



Coastal Workforce Development Success: The U.S. Coastal Research Program & the Keystone Variable Concept

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ABSTRACT

Complex societal issues surrounding future climate impacts and responses within coastal regions represent multifaceted non-stationary problems requiring a large, diverse and skilled workforce to develop and evolve solutions. The coastal zone represents a present and future challenge as the global nexus of nature, society, infrastructure, and development. In the last 25 years, 1999–2024, several of U.S. organizations have formally called for increasing the coastal workforce as complex coastal issues grow surrounding changing environmental conditions related to coastal hazards (e.g., sea level rise, increased storm frequency and intensity) and increased societal pressures such as development. Has society responded to these calls for action and if not, how can we more effectively work to do so? This paper presents a broad overview of global coastal zone issues necessitating workforce development. We posit tactics for workforce development across employment sectors and highlight the Keystone Variable Framework used by the U.S. Coastal Research Program (USCRP) to target actions leading to coastal sector workforce growth. Lastly, we discuss coastal student survey results to glean current and future deterrents to coastal workforce development and how to overcome them. This paper represents a renewed and imperative call to action for globally developing the coastal workforce across industries and disciplines, providing a framework to do so in the Keystone Variable Concept, that can be utilized across employment sectors.

1.1. The need for a skilled coastal workforce

The coastal zone is a complex system providing numerous valuable ecosystem services globally across economic and social sectors. The coastal zone is defined as the onshore and offshore region of a coast directly influenced by marine hydrodynamic processes (USACE, 1995; Ahlhorn, 2018). This zone hosts interconnected critical terrestrial and marine habitats and the contiguous region between sea level and 10 m elevation contains >10% of the world population despite only covering 2% of land area (McGranahan et al., 2007). It is historically and presently one of our planet's most highly productive, populated, and used areas, generating 14% of global Gross Domestic Product (Lazarus, 2017;

Magnan et al., 2019; IPCC, 2021). Nearly all coastal zone environments have been anthropogenically impacted. Despite geological instability and increasing vulnerability to changing environmental conditions related to increased coastal hazards (e.g., sea level rise, storm impact, and flooding events), these areas continue to be exploited and developed, compounding issues of increasing coastal hazards (McGranahan et al., 2007; Lazarus, 2017; IPCC, 2021 & 2022; Cooley et al., 2022). Coastal zone management action and inaction have cascading impacts on how associated social-ecological systems evolve and respond to extreme events (Masselink & Lazarus, 2020).

Globally, independent industries, organizations, economies, and communities (hereafter referred to as stakeholders) relying on the coastal zone are diverse, but intrinsically and inextricably linked (Weber & Nevela, 2006; Magnan et al., 2019). Actions by one stakeholder often

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impact another. Differing perceptions, interests, and needs must be acknowledged and accounted for to achieve balance in effective Integrated Coastal Zone Management (ICZM; Ahlhorn, 2018). Globally, ICZM is strived for, but difficult to both practice and define success given countless competing interests (Fig. 1) rooted in ethical and economic concerns (Ahlhorn, 2018; Magnan et al., 2019; Sagoff, 2008). Stakeholder priorities inform decisions and actions that alter and influence the physical state and sense of place (Milne & Ateljevic, 2001; Green, 2009; Fig. 1). Within and among countries, public opinions and scientific opinions on pressures related to the ocean are often not in alignment (Potts et al., 2016). Coastal zone practitioners must maintain a delicate social-ecological balance and receive specialized training in relevant coastal processes to implement effective ICZM solutions (NRC, 1999; Sagoff, 2008; Ahlhorn, 2018; NOAA, 2023).

To address future coastal community needs, experts must stem from diverse and multi-disciplinary fields spanning traditional and non-traditional backgrounds (Weber & Nevela, 2006; USNRC, 2016). Traditional experts such as coastal engineers and scientists work today, to some degree, with a range of experts including sociologists, economists, policy analysts, planners, communication specialists, data scientists, spatial analysts, and educators. Expanded engagement with these professionals and others in emergency response, renewable energy, tourism, aquaculture and supporting fields can expand traditional approaches and lead towards novel coastal strategies as well as develop the next-generation of experts. Trained individuals are needed across employment sectors, governments, education levels, and academic disciplines. Both cross-disciplinary knowledge and the ability to effectively communicate and build consensus with diverse teams are necessary skills, as are the abilities to listen and account for a diversity of opinions and priorities; these skills will grow more important as coastal zones have increasing impacts and multi-sector benefits. Stakeholders work independently, but task and project success and completion are contingent on collective efforts that often necessarily spans international borders (Hagermann & Kluge, 2017; CPMR, 2020). These interdependent teams bear high responsibility in addressing complex problems with joint action amid non-transparent and dynamic conditions (Kluge, 2014). A large, diverse, and skilled workforce is needed to effectively tackle evolving complex coastal issues (Vermillion & Higbie, 1994).

In the last 25 years, independent U.S. stakeholders made formal calls to increase the coastal workforce (Table 1). In 1999, a U.S. National Research Council (NRC) committee of experts concluded there was an explicit need for increased coastal engineering academic programs and funding, while also acknowledging a need for coastal geologists and physical oceanographers (NRC, 1999). A similar meeting of experts 15 years later echoed these sentiments and called for diversification of both coastal research themes and trained disciplines, including biology, ecology, chemistry, and social science (USNRC, 2016), indicating progress towards interdisciplinary approaches to research becoming more commonplace (Enquist, 2017). Recently, in 2023, NOAA dedicated a funding opportunity dedicated to training tomorrow's coastal leaders (NOAA, 2023) and in 2024 10 of 21 coastal U.S. Army Corps of Engineers (USACE) Districts independently stated needing a skilled coastal workforce as a major future societal issue (BCER, 2024). These issues are not limited to the U.S., in a report prepared for the European Commission on Fisheries and Maritime Affairs, Weber and Nevela (2006) call the maritime workforce “the very core of economic growth” and emphasize knowledge-dependency and specialized skill acquisition around filling these essential roles. The European Social Fund (ESF+) presents the labor force as an effective approach to climate change adaptation requiring continued investment. Similarly, two recent EU-based reports, one produced by Spain as a 2021 to 2030 action plan (MITECO, 2020) and another for the European North Sea Region (CPMR, 2020) both express the desire and need for continued investment in a skilled coastal labor force that includes further training for existing workers, the creation of new jobs, and expansion of capabilities. These sentiments are also felt in Australia, where community coastal needs are rapidly growing at a pace greater than the capacity to address them (van Putten et al., 2020; Elrick-Barr et al., 2025). Continued global calls for skilled workforce development indicate we, as a collective society, have inadequately responded to these calls. Addressing higher-level systemic and or structural problems, like barriers to entry, will likely hold more avenues for change and therefore have greater potential for positive impact (Scoones et al., 2020).

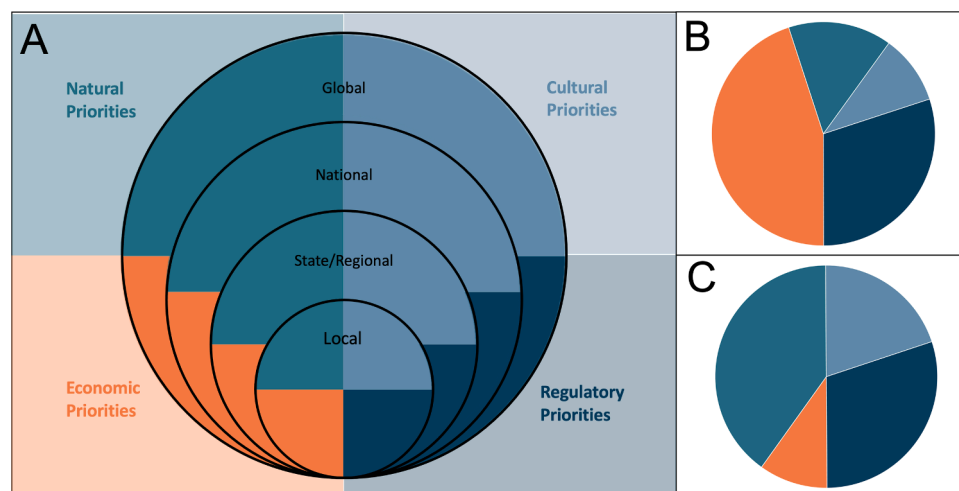


Fig. 1. Actions in the coastal zone with one priority intent are complex and affect others where coastal stakeholders (groups and individuals) maintain different cultural (i.e., historic, religious, spiritual), natural (i.e., biotic and abiotic processes and communities), economic (i.e., job creation, tourism, recreation, transportation, and commerce), and regulatory (i.e., governance and policy) priorities (A). Theoretically, a circle can represent a stakeholder, its priority balance (pie chart slices), and operation or influence scale (circle size; A). A circle can also represent a specific coastal locale where the aggregated stakeholder priorities acting on it define and impact the physical and abstract sense of that place. The priority balance at all scales is even (25%) in block A, but in reality, this is unlikely because of competing interests. As an example, a heavily developed coastal region might maintain a priority balance that enlarges the economic and regulatory wedges in how they support tourism and recreation, with corresponding decreases in the cultural and natural priority wedges to accommodate this (B). Conversely, an area with a greater emphasis on natural priorities may also focus on regulatory compliance as required to protect these natural resources, where the emphasis on nature would commensurately enhance cultural heritage in the region and likely diminish opportunities for some economic drivers and outcomes (C).

Table 1

U.S. organizations that have explicitly produced a formal call (public-facing directive, official release, or peer-reviewed literature) for developing the coastal workforce in the last 25 years, 1999–2024.

Organization	Call Type	Source Details	Source
National Research Council (NRC)	1999 Report	Findings of a committee of four U.S. Federal agencies regarding the state of current and future research and education needs surrounding coastal engineering.	NRC, 1999
American Shore & Beach Preservation Association (ASBPA)	2012 Publication	Organizational policy statement on the perceived state of U.S. coastal engineering and science.	ASBPA, 2012
U.S. Nearshore Processes Community (NPC)	2014 Publication	Findings of a 2014 meeting of members of academia, industry, and U.S. Federal agencies, representing the U.S. nearshore community, regarding future nearshore research needs where science and society intersect.	NPC, 2014
U.S. Nearshore Research Community (USNRC)	2016 Report	Findings from a 2014 meeting of 70 individuals representing 32 U.S. Federal and non-Federal stakeholders across academia and industry surrounding the state of nearshore research and community needs.	USNRC, 2016
ASBPA	2018 Publication	Organizational white paper about the state of the coastal engineering and science profession viewed through the lens of U.S. academic opportunities and Federal research needs.	Elko et al. 2018
National Oceanic and Atmospheric Administration (NOAA)	2023 Targeted Funding	Funded by the Inflation Reduction Act, the Climate Ready Workforce for Coastal States, Tribes, and Territories funding opportunity aims to grow the U.S. coastal workforce by training and then placing workers in existing and emerging jobs to enhance coastal climate resilience.	NOAA, 2023
U.S. Army Corps of Engineers (USACE)	2024 Report	In March 2024, the Board on Coastal Engineering Research (BCER) identified top coastal priorities in each coastal U.S. Army Corps of Engineers (USACE) District. Results indicated that 10 of 21 coastal Districts expressed an expected decline in the skilled coastal workforce in the coming decade as a future challenge to address.	BCER, 2024

1.2. Training a skilled coastal workforce

Workforce development challenges are not novel to the coastal sector or to the U.S. (e.g., Roche 2002; MITECO, 2020; CPMR, 2020;

Elrick-Barr et al., 2025), and challenges in this sector are shared globally across industries and coastlines (Magnan et al., 2019; CPMR, 2020). Definitions of the coastal sector are known to vary in the EU (Weber & Nevela, 2006). In this body of work, the coastal sector or workforce is defined as the population of people and organizations relying on, located in, and/or directly supporting communities in the coastal zone. This workforce may be exclusively or temporarily supporting coastal project development with their expertise and advanced training that is predominantly STEM-based (Science, technology, engineering, and mathematics). Workforce development throughout this paper refers to specialized training or education required to attain job skills; this training creates the talent pool from which workforce members are recruited. Workforce members must be retained in that sector with influx matching or exceeding outflux to maintain or meet growing demand (Jacobs & Hawley, 2009; Garcia, 2015). The coastal sector demand will increase relative to coastal population growth, climate change, and the aging out and retirement of long-standing leaders (McGranahan et al., 2007; Henderson et al., 2017; Magnan et al., 2019; IPCC, 2022). We require more individuals across professions serving the coastal community to perform technical, educational, managerial, and sociological duties affecting how we handle current coastal issues and predict and approach future hazards occurring more frequently and with greater impact relative to both lives affected and mitigation dollars spent (Magnan et al., 2019; IPCC, 2022; Elrick-Barr et al., 2025).

Presently, in the U.S., educational institutions are not meeting workforce demands in degree areas traditionally supporting the coastal workforce. According to data from the U.S. Bureau of Labor Statistics (2024), and using aggregated statistics from Data USA (2024), the U.S. is currently graduating students in engineering and geosciences at about one-half the annual demand, compounding the workforce deficit annually. For example, the number of engineering graduates is growing at 3.5%, but jobs are growing at 5–6% in that sector. Similarly, the number of geoscience graduates is growing at 2.1%, while labor demand is expanding at 5%. Meanwhile, the aging of the U.S. population 2010–2020 occurred 5x faster than the previous century for those age 65 and over (Caplan, 2023). Aging of the so-called “baby boomers” is contributing to what some refer to as the “silver tsunami” (Flood, 2020) or “great retirement boom” (Montes et al., 2022). After peaking in 2027, the proportion of retirement eligible people in the U.S. will decrease by 8% in 2030 but will be followed by >33% increase over the subsequent 20 years (U.S. Census Bureau, 2024). Both within academia and industry, the increasing rates of retirements lead to a loss of institutional knowledge and fewer training opportunities for students and young professionals. Concerns with the retiring of coastal industry leaders and associated loss of best practices are shared between the USA and EU (Weber & Nevela, 2006). However, in other countries, like those in the EU and Australia, concerns for workforce development are not also occurring concomitantly with overall reductions in the rates of higher education attainment; in both Australia and the broader EU, levels of higher education, university degrees, have been increasing in the last decade (Eurostat, 2024; Statista, 2024).

In the coastal sector, the full spectrum of novice to subject matter expert on the continuum of skill acquisition is needed, with proficiency and training varying (Dreyfus & Dreyfus, 1980; Vermillion & Higbie, 1994). Generally, training or specialization is needed when actions hold meaningful responsibility, such as decisions that impact lives directly or indirectly by affecting management, policy, public safety, health, education, or advocacy (Kluge, 2014). A well-developed coastal workforce requires STEM skills-based training with an undergraduate degree or higher (Vermillion & Higbie, 1994; NRC, 1999). Issues with impending enrollment cliffs at academic institutions will be felt most strongly in workforce sectors where degree-conferred skills are needed (Bauman, 2024) and with differing trends in degree attainment, will likely be felt more acutely in some countries than others (Eurostat, 2024). This issue is compounded by known difficulties surrounding hiring quality staff with both the interest and skills required in the coastal sector

(Vermillion & Higbie, 1994; Elko et al., 2018; Phillips, 2018a; BCER, 2024; Elrick-Barr et al., 2025).

To our knowledge, no workforce or managerial framework has been applied broadly to the coastal workforce. Thus, rather than posing methods that could theoretically be employed, we discuss the approach taken by the U.S. Coastal Research Program (USCRP). The USCRP is a community-based program conceptualized in 2014 in response to the call to develop a skilled coastal workforce (NPC, 2014; USNRC, 2016). Informed by the U.S. coastal community needs at large, the program objectives are to (1) identify societally relevant coastal research priorities/gaps, (2) enhance funding for academics and students to support the future workforce, (3) foster collaborations, and (4) support science translation for coastal communities (USCRP, 2024). The program is led by Executive Director coastal experts with Federal, Academic, and Stakeholder representation. In its first five funding years, USCRP received 442 project proposals totaling \$111 million requested from universities across 39 U.S. states and territories and supported 62 projects at \$14.6 million. Various U.S. agencies support coastal research (e.g., NOAA, NSF), but USCRP is uniquely dedicated to coastal nearshore research *alone*. The USCRP reduces duplication of effort by consolidating and coordinating U.S. coastal federal research needs to address priority societal demands that deliver results to improve coastal community resilience. The breadth of proposals funded versus submitted (13% funding rate) speaks to the need USCRP fills in this diverse and important research arena. More details on USCRP are in Supplementary Material S1.

1.3. The Keystone Variable Concept as an effective approach to complex problems

Reducing phenomena to their base constituents can be an effective approach to tackling complex problems (Ney, 2021). In the 1980s, to efficiently resolve psychological issues, the human behavior field adapted the ecological keystone species concept (Evans & Meyer, 1985).

Ecological keystone species are those with a disproportionate community impact relative to their abundance (Paine, 1969), whereas keystone variables are behaviors that, if changed, are likely to have multiple positive impacts or benefits on the greatest set of associated elements (Evans & Meyer, 1985). In the psychological field, this concept became a loose framework for approaching psychological issues by reducing them to their most defining or impactful elements (i.e., keystone variables) to target action on a desired outcome (Fig. 2). When applying this framework, the appropriate balance must be found both for the number of keystone variables targeted and action taken on them (Loehle, 1990; Barnett et al., 1996), no easy task in complex systems where there are fine lines between oversimplification, misrepresentation, and overall complexity (Grimm et al., 2005; Ntoumanis et al., 2014; Ward et al., 2020). Empirical interdisciplinary methods have been suggested for selecting behavioral or psychological target variables or outcomes (Barnett et al., 1996). However, to our knowledge this approach and its employment, hereafter the Keystone Variable Concept, appears to have been largely overlooked and underused in the literature as a whole and has never been applied to a workforce (Barnett et al., 1996). USCRP has adopted and adapted this approach by acting on targeted groups, identified by the Nearshore Research Community as keystone variables to efficiently tackle a system-level societal issue (NPC, 2014; Fig. 2).

To facilitate the desired outcome (Fig. 2A), coastal workforce development, USCRP focuses on actions to create opportunities and support coastal students and (2) stakeholders as keystone variables (Fig. 2B & C). The U.S. nearshore community suggested focusing on students with emphasis on research funding and training opportunities in 2014 (NPC, 2014); the U.S. National Plan reiterates this recommendation, which partly guides USCRP, as a directive for coastal workforce development (USNRC, 2016). Students are considered the most impactful keystone variables as it is from this trained pool that recruitment to the coastal workforce can occur (Fig. 3). The second variable, stakeholders, emerged organically as a common theme in the 2014 Nearshore Meeting and the National Plan, to tie fundamental and applied

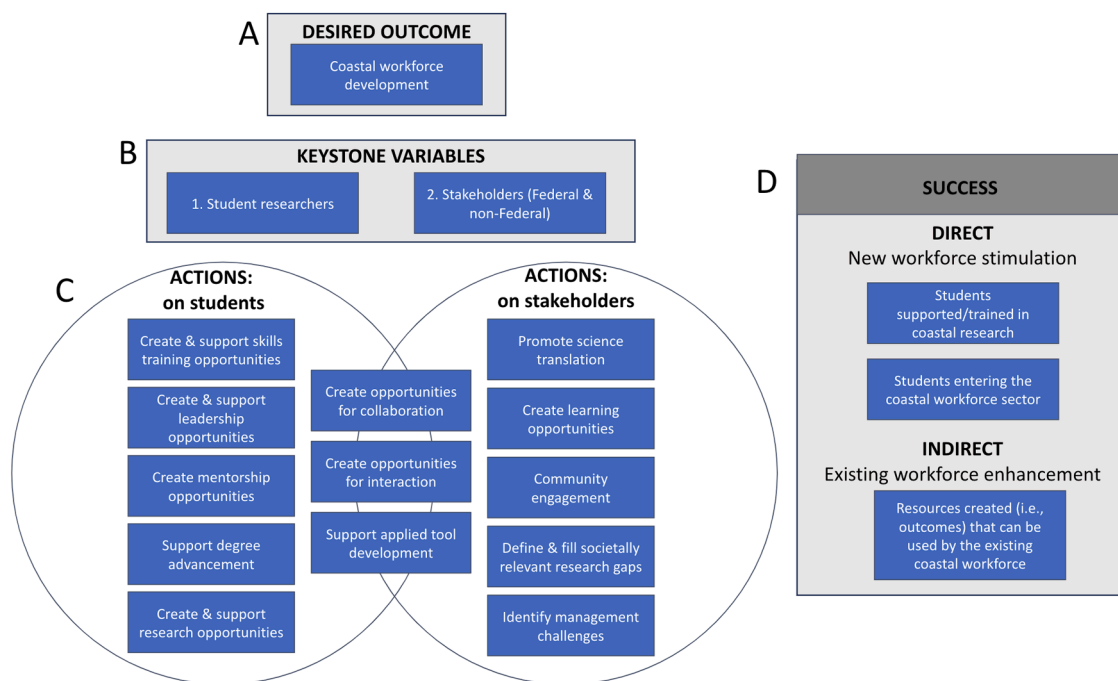


Fig. 2. Application of the Keystone Variable Concept begins by identifying the desired outcome(s) (A) that are based on keystone variables (B) with disproportionate impact where change or action (C) is targeted on them to achieve measurable success (D) toward a desired outcome (A). Action on keystone variable 1, students, to support their education and training is direct when performed by USCRP such as in workshops, and indirect when performed by a USCRP funded researcher acting as a mentor; these direct and indirect actions collectively enhance and expand educational experiences and opportunities. Actions on keystone variable 2, stakeholders, are largely indirectly mediated and controlled by principal investigators and their students, but tangible research products are in direct support of the stakeholder community at large especially those produced in consort with stakeholders.

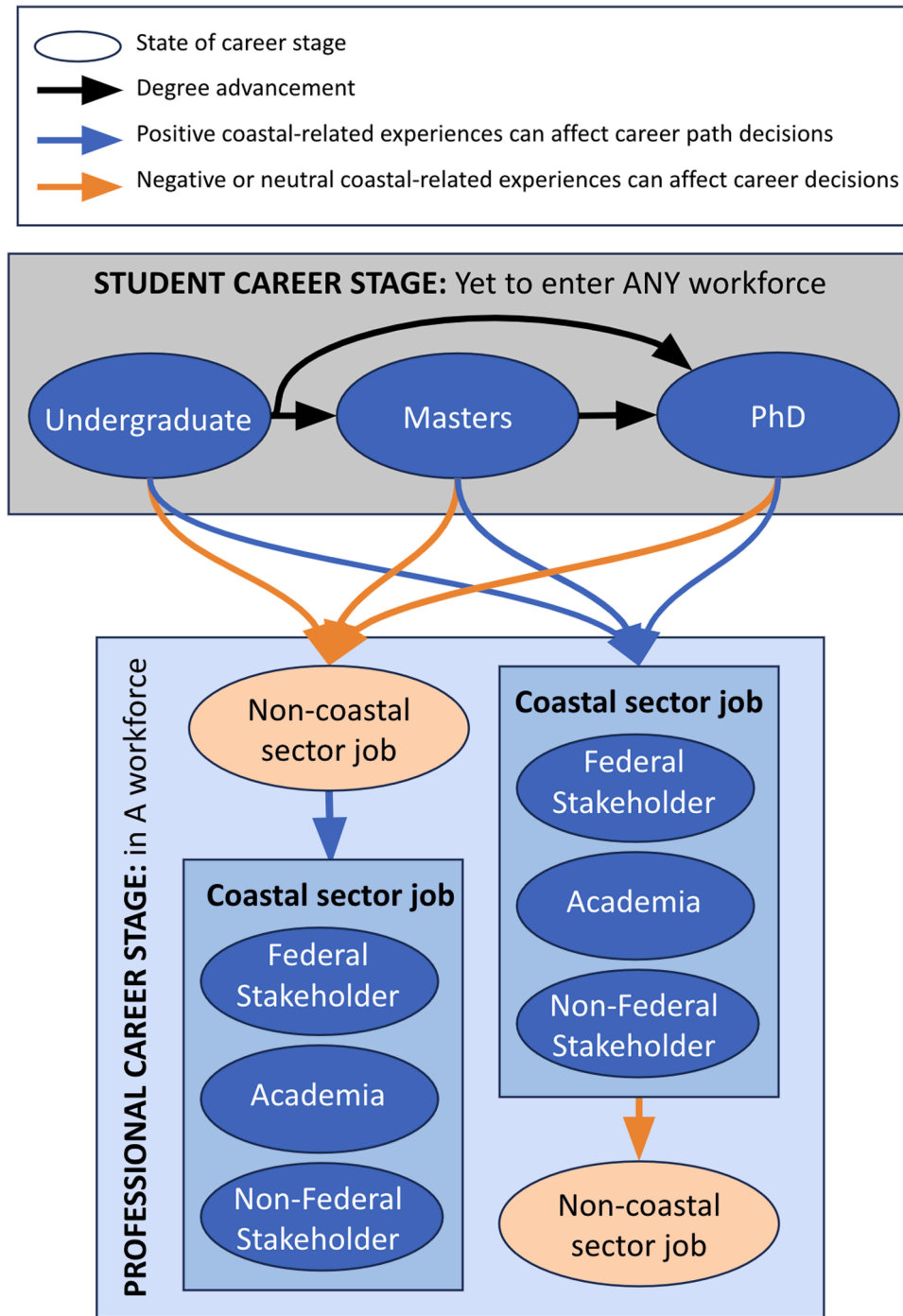


Fig. 3. Recruitment of students is an efficient way to support the coastal workforce, as students in higher education exposed to coastal topics (e.g., research, policy, management) are the skilled and trained workforce required in the coastal sector. After graduating, a student may join a workforce, where experiences can push them in different sector directions. Graduations represent inflection points to become a professional or continue schooling. Each degree offers the potential for additional positive and negative opportunities that could push a student toward or away from a sector. Professionals already in the workforce can swap between a coastal and non-coastal employer or focus although this may also be out of their control (e.g., employer mandated). Formal and non-formal skills-based credentialing programs, such as the Coastal Zone Foundation's Certified Coastal Practitioner® (CCP) Program can create a pathway to a coastal career for those with an interest, but no prior experience in non-traditional disciplines. Here non-Federal stakeholders is a catch all for all U.S. non-Federal government positions, including, but not limited to local government, non-profit organizations, corporations, etc. whereas examples of U.S. federal positions include those such as with NOAA, USGS, and USACE.

nearshore research outcomes back to stakeholder needs and priorities.

Quantifying successful employment of the Keystone Variable Concept should be considered and defined at the onset of its use and vary in each application (Evans & Meyer, 1985; Fig. 2). In the behavior field, quantifiable behavioral modification is used to assess success (Barnett et al., 1996). Quantifying additions to the coastal workforce would

parallel the behavioral approach, but this not possible given the size of the sector and issues with many coastal stakeholders having sector-spanning private project portfolios in the U.S. and EU (Weber & Nevela, 2006). Programmatically, USCRP defines success (Fig. 2D) in terms of three quantified metrics: number of (1) students supported, (2) outcomes representing resources for the existing coastal workforce, and

Table 2
Three main themes emerged in grounded theory analysis when students were asked to list/state factors important for choosing to pursue employment sector as opposed to another employment sector. Factors grouped in the themes were provided by at least 10 students or placed in the other category. This survey question was open-ended with no response length maximum or minimum. Numbers in parentheses after responses denote frequency of occurrence where students provided between 1 and 6 factors. These results reflect the responses of 90 students as six failed to answer the question.

Factors provided as responses by students in response to open-ended survey question	Work (i.e., Perceived work) Theme			Other		
	Pragmatic Theme	Passion Theme	Work (i.e., Perceived work) Theme	Other		
	1) Use knowledge/skills (18) 2) Location (26) 3) Salary (23) 4) Job/opportunity availability (25)	1) Contribute to positive change (25) 2) Sense of community (11) 3) Field of interest or passion (30)	1) Ability to conduct research (13) 2) Resource availability/access (funding, mentorship, networking, data) (11) 3) Nature of work (specific projects, interdisciplinary, or complex) (18)	1) Office/work culture (3) 2) Job security (4) 3) Advancement opportunities (6) 4) Work-life balance (6)		
Students providing at least one factor in theme	50 students	59 students	35 students	17 students		
Students providing factor/s in only this theme	15 students	20 students	3 students	3 students		

(3) students entering the coastal workforce. All requests for proposals to date have emphasized supporting student research, producing tangible outcomes, and collaborating with stakeholders. Underlying successful Keystone Variable Concept employment and implementation is the need for the (A) desired outcome and (D) success metrics to be both generally attainable and attainable specifically via the (C) actions taken on the (B) identified keystone variables (Fig. 2); if any of these four elements are unattainable or viewed as unattainable by the working team, then success around the desired outcome may be unlikely (Ntoumanis et al., 2014).

2. Methods

The goal in quantifying USCRP's impact is to understand how the program has supported the coastal workforce and if the framework (focusing on keystone variables) and actions around it have been successful. Specifically, we quantify the Program's currency for success in the number of students supported and outcomes produced and poll USCRP student researchers, who are national and international students at U.S.-based academic institutions, about their decisions and opinions surrounding career choices. Both efforts focus on the first five years of the Program's funding. During this time there were four requests for proposals in 2016, 2018, 2019, and 2021 resulting in 62 funded projects. Some of these projects are ongoing ($n = 13$), but the majority ($n = 49$) are complete. Active contracts will finish in 2025. Project outcomes (i.e., publications, data, presentations, etc.) will continue to be produced after project contracts conclude and are as of June 2024. Projects completed earlier (2016 versus 2021) could be expected to have produced more outcomes, but years since completion is unrelated to outcomes produced in our sample ($R^2 = 0.01$, $P = 0.52$) and anecdotally appears related to leadership or team dynamics.

2.1. Quantifying USCRP success metrics

USCRP defines success for supporting both the coastal community at large and the coastal workforce in the number of students supported, student recruitment to the coastal workforce, and outcomes produced. Student endeavors support the development of the future coastal workforce, whereas outcomes support the current coastal workforce indirectly as tools (Fig. 2, box D). In 2023, USCRP began tracking project impacts by developing a database of relevant information on project research teams, outcomes, and the science they conducted. Data were compiled via internal materials (e.g., proposals and progress reports) and then validated by Principal Investigators (PIs) as both accurate and complete; where appropriate, data were also cross-validated in Google Scholar, Scopus, or LinkedIn. From the database we use team member data, representing funded and non-funded PIs, co-PIs, students, collaborators, and Federal and non-Federal stakeholders. For students, this information includes degree status, affiliation, if they graduated from the degree that they were pursuing while engaging with USCRP, and the first full-time position taken as a new professional categorized as an Academic, Federal, or Stakeholder position (Supplementary Material S2). Outcomes include those that acknowledge USCRP as supporting the research and span different outcome classes and types (Supplementary Material S3). All means reported \pm standard error.

2.2. USCRP Student Coastal Workforce Impact Survey

We developed a 13 item survey (12 multiple choice, 1 free-response) to explore what decision factors or experiences (relative to the arrows in Fig. 3) influence student career considerations around joining the coastal sector. The questions explore how students feel about joining or being in the coastal workforce and how USCRP has impacted opportunities for coastal funding, research, networking, and professional development. All questions were required except optional demographic information. The full survey tool is available in Supplementary Material

S4 where we designed the survey questions to limit bias and leading questions. Prior to its distribution, we validated the survey by having both coastal experts and a pilot subset of our intended student population evaluate it for errors, clarity, and consistency and addressed any issues raised in these reviews prior to distribution to the full USCRP student population (265 students) via emails from their PIs (Aithal & Aithal, 2020). The pool of 265 students attend or attended educational institutions across 24 of the 30 U.S. coastal states along the U.S. Pacific, Atlantic, Great Lake, and Gulf coasts and three inland states (Arizona, Arkansas, and Utah) as both national or visiting international students. Survey participation was voluntary. The survey was open March 3, 2024 to April 16, 2024, and we had a 36.0% (96 students) respondent rate, which could introduce non-response bias. However, a total of 55 students shared their name in the survey, making it possible to cross-reference their responses with known employment information to determine if they work in the coastal sector and examine their location. These 55 students span 19 U.S. coastal states along the U.S. Pacific, Atlantic, Great Lake, and Gulf coasts, with one student from one inland state and this pool includes both national and international students. Ten percent or more of respondents, were international students attending U.S. academic institutions.

We employed grounded theory to inductively analyze the open-ended question (Corbin & Strauss, 2008). This question asked respondents to provide factors important for deciding to enter the coastal employment sector as opposed to another employment sector. Students could provide any answer, as we did not limit the number of factors that could be provided or length of answer allowed. A total of 90 of 96 respondents answered the question. Ten consistent decision factors emerged across respondents where each answer was provided independently by at least 10 individuals; these ten categories distilled into one of three conceptual categories of (1) driven by a pragmatic response, (2) a response speaking to a personal interest or passion, or (3) the theoretical nature of the perceived work (Table 2).

To explore patterns in survey responses, we computed response frequencies both to single select responses and grounded theory analyses

and performed Likelihood Ratio Chi-Square analyses to see if the likelihood of providing a response varied from chance across different student groupings. Specifically, we grouped and compared students (1) in two categories as those that graduated and are now young professionals ($n = 54$) or those that are still students ($n = 42$), (2) in two categories as those that were or are doctoral students ($n = 49$) versus masters or undergraduate students ($n = 45$) when engaged with USCRP, and (3) among those that optionally self-identified their gender in two groups as male ($n = 36$) or female ($n = 41$). We included one additional uneven grouping as responding positively ($n = 73$) or negatively ($n = 21$) regarding the desire to enter or be in the coastal workforce (survey response item 6 or 7, respectively, Supplementary Material S4). Additional information on the manual carrying out of the grounded theory analysis and accompanying open-ended responses can be found in Supplementary Material S5.

3. Results

3.1. Coastal workforce development: Direct successes

3.1.1. Students trained in coastal sciences

In its first five years (2016–2021), USCRP provided research opportunities to 265 students. Each project involved 1 to 14 graduate or undergraduate student researchers ($\bar{x} = 4 \pm 0.5$) enrolled in academic disciplines supporting the coastal workforce (Fig. 4). Students were among project teams of stakeholders (97 non-Federal stakeholder affiliations represented) and Federal (14 U.S. Federal agencies represented) and academic researchers (spanning 75 academic institutions and 29 U.S. states) representing potential future coastal employers. Most non-Federal stakeholders were state agencies (19.5%), coastal NGOs (17.5%), or local governing agencies (34%).

3.1.2. Students entering the coastal workforce

The majority of USCRP students join or have a desire to join the coastal workforce post-graduation. Of the 195 USCRP supported

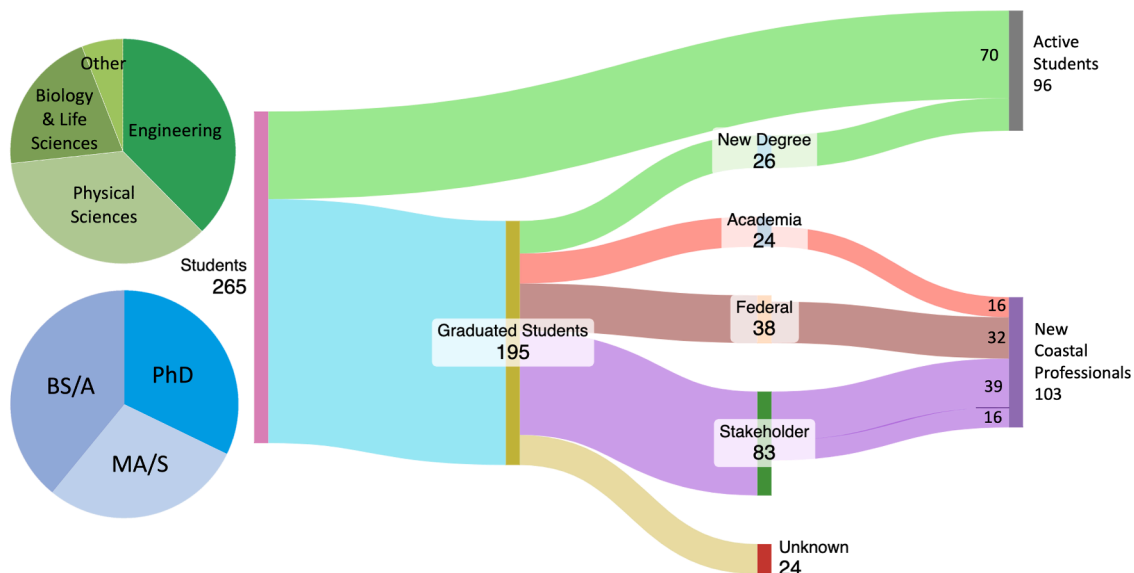


Fig. 4. Most past USCRP student researchers (51.4%–60.9%) have graduated, between 2017 and 2023, to become new coastal sector professionals. Of USCRP's 195 graduated students, at least 87 work in the coastal sector, this is 51.4% of graduated students that did not go on to get an additional degree. Note the split in the stakeholder flow (purple), as conservatively, an additional 16 students likely do coastal work, but for stakeholder companies that are not coastal-specific (e.g., general engineering, consulting, environmental firms). Including these 16 students in the count, up to 60.9% of 195 graduated past-USCRP students have joined the coastal sector as new professionals. Students span degrees (blue pie chart) and training from disciplines traditionally and not traditionally serving the coastal sector (green pie chart, other discipline category encompasses Policy, Planning, and Social Sciences or Environmental Studies and Conservation). After graduating, most students transitioned into a stakeholder (42.6%) employment position (i.e., local government, corporate, local business, state agency, or Non-Governmental Organization (NGO)), of which 19.5% took positions with a U.S. Federal agency, 12.3% remained in an academic setting, and 13.8% have pursued new advanced degrees. The remaining 11.8% are yet to accept a position after graduation or are unknown.

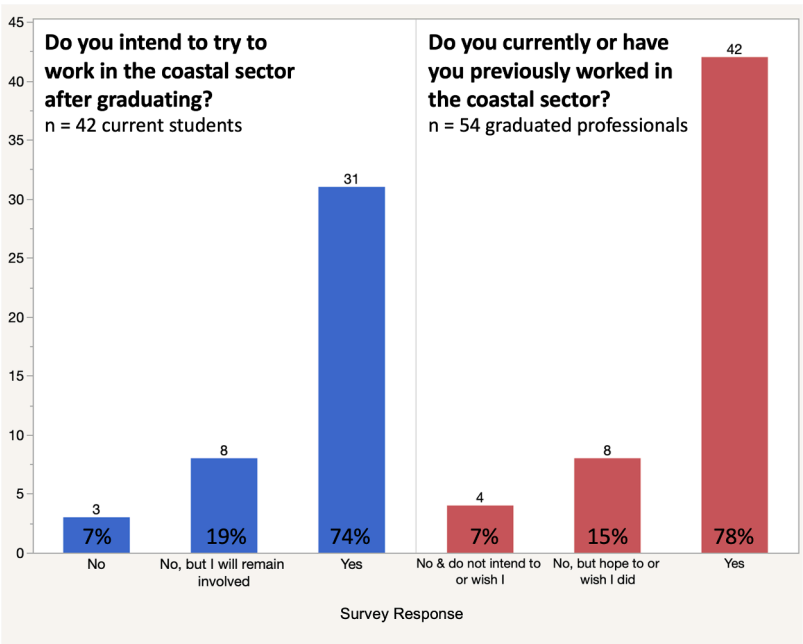


Fig. 5. Students and graduated young professionals show a strong desire to enter the coastal workforce. In total, 92.8% (39 of 42) of students intend to remain involved in or work in the coastal sector after graduating.

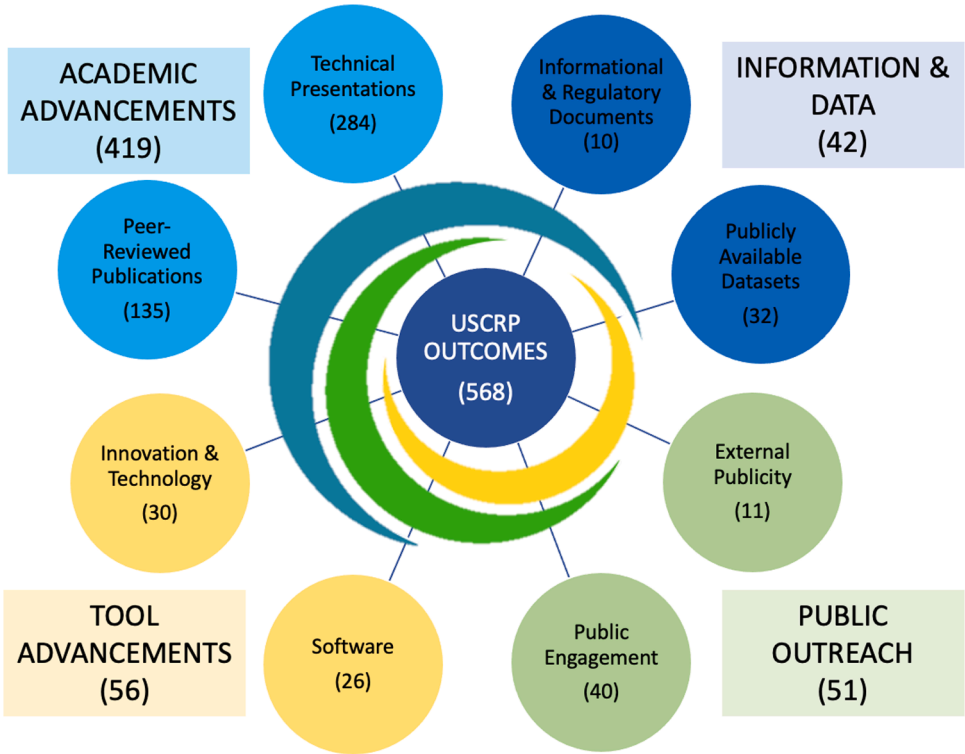


Fig. 6. In its first five years of funding, USCRP projects have produced 568 outcomes that indirectly support the coastal workforce. USCRP defines outcomes as tangible products that can be found and utilized (i.e., searchable, maintaining a digital footprint or online presence) across four groupings. 47.0% of these outcomes were student researcher-led such as publication lead author or presenter.

students that have graduated, at least 51.4% and up to 61.0% of those that are now new coastal sector professionals (Fig. 4). Most graduated students currently or previously worked in the coastal sector, and most current students hope to enter the coastal workforce upon graduation (Fig. 5). Of graduated respondents (n = 54), 32 provided their name; of those 32, 26 stated currently or previously working in the coastal sector,

having graduated between 2017 and 2023. We confirmed that all 26 of those students are still in the coastal sector, specifically working for a non-Federal stakeholder (n = 14), Federal stakeholder (n = 4) or are pursuing academia studying coastal topics (n = 8). A total of 80.0% of graduated and 54.0% of not graduated respondents stated their experience working on a USCRP-funded research team positively affected

their outlook on pursuing a coastal sector job.

3.2. Indirect coastal workforce support: outcomes produced

The 62 projects produced 568 outcomes as of June 2024 (Fig. 6), 47.0% of which involved students as lead researchers (i.e., first authors). Maximum outcomes for a project is 34 ($\bar{x} = 9.2 \pm 0.9$). These outcomes encompass academic advancements (73.7%), tool advancements (9.9%), information and data (7.4%), and public outreach materials (9.0%; Fig. 6). Details on outcomes are in Supplementary Material S2. Outcomes indirectly support the coastal workforce and community, but it is important to note that many were produced in collaboration with both non-Federal and Federal stakeholders for specific management goals to directly aid a coastal community. For example, many of the USCRP-sponsored modeling efforts are improvements to components of the Coastal Storm Modeling System (CSTORM-MS) developed by USACE, which provides publicly accessible historical and potential future calculated coastal hazard data for use by academia, industry, agency, stakeholders, and the public..

3.3. Creating and promoting positive coastal science experiences

3.3.1. Supporting first time student experiences

USCRP-funded research offers avenues for foundational coastal research. Prior to engaging in USCRP-funded research, 43 students (44.8% of survey respondents) had not previously performed coastal research. Relative to what would be expected by chance, undergraduate respondents were more likely to have had their first research experience associated with USCRP, whereas doctoral students were less likely to have had their first coastal research experience with USCRP ($\chi^2 = 13.07$, $DF = 2$, $P < 0.01$).

USCRP-funded research creates opportunities for community and stakeholder engagement. A total of 33 (34.4%) survey respondents had not previously had any experience in coastal education, advocacy, management, or engagement, prior to their USCRP experience. Relative to what would be expected by chance, undergraduates were less likely to have engaged in these activities, whereas both masters and doctoral students had more experience in this arena ($\chi^2 = 6.15$, $DF = 2$, $P < 0.05$).

3.3.2. Expanding coastal research opportunities

In regards to coastal research funding, 25% of respondents identified USCRP as their only option, 49% identified alternative sources, and 26%

responded that they did not know what funding was available to them. Degree level impacted responses as, relative to chance, doctoral students were more aware of alternative funding, whereas masters students said USCRP was the only option available to them, and undergraduates were less aware of opportunities ($\chi^2 = 10.84$, $DF = 2$, $P < 0.03$).

The majority of student respondents, 74.0% (71 of 96) agree (46 students) or somewhat agree (25 students) with the statement “I would not have pursued or considered pursuing a career in the coastal sector without exposure to coastal topics in an academic setting.” Remaining students neither agreed or disagreed with the statement (14), somewhat disagreed (6), or disagreed (5).

Students expressed that USCRP positively impacted their outlook to enter the coastal workforce. Specifically, 84.4% of respondents (81 of 96) agree (60 students) or somewhat agree (21 students) with the statement “My experience working on a USCRP funded research team positively affected my decision to pursue or want to pursue a career in the coastal sector.” The remaining 16 students neither agreed or disagreed with this statement, except one “somewhat disagree.”

3.3.3. Decision factors to enter the coastal sector versus another field

Student’s open-ended answers about factors important to them when considering entering the coastal employment sector distilled into three themes in grounded theory analysis: (1) pragmatic, (2) passion, and (3) work (Table 2). Respondents provided 14 unique decision factors, where 10 fall into the three themes and were independently provided by >10 respondents (Table 2). The four responses not shared by the collective group are in an ‘Other’ category.

Providing a response in any one of the three categories appears individual-based, not explained by groupings. Graduated and not graduated students did not differ in their likelihood of providing a pragmatic ($\chi^2 = 1.12$, $DF = 1$, $P = 0.29$), passion ($\chi^2 = 0.12$, $DF = 1$, $P = 0.73$), or work response ($\chi^2 = 0.56$, $DF = 1$, $P = 0.46$). Responding positively versus negatively regarding the desire to join the coastal workforce and degree being obtained (doctoral versus masters or undergraduate) did not explain the likelihood of providing responses in the themes.

Gender explained some patterns in theme responses. Specifically, females provided a response in the work theme more than expected by chance ($\chi^2 = 5.38$, $DF = 1$, $P = 0.02$) and independently provided more answers (i.e., factors) responding to this question than males ($\bar{x}_F = 2.71 \pm 0.20$, $\bar{x}_M = 2.03 \pm 0.22$; Student’s t-test, $t_{74} = -2.30$, $P = 0.02$). Gender did not explain the likelihood of providing a pragmatic or

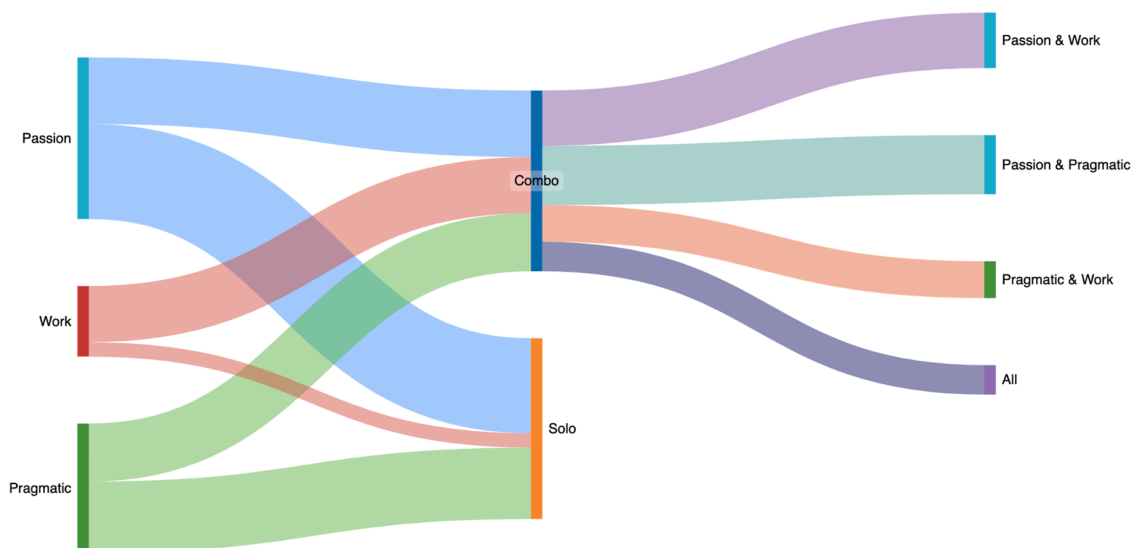


Fig. 7. Passion is the strongest draw to the coastal sector as the most prominent theme independently provided when students were surveyed about what factors were most important to them when considering entering the employment sector. Flows represent proportions.

passion response.

Passion is the strongest theme influencing students to join the coastal field. Students provided decision factors in the passion theme most and more than would be expected by chance whereas they provided decision factors in the work theme less than expected ($\chi^2 = 12.97$, $DF = 2$, $P = 0.001$; Fig. 7). Students provided between 0-3 factors per theme. When a student provided an answer in the passion theme, they provided two or more factors more than expected whereas more students than would be expected by chance did not provide at least one work theme factor ($\chi^2 = 23.10$, $DF = 4$, $P < 0.0001$). A passion-based response was the most common when only a single theme was provided alone or in combination, followed by pragmatic (Table 2 & Fig. 7). Only eight students provided an answer touching on each of the three themes. There are no discernable patterns (gender, degree, desire to enter coastal workforce) when examining who provided the top two factors in the passion theme (Table 2 - positive change or field of passion).

4. Discussion

4.1. Recruiting and retaining students desiring to enter the coastal workforce

USCRP has had direct success in new coastal workforce stimulation and these new professionals must be retained in the sector. In just five years, USCRP supported over 250 students, 195 have graduated and began their professional careers, or began new degree ventures, where the desire to enter the coastal workforce matches the action to do so (Fig. 5), as 51% or more of USCRP young professionals have entered the coastal workforce (Fig. 4). This 51+% (87+ new professionals) is a significant addition to the trained U.S. coastal workforce as in 2018 USACE reported having 201 coastal staff in the entire agency (Elko et al., 2018). The 195 students all graduated 2017-2023, so these data support short-term (i.e., <10 year) retention of up to eight years for students entering the U.S. coastal sector; in the future, these data can be used to examine long-term retention relative to the course of career trajectories. How can the U.S. retain these students who are likely to have more careers in their lifetime than previous generations (Carless & Arnup, 2011)? We know that today the concept “one life—one career” is largely irrelevant and this is especially true among turnover-prone millennial employees (Arthur & Rousseau, 1996; Twenge, 2010; Wiggins, 2016). Should retention be aimed at the sector-level as opposed to position or organization and how can we encourage retention? We suggest that the three themes gleaned can be tools used to work to retain students in the coastal sector in the U.S. and beyond.

Knowing personal passion motivates coastal students can be used to attract and retain qualified candidates. An EU survey of younger students suggested that personal interest or passion impacted general interest in science; the findings of this body of work support this and extend it (Ainley & Ainley, 2011; Fig. 7). Satisfaction can increase employee retention, and retention is a hallmark of increased job satisfaction and work performance (Garcia, 2015; Hassan et al., 2021). Professional satisfaction affects life satisfaction in which the extent one pursues their passions has been linked to both higher job and life satisfaction (O’Keefe et al., 2021). Satisfaction, passion and retention are linked (Garcia, 2015; Hassan et al., 2021; O’Keefe et al., 2021) and this may be especially true in younger generations (i.e., the future workforce) whose life and work values differ from older generations (Twenge, 2010; Hassan et al., 2021).

We argue students must be aware that positions and opportunities matching their passions exist, and are available, and attainable (a prominent factor in the pragmatic theme). Early discipline-specific courses have been shown to increase student degree track retention. With this in mind, specialized coastal-specific courses or degree tracks can both spark and stoke this passion (Black et al., 2015). The stated need for specialized coastal education has been expressed in both the U.S. (see Table 1) and EU countries; in these countries, and in Australia,

specialized degree tracks in coastal-specific disciplines exist in higher education at the university level, but are also relatively limited or restricted to a small proportion of schools, which can make them difficult to find (Weber & Nevela, 2006). To stave this issue, in the U.S. and for U.S. academic institutions, ASBPA has created a Coastal Universities Guide with the goal of making prospective students aware of U.S. institutions offering these specialized programs (ASBPA, 2025). There is a program in the EU, the European University of the Seas (SEA-EU) program, with the goal of promoting coastal education through joint degree attainment in coastal fields at European universities (SEA-EU, 2025). The underlying passion of potential employees should be considered around generational differences in attention spans, information retrieval strategies, and influence when choosing where and how to advertise coastal jobs and opportunities (Twenge, 2010). Programs and organizations like ASBPA and SEA-EU broaden student opportunities by making them visible and in doing so create and support a network from which coastal employers might be more successful in targeting talent from.

Passion can outweigh the importance of salary (O’Keefe et al., 2021), but pragmatic factors are a consideration around joining the coastal sector. The pragmatic theme was the second most prominent with location and salary as predominant motivating factors. A desire to be well-compensated generally positively increases motivation, satisfaction, and retention and can be inextricably linked to location (Kathawala et al., 1990; Hassan et al., 2021). Location as a factor was often provided with salary relative to a perceived higher cost or living at or near the coast with some interest or stated need for remote options (Table 2). While remote work is not a novel concept (Olson, 1983), its recent traction as a viable business strategy is new (Ferreira et al., 2021; Ozimek, 2020). Adoption of more flexible remote options where appropriate may benefit all parties – remote work can reduce operational costs where it is a premium such as at the coast, offer employees more flexibility which can translate to higher productivity (Golden et al., 2013), and reduce cost of living on a case-by-case basis that can be reflected in salary (Ozimek, 2021). Attractive salary and remote options together could prompt career shifts (Carless & Arnup, 2011; Golden et al., 2013) to the coastal sector (relative to Fig. 3) and catch students with inherent passion for coastal work that are ‘slipping through the cracks.’ Students need to be aware that coastal jobs and opportunities exist, are available, and are attainable, but also that they are pragmatically viable around salary and location.

4.2. The growing demand for a skilled coastal workforce

Social-ecological issues surrounding increasing coastal development, increasing coastal populations, and growing need for solutions to the observed and anticipated effects of changing environmental conditions, will continue to be debated across nations (McGranahan et al., 2007; Magnan et al., 2019; IPCC, 2022). Research on the implementation and viability of managed retreat has seen a marked increase in the last five years (O’Donnell, 2022). No single management solution will be best for all coastal communities and public opinions will vary locally, regionally, and nationally (Potts et al., 2016). Regardless of these sources of societal friction and lack of general consensus around them, coastal areas will continue to be disproportionately chronically and episodically impacted by climate change (IPCC, 2021 & 2022; Cooley et al., 2022). Issues around climate change and ICZM have been discussed for decades (Ahlhorn, 2018), and while our tools to reduce coastal vulnerability have improved, they require a skilled coastal workforce to continue to develop and employ towards innovative solutions to complex coastal issues (Dyckman et al., 2014; Masselink & Lazarus, 2020; Ward et al., 2020).

U.S. students show a desire to graduate and join the coastal workforce, but amid an overall reduction in university matriculation rates and faculty recruitment. After peaking around 2025, the U.S. population of college-age citizens is expected to contract by nearly 15% over the

next 5-10 years (Bauman, 2024). This shrinking population of high-school graduates, combined with declining interest in pursuing college degrees (i.e., 6% reduction 2010-2021), equates to fewer U.S. students pursuing degrees in areas often serving the coastal workforce (NRC, 1999); compounding this issue, fewer PhD graduates are pursuing academic careers in engineering and geosciences even though awarded doctorates increased by 74% from 2002 to 2022 (NCSES, 2023). The proportion of U.S.-based PhD graduates with jobs in industry doubled since 2002, with the largest increases seen in geosciences, ocean sciences, and biological sciences. Fewer college graduates and declining faculty will naturally lead to reduced training opportunities after high school. This is a major concern considering undergraduates are more likely to have their first research or stakeholder experience with a targeted coastal-specific program like USCRP and also least likely to understand avenues for opportunities. It is important to note that these concerning declines are not exclusive to the US, in the EU, especially Western Europe, and Australia, there has been a documented reduction in general student interest in science (Lyons, 2007; Ainley & Ainley, 2011).

Students in disciplines that have not traditionally served the coastal workforce (e.g., computer science, social science) can be recruited if they develop an interest and have support to explore it. Academics can tend to work with students whose backgrounds and interests align with theirs (Roebken, 2010). However, many academics also consciously or subconsciously engage in Learner-Centered Research Mentoring (LCRM) where the student's independent passion and motivation drive the focus, mediated and nurtured by the mentor providing transferable skills within the framework of their expertise (Phillips, 2018b). Formal and informal LCRM training opportunities in academic departments and universities can encourage mentors to flex their skills beyond their own interests to the benefit of many employment sectors (Kiltz et al., 2004). Among other needs, a driving student passion and work ethic are needed for successful LCRM (Roebken, 2010). To develop this passion in coastal, teaching coastal socioecological topics in early development and adolescence (ages 7-18), when students are more likely to develop an interest that might grow into a passion, could increase demand for coastal education opportunities in higher education, ultimately trickling into the employment sector (Jacobs, et al., 2002; Dotterer et al., 2009; Black et al., 2015).

4.3. The Keystone Variable Concept to tackle complex system problems

USCRP is a unique and strong example of a successful application of the Keystone Variable Concept to support a growing trained student workforce pool with paths into the coastal sector by engaging both students and stakeholders (i.e., potential employers). To do this, USCRP ingested the needs and concerns expressed by the U.S. nearshore community (NPC, 2014) when choosing to focus on coastal workforce development as a main organizational initiative and desired outcome, and then choose to focus on stakeholders and students as their keystone variables. Their actions on these variables reflect the guiding motivation, goals, and objectives of the organization (USCRP, 2024) and their success metrics are both measurable and attainable for reporting and defining success. The Keystone Variable Concept can be used to tackle coastal workforce development and other complex problems because it does not offer a solution, rather it offers a working framework on which to build.

4.4. Conclusion: A new call to action for developing the coastal workforce

In the last 25 years, there have been formal calls by various and diverse U.S. stakeholders to bolster the coastal workforce (Table 1) and similar sentiments have been expressed in regulatory documents and publications from Europe and Australia — have we as a society adequately responded to those calls? While it was outside the scope of this paper to quantitatively answer this question, we feel it is reasonable

to say no, given that U.S. Congress recently provided funding to address this issue in 2023, multiple large EU bodies have called for the need to invest in the coastal workforce, and recent Australia-based publications state the need in coastal not meeting the current and future demand (MITECO, 2020; CPMR, 2020; van Putten et al., 2020; NOAA, 2023; Elrick-Barr et al., 2025). In addition, 10 of 21 coastal USACE Districts have concerns for meeting future needs with their current and forecasted future workforce (BCER, 2024). In just 10 years, USCRP has increased the pool of qualified U.S. candidates (i.e., trained students) for skilled coastal jobs and supported the production and availability of coastal management tools for the existing coastal workforce and community at large. The Keystone Variable Concept offered the framework for USCRP to do this, and can be applied to other complex problems and in other countries to make solutions more attainable. Student survey results highlight the importance of both coastal-specific funding and academic training to support the future coastal workforce, where recruitment and retention of skilled individuals must consider both pragmatic considerations and passion. While the student survey responses here were predominantly of a U.S. perspective, international students were also part of the polling body, but repeating the open ended aspects of the survey tool in different countries and with different student groups would be helpful for ensuring these themes hold value beyond the U.S. The future challenges surrounding the global coastal zone will grow relative to climate change and sea level rise. We must take direct action to globally develop the coastal workforce now, and the Keystone Variable Concept can offer an effective and viable framework to approach and work to solve this and other complex problems.

CRedit authorship contribution statement

B.R. Charbonneau: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.A. Cialone:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **B.M. Webb:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **A. Mercer:** Writing – review & editing, Visualization, Investigation, Conceptualization. **J.D. Rosati:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **N. Elko:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **J.A. Straub:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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