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Boundary spanning among research and policy communities to address the emerging industrial revolution in the ocean

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ABSTRACT

Boundary spanning – the practice of facilitating knowledge exchange to address complex sustainability challenges – has the potential to align research and policymaking and increase the uptake of research in decision making. But the goals, methods, and outcomes of boundary-spanning activities in the environment sector can be difficult to describe, missing an opportunity to share lessons learned and improve as a community of practice. This paper describes boundary-spanning activities to integrate research about environmental sustainability with federal ocean policy dialogues in the U.S. We describe the process of organizing, facilitating, and learning from a series of meetings in which five interdisciplinary researchers engaged with federal ocean policy audiences. While the longer-term impacts of the activities associated with these meetings are subtle and remain difficult to detect, more immediate outcomes are observable. These include new professional relationships among researchers and policy staff, reported relevance of the research to general policy discourse, and a narrative that frames the opportunity for policymakers to learn from past industrialization on land as they manage an emerging industrial revolution in the ocean. By presenting the process and outcomes of our boundary-spanning activities, we aim to stimulate timely debate within ocean policy, management, and research communities about the importance of multiple benefits provided by healthy and intact ocean ecosystems and how to protect them in the face of the expanding industrialization of the ocean.

1. Introduction

There is growing interest in how academic researchers can impact policy (Oliver and Cairney, 2019). Boundary spanning, defined as "work to enable exchange between the production and use of knowledge to support evidence-informed decision-making in a specific context" (Bednarek et al., 2018), has emerged as a practice of facilitating interactions among research and policy communities to address complex social challenges such as sustainability (Guston, 2001). The academic study of boundary spanning developed from theories about the roles of boundary organizations (Kates et al., 2001; Cash et al., 2003) to more recent studies of the function of boundary organizations (Leith et al., 2015) and boundary-spanning efforts (Bednarek et al., 2015; Posner et al., 2016; Cvitanovic et al., 2018). Recent literature highlights a need to better articulate and evaluate boundary-spanning efforts (Pitt et al., 2018; Posner and Cvitanovic, 2018).

Boundary spanning can have important implications for ocean policy. In the United States, the expanding industrialization of the

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ocean through energy infrastructure and distribution of use rights is a salient topic in policy circles, suggesting an opportunity for the use of relevant science. Facilitating interactions among research and policy communities can help researchers align their work with the questions and interests of policymakers (Bednarek et al., 2018). Deliberate knowledge exchange activities can provide greater clarity and understanding about current research, as well as identify what kinds of research would be most useful and why (Lemos et al., 2012).

Boundary spanning can also build capacity among researchers and decision makers to further engage with each another (Smith et al., 2013) by contributing to the development of relationships and social networks that are critical to facilitate the uptake of research (Jasanoff, 2004; Cvitanovic et al., 2017). Boundary-spanning activities lead to research being used in long-term shifts in policy discourse and framing (Weiss, 1979).

The impacts of boundary-spanning activities in a complex, real-world interface of science and policy can be subtle and difficult to detect (Bednarek et al., 2018; Posner and Cvitanovic, 2018). As a result, there is a shortage of published studies that observe and describe boundary-spanning efforts in the environment sector. Filling this gap in the literature could promote shared learning among boundary-spanning individuals and organizations, advance a community of practice focused on boundary spanning, and foster a culture of evaluation and improvement.

This paper describes boundary spanning among research and policy communities in 2017 in the U.S. The co-authors, who represented boundary-spanning professionals and researchers, engaged in this work in order to advance research about solutions for environmental sustainability within federal ocean policy dialogues. The goals included:

1 To facilitate knowledge exchange among researchers and federal policy actors;
2 To identify policy windows, defined as windows of opportunity for policy change and the sudden uptake of knowledge (Rose et al., 2017; Kingdon, 2003), and create opportunities for research to inform decision making; and
3 To build the capacity of researchers to engage with policy processes so that research evidence could have a more prominent role in decision making.

The boundary-spanning efforts involved interdisciplinary researchers and professionals who work at the interface of science and policy interacting with federal U.S. policy staff. The initial focus centered on key questions about the benefits that people receive from the ocean and coasts (including economic and non-economic benefits) and how they are relevant to federal policymaking. In the process, the co-authors developed a narrative to frame principles that could guide a sustainable path for industrial development in the ocean, what is to be gained with such principles, and what is at risk if guiding principles based on sustainability and thoughtful planning are ignored.

The industrial revolution in the ocean is a particularly good marine case study to apply this method of boundary spanning in the U.S. It was an area of key immediate interest among policy makers in the U.S. specifically, within a global context of interest in growing the blue economy and expanding industrialization in the ocean (Golden et al., 2017; World Bank and United Nations Department of Economic and Social Affairs, 2017). This topic also necessitated a strategic approach for engagement and a diverse set of experts and thought perspectives (e.g. ocean policy, conservation social science, marine ecology, environmental resource economic) to analyze and communicate complexities in the research. By presenting here about the process and outcomes of the coauthors' boundary-spanning activities, we aim to frame and stimulate timely debate about how healthy and intact ocean ecosystems provide multiple benefits to people that must be protected in the face of the expanding industrialization of the ocean.

2. Methods

2.1. Preparation

The co-authors include 5 interdisciplinary researchers (EPF, DJM, KB, RB, CC) who engaged in a series of policy meetings, 3 boundary-spanning professionals (SMP, EG, HM) who designed the boundary-spanning activities, and a researcher (FHJ) who assisted with data synthesis and visualization. The researchers brought a diversity of expertise in relevant ocean science, including ecology, social psychology, economics, and applied management. We chose the meeting dates in June 2017 strategically to lead into an 'Ocean Science on the Hill' week (Capitol Hill Ocean Week). To plan the policy engagement meetings, the co-authors 1) conducted real-time assessment of policy conditions through in-person conversations and phone calls with key policy staff; 2) prepared and practiced science communication techniques such as using the Message Box to distill key messages from complex research, tailor messages to specific audiences, and avoid jargon (Baron, 2010); and 3) co-developed written products and spoken messages through a series of meetings among the researchers to prepare to engage policy experts about relevant research.

Leading up to the meetings, the boundary-spanning professionals at COMPASS conducted rapid field assessments of the state of knowledge, interest, and intentions among policy actors who might participate in meetings with the group (Posner and Cvitanovic, 2018). This provided real-time information about the alignment between research knowledge and decision-making needs (Bednarek et al., 2015) and the potential for policy windows – opportunities for the uptake of science in policy (Rose et al., 2017). The COMPASS field assessments were part of a program to connect ocean research with federal policy.

At the same time, the researchers prepared for in-person meetings by discussing their individual perspectives as a group and sharing publications with one another to build a cohesive yet interdisciplinary framing. They drafted key messages from their research and tailored the messages to the interests of each audience (Smith et al., 2013). The group met over video chats to practice delivering spoken remarks, provide feedback to one another, and develop a frame for engaging with policy experts about the benefits that people receive from the ocean and coasts.

Finally, the co-authors developed a short policy brief document through a collaborative writing process before they met in Washington, D.C. (Appendix 1). The boundary-spanning professionals used the policy brief before the meetings in D.C. to facilitate conversations with policy experts and identify 'navigators' who could help find and convene interested policy staff for meetings.

2.2. Implementation

The extensive planning and preparation by boundary-spanner professionals resulted in a series of meetings and briefings (Table 1) scheduled over a 2-day period in Congressional office buildings, department offices, and in the Council on Environmental Quality offices. The Congressional briefing drew about 75 attendees, and the meetings with agency and executive office staff involved the five researchers, the 3 boundary-spanners as facilitators, and between 7–10 policy staff. The diversity of represented research disciplines increased the probability of impacts to the various policy audiences.

During and following the policy engagement meetings, the boundary spanners and researchers listened and took careful notes on how decision-makers described their current priorities, interests, and knowledge needs. Of particular interest were any unanswered questions or areas of research that would be useful for advancing particular policy dialogues.

After each meeting, the team of researchers and boundary spanners met for a minimum of thirty minutes to share notes, validate their individual interpretations of the meeting, and identify common themes

Table 1
"Ocean Benefits" policy engagement meetings with policy experts in the U.S. federal government. Boundary-spanning professionals assessed policy interest and the potential for policy windows leading up to the meetings, and organized for five ocean researchers (included as co-authors) to engage with these audiences.

U.S. federal government group engaged with	Individuals, offices, or units represented by meeting attendees	Interests among policy experts
Congressional Research Service (CRS)	Analysts and specialists in energy, natural resources, and science and technology policy	CRS serves as shared staff to congressional committees and members of Congress. CRS experts assist at every stage of the legislative process — from the early considerations that precede bill drafting, through committee hearings and floor debate, to the oversight of enacted laws and various agency activities. CRS approaches complex topics from a variety of perspectives and examines all sides of an issue. Staff members analyze current policies and present the impact of proposed policy alternatives.
Congressional staff briefing "Counting on Ocean Benefits:A science briefing on the links between the ocean, our economy, and human well-being"	Diverse audience, including mostly Senate staff, interested NGOs	The audience for this briefing was very broad, including junior staff members, senior staff, and interns from Congressional offices, as well as staff from NGOs and federal agencies interested in these issues.
House office staff	Staff members in House of Representatives offices part of a House Oceans Caucus	Meeting attendees were especially interested in how ocean-related issues affect their constituents locally or at the state-level, as well as connections among environment, natural resources, and other topics such as transportation, health, or community development.
Executive Office of the President	National Ocean Council; Office of Science and Technology Policy; Council on Environmental Quality; Office of Information and Regulatory Affairs; Office of Management and Budget	The meeting attendees represented a range of interests and perspectives, including policy analysis, national ocean policy, ecosystem services in federal decision-making, wealth accounting, efficiency and effectiveness of government programs, performance metrics, large-scale ecosystem restoration, and administration priorities such as infrastructure and domestic economic growth.
U.S. Department of State	Office of Conservation and Water; Office of Development Finance; Office of Marine Conservation; Office of Polar Affairs in the Bureau of Oceans and International Environmental and Scientific Affairs	Meeting attendees were interested in the international implications of ocean benefits, such as the "blue economy" in a global context, foreign affairs, and what ocean benefits mean for international diplomacy.
U.S. Department of Treasury	Environment and Energy Office (no longer exists due to reorganization); Office of International Affairs; Office of General Counsel	Meeting attendees were interested in a broad, open discussion about the latest research and ideas, rather than a narrow conversation about any specific policy area. They were interested in how to translate research with a domestic focus to their international work regarding multi-lateral funds and institutions (e.g. multilateral development banks, Global Environment Facility), international negotiations (e.g. climate diplomacy), catastrophic risk insurance funds, debt restructuring, and macroeconomic forecasting.

that could improve a more holistic scientific communication with policymakers. In response to these assessments, the researchers and boundary-spanning professionals developed a new narrative frame: the chance to learn from past industrialization on land in order to manage the emerging industrial revolution in the ocean. This frame responded to the current policy environment by speaking directly to priorities of expanding industry and growing the ocean economy. It also provided a platform for discussing interdisciplinary research perspectives and had the potential to shift policy dialogues from a focus on purely economic benefits to a consideration of a broader suite of benefits provided by the ocean. In the following Section 3, we present the narrative that emerged from the boundary-spanning activities and discuss guiding principles and their relevance to current ocean research and policy. To further explore the ocean industrial revolution framing and provide visual evidence of trends over time, we synthesized social and marine industry data from public sources in the statistical platform R (R Core Team, 2017) to create indicators that represent the emerging industrial revolution in the ocean.

3. Development of a narrative for an emerging industrial revolution in the ocean

In preparing and adapting our message during the two-day meetings, we found federal policymakers were interested in the following narrative: industrial activity in the ocean is mirroring broad trends from the land-based industrial revolution, and policymakers could harness lessons from that process to inform future marine management.

To better inform this line of conversation, we evaluated evidence for a growing industrial revolution in the ocean that was described in the literature two decades ago (Smith, 2000). We analyzed data for key indicators and showed that over the last 20–30 years, there have been steep rises, and in some cases exponential growth, in industrial activity in the ocean (Fig. 1). These indicators show growth trends over time in ultra deepwater oil production, global aquaculture production of marine animals, cumulative number of offshore and nearshore wind turbines installed globally, exploration contracts for seabed mining in international waters, container port traffic as a measure of marine shipping, and global human populations residing in low elevation coastal zones (< 20 m).

As human influence on the ocean intensifies on a global scale, impacts on ecosystems and human well-being are already manifesting, for example, shifts in the abundance and distribution of ocean species that communities depend on, increasing levels of ocean acidification that affect shellfish aquaculture, direct impacts of increased shipping traffic on species and multiple human uses of the ocean, and loss of coral reefs and mangroves(McCauley et al., 2015; Pecl et al., 2018). Many impacts from this increase in industrial activity, such as direct impacts from the extraction of minerals and energy resources, are at risk of not rising to the top of public attention despite the increasing scales of activity and impact to new regions of the ocean. More public awareness of the situation could inspire better management of the increasing impacts.

There are multiple drivers for this industrial activity and associated impacts. Industrialization in the ocean is accelerating with increasing demand for natural resources, increasing costs to access resources on

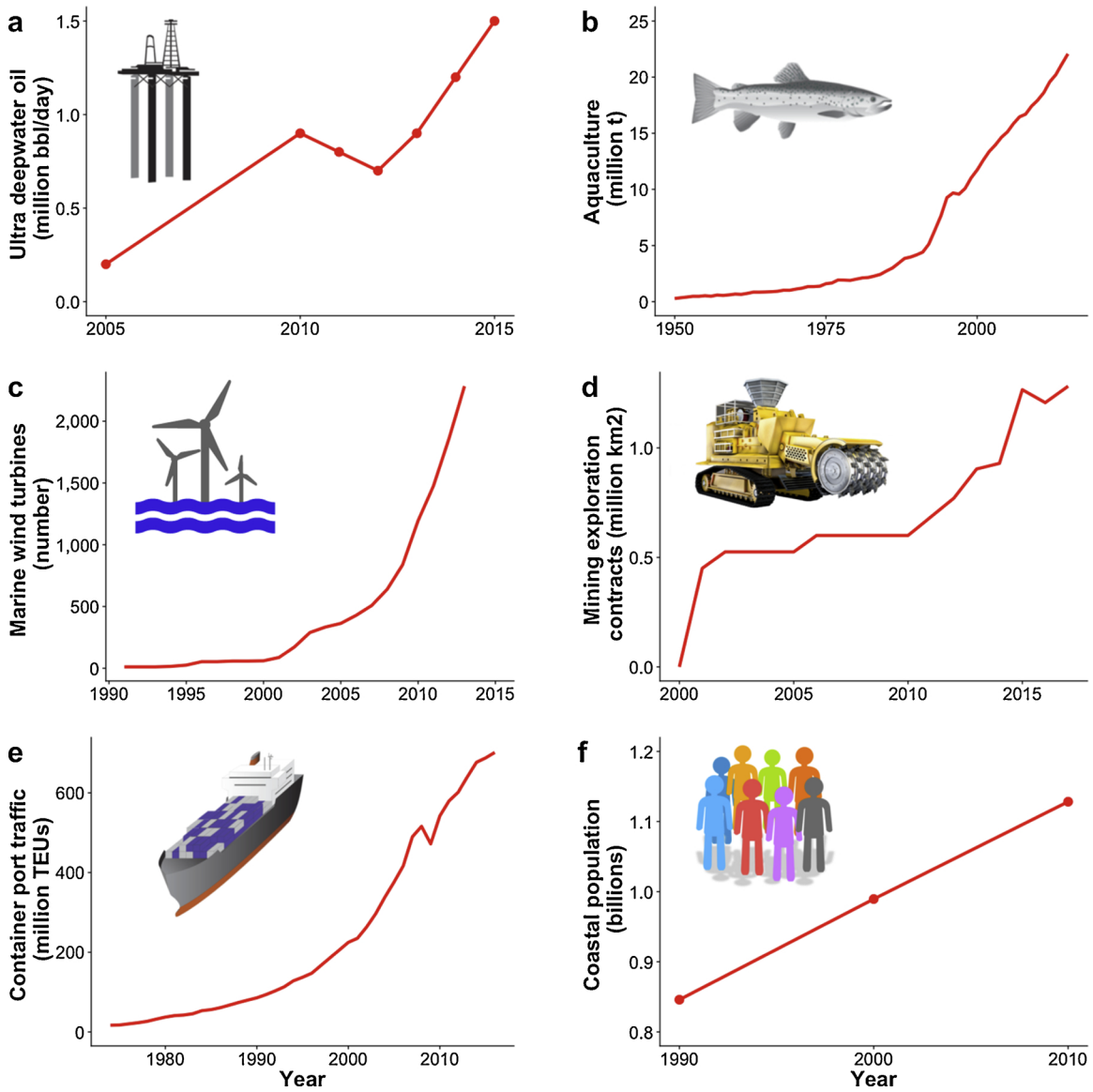

Fig. 1. Growth patterns that support the narrative of an emerging industrial revolution in the ocean. Trends in six representative marine industry and societal indicators reveal increasing anthropogenic use of the ocean environment: (**a**) Ultra deepwater (> 1500 m) oil production (2005–2015) (Statista, 2018); (**b**) global aquaculture production of marine animals (1950–2015) (Food and Agriculture Organization of the United Nations, 2014); (**c**) cumulative number of offshore and nearshore wind turbines installed globally (1991–2013) (The European Wind Energy Association, 2019); (**d**) exploration contracts for seabed mining in international waters (2000–2017) (International Seabed Authority, 2018); (**e**) container port traffic (1974–2016) as a measure of marine shipping (The World Bank, 2018); and (**f**) global human populations residing in low elevation coastal zones (< 20 m) (1990–2010) (CIESIN, 2013). Illustration credits (Illustrations by Diane Kleine (a) et al., 2019).

land (e.g. cobalt for battery manufacturing), and decreasing costs to access resources in the ocean. Technological advances and overall demand for resources are driving rapid growth in ocean industries such as aquaculture, energy production, and deep-sea mining (Beaudoin et al., 2014; Golden et al., 2017). New technologies now enable access to resources at ever-greater depths and extend industry into historically remote parts of the ocean (Mengerink et al., 2014). This situation opens new frontiers for economic activity and underscores the need to consider environmental sustainability (Stojanovic and Farmer, 2013).

The history of industrial development is largely the story of how people convert natural resources into economic output, income, and human and built capital (Barbier, 2011). The vast size of the potential ocean-related economy coupled with the lack of clear ownership and rights fuels a temptation to explore and access resources as quickly as possible (Hoegh-Guldberg et al., 2015; Patil et al., 2016). This inclination applies to resources found in the high seas, as well as within national waters of countries with developed and developing economies alike.

National ocean policy priorities in the U.S. reflect this societal tendency. For example, recent declarations outline goals to “harness the vast resources of the Exclusive Economic Zone” (EEZ) in order to grow national economies (White House, 2018a). An executive order on ocean policy revokes a prior executive order titled “Stewardship of the Ocean, Our Coasts, and the Great Lakes” and replaces it with one titled “Ocean Policy to Advance the Economic, Security, and Environmental Interests of the United States.” A stated goal for the new ocean policy is to “facilitate the economic growth of coastal communities and promote ocean industries” (White House, 2018b), while a federal research and development priority area includes “approaches to efficiently map, explore, and characterize the resources of the U.S. exclusive economic zone” (White House, 2019).

3.1. Demonstrating the opportunity to learn from past industrialization

After presenting these facts, we then guided policymakers through a conceptual exploration of similarities/differences with past industrialization and the opportunities to learn from history. We explained that today, nations everywhere are at a cross-roads with respect to the global ocean (as evidenced by a UN-supported High Level Panel on Ocean Sustainability https://oceanpanel/org). It is critical for society to confront how prevailing institutions may unintentionally create incentives for a development path that focuses on narrowly distributed short-term gains by liquidating the natural wealth contained in the ocean (Feinchel et al., 2016; Yun et al., 2017; Vardon et al., 2017). This path could create externalities and long-term costs that impair the ability of future generations to meet their needs. Integrated analysis of the complex ecological, economic, social, and governance aspects of the industrial revolution in the ocean is important for understanding the status and trajectory of industrial activity in the global ocean, and also for suggesting paths forward for sustainable ocean development (Hoegh-Guldberg et al., 2015; Kates et al., 2001).

The current societal push to industrialize in the ocean mirrors the land-based industrial revolution in the 18th and 19th century, with new technology and a drive to explore and exploit vast, newly available resources. The industrial revolution on land enhanced human well-being in a number of ways and generated economic benefits. However, during the first industrial revolution on land, society lacked guidelines for mapping and conserving large-scale resources or managing growth in industrial activity in ways that met goals for human progress while providing adequate environmental safeguards. This led to unintended consequences such as concentration of wealth, displacement of communities (Wilkinson and Pickett, 2018), and irreversible ecological burdens, such as species extinctions (Vitousek et al., 1997). Widespread externalities have led to logical concerns about the sustainability of large-scale industrial development that is divorced from stewardship and governance (United Nations, 1987).

The world faces a different situation with respect to the ocean today: we have hindsight, knowledge of complex social and ecological systems, more and better data that increase our ability to account for ocean wealth, and promising governance tools and structures to stitch these features together for ocean conservation and planning. Society is increasingly aware of the valuable benefits the ocean provides and the importance of designing institutions and “rules of the game” to lessen externality and resource equity issues (Fenichel et al., 2016; Golden et al., 2017). Even within current political constraints, industrial development in the ocean provides an opportunity to learn from experiences on land and to reorient to meeting current needs while safeguarding the ocean’s continued productivity and ecological health.

3.2. Guiding principles

To make the messages more tangible, the co-authors then synthesized three guiding principles to address the largest drivers of negative consequences from the industrial revolution on land: Account for a full range of ocean benefits; Allocate ownership and user rights with related institutions, and; Leverage the power of new data technology (Table 2). Broad and inclusive dialogue on guiding principles provides an opportunity for reflection, learning from past experiences, and further aligning ocean policy and management decisions with current scientific understanding.

3.2.1. Principle 1: account for short- and long-term ocean wealth and the diversity of social preferences and objectives through inclusive and transparent ocean planning processes

Accounting for a full range of benefits reveals the ocean as a store of diverse wealth that is worthy of investment (Fenichel et al., 2016; Yun et al., 2017). Rather than rapidly liquidating ocean wealth (which includes energy and mineral resources, regenerative biological stocks, and less tangible intrinsic value), society could capture dividends from the ocean while maintaining its capital wealth (Lange et al., 2018). For example, policymakers could help balance among the drive to acquire valuable mineral resources today, the desire to increase the value of those resources in the future, and commitments to minimize damage to corals that protect coastal areas and fish stocks, support tourism, and provide socio-cultural benefits to communities over the longer-term. A more accurate accounting of ocean assets across sectors such as mining, fisheries, and tourism would help policy makers with the important goal of conserving ocean wealth for the future (UNU-IHDP and UNEP, 2012).

National economic accounts that track ocean wealth can provide valuable information about how the ocean contributes to national economic well-being. Efforts are underway to develop ocean economy accounts in several countries, including the Philippines (Talento, 2016), the U.S. (NOAA, 2018), and Canada (De Maio and Irwin, 2016). Ocean economy accounts integrate information in terms that are useful for policy and management and can enable effective management action to maintain and build ocean wealth (Boyd et al., 2018). With information about ocean wealth, decision makers can more effectively invest in key contributions to the economy; conduct cost-benefit analysis with more complete information; and evaluate integrated trends in the ocean economy and ocean ecosystems. Accounting as a way to sustainably manage ocean wealth requires processes to engage with a wide variety of governmental, business, and community stakeholders across nations (Word Bank and UN, 2017).

Beyond providing economic benefits, the ocean also evokes a sense of awe, provides people with a sense of place, and inspires exploration, discovery, and stewardship (Cerveny et al., 2017; Roman et al., 2018). Money does not always change hands when the ocean produces such valuable benefits to people, making measurement or trade of these benefits difficult if not impossible. What’s more, ocean benefits are not equally experienced or valued by all individuals, or within or between all regions. Nevertheless, losing these opportunities is a real cost to those who receive these benefits, and to society as a whole (Krutilla, 1967). Measuring, monitoring, and articulating diverse values of ocean wealth can reveal how ecosystems contribute to human well-being beyond purely financial benefits and ensure people's sense of social justice in the governance of ocean wealth (Biedenweg et al., 2017).

3.2.2. Principle 2: Align private and social long-run goals by allocating ownership and user rights (including privileges, preferences, entitlements, and responsibilities in the ocean) and design related institutions to manage the conservation and use of complex and dynamic ocean resources

Governance and institutions create a platform on which an expanding ocean economy can be built. Thus institutions play a crucial role in ensuring sustainability within the emergent industrial revolution in the ocean. A key lesson from past industrialization on land in the United States is the need to align private incentives with social long-run goals. A system of clearly defined rights can help to align private, short-term interests with shared, longer-term prosperity. During westward expansion, institutions for defining ownership and use rights lagged, leading simultaneously to over-exploitation of resources and under-investment in infrastructure for safe, reliable, and sustainable resource management (Libecap, 1994).

Past experience can make defining and establishing property rights seem conceptually easier on land, but creativity and innovation can create a workable system of ownership, use rights, and conservation in the ocean. Contrasting visions include a top-down, centrally planned ocean in which rules and command-and-control regulations permit or forbid activities, versus a bottom-up approach of rights and voluntary exchange for allocating and exercising rights in an open economic system. A key feature of a rights-based system is that it provides the right-holder a durable and vested interest in the long-run performance of the underlying asset, which can help align private incentives and long-term social and environmental goals.

Table 2
Highlights, drawbacks, and examples for guiding principles to manage an ocean industrial revolution.

Guiding Principle	Account for a full range of ocean benefits	Allocate ownership and user rights, and design related institutions	Leverage the power of new data technology
Highlights	- Better position society to capture dividends from the ocean while maintaining its capital wealth.	- A system of clearly defined rights can help align private, short-term interests with shared, longer-term prosperity.	- Centralized information can underpin efficient resource use and allow for increasingly fair and efficient ways to design, allocate, monitor, and enforce rights.
	- Provide valuable information about how the ocean contributes to national economic well-being	- Could mitigate over-exploitation of resources and under-investment in infrastructure for safe, reliable, and sustainable resource management.	- Compared with past industrialization on land, we have relatively more data on the ocean economy and sophisticated ways to assess ocean conditions, monitor changes in how people use and value the ocean, and visualize the distribution of resources at large scales.
	- Integrate information in terms that are useful for policy and management.	- Clearly defined rights are a precursor to authorizing certain industrial activities.	
Risks/Drawbacks	- Could potentially require time-consuming processes to engage with a wide variety of governmental, business, and community level stakeholders across nations.	- Conceptually more difficult in the ocean than on land.	- More real-world test cases that harness new technology and data are needed to explore the potential of a dynamic ocean management approach at varying ecological scales and across industrial sectors.
	- Diverse values of ocean wealth are not always represented, risking an overly economic focus that could miss important aspects of how ecosystems contribute to human well-being beyond financial benefits.	- Contrasting top-down vs. bottom-up approaches could hinder progress.	- Integrating across data sources and layers requires mechanisms for sustained cross-agency communication and coordination
		- Effective planning processes must grapple with trade-offs among potentially-competing ocean uses such as aquaculture, fisheries, and offshore wind.	
Examples	- The Philippines (Talento, 2016), the U.S. (NOAA, 2018), and Canada (De Maio and Irwin, 2016).	- Ocean aquaculture could receive more substantial business investment if there were a system for leasing suitable areas of the ocean, establishing guidelines, and monitoring impacts (Lester et al., 2018; Massaua and Castner, 2018).	- Real-time, spatial data can show activities such as extractive effort and tourism use along with assets such as storm protection and vulnerable coastal resources at risk, habitat for growing fish, and culturally important sites (Spalding et al., 2017; McCauley et al., 2016).
	- Accounting for natural capital can show how it's economically important (Ruijs et al., 2018) and inform policy decisions (Vardon et al., 2017; Yun et al., 2017)	- In the deep-sea mining sector, institutions already exist, but the design of ownership and use rights would benefit from a careful regional planning process and more scientific analysis of the deep sea (Wedding et al., 2015; Dunn et al., 2018).	- Dynamic ocean management can integrate biological, oceanographic, and social data to inform timely management responses (Maxwell et al., 2015; Dunn et al., 2016).

In an increasingly busy ocean, society needs to address pressing questions about how, where, and when to allocate rights. Open access to resources in the high seas and many national waters incentivizes over-extraction, creates the conditions for externalities and hazards to worker safety, and risks depletion of valuable capital stocks. A system of rights must seek to limit externalities and provide a remedy when they emerge. Otherwise, without clearly defined rights, economic activity in the ocean by one group will likely cause incidental harm to another group with no clear basis for negotiating a solution, threatening long-term sustainability and the shared conservation of valuable ocean environments (Beck et al., 2004). Clearly defined rights are also a precursor to authorizing certain industrial activities, such as offshore finfish aquaculture which could receive more substantial business investment if there were a system for leasing suitable areas of the ocean, establishing guidelines, and monitoring impacts.

Policymakers in international settings will need to carefully examine the balance between private sector autonomy and centralized planning in delineating, allocating, and establishing systems of transfer for ocean ownership and use rights. For example, rights could be defined over extraction or transit rights (and are thus not necessarily spatial), and could be allocated to communities or cooperatives (and are thus not necessarily held by individuals or corporations). These design elements are relevant everywhere, but may be especially relevant in areas beyond national jurisdiction and EEZs, which includes the majority of the ocean (United Nations Preparatory Committee, 2017). Regardless of their delineation, a mechanism for transfer can lead to market driven incentives for harmonizng standards among jurisdictions.

Institutions already exist in the deep-sea mining sector, but the design of ownership and use rights would benefit from a careful regional planning process and more scientific analysis of the deep sea (Wedding et al., 2015; Dunn et al., 2018). As an ocean industrial revolution gains speed, seabed mining is poised to expand rapidly as the global demand for minerals grows, terrestrial supplies of minerals become harder to access, and advanced technology allows exploration and mining in remote, deep-sea areas (Voosen, 2018). The International Seabed Authority is charged with overseeing claims to explore deep-sea minerals in international waters (UNCLOS, 1982), protecting the marine environment from harm due to mining-related activities on the seabed (Article 145), and developing seabed resources as "common heritage for the benefit of mankind as a whole" (Article 150). The design of marine reserve networks provides an opportunity to expand this sector of the ocean economy while measuring performance toward conservation and management targets (Dunn et al., 2018). An effective planning process to allocate ownership and use rights for deep-sea resources alone would be incomplete if it didn't also explore interactions with other potentially-competing objectives or activities, such as aquaculture, fisheries, or offshore wind development.

3.2.3. Principle 3: leverage the power of new technology to collect big data on industrial activities and the effects they are having on ocean ecosystems, people, and the economy

Digital and analytical innovations can drive the design, allocation, monitoring, and enforcement of rights in the ocean. In the early 20th century, economic data became increasingly sought-after and useful for managing the explosion of industrial activity on land, in part because

centralized information provision can underpin efficient resource use (Grossman and Stiglitz, 1976). At the present stage of industrial development in the ocean, we have relatively more data on the ocean economy and sophisticated ways to assess ocean conditions, monitor changes in how people use and value the ocean, and visualize the distribution of resources at large scales.

Combining biophysical, market, and social data with spatial information expands our understanding of the ocean's role in providing benefits for economic sectors like tourism and in contributing to human well-being more broadly. Real-time, spatial data can inform conservation planning and decision-making by showing activities such as extractive effort and tourism use along with assets such as storm protection and vulnerable coastal resources at risk, habitat for growing fish, and culturally important sites (Spalding et al., 2017; McCauley et al., 2016). Integrating across layers of information enhances ocean planning and facilitates the design of institutions to govern the emergent industrialization of the ocean (Costello et al., 2016).

Dynamic ocean management is an example of integrating biological, oceanographic, and social data to inform timely management responses (Maxwell et al., 2015). Utilizing available data and predefined frameworks for balancing ecological and social/economic objectives, dynamic ocean management can increase the speed and efficacy of decisions about managing living ocean resources such as fisheries (Dunn et al., 2016). More real-world test cases that harness new technology and data are needed to explore the potential of a dynamic ocean management approach at varying ecological scales and across industrial sectors.

3.3. Underscoring the sense of urgency

Finally, we presented policymakers with a sense of urgency to address these guidelines by explaining that changes in the ocean such as temperature increases and acidification are already affecting the course of the industrial revolution in the ocean. For example, ocean change is shifting the location, interactions, and requirements to effectively manage fish species (Morley et al., 2018; Pecl et al., 2018; Pinsky and Fogarty, 2012). While regional Fishery Management Councils in the U.S. may recognize that dealing with climate-related shifts is important and increasingly urgent, their ability to focus on long-term solutions can be constrained by the day-to-day urgency of current management responsibilities. Many mechanisms that can help effectively manage the impacts of ocean change on fisheries, some of which already exist, demonstrate how the guidelines we propose can be put into action. For example, rights-based programs can foster a long-term conservation ethic, and adaptive harvest rules can use data technology to inform managers and stakeholders about needed management changes (Costello et al., 2016; Gaines et al., 2018; Sanchirico, 2009).

As ocean change affects industrial activity in the ocean, meaningful collaboration and communication between managers, scientists, and policy staff is necessary to reduce conflict and encourage adaptive decision making. Forecasting change on shorter, decision-relevant time scales could close the gap between signal and response for shifting fish distributions and allow more effective management actions. This requires sustained collaboration across scales of governance (including local fishing stakeholders, regional fisheries management, and national fisheries policy) and between jurisdictions (Pinsky et al., 2018). Systems to support collaboration and communication among stakeholders would enhance efforts to incorporate ocean change into planning an industrial revolution in the ocean.

4. Results and discussion

Evaluating the impacts of boundary-spanning activities is an important aspect of knowing what can work at the science-policy interface (Pitt et al., 2018; Posner and Cvitanovic, 2018). The scope of this effort did not provide ample resources to design robust evaluation methods into the early planning of the meetings. However, the meetings did result in observable outcomes and evidence that we made progress toward each of our three broad goals for these boundary-spanning activities.

Congressional and agency staff contacted researchers afterwards to follow up and request additional information. Ongoing communication initiated by policy staff is a sign of researchers becoming trusted resources. In addition, policy audiences reported during and after the meetings that the narrative about ocean benefits and the industrial revolution in the ocean was salient, credible, and legitimate – important enablers for the use of research in decision making (Cash et al., 2003; Posner et al., 2016). Meeting participants were also receptive to learning about opportunities for sustainably managing growth in industrial activity. Policy staff reported in follow-up conversations that they found the framing useful and planned to draw from it in future discussions. In hearings that followed this event, Members of Congress mentioned the benefits provided by ocean ecosystems and the ocean economy.

While it is impossible to determine the degree to which our boundary-spanning efforts influenced the broader policy dialogue, the boundary-spanning activities created opportunities for researchers to shape an evolving ocean policy discourse. This was an example of "policy assemblage" in which participants were drawn together to co-produce policy-relevant ideas and questions (McCann and Ward, 2012; Prince, 2012). The conversations and exchanges before, during, and after the June meetings also served to inspire and develop new questions from policy staff that they did not previously realize were of interest.

We succeeded in our first goal (to facilitate knowledge exchange among researchers and federal policy actors) by facilitating exchange among researchers and federal policy actors that both communities found valuable. The exchange included discussions about how relevant research could advance ocean policy and management.

We met our second goal (to identify and create policy windows) to a lesser degree, partially because of the broad focus of the meetings. While a narrower focus may have contributed to more specific, tangible policy outcomes in the near-term, the deliberately broad focus allowed the groups to explore a wide variety of potentially-relevant topics. The boundary-spanning activities were not aligned with one particular policy window or specific instance where research could be used in policymaking, rather they were designed to identify and create new policy windows (Rose et al., 2017) and to introduce missing research voices into policy dialogues. The narrative about the industrial revolution in the ocean frames broad policy thinking and action (Lubchenco and Gaines, 2019) and could be an intermediate step toward creating policy windows.

We achieved our third goal (to build the capacity of researchers to engage with policy processes) through preparing for the meetings, engaging directly with policy actors, and practicing how to frame research messages for policymakers. The narrative itself demonstrates the increased capacity for scientists to engage with policy processes and frame their research in policy relevant ways.

One of the clear limitations of this approach is that even while it can lead to conceptual changes among policymakers and subtle shifts in the policy dialogue (James, 2000), it is difficult to track specific changes or knowledge use outcomes that were due only to the boundary-spanning activities (McKenzie et al., 2014). However, this case is an example of how policy-relevant framing can emerge from iterative boundary-spanning activities. This case also highlights the importance of interdisciplinary groups that can introduce research about ecology, economics, and the human and social dimensions of the benefits provided by the ocean into federal policy dialogue.

Regarding the guiding principles, it is a challenge to rely on statistical evidence that these proposed guiding principles would work in ensuring sustainability and managing industrial activity in the ocean, for two main reasons. First, there is no way to know for certain what

might have occurred differently during the land-based industrial revolution if these principles had been applied. Second, while the use of rigorous evaluation methods in the environmental conservation field is growing, currently it could provide only limited evidence for the long-term effectiveness of these approaches (Ferraro et al., 2019). Important future research questions remain about the evidence that natural capital accounting, planning, or big data technology are causally linked to measurable policy or management outcomes, and what conditions need to be in place for these principles to work.

The need for more rigorous evaluation in ensuring positive environmental outcomes is well understood (Baylis et al., 2016; Fisher et al., 2014), and promising new techniques in evaluation (Ferraro, 2007; Gill et al., 2017) and evidence synthesis (Sutherland and Wordley, 2018) are beginning to demonstrate more rigorously what works in conservation, what doesn't, and why. In cases where these proposed guiding principles have been applied (see examples summarized in Table 2), there is no counterfactual situation (either real or quasi-experimental) that can be examined to evaluate what might have happened if these guiding principles had not been applied. This is often the case with real-world environmental management interventions and remains a challenging topic to discuss with policymakers and managers.

5. Conclusion

Researchers engaging with policymakers can shape the future development path in the ocean. The boundary-spanning goals, methods, and outcomes described here have contributed to the evolution of federal ocean policy thinking in the U.S. A focus on growing the ocean economy can glean lessons from past industrial development on land, including the importance of stewardship, accounting for natural capital, governance, institutions, and clarity around property rights.

An emerging industrial revolution in the ocean is exciting and promises to provide nutritious food, low carbon energy, and new sources of income. The push for industrialization in the ocean seems inevitable. However, the rates, locations, and trajectories for industrial activity are debatable. A powerful frame for policy thought and action lies in the notion that the ocean of today presents a promising second chance to see the sequence of industrialization play out better over a vast section of our living planet.

There are a diversity of end points and goals for shaping the emerging industrial revolution in the ocean. Society faces an imperative to respect both our short- and long-term needs while realizing the diversity of wealth and value that already exist in the ocean. Strategies that account for ocean wealth, design institutions to manage rights at sea, and engage new forms of ocean big data could facilitate more effective decision-making. Boundary spanning plays an important role in connecting researchers with policymakers and advancing ideas about solutions. Decisions made in the next decade will fundamentally shape the future of the ocean and the benefits it will be able to provide, and in turn significantly shape the future of our ocean-dependent global society.

Author contributions

All authors contributed to framing and outlining ideas. S.M.P., E.F., D.J.M., K.B., R.B., and C.C. wrote the manuscript. S.M.P., D.J.M., and F.H.J. created the figure.

Declaration of Competing Interest

The authors have no conflict of interest involved in preparing this manuscript or publishing it

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Appendix A. Supplementary data

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