Opportunities for Ocean-Climate Action in the United States

Methodology Appendix

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Methodology Appendix

1. Offshore wind and other marine renewable energy deployment

Ocean Renewables Deployment

The mitigation potential of deployment of ocean renewables will depend on how much ocean renewables are expected to be part of future U.S. electric system portfolios.

There are a variety of projections on global and national deployment of offshore wind. Table 1 shows a selection of scenarios for offshore wind deployment from several studies and institutions. In the most bullish scenarios, offshore wind will grow to over 150 GW in the U.S. by 2050, while more moderate projections expect half that capacity. Projections for U.S. deployment of marine renewable technologies are provided in Table 2. Source descriptions are provided at the end of this appendix.

Table 1. Gigawatts of offshore wind in the U.S. in 2030 and 2050 under different scenarios

Source	Gigawatts offshore wind			
	2030		2050	
	Baseline scenarios	Clean scenarios	Baseline scenarios	Clean scenarios
GreenPeace Energy Revolution 2015 (OECD North America) (18)	5	30 - 40	20	156 - 209
DOE Wind Vision 2015 (32)[1]	0.0	21.8	0.0	85.9 - 87.3
IEA ETP 2017 (6)[2]	1	10.4	7.7	38.5 - 47.0
EIA AEO 2019 (19)	0.06	n/a	0.06	n/a
Wood Mackenzie April 2020 (20)	17	23.3 - 31.3	n/a	n/a
IRENA Future of Wind 2019 (5)	n/a	23	n/a	164
IRENA REmap for U.S. 2015 (21)	n/a	40	n/a	n/a

Table 2. Projections for marine renewable energy deployment

Source	Gigawatts marine renewable energy			
	2030		2050	
	Baseline scenarios	Clean scenarios	Baseline scenarios	Clean scenarios
GreenPeace Energy Revolution 2015 (OECD North America) (18)	1	26 - 33	4	149 - 193
IEA ETP 2017 (6)	0	9.7 - 10.4	0	28.8 - 38.5
OES MHK US Roadmap 2011 (24)	n/a	15		

[1] A lead researcher from DOE noted that, when developed in 2015, these numbers were aspirational. From today's perspective, the 2030 target may be a reach and the 2050 target may be too low.
[2] IEA's Offshore Wind Outlook 2019 says the IEA Stated Policies Scenario and Sustainable Development Scenario add 38 GW and 68 GW of offshore wind by 2040, suggesting the IEA ETP scenario for offshore wind is conservative.

Methodology

Our analysis of offshore wind mitigation potential is based on the clean energy scenarios developed for the IEA Energy Technology Perspectives (ETP) 2017,[3] U.S. Department of Energy Wind Vision 2015, and IRENA's Future of Wind 2019. Compared to the range of scenarios examined, the IEA and DOE scenarios for offshore wind and marine renewables are relatively conservative. For offshore wind, the IRENA projections are more aggressive, but certainly achievable with sufficient policy support. Thus, we believe the range of mitigation potentials for ocean renewables presented in this report provide a good indication of the opportunity.

The IEA ETP scenarios are designed to achieve major carbon reductions to limit global warming to 2 degrees Celsius. The "2DS" scenario reduces emissions to limit warming to 2 degrees Celsius, and the "B2DS" scenario limits warming to 1.75 degrees Celsius. The IEA scenarios achieve greater decarbonization in the electric sector overall than the DOE Wind Vision study, which was designed to assess the feasibility of achieving specific wind energy deployment levels. However, the Wind Vision study projects offshore wind could be a greater part of the U.S. electric system in 2030 and 2050 compared to IEA.[4]

Table 3. Average emissions factors in IEA and DOE Wind Vision scenarios

Average emissions factor (MT/GWh)		
	2030	2050
IEA ETP RTS	0.327	0.282
IEA ETP 2DS	0.233	0.011
IEA ETP B2DS	0.232	-0.031
Wind Vision Base	0.475	0.369
Wind Vision Central	0.461	0.282
Wind Vision High	0.461	0.277

For MRE, we rely solely on IEA scenarios.

To assess the carbon reduction potential from OSW and MRE in the U.S. in the 2030 and 2050 study years, we use two primary methods. In "Method A," we assume that OSW/MRE's contribution to the increase in total "clean" energy and energy efficiency in the more aggressive scenario would be equivalent to OSW/MRE's contribution to total emission savings between the baseline and more aggressive scenarios. In "Method B" we calculate a weighted average emissions rate for displaced coal and natural gas in the more aggressive scenario and apply that rate to the change in OSW/MRE generation between the baseline and more aggressive scenarios. Method C and D are designed to calculate the mitigation potential associated with IRENA Future of Wind 2030 and 2050 projections for offshore wind deployment. This methodology applies a 50 percent capacity factor for offshore wind to the IRENA OSW capacity projections to calculate additional OSW generation from IEA's reference scenario. We then apply the weighted average emissions factor from displaced coal and gas (as in Method B) for Method C or the avoided emissions from offshore wind in California (low range) and Mid-Atlantic (high range) regions provided in the EPA's AVERT tool.`

Box 1: Method A

OSW % contribution to change in "clean" energy = OSW % contribution to projected emissions savings

$$\text{GHG savings} = x * (y/(a+b+c))$$

x = Change in power sector emissions total from baseline to scenario in year, as reported in scenario
y = Change in TWh OSW between reference and scenario in year
a = Change in total TWh renewables between reference and scenario in year
b = Change in total TWh other emissions free between reference and scenario in year (e.g., nuclear, gas with carbon-capture and storage)
c = Change in TWh energy efficiency, calculated as savings in total electric generation between baseline and scenario in year

[3] IEA's 2020 Offshore Wind Outlook says the IEA Stated Policies Scenario and Sustainable Development Scenario add 40 GW and 70 GW of offshore wind by 2040, suggesting the IEA ETP scenario for offshore wind is conservative.
[4] For example, Wind Vision projects an increase in solar PV capacity to 110 GW by 2050 whereas the IEA ETP projections increase solar to ~500 GW.

Box 2: Method B

Change in OSW generation offsets coal and gas emissions

$$\text{GHG savings} = [(d*f)+(e*g)]/(d+e)*z$$

d = change in coal TWh from baseline to scenario in year minus change in coal with CCS
e= change in gas TWh from baseline to scenario in year minus change in gas with CCS
f = coal emissions factor calculated from EIA average U.S. 2018 coal electric generation and emissions
g = natural gas emissions factor calculated from EIA average U.S. 2018 natural gas electric generation and emissions
z = change in OSW TWh between reference and scenario in year

Box 3: Method C

Change in OSW Generation offsets coal and gas emissions

$$\text{GHG savings} = [(d*f)+(e*g)]/(d+e)*h$$

h = change in OSW TWh between reference (IEA) and IRENA projection in year, calculated as expected change in OSW capacity * 8760 * annual capacity factor of 50%

(d, e, f, g as defined in Method B)

Box 4: Method D

Regional high/low avoided emissions from change in OSW Generation

$$\text{GHG savings} = h*i$$

i = avoided emissions factor for offshore wind, calculated from EPA AVERT tool for California (low range) and Mid Atlantic (high range)

(d, e, f, g as defined in Method B)

The results of this analysis are presented in Table 4. We note that mitigation potential for offshore wind goes down between the 2DS and B2DS IEA scenarios in 2030, despite B2DS being the more aggressive of the two scenarios, due to the fact that B2DS assumes a major increase in CCS that lowers the incremental emissions potential from offshore wind.

Table 4. Mitigation potential of ocean renewables

Mitigation		2030 Mitigation potential (Mt CO_2)		2050 Mitigation potential (Mt CO_2)	
Offshore wind deployment	IEA	**2DS**	**B2DS**	**2DS**	**B2DS**
	Method A	35.0	30.8	75.1	96.9
	Method B	27.4	37.9	81.9	106.2
	US DOE Wind Vision				
	Method A	45.8		145.1	
	Method B	48.0		171.0	
	IRENA Future of Wind				
	Method C	95.8		427.7	
	Method D	46.2 - 67.9		314.3 - 462.2	
Marine renewable energy deployment	IEA	**2DS**	**B2DS**	**2DS**	**B2DS**
	Method A	0	0	43.6	53.0
	Method B	0	0	47.5	58.0
Total potential range		**27.4 - 95.8**		**118.7 - 520.3**	

Ocean renewables

Source: IEA Energy Technology Perspectives 2017

https://webstore.iea.org/energy-technology-perspectives-2017

Description

- Projections are designed to achieve major carbon reduction goals toward 2 degree and 1.75 degree warming limits. Projections cover all generation technologies, plus energy-efficiency gains, CCS, and electrification. Not focused on any one technology. Driven by sourcing primary energy supply and solving for end-use energy consumption.

Description of scenarios

- Reference Technology Scenario (RTS): baseline based on existing energy and climate commitments by country. Doesn't achieve global climate goals, but significantly better than BAU. Energy demand continues to grow by 50 percent to 2060. Cumulative emissions grow by 1,750 GT.
- 2DS: Based on 2009 Copenhagen Accord acceptance that global temperature limit should be below 2 degrees. Scenario is consistent with 50 percent chance of limiting temperature increase to 2 degrees by 2100. Carbon neutrality in electric sector occurs near 2100.
- B2DS: Energy sector achieves carbon neutrality by 2060, limiting future temperature increases to 1.75 degrees C by 2100. Pushes deployment of clean energy technologies currently available to maximum practical limits.

Basis for projections

- Combines forecasting of known trends and "backcasting" to develop plausible pathways to a desired long-term outcome. Not predictions but analysis of how we might get there.
- All technology options currently available.
- Applies a "portfolio approach within a cost minimization framework" to avoid overreliance on any one technology.
- ETP Model starts with primary energy source and runs conversion and solves for demand across sectors and region. Supply model is supplemented with linear dispatch model and can add storage or flexible gen or DR from other sectors for enhanced reliability.

Note on estimates based on this source

- Because projections to 2030 and 2050 Reference Technology Scenario assume active steps toward carbon mitigation (better than BAU), using this as a baseline scenario may underestimate benefit of OSW when comparing growth from reference to the 2DS and BSDS scenarios.
- IEA's 2DS and B2DS scenarios rely heavily on carbon capture and storage of natural gas and coal facilities. If this strategy is not successful, actual emissions in the study years may be much higher, or a much greater quantity of renewables may be needed to balance the electric system.
- Generally, estimates based on this source seem relatively conservative. Since this 2017 ETP, IEA's 2019 Offshore Wind Outlook projects 2x more offshore wind globally by 2050 than the 2017 ETP did. If the portion of offshore wind deployment expected to occur in the U.S. remains the same and is applied to this higher 2019 OSW Outlook Projection for global deployment, we could expect nearly 2x the OSW included in the 2050 BSDS scenario for the U.S. (90 GW, rather than 47).
- B2DS: globally 74 percent generation from renewables, 15 percent nuclear, 7 percent fossil with CCS, remainder natural gas. Bioenergy with CCS delivers 5 GT of negative emissions in 2060.

Source: US DOE Wind Vision

https://www.energy.gov/eere/wind/wind-vision; https://openei.org/apps/wv_viewer/

Description/purpose: Evaluate future pathways for the wind industry to contribute to U.S. clean, reliable electric system and related economic and societal benefits. Includes both onshore and offshore wind.

Models three core scenarios:

- Baseline: Assumes no growth from 60 GW land-based wind and 0 GW offshore wind from 2014 (study year).
- Study scenario: Examines current manufacturing capacity and applies projections on wind power costs, fossil fuel costs, energy demand. "The resulting Study Scenario—10% by 2020, 20% by 2030, and 35% by 2050 wind energy as a share of national end-use electricity demand—is "An ambitious but viable study scenario" that could be cost effective and reliable and supported by the supply chain."

Basis for projections

- Looked at feasability and pathways for getting to 20 percent wind by 2030 and 35 percent wind by 2050 (ended at ~32 percent wind by 2050).

Key assumptions and factors in projections

- Appears to adjust supply mix by adjusting coal and natural gas downward and adjusting wind up, without other major changes to supply portfolio.
- Does look at state-level deployment and assumes OSW will be deployed in all coastal states plus 1.1 GW in Great Lakes states.
- Unclear whether the resulting portfolios were run through a dispatch model to test reliability or simply solved for expected demand.

Source: EIA Annual Energy Outlook

https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581(2018).pdf

Description

Utilizes EIA's national energy modeling system. "The Electricity Market Module (EMM) represents the capacity planning, generation, transmission, and pricing of electricity, subject to delivered prices for coal, petroleum products, natural gas, and biomass; the cost of centralized generation facilities; macroeconomic variables for costs of capital and domestic investment; and electricity load shapes and demand."

Basis for projections

- Technologies are compared on the basis of total capital and operating costs incurred during a 30-year period. As new technologies become available, they compete against conventional plant types. Fossil fuel, nuclear, and renewable generating technologies are represented as listed in Table 3. Base overnight capital costs are assumed to be the current cost per kilowatt for a unit constructed today.
- Because EIA is policy-neutral, AEO projections are generally based on federal, state, and local laws and regulations in effect at the time of the projection. The potential impacts of pending or proposed legislation, regulations, and standards are not reflected in the system.
- Assumes U.S. still has 150 GW of coal and nearly 500 GW of CCGT in 2050 (down from 227 in 2020). Natural gas increase from ~250 GW in 2020. Renewables grow from ~240 GW in 2020 to ~500 GW in 2050. Renewable growth overall is modest from ~200 GW to 450 GW in 2050. Electric power system emissions decrease by only 65 million tons total, from 2020 to 2050 in the reference case. By comparison, the IEA ETP's projected reference case has 700 GW of renewables in 2050 and the more aggressive scenarios have 1,200 -1,400 GW of renewables.
- OSW projection is highly conservative, assuming only 60 GW of OSW and zero growth in OSW after 2021.

Source: GreenPeace Energy Revolution, 2015

https://storage.googleapis.com/planet4-canada-stateless/2018/06/Energy-Revolution-2015-Full.pdf

Description

The Energy [R]evolution scenario series follows a "seven-step logic," which stretches from the evaluation of natural resource limits to key drivers for energy demand and energy-efficiency potentials, an analysis of available technologies and their market development potential, and specific policy measures required to implement a theoretical concept on real markets.

Basis for projections

- The energy [r]evolution scenario (e[r]) is an update of the energy [r]evolution scenario published in 2012, which followed the key target to reduce worldwide carbon dioxide emissions from energy use to a level of around 4 gigatonnes per year by 2050 in order to hold the increase in global temperature under 2°C.
- The new advanced energy [r]evolution scenario (adv e[r]) needs much stronger efforts to transform the energy systems of all world regions toward a 100 percent renewable energy supply.
- Offshore wind projections are for OECD North America, which includes Canada, the U.S., and Mexico, and they thus overestimate deployment for the U.S. alone.
- Wind energy—including offshore and onshore—grows to 32 percent of electricity share by 2050 in the advanced energy [r]evolution scenario.

Source: Wood Mackenzie April 2020

https://www.woodmac.com/reports/power-markets-us-offshore-wind-market-outlook-2020-2029-413861

Description

An independent assessment of the offshore wind market in the U.S.

Basis for projections

- Base scenario looks at current development based on development potential in areas under lease through BOEM auctions.
- Bull scenario based on expanding state RPS carveouts and contracting.

Source: IRENA Future of Wind

https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf

Description

- "Irena has explored two energy development pathways to the year 2050 as part of the 2019 edition of its global energy transformation report. The first is an energy pathway set by current and planned policies (Reference Case). The second is a cleaner climate-resilient pathway based largely on more ambitious, yet achievable, uptake of renewable energy and energy efficiency measures (REmap Case) which limits the rise in global temperature to well below 2 degrees and closer to 1.5 degrees above pre-industrial levels and is aligned within the envelope of scenarios presented in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C."
- The REmap Case sets a pathway to achieve a renewables share of 86 percent in the power generation mix by 2050.

Basis for projections

- Wind power would supply more than one-third of total electricity demand by 2050 in the REmap case.
- Wind power would contribute to 6.3 Gt of CO_2 emissions reductions in 2050, representing 27 percent of the overall emissions reductions needed to meet Paris climate goals.
- For offshore wind power, the global cumulative installed capacity would increase almost tenfold by 2030 (to 228 GW) and nearing 1,000 GW by 2050.
- The LCOE of offshore wind would drop from an average of $0.13/kWh in 2018 to an average between $0.05 to 0.09/kWh by 2030 and $ 0.03 to 0.07/kWh by 2050.
- Wind—offshore and onshore—grows to 35 percent of global generation share in the REMAP case.

Source: IRENA REmap for U.S., 2015

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_REmap_USA_report_2015.pdf?la=en&hash=AF59FC4E6EDCF241F5AF7CC74E9087A154AA3C6A

Description

- "REmap 2030, a global roadmap by the International Renewable Energy Agency (IRENA), looks at the realistic potential for higher renewable energy uptake in all parts of the US energy system, including power, industry, buildings, and the transport sectors. It also provides an overview of how higher shares of renewable energy can be achieved, what the technology mix would entail, and the benefits of renewable energy deployment."

Basis for projections

- The REmap case for the U.S. increases renewable energy share to 27 percent by 2030 from the reference case, in which renewable share only increases to 14 percent.

Source: Ocean Renewable Energy Coalition, "U.S. Marine and Hydrokinetic Renewable Energy Roadmap." Ocean Renewable Energy Coalition, November 2011.

http://www.policyandinnovationedinburgh.org/uploads/3/1/4/1/31417803/mhk-roadmap-executive-summary-final-november-2011.pdf

Description

Trade association goal, set in 2011 for 2030

Basis for projections

A goal achievable through the commercialization path set forth in the trade association roadmap.

Coastal "blue carbon" ecosystem protection, restoration, and cultivation

1. Mangroves

a. Mangrove conservation model

i. Areal extent of 2,551 km^2 is based on the most recent published data from the U.S. Gulf of Mexico (Thorhaug et al. 2019), and is higher than the 1,553 km^2 estimate of Hamilton and Casey (2016) but similar to the 2,350 km^2 estimate from Global Mangrove Alliance (2020).

ii. Rate of mangrove areal decline (0.27%/yr^{-1}) was based on the estimated 3.66 percent loss from 2000 to 2014 (Hamilton and Casey 2016).

iii. Mangrove carbon stock of 645 Mg C ha^{-1} was based on Atwood et al. (2017), assuming the ratio of 4.4 Gt of total stock to 2.6 Gt of soil stock to calculate living biomass portion from soil carbon (381 Mg C ha^{-1}). This value is significantly higher than the global mean of 407 Mg C ha^{-1} (Pendleton et al. 2012).

iv. Remineralization rates of carbon stock was assumed to be 66 percent, based on the assumption that 43 percent of soil carbon is remineralized (Atwood et al. 2017), and adjusting for an additional assumption that 100 percent of living biomass is remineralized too.

v. Mangrove carbon burial rate (92.4 g C /m^2) is based on mean burial rates measured in Florida (Marchio et al. 2016), and significantly lower than the global estimate of 226 g C /m^2 (Mcleod et al. 2011).

b. Mangrove restoration model

i. Assumes full restoration of 204 km^2 (Worthington and Spalding 2018) by 2050.

1. This requires 680 ha to be restored annually starting in 2021.
2. At a realistic project size of 1 ha yr^{-1} (Bayraktarov et al. 2016), that would require implementing 680 projects per year for 30 years.
3. At a median cost of mangrove restoration of \$38,700 ha^{-1} yr^{-1} (Bayraktarov et al. 2016), that would cost a total of \$790 million.

ii. Assumes restored area has the same carbon drawdown as the historic mangrove (92.4 gC/m^2).

iii. Carbon drawdown potential is scaled by an observed a 64 percent success rate of restoration efforts (Bayraktarov et al. 2016).

2. Saltmarsh

a. Saltmarsh conservation model

i. Areal extent of 18,200 km^2 is based on Holmquist et al. (2018).

ii. Rate of saltmarsh areal decline (0.541%/yr^{-1}) was estimated based on data presented in Holmquist et al. (2018), with approximately 500 km^2 saltmarsh converted to open water between 2006 and 2011.

iii. Carbon stock of 206 Mg C ha^{-1} was based on U.S. Gulf of Mexico saltmarshes only (Thorhaug et al. 2019), and is slightly lower than the global mean of 259 Mg C ha^{-1} (Pendleton et al. 2012).

iv. As most lost area is converted to open water (Holmquist et al. 2018), remineralization rates of carbon stock was assumed to be 100 percent (Pendleton et al. 2012).

v. Saltmarsh carbon burial rate (121 g C /m^2) is based on data presented by Holmquist et al. (Holmquist et al. 2018), and significantly lower than the global estimate of 218 g C /m^2 (Mcleod et al. 2011).

b. Saltmarsh restoration model

i. Assumes full restoration of 644 km^2, based on the summed annual losses from 1986 to 2009 (U.S. Fish and Wildlife Service 2013), by 2050.

1. This requires 2,146.67 ha to be restored annually starting in 2021.
2. At a realistic project size of 0.18 ha yr^{-1} (Bayraktarov et al. 2016), that would require implementing nearly 12,000 projects per year for 30 years. Alternatively, at an ambitious project size of 2,666 ha yr^{-1} (Bayraktarov et al. 2016), that would require implementing < 1 project per year for 30 years.
3. At a median cost of saltmarsh restoration of \$55,540 ha^{-1} yr^{-1} (Bayraktarov et al. 2016), that would cost a total of \$3.6 billion.

ii. Assumes restored area has the same carbon drawdown as the historic saltmarsh (121 gC/m^2).

iii. Carbon drawdown potential is scaled by an observed a 55 percent success rate of restoration efforts (Bayraktarov et al. 2016).

3. Seagrass

a. Seagrass conservation model

i. Areal extent of 14,422 km^2 includes data from the following ecoregions: temperate North Atlantic, tropical Atlantic, temperate North Pacific, and tropical Indo-Pacific (Hawaii) (McKenzie et al. 2020). The majority of seagrass (12,769 km^2) is located in the tropical North Atlantic ecoregion (McKenzie et al. 2020), with 9,473 km^2 located in the U.S. Gulf of Mexico (Thorhaug et al. 2019).

ii. Rate of seagrass areal decline (1.24%/yr-1) were averaged from available U.S. timeseries (*N*=114), with measurements starting in the period 1879-2001, and ending in the period 1969-2006 (Waycott et al. 2009). A total of 33 percent of seagrass area (3,131 km^2) was lost during these observation periods (*N*=128; Waycott et al. 2009).

iii. Seagrass carbon stock estimates vary, with both 170 and 152 Mg C ha^{-1} based on U.S. Gulf of Mexico data only (Thorhaug et al. 2019; Fourqurean et al. 2012). Global estimates for carbon stock in seagrass meadows is 142 Mg C ha^{-1} (Pendleton et al. 2012). As a locally relevant intermediate estimate, 152 Mg C ha^{-1} (Fourqurean et al. 2012) was used in the model.

iv. Remineralization rates of carbon stock was assumed to be 62.5 percent, as an intermediate assumption from Pendleton et al. (2012).

v. The global estimates of seagrass meadow carbon burial rate of 119 g C /m^2 was used (Duarte et al. 2010), and this introduces uncertainty to the annual U.S. carbon burial estimate.

b. Seagrass restoration model

i. Assumes full restoration of the documented 3,131 km^2 of known seagrass lost (Waycott et al. 2009), by 2050.

   1. This requires 10,437 ha to be restored annually starting in 2021.
   2. At a realistic project size of 1 ha yr^{-1} (Bayraktarov et al. 2016), that would require implementing 10,437 projects per year for 30 years. Alternatively, at a project size of 5 ha yr^{-1} (Bayraktarov et al. 2016), that would require implementing 2,087 projects per year for 30 years.
   3. At a median cost of seagrass restoration of \$100,526 ha^{-1} yr^{-1} (Bayraktarov et al. 2016), that would cost a total of more than \$31 billion.

ii. Assumes restored area has the same carbon drawdown as the historic seagrass meadow (119 gC/m^2).

iii. Carbon drawdown potential is scaled by an observed a 41 percent success rate of restoration efforts (Bayraktarov et al. 2016).

4. Seaweed

a. Seaweed conservation model

i. There is no central database for seaweed cover. However, there are estimates for seaweed with floating canopy, such as giant kelp. Kelps are also used in seaweed farming and are the fastest growing seaweed, so the modeling is focused on kelp (brown algae). Giant kelp areal extent is 1,352 km2 (Mora-Soto et al. 2020).

ii. Rate of kelp decline (1.16%/yr^{-1}) was estimated by extracting proportional changes reported in various U.S. ecoregions (Krumhansl et al. 2016).

iii. Kelps do not trap carbon in soils where they grow; carbon stock is based on live biomass only. Biomass carbon stock was estimated from California kelp beds with biomass density of 4.24 dry kg/m^2 (Cavanaugh et al. 2010) with a 28 percent carbon content (Stewart et al. 2009), resulting in a live carbon stock of 11.9 Mg C ha^{-1}.

iv. Remineralization rates of live carbon stock was assumed to be 89.2 percent, based on the estimate that 10.8 percent of seaweed primary production is sequestered (Krause-Jensen and Duarte 2016).

v. Kelp carbon burial rate was estimated to be 1.28 g C/m^2, based on the assumption that 10.8 percent of seaweed primary production is sequestered (Krause-Jensen and Duarte 2016).

b. Seaweed restoration model

i. Assumes full restoration of 351 km^2 of kelp lost by 2050. This area is based on hindcasting the loss rate of 1.16%/yr^{-1} (Krumhansl et al. 2016) for the past 20 years and using present-day areal extent (Mora-Soto et al. 2020). This requires 1,169 ha to be restored annually starting in 2021.

ii. Assumes restored area has the same kelp density, and so same carbon burial rate, as undisturbed forests.

iii. Carbon drawdown potential is scaled by a hypothetical 53 percent success rate of restoration efforts, as determined by the mean restoration success rates of mangrove, saltmarsh, and seagrass (Bayraktarov et al. 2016).

c. Seaweed cultivation expansion

i. Assumes a starting area of 3,000 ha by 2025, and an industry growth rate of 9 percent (global expansion rate for the period 2007-2011) (World Bank Group 2016).

ii. Assumes 84 percent of net primary production is sequestered, which translates to a carbon burial rate of 706 g C/m^2. This is based on the production goal of 30 dry metric tons ha^{-1}, based on experimental data (ARPA-E 2017), a 28 percent carbon content of dry weight (Stewart et al. 2009), 100 percent sequestration of the cultivated biomass, but a 16 percent sequestration potential loss due to CO_2e emissions from the farming practices (Froehlich et al. 2019).

Decarbonizing U.S. shipping

To construct our estimates of U.S. shipping emissions and mitigation potential, we use CO_2 emissions projections from the U.S. Energy Information Administration (EIA) Annual Energy Outlook (AEO) (2020). The Energy-Related Carbon Dioxide Emissions by End Use table separates shipping emissions to 2050 by domestic and international shipping, which we summed together to capture total shipping emissions. Recreational boat emissions were excluded from our analysis. The AEO 2020 report uses the industrial output by North America Industry Classification System (NAICS) code to project domestic marine ton-miles by census division and industrial commodity to develop domestic marine travel. International shipping fuel consumption is separated based on historical data through 2016. The report accounts for marine fuel choice for ocean-going vessels within the North American ECA by modeling compliance options as a logit choice function based on marine fuel prices. Though emissions from vessels in port are not independently quantified, they are included in the overall emissions from the vessels. The reference case for emissions projections to 2050 only incorporates existing U.S. and international policies and does not incorporate elements of the non-binding IMO GHG targets. Approximate values for present-day total shipping CO2 emissions were cross-referenced for consistency with the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks (1990-2018).

For our mitigation scenarios, we followed the scenarios from the High Level Panel for a Sustainable Ocean Economy 2019 report, "The Ocean as a Solution to Climate Change: Five Opportunities for Action" (Hoegh-Guldberg, Caldeira, et al. 2019). For the upper bound scenario, a 39 percent emissions reduction in 2030 from 2008 levels is applied following Bouman et al. (2017), which reviewed multiple papers and models to produce consensus median estimates of possible mitigation potentials. A full decarbonization (100 percent reduction of shipping emissions) is used for 2050, consistent with the technical feasibility of decarbonizing the sector in that timeframe. Importantly, this scenario requires the full upstream decarbonization of the energy grid to provide zero-carbon electricity to power electric port infrastructure and ships.

For the lower bound, we used a 20 percent emissions reductions from 2008 levels for 2030, taken from Kollamthodi et al. (2013), the study with the lowest emissions reductions estimate in the Bouman et al. (2017) review. The 2050 emissions target was set at 50 percent reductions from 2008 levels, consistent with the IMO GHG target. The HLP paper applied the same percentage reduction to domestic and international shipping emissions because the group of technologies to mitigate emissions in the shipping sector are the same for all geography types, even though the IMO GHG Strategy does not include domestic shipping. We used the same approach in our model.

Targets for domestic shipping in the lower bound scenario of our model were adjusted to match BAU emissions to 2050 and in the upper bound scenario were adjusted to match BAU emissions to 2030 due to the decrease in accounted shipping emissions that has occurred between 2008 and 2019. However, the dramatic change of accounted emissions for domestic shipping between 2008 and 2019 is likely due to a shift in the way the EIA accounts for domestic shipping emissions. The number of U.S. flagged ships fell from 225 in 2018 to 182 in 2019 (Bureau of Transportation Statistics 2019) and there has been some increase in the efficiency of ships and a shift toward LNG fuels. But these changes do not fully account for the 65 percent drop in domestic shipping emissions from 2008 to 2019. This accounting change increases the uncertainty of our analysis—however, domestic shipping makes up <10 percent of total U.S. shipping emissions so this uncertainty does not have an outsize influence on the total mitigation potential of the U.S. shipping sector for 2030 and 2050.

Due to data availability, we differed from the HLP paper in using emissions projections of only CO_2, as opposed to all GHG emissions from ships. The HLP paper set the 2050 mitigation target of the lower bound as 50 percent of total GHG emissions, which we applied only to CO_2 due to available data in the AEO. This likely provided a conservative underestimate of the total shipping emissions and corresponding mitigation potential. All numbers are displayed accordingly in units of Mt CO_2.

Fisheries and aqaculture efficiency improvements and dietary shifts

Wild-capture fisheries fuel use emissions

There are two approaches for estimating fishing emissions: applying an emissions factor to landed seafood volume, or estimating fuel use based on fishing effort (Greer et al. 2019b). Estimating emissions from landed volumes should be more accurate for developed economies where there is better data on catch-based fuel use intensity. This approach formed the basis for global fishing emissions estimates reported in Parker et al. (2018) and was used by the High Level Panel for a Sustainable Ocean Economy in its global estimates (Hoegh-Guldberg, Chopin, et al. 2019). A second approach for estimating fishing sector emissions is based on effort and effort-based fuel use intensity. This approach can be particularly useful for developing economies where data to inform catch-based fuel use intensity are not available (Greer et al. 2019a).

The High Level Panel for a Sustainable Ocean Economy reported that the most consistent driver of emissions within a fishery is catch-per-unit effort (Hoegh-Guldberg, Chopin, et al. 2019). Acknowledging the limitations to estimating emissions based on effort and landings, the estimates provided in the body of this paper are built using both approaches to create and compare top-down and bottom-up estimates of total emissions from the U.S. fishing fleet. The top-down estimate applies a standard emissions-per-catch factor for all capture landings, and the bottom-up estimate calculates emissions based on sector, vessel-specific engine capacity, active engine use time, fuel efficiency, fuel-use rate, and fuel-specific emissions factors (Greer et al. 2019a). We assume U.S. landings remain constant for the next 30 years, which is consistent with landing trends since 1990.

Top-down model:

U.S.fishing fleet emissions = $SL * EI$

Where *SL* are total seafood landings as reported by the Sea Around Us Project for each fishing sector (i.e., industrial, artisanal, recreational, subsistence) in the U.S., reported most recently for 2014, and EI is an emissions intensity factor (t CO_2e * t catch^{-1}). In the mitigation scenario, we assume that the fleet can achieve an emissions intensity of 1.10 t CO_2 per tonne of catch, which is the global average emissions intensity under an optimal management scenario (World Bank 2017).

Top-Down Model	Reported Landings	Unreported Landings	Emissions Intensity (EI)	Emissions (Baseline)	Emissions Intensity (EI)	Emissions (Optimal)
Unit	millions t	millions t	t CO_2 per t Catch	millions t	t CO_2 per t Catch	millions t
Source	SAUP (2014)	SAUP (2014)	Table 1, Parker et al 2018		Table 9, HLP 2019	
Industrial	3.57	0.76	1.70	7.36	1.10	4.76
Artisanal (small-scale)	1.19	0.10	1.70	2.20	1.10	1.43
Recreational (small-scale)	0.00	0.15	1.70	0.25	1.10	0.16
Subsistence (small-scale)	0.00	0.00	1.70	0.01	1.10	0.01
				9.81		**6.35**

Bottom-up model:

$$\textbf{U.S. fishing fleet emissions} = \sum_{l=1}^{6} \left(\frac{(kW_{v,l} * FR_l * FC_l * EF_l)}{(VOCF_1)} \right)$$

Where *l* is vessel class lengths, *kW* is vessel-specific capacity for all U.S. fishing vessels, *FR* is fuel use rate (t fuel * kW^{-1}), FC is a fuel efficiency index coefficient, *EF* is an emission factor (t CO_2*t fuel^{-1}), and *VOCF* is vessel-omission-correction factor (Global Fishing Watch, n.d.; Greer et al. 2019a).

Potential mitigation scenarios for the U.S. are difficult to extrapolate from the global estimates. Existing papers report data at the continental level and do not include country-level estimates (Greer et al. 2019a; Parker et al. 2018). Thus, we applied the most relevant mitigation scenarios (e.g., for North America) from the leading studies estimating fishing effort reduction under improved management scenarios. However, U.S. fisheries management is already among the best in the world, and many of the U.S.'s largest fisheries are already among most efficient per unit catch, so there is less opportunity for emissions reductions through better management. As a result, these may represent optimistic improvement scenarios.

Bottom-up Model	Length class	Range	Sector	Total fishing effort (sum of all vessel-specific kWh)	Specific fuel rate	Fuel used fishing	Fuel coefficient	Vessel omission correction factor (VOCF)	Modified fuel used (baseline scenario)	Emissions factor	Emissions (baseline)	Modified fuel used (optimal scenario)	Emissions factor	Emissions (optimal)
Unit		m		kWh	t fuel per kWh	t fuel	Engine Fuel Index, base 2000	FAO vessel count *GSF vessel count^{-1}	t fuel	t CO_2 per t fuel	t CO_2 per t fuel	t fuel	t CO_2 per t fuel	t CO_2
Source	Table 1, Greer et al. 2019	Table 1, Greer et al. 2019	Table 1, Greer et al. 2019	CEA Calc using GFW data	Table 4, Greer et al. 2019	CEA Calculation	Table 5, Greer et al. 2019	CEA Calculation based on FAO, GFW data	CEA Calculation	Table 4, Greer et al. 2019	Table 4, Greer et al. 2019	26% effort reduction (*Sunken Billions*)	Table 4, Greer et al. 2019	CEA Calculation
2019	1	< 7.9	Small-scale	96,743	0.00035	34	0.99	0%	13,710	3.01	3.01	10,146	3.01	30,538
2019	2	8 - 15.9	Small-scale	102,066,221	0.00035	35,723	0.99	2%	2,090,790	3.01	3.01	1,547,185	3.01	4,657,026
2019	3	16 - 24.9	Industrial	823,399,813	0.0002	164,680	0.99	11%	1,523,600	3.17	3.17	1,127,464	3.17	3,574,061
2019	4	25 - 49.9	Industrial	516,873,360	0.0002	103,375	0.99	104%	98,166	3.17	3.17	72,643	3.17	230,277
2019	5	40 - 99.9	Industrial	611,896,215	0.0002	122,379	0.99	104%	116,668	3.17	3.17	86,334	3.17	273,680
2019	6	100 - 150	Industrial	24,379,416	0.0002	4,876	0.99	100%	4,827	3.17	3.17	3,572	3.17	11,323
											11,860,684			**8,776,906**

Wild-capture fisheries refrigerant emissions

Refrigerant emissions have been estimated to account for between 13 percent and 37 percent of total GHG emissions up to the dock for wild-capture fisheries (Ziegler et al. 2013). Pelagic fisheries are at the lower end of the range, while demersal fisheries are at the higher end. To estimate a plausible range of refrigerant emissions from U.S. fisheries, we assume that refrigerant emissions account for between 13 percent and 25 percent of total GHG emissions up to the dock. Applying these percentages to estimated annual fuel use emissions from U.S. fisheries of between 8.2 and 11.9 Mt CO_2e yields an estimate of annual refrigerant emissions of 1.2 and 4.0 Mt CO_2e. We assume mitigation potential of 70 percent in 2030 and 85 percent in 2050, which is aligned with HFC consumption reductions that would be required if the U.S. were to ratify the Kigali Amendment. This yields a range of annual mitigation potential of between 0.8 and 3.4 Mt CO_2e from adopting more climate-friendly refrigerants on U.S. fishing vessels.

Aquaculture

To estimate the carbon mitigation potential of U.S. aquaculture we calculated the proportion of global aquaculture produced by the U.S. in 2017 (0.39 percent) according to FAO and attributed that share of the High Level Panel's estimated global potential for reduced emissions from aquaculture in 2030 (i.e., 0.016 Gt CO_2e) and 2050 (i.e., 0.043 Gt CO_2e) to the U.S. The U.S.'s proportion of global farmed finfish production (0.38 percent) is nearly the same as its proportion of all aquaculture (0.39 percent).

Shifting diets

We use two approaches for estimating the emissions reduction potential from shifting diets. The first is based on the efficacy of previous behavior-change campaigns, and the second is based on the estimated impact on diets from the application of a carbon tax.

Business as usual emissions

For our business as usual (BAU) projections, we use predicted U.S. emissions in 2030 from the recent publication, "Implications of Future US Diet Scenarios on [GHG] Emissions" (Heller, Keoleian, and Rose 2020). We use scenario 2 as our baseline, which is based on U.S. Department of Agriculture meat consumption projections. This publication does not estimate emissions in 2050, so we extrapolate estimated emissions in 2050 by applying the annual growth rate of emissions from 2016 to 2030. Using this approach, we estimate BAU emissions of 665.7 Mt CO_2e in 2030 and 795.6 Mt CO_2e in 2050.

Behavior change approach

Under this scenario, we assume that behavior change efforts shift consumers to a more pescatarian diet. Based on the literature on the efficacy of large-scale efforts to change behavior, the median effectiveness has been 11 percent (Hoegh-Guldberg, Chopin, et al. 2019). We therefore assume that 11 percent of the U.S. population shifts to a pescatarian diet as described in Tilman and Clark 2014. The global pescatarian diet is estimated to have a 45 percent lower emissions intensity than the average diet (Tilman and Clark 2014). Thus, we assume that 11 percent of U.S. food consumption emissions under the BAU scenario are reduced by 45 percent.

Carbon tax approach

Modeling suggests that a global price on methane emissions from livestock of \$15/tCO_2e would reduce methane emissions by 2.8 percent (Key and Tallard 2012). Applying this emissions reduction estimate to the BAU emissions from beef and lamb would reduce overall emissions from food by 1.2 percent. This emissions reduction is applied to the BAU emissions described above.

Carbon dioxide storage below the seabed

Variable	Value	Source	Comment
Theoretical U.S. offshore storage volume in sub-seabed geological formations	36,000 Gt	House et al. 2006	This refers to total (not annual) capacity and would allow storing thousands of years of current U.S. CO_2 emissions.
Technical potential of CCS from stationary emissions	2.6 Gt/yr	National Petroleum Council 2019	Stationary emission sources from industrial and power generation facilities represent nearly 50% of total U.S. CO_2 emissions. The U.S. has more than 6,500 large stationary sources.
Current economic potential of CCS, assuming increasingly favorable economics and policy incentives	25 Mt/yr in 2020	National Petroleum Council 2019	Only 1Mt/yr is CCS; the remainder is EOR. The only operational CCS plan in the U.S. is located in Illinois.
Future economic potential of CCS, assuming increasingly favorable economics and policy incentives	120 Mt/yr in 2030, 5% annual growth thereafter	King et al. 2020; Friedmann, Ochu, and Brown 2020	Assumes that enhanced and permanent 45Q tax credits are implemented and trigger CCS investments.
Current economic potential for offshore storage of CO_2 captured in the U.S.	0 Mt/yr In 2030, 1 project is in place After that, another one goes online every 2 years	Author's estimate	Currently, no offshore CCS projects exist or are planned within the U.S. exclusive economic zone.
Future economic potential for offshore storage of CO_2 captured in the U.S.	Each project grows to a capacity of 5M tons/yr		Experience in the EU shows that offshore CCS takes 5-10 years from planning to deployment, even when supply chains run efficiently and projects have full governmental support. Deployment before 2030 is ambitious since, to our knowledge, no offshore projects are currently in planning.

Bibliography

ARPA-E. 2017. "Macroalgae Research Inspiring Novel Energy Resources (MARINER) Program Overview." Washington D.C.: Advanced Research Projects Agency - Energy, U.S. Department of Energy. https://arpa-e.energy.gov/sites/default/files/documents/files/MARINER_ProgramOverview_FINAL.pdf.

Atwood, Trisha B., Rod M. Connolly, Hanan Almahasheer, Paul E. Carnell, Carlos M. Duarte, Carolyn J. Ewers Lewis, Xabier Irigoien, et al. 2017. "Global Patterns in Mangrove Soil Carbon Stocks and Losses." *Nature Climate Change* 7 (7): 523–28. https://doi.org/10.1038/nclimate3326.

Bayraktarov, Elisa, Megan I. Saunders, Sabah Abdullah, Morena Mills, Jutta Beher, Hugh P. Possingham, Peter J. Mumby, and Catherine E. Lovelock. 2016. "The Cost and Feasibility of Marine Coastal Restoration." *Ecological Applications* 26 (4): 1055–74. https://doi.org/10.1890/15-1077.

Bouman, Evert A., Elizabeth Lindstad, Agathe I. Rialland, and Anders H. Strømman. 2017. "State-of-the-Art Technologies, Measures, and Potential for Reducing GHG Emissions from Shipping – A Review." Transportation Research Part D: *Transport and Environment* 52 (May): 408–21. https://doi.org/10.1016/j.trd.2017.03.022.

Bureau Of Transportation Statistics. 2019. "Number and Size of the U.S. Flag Merchant Fleet and Its Share of the World Fleet." Not Available. 2019. https://www.bts.gov/content/number-and-size-us-flag-merchant-fleet-and-its-share-world-fleet.

Cavanaugh, Kyle C., David A. Siegel, Brian P. Kinlan, and Daniel C. Reed. 2010. "Scaling Giant Kelp Field Measurements to Regional Scales Using Satellite Observations." *Marine Ecology Progress Series* 403 (March): 13–27. https://doi.org/10.3354/meps08467.

Duarte, Carlos M., Núria Marbà, Esperança Gacia, James W. Fourqurean, Jeff Beggins, Cristina Barrón, and Eugenia T. Apostolaki. 2010. "Seagrass Community Metabolism: Assessing the Carbon Sink Capacity of Seagrass Meadows." *Global Biogeochemical Cycles* 24 (4). https://doi.org/10.1029/2010GB003793.

EIA. 2020. "Annual Energy Outlook 2020."

Fourqurean, James W., Carlos M. Duarte, Hilary Kennedy, Núria Marbà, Marianne Holmer, Miguel Angel Mateo, Eugenia T. Apostolaki, et al. 2012. "Seagrass Ecosystems as a Globally Significant Carbon Stock." *Nature Geoscience* 5 (7): 505–9. https://doi.org/10.1038/ngeo1477.

Friedmann, S. J., Emeka R. Ochu, and Jeffrey D. Brown. 2020. "Capturing Investment: Policy Design to Finance CCUS Projects in the US Power Sector," April, 60.

Froehlich, Halley E., Jamie C. Afflerbach, Melanie Frazier, and Benjamin S. Halpern. 2019. "Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting." *Current Biology* 29 (18): 3087-3093.e3. https://doi.org/10.1016/j.cub.2019.07.041.

Global Fishing Watch. n.d. "Global Fishing Watch US Fishing Fleet Activity Data."

Global Mangrove Alliance. 2020. "Global Mangrove Alliance Data Portal." 2020. https://gma-panda.opendata.arcgis.com/.

Greer, Krista, Dirk Zeller, Jessika Woroniak, Angie Coulter, Maeve Winchester, M.L. Deng Palomares, and Daniel Pauly. 2019a. "Global Trends in Carbon Dioxide (CO2) Emissions from Fuel Combustion in Marine Fisheries from 1950 to 2016." *Marine Policy* 107 (September): 103382. https://doi.org/10.1016/j.marpol.2018.12.001.

———. 2019b. "Reply to Ziegler et al. 'Adding Perspectives to: Global Trends in Carbon Dioxide (CO2) Emissions from Fuel Combustion in Marine Fisheries from 1950-2016' and Addressing Concerns of Using Fishing Effort to Predict Carbon Dioxide Emissions." *Marine Policy* 107 (September): 103491. https://doi.org/10.1016/j.marpol.2019.03.004.

Hamilton, Stuart E., and Daniel Casey. 2016. "Creation of a High Spatio-Temporal Resolution Global Database of Continuous Mangrove Forest Cover for the 21st Century (CGMFC-21)." *Global Ecology and Biogeography* 25 (6): 729–38. https://doi.org/10.1111/geb.12449.

Heller, Martin, Gregory Keoleian, and Diego Rose. 2020. "Implications of Future US Diet Scenarios on Greenhouse Gas Emissions." CSS20-01. Ann Arbor, MI: Center for Sustainable Systems. http://css.umich.edu/sites/default/files/publication/CSS20-01.pdf.

Hoegh-Guldberg, Ove, Ken Caldeira, Thierry Chopin, Steve Gaines, Peter Haugan, Mark Hemer, Jennifer Howard, et al. 2019. "The Ocean as a Solution to Climate Change: Five Opportunities for Action." Washington, DC: World Resources Institute. https://www.oceanpanel.org/climate.

Hoegh-Guldberg, Ove, Thierry Chopin, Steve Gaines, Peter Haugan, Mark Hemer, Jennifer Howard, Manaswita Konar, et al. 2019. "The Ocean as a Solution to Climate Change: Five Opportunities for Action." Washington, DC: World Resources Institute. https://www.oceanpanel.org/climate.

Holmquist, James R., Lisamarie Windham-Myers, Blanca Bernal, Kristin B. Byrd, Steve Crooks, Meagan Eagle Gonneea, Nate Herold, et al. 2018. "Uncertainty in United States Coastal Wetland Greenhouse Gas Inventorying." *Environmental Research Letters* 13 (11): 115005. https://doi.org/10.1088/1748-9326/aae157.

House, K. Z., D. P. Schrag, C. F. Harvey, and K. S. Lackner. 2006. "Permanent Carbon Dioxide Storage in Deep-Sea Sediments." Proceedings of the National Academy of Sciences 103 (33): 12291–95. https://doi.org/10.1073/pnas.0605318103.

Key, Nigel, and Gregoire Tallard. 2012. "Mitigating Methane Emissions from Livestock: A Global Analysis of Sectoral Policies." *Climatic Change* 112 (2): 387–414. https://doi.org/10.1007/s10584-011-0206-6.

King, Ben, Whitney Herndon, John Larsen, and Galen Hiltbrand. 2020. "Opportunities for Advancing Industrial Carbon Capture." *Rhodium Group* (blog). 2020. https://www.rhg.com/research/industrial-carbon-capture/.

Kollamthodi, Sujith, Ana Pueyo, Gena Gibson, Rasa Narkeviciute, Adam Hawkes, Robert Milnes, and James Harries. 2013. "Support for the Impact Assessment of a Proposal to Address Maritime Transport Greenhouse Gas Emissions." Ricardo-Aea.

Krause-Jensen, Dorte, and Carlos M. Duarte. 2016. "Substantial Role of Macroalgae in Marine Carbon Sequestration." *Nature Geoscience* 9 (10): 737–42. https://doi.org/10.1038/ngeo2790.

Krumhansl, Kira A., Daniel K. Okamoto, Andrew Rassweiler, Mark Novak, John J. Bolton, Kyle C. Cavanaugh, Sean D. Connell, et al. 2016. "Global Patterns of Kelp Forest Change over the Past Half-Century." *Proceedings of the National Academy of Sciences* 113 (48): 13785–90. https://doi.org/10.1073/pnas.1606102113.

Marchio, Daniel A., Michael Savarese, Brian Bovard, and William J. Mitsch. 2016. "Carbon Sequestration and Sedimentation in Mangrove Swamps Influenced by Hydrogeomorphic Conditions and Urbanization in Southwest Florida." *Forests* 7 (6): 116. https://doi.org/10.3390/f7060116.

McKenzie, Len J., Lina M. Nordlund, Benjamin L. Jones, Leanne C. Cullen-Unsworth, Chris Roelfsema, and Richard K. F. Unsworth. 2020. "The Global Distribution of Seagrass Meadows." *Environmental Research Letters* 15 (7): 074041. https://doi.org/10.1088/1748-9326/ab7d06.

Mcleod, Elizabeth, Gail L. Chmura, Steven Bouillon, Rodney Salm, Mats Björk, Carlos M. Duarte, Catherine E. Lovelock, William H. Schlesinger, and Brian R. Silliman. 2011. "A Blueprint for Blue Carbon: Toward an Improved Understanding of the Role of Vegetated Coastal Habitats in Sequestering CO2." *Frontiers in Ecology and the Environment* 9 (10): 552–60. https://doi.org/10.1890/110004.

Mora-Soto, Alejandra, Mauricio Palacios, Erasmo C. Macaya, Iván Gómez, Pirjo Huovinen, Alejandro Pérez-Matus, Mary Young, et al. 2020. "A High-Resolution Global Map of Giant Kelp (Macrocystis Pyrifera) Forests and Intertidal Green Algae (Ulvophyceae) with Sentinel-2 Imagery." *Remote Sensing* 12 (4): 694. https://doi.org/10.3390/rs12040694.

National Petroleum Council. 2019. "Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage." Report Summary Volume I.

Parker, Robert W. R., Julia L. Blanchard, Caleb Gardner, Bridget S. Green, Klaas Hartmann, Peter H. Tyedmers, and Reg A. Watson. 2018. "Fuel Use and Greenhouse Gas Emissions of World Fisheries." *Nature Climate Change* 8 (4): 333–37. https://doi.org/10.1038/s41558-018-0117-x.

Pendleton, Linwood, Daniel C. Donato, Brian C. Murray, Stephen Crooks, W. Aaron Jenkins, Samantha Sifleet, Christopher Craft, et al. 2012. "Estimating Global 'Blue Carbon' Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems." *PLOS ONE* 7 (9): e43542. https://doi.org/10.1371/journal.pone.0043542.

Stewart, H. L., J. P. Fram, D. C. Reed, S. L. Williams, M. A. Brzezinski, S. MacIntyre, and B. Gaylord. 2009. "Differences in Growth, Morphology and Tissue Carbon and Nitrogen of Macrocystis Pyrifera within and at the Outer Edge of a Giant Kelp Forest in California, USA." *Marine Ecology Progress Series* 375 (January): 101–12. https://doi.org/10.3354/meps07752.

Thorhaug, Anitra L., Helen M. Poulos, Jorge López-Portillo, Jordan Barr, Ana Laura Lara-Domínguez, Tim C. Ku, and Graeme P. Berlyn. 2019. "Gulf of Mexico Estuarine Blue Carbon Stock, Extent and Flux: Mangroves, Marshes, and Seagrasses: A North American Hotspot." *Science of The Total Environment* 653 (February): 1253–61. https://doi.org/10.1016/j.scitotenv.2018.10.011.

Tilman, David, and Michael Clark. 2014. "Global Diets Link Environmental Sustainability and Human Health." *Nature* 515 (7528): 518–22. https://doi.org/10.1038/nature13959.

U.S. Fish and Wildlife Service. 2013. "Wetlands Status and Trends." National Wetlands Inventory. 2013. https://www.fws.gov/wetlands/status-and-trends/index.html.

Waycott, Michelle, Carlos M. Duarte, Tim J. B. Carruthers, Robert J. Orth, William C. Dennison, Suzanne Olyarnik, Ainsley Calladine, et al. 2009. "Accelerating Loss of Seagrasses across the Globe Threatens Coastal Ecosystems." Proceedings of the National Academy of Sciences 106 (30): 12377–81. https://doi.org/10.1073/pnas.0905620106.

World Bank. 2017. *The Sunken Billions Revisited: Progress and Challenges in Global Marine Fisheries.* Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/24056.

World Bank Group. 2016. "Seaweed Aquaculture for Food Security, Income Generation and Environmental Health in Tropical Developing Countries." World Bank. https://doi.org/10.1596/24919.

Worthington, Thomas, and Mark Spalding. 2018. "Mangrove Restoration Potential: A Global Map Highlighting a Critical Opportunity." Report. https://doi.org/10.17863/CAM.39153.

Ziegler, Friederike, Ulf Winther, Erik Skontorp Hognes, Andreas Emanuelsson, Veronica Sund, and Harald Ellingsen. 2013. "The Carbon Footprint of Norwegian Seafood Products on the Global Seafood Market." *Journal of Industrial Ecology* 17 (1): 103–16. https://doi.org/10.1111/j.1530-9290.2012.00485.x.