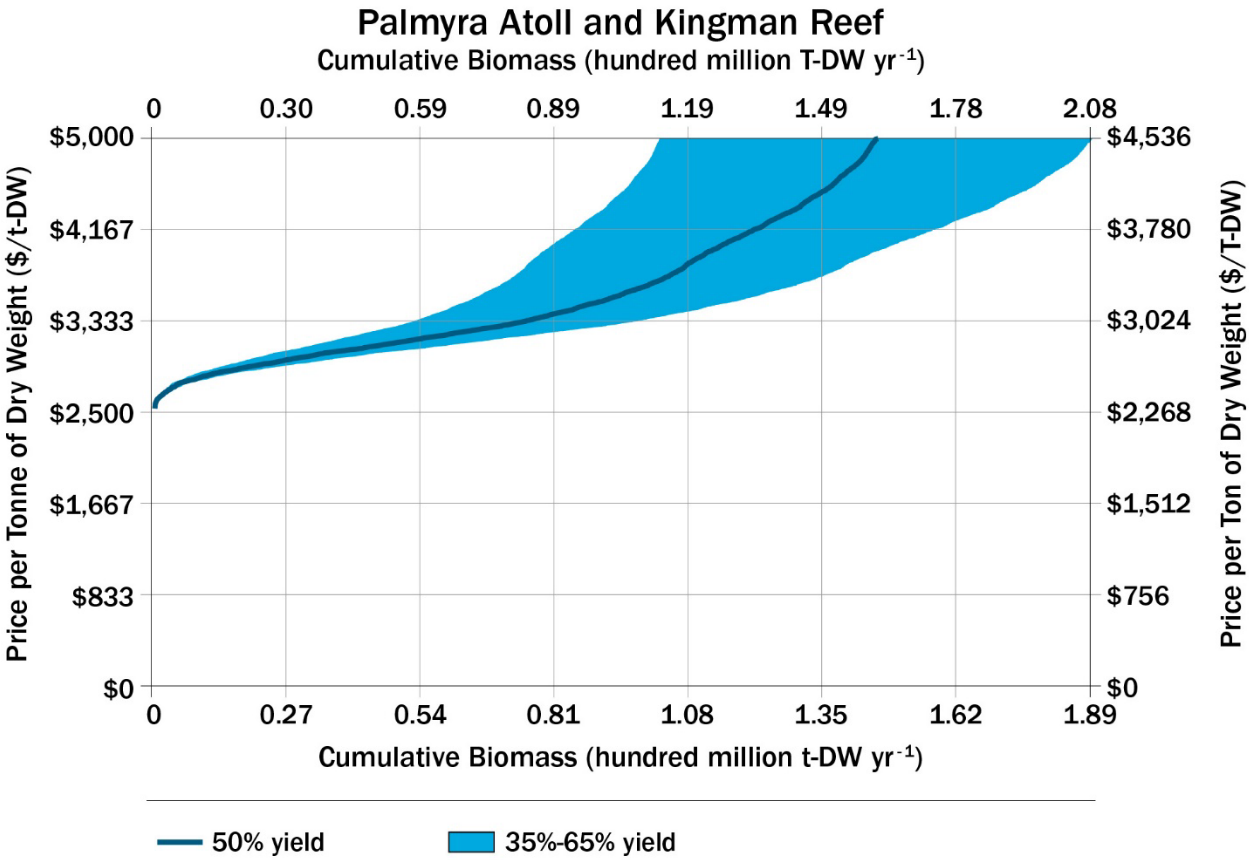

Figure E-21. Cost-supply curve of the Palmyra Atoll and Kingman Reef EEZ region for the representative scenario at 35%, 50%, and 65% area coverage

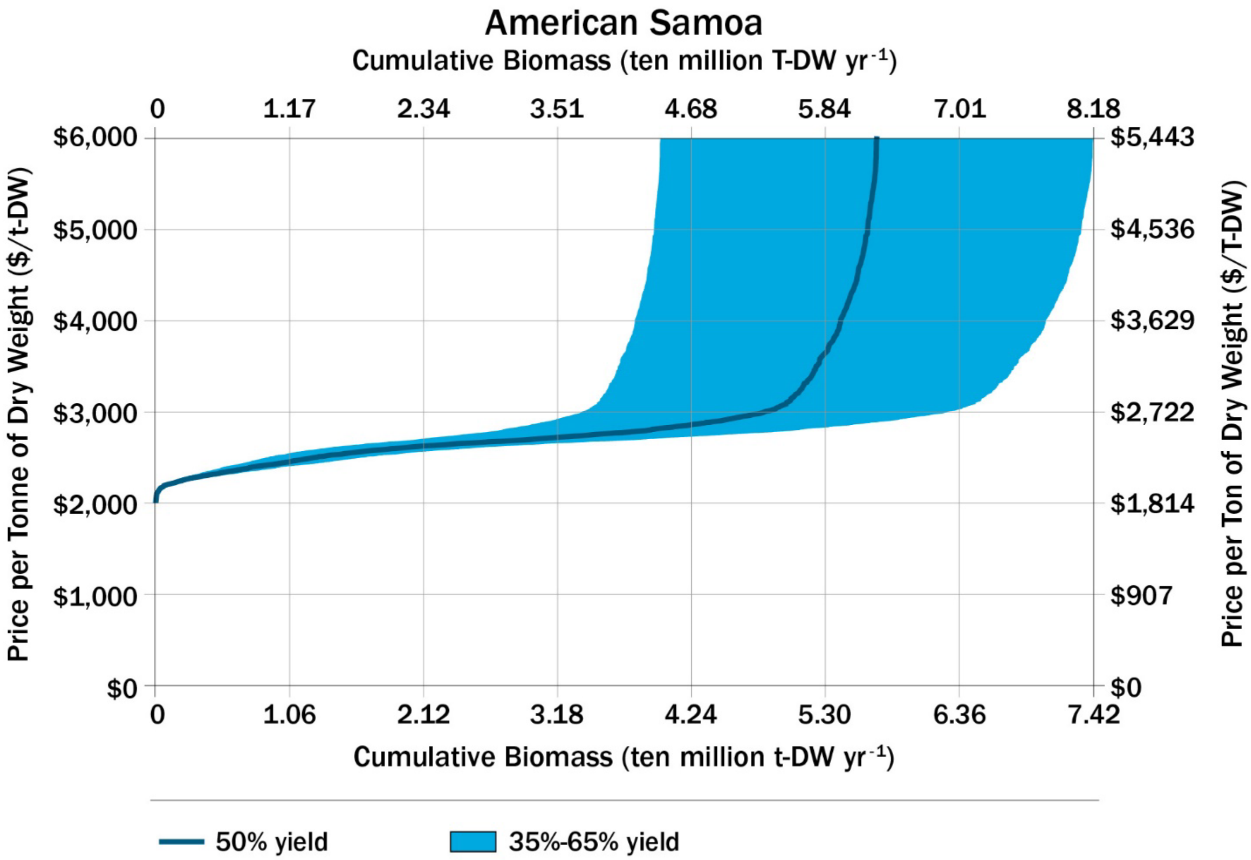

Figure E-22. Cost-supply curve of the American Samoa EEZ region for the representative scenario at 35%, 50%, and 65% area coverage