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Scientists' prioritization of global coastal research questions

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ABSTRACT

Complex coastal management challenges often span ecological and political boundaries, and involve competing demands from groups advocating alternative coastal management strategies. As a consequence, policy-makers require scientific evidence from across a range of disciplines. Implementing cross-disciplinary research and facilitating science-policy engagement are, however, a significant challenge in its own right. Seven recent ecologically oriented 'big question' exercises identified a variety of research questions potentially important for coastal and marine management. In this research, 592 coastal scientists from 91 different countries completed a survey that ranked those 20 coastally oriented research questions. There was a clear overall ordering of aggregated coastal research priorities but scientists did exhibit heterogeneity regarding priorities. Some prioritized ecological issues while others focused more on issues such as coastal resource use or global environmental change. The differences in opinion were largely disciplinary-based, highlighting the importance of, and challenges in, encouraging scientific collaboration across disciplines to support effective coastal zone management. In addition to the ranking of existing questions, scientists submitted an additional 340 potential priority research questions, thus broadening the participatory nature of the original exercises. New questions regarding coastal processes, contaminants and pollution, and monitoring were prominent. This first synthesis across 'big question' exercises should provide valuable insights into the diversity of scientists' opinions and help policy makers understand potentially conflicting science advice.

1. Introduction

Coasts of the world face multiple threats from resource exploitation [1], upland activities that affect land cover and watershed hydrological services [2,3], changes in watershed hydrology and coastal zones due to climate change [4,5], and sea level rise [6]. Policy makers need scientific research aligned with policy needs [7,8] to help inform choices regarding the conservation and management of coastal species and habitats, resolve conflicts over coastal resources, and contribute knowledge needed to help solve earth science grand challenges [9,10]. Coastal challenges, many of which span multiple spatial and temporal scales, require engagement with policy-makers on regional to international levels [11,12]. The complex and inter-related drivers of environmental change e.g., [9,13,14] and the urgent need for policy-relevant knowledge to manage the biosphere have led to a call for a new 'social contract' for science that would proportionally address the most urgent needs of society and communicate that knowledge widely in order to inform individual and governance decisions [12]. The scale of global environmental problems suggests that the coastally oriented scientific community has a collective responsibility to periodically reexamine its goals and activities in order to most effectively create and communicate knowledge needed to address those challenges.

Global coastal zone research themes that are integrative across biogeochemical, physical, and human dimensions of coastal change have been identified for the Land–Ocean Interactions in the Coastal Zone (LOICZ) Science Plan and Implementation Strategy [10]. Such global research themes are, however, necessarily broad at the global scale. The need to operationalize research prioritization has recently led to a variety of participatory 'big question' exercises between scientists and policy makers [15–21]. These ecologically oriented exercises have identified narrower research questions that are both relevant to policy-makers' needs and actionable in discrete research programs [8]. Facilitating and encouraging cross-disciplinary collaboration among disciplinary experts are central for answering these questions because complex problems at the intersection of environmental management and societal decision-making require expertise beyond that offered by any single discipline e.g., [9,22]. One goal of the LOICZ strategy, for example, was to overcome traditional disciplinary fragmentation between the natural and social sciences for coastal science [10].

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In this research, global coastal scientists' research priorities were assessed with a survey that asked scientists to rank 20 coastally oriented research questions derived from seven recent 'big question' exercises [15–21]. The first goal was to quantify and compare research priorities and orientation among scientists with different demographic profiles and from various professional disciplines. This could help increase our understanding of the opportunities for, and constraints to, cross-disciplinary collaboration for solving complex coastal conservation and management issues. The second goal was to use the survey as a platform for collecting additional research questions that may have been overlooked during the initial big question exercises. Five of the original exercises [16,17,19–21] specifically focused on the conservation of biological diversity, whereas this survey targeted coastal scientists from all disciplines. The results suggest that such syntheses can help build understanding of research prioritization that should, if used to inform the design of cross-disciplinary scientific collaboration, increase the potential for scientists from different disciplines to effectively align their coastal research with the needs of policy makers.

2. Methods

2.1. Selection of questions

Sixty coastally oriented candidate questions from among recent exercises [15–21] were identified. Those questions fell from eight broad themes: aquaculture; coastal management; fisheries; human health; marine systems; marine protected areas; species management; and watershed management. After accounting for redundancies, questions that were primarily marine or terrestrial – rather than specifically coastal – in orientation, or questions that were very broad in scope, the number of questions for this survey was reduced to 20.

2.2. Survey instrument

An Internet survey was used for data collection (an example of a full survey is available from the corresponding author). In the survey, respondents were randomly assigned to 1 of 300 sets of best-worst scaling (BWS) ranking comparisons [23]. In each of 15 ranking comparisons (e.g., Fig. 1) per survey asked each respondent was asked to choose her or his relatively most and least important research question from among subsets of 4 of the 20 questions. BWS rankings force respondents to discriminate among the research questions by choosing the most distinct pairs. This prevents respondents from consistently using the middle points or one of the end points as they might with rating scales.

The BWS approach permitted a full ranking of all 20 questions for each individual completing the survey. At the end of the BWS comparisons, respondents could replace up to three of their least preferred research questions (i.e., those ranked 18, 19, or 20, which were calculated 'on the fly' during the survey) with alternatives and provide rationale about why they proposed those questions. Each replacement question was then rated by the authors as to how close it was to any of the 20 existing questions in the survey with a simple scale of 1 (extremely close) to 5 (unique). There was also an additional category for very broad questions or questions that had been explicitly dealt with in prior big question exercises [15–21]. Passages from these questions were then coded (using NVivo 9, www.qsrinternational.com) with user-defined labels based on emergent themes from the initial set of priority questions and iteratively derived from the newly submitted questions.

2.3. Sample

In order to collect opinions across the broad range of the coastal science community, an ISI Web of Science search was used to identify 1947 articles (2005–2010) on coastal threats, aquatic pollution, management, and governance from 470 journals (full list available from corresponding author). From these, a sample of 2078 unique authors (from 91 countries) with email contact information was constructed. Following standard protocol [24], individuals were contacted up to five times by email between 24 May and 23 June 2011.

2.4. Data analysis

2.4.1. Quantification of aggregate and individual priorities

The statistical analysis proceeded in three stages. First, mean probabilities for each respondent choosing each of the 20 questions as their top priority in the BWS comparisons were calculated with Hierarchical Bayesian (HB) analysis [25]. The HB approach is useful because it permits individuallevel probabilities of choice to be estimated. In non-technical terms, the HB algorithm estimates how different individual scientists' research priorities are relative to other scientists, a simpler task that than estimating each scientist's priorities independently. Individual-level data on how much priorities differ from the sample average are then used to adjust the algorithm to reflect the optimal mix of individual preferences and sample average.

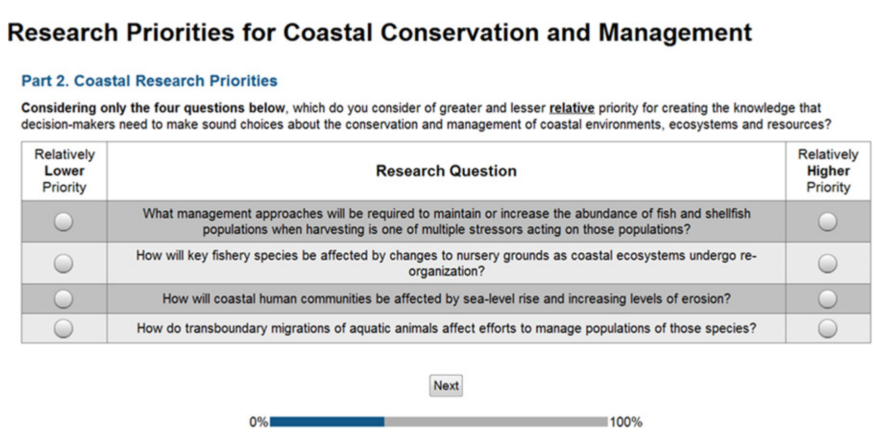

Fig. 1. Example of a best-worst scaling (BWS) ranking comparison.

2.4.2. Latent class analysis to assess heterogeneity in priorities

In the second stage, latent class (LC) analysis [26] was then applied to cluster scientists with common patterns of research priorities. The probabilistic LC clustering methodology minimizes within-cluster variation while maximizing between-cluster variation [27], an advantage compared to traditional clustering methodologies where choice of the cluster criterion can be arbitrary. Bayesian Information Criteria (BIC) was used to identify the most parsimonious model and local interactions between indicators were eliminated by systematically deleting those with significant interactions. BIC and other information criterion apply a penalty factor to the number of estimated parameters in a model. In LC cluster models, BIC penalize extra parameters more heavily, and tend to suggest fewer clusters in total, than alternative criteria such as Akaike Information Criteria (AIC) [28]. This can make model interpretation simpler.

LC models contain both latent, or unobserved, variables and manifest, or directly observed, variables [29]. In this research, the manifest variables, research question rank (i.e., priority) for each scientist, reflect the unobserved latent variable, research orientation. The assumption of local independence implies that the manifest variables are all conditionally independent of each other [29]. A significant bivariate residual Pearson chi-squared statistic ($\chi^2 > 3.84$, $df=1$, $p < 0.05$) signifies that an assumption of local independence is erroneous. When significant interactions between indicators were found, research questions with the highest number of significant bivariate residuals were sequentially deleted until all significant interactions were eliminated.

2.4.3. Identification of predictors of heterogeneity

After the first step, where individual research priorities were measured by the probability of each scientist choosing each research question as their most important, the second step in the analysis clustered scientists solely according to their patterns of priorities (referred to as their research orientation for the balance of this paper). In the third step, the relationships between those patterns of research orientation and a full range of covariates were explored in order to identify which, if any, covariates were significant predictors of research orientation.

Chi-square tests (Bonferroni adjusted) were used to identify demographic and professional characteristics predictive of LC membership patterns. Covariates tested included: age; career length; discipline (agriculture and aquaculture; biological sciences; engineering and the applied sciences; health professions; law; physical sciences and mathematics; social sciences; and other); education level; gender; sector (academia, environmental non-governmental organizations, government agencies [scientists and non-scientists], and the private sector); and, for scientists only, total number of articles published. The Chi-Squared Automatic Interaction Detection (CHAID) software [30] was used to systematically test all possible combinations of covariates and identify all those that were statistically significant.

3. Results

3.1. Sample characteristics

Of 2078 article authors with email contact information, 1684 with professional interests in coastal management appeared to be successfully contacted (Table 1); because some email accounts do not return messages that they have expired, our response rate estimates are likely conservative. A total of 35.2% ($n=592$) of those contacted completed the full survey. The majority of the 592 authors were in academics or were government scientists (89.4%), male (69.1%), and from the West (70.9%). There was no evidence of regional self-selection bias for those completing the survey versus the sample frame ($\chi^2=7.99$, $df=5$, $p=0.1566$). A total of 70.9% of respondents were aged 40 years or more and 62.5% of authors had over 10 years professional experience (25.5% had 20 years or more). Of the 529 academic and government scientists completing the survey, 47.3% had published more than 10 peer-reviewed journal articles on coastal issues (10.8% had published over 50 articles). The full dataset from the study is available upon request from the corresponding author.

3.1.1. Aggregate coastal research priorities

Aggregate scores for each question, from most to least important, are shown in Table 2. Scores are scaled to sum to 100 for each individual, thus representing the likelihood of each question been chosen as first choice [23].

With purely random choices, all 20 questions would have an equal chance (mean likelihood = 5.0%) of being ranked first. The top 5 (integrated upland-coastal management; ocean acidification; freshwater response to sea level rise; sea level rise effects on humans; long-term coral reef survival) and bottom 3 (harvest effects; aquaculture impacts on wild species; management of migratory species) research questions are relatively closely grouped.

3.1.2. Heterogeneity of respondents' coastal research priorities

The objective of LC modeling was to assess heterogeneity in scientists' research priorities, testing whether research orientation differed significantly among sample sub-segments. A 8-cluster LC model minimized BIC (see Table A1 for diagnostics summary), but when all 20 questions were included in the model there were 31 significant local interactions. That is, the assumption of conditional independence was violated for many pairings of research questions. Nine questions (Q08, Q18, Q13, Q20, Q11, Q03, Q01, Q07, Q09) were dropped sequentially from the model to eliminate all significant bivariate residuals. The final eight LCs were thus based on 11 research questions that were conditionally independent and differentiated

Table 1
Summary of survey distribution and responses.

Survey distribution	Number	Number	%
Sample – unique authors identified		2078	
Less:			
Email bounced	329		
Long-term leave or retired	7		
No professional interests in coastal zone issues	58		
Subtotal – not contacted/no professional interests in field		394	
Surveys presumably delivered successfully		1684	100.0
Did not start survey		726	43.1
Opted out of survey (qualified, but not interested in participating)		64	3.8
Started but not finished full survey		302	17.9
Finished full survey – completes		592	35.2

Table 2
Twenty coastally oriented research questions drawn from 7 'big question' exercises and summary of best-worst scaling score (n=592).

Research question (Source[a])	Score[b]
1. How do policy, legal, or institutional arrangements shape the effectiveness of integrated management for terrestrial watersheds and adjacent coastal environments? [7, Q38]	7.574 (7.181–7.967)
2. How will ocean acidification affect marine biodiversity and ecosystem function, and what measures could mitigate these effects? [20, Q46]	7.359 (6.946–7.772)
3. How will coastal aquifers and groundwater resources respond to sea level rise through effects such as saltwater intrusion, and how can freshwater quality be maintained under these conditions? [17, Q17]	7.084 (6,715–7.454)
4. How will coastal human communities be affected by sea-level rise and increasing levels of erosion? [16, Q37]	6.855 (6.453–7.257)
5. Which management actions are most effective for ensuring the long-term survival of coral reefs in response to the combined impacts of climate change and other existing stressors? [20, Q48]	6.679 (6.353–7.005)
6. What management approaches will be required to maintain or increase the abundance of fish and shellfish populations when harvesting is one of multiple stressors acting on those populations? [7, Q08]	6.156 (5.860–6.452)
7. To what extent can coastal habitat restoration or rehabilitation compensate for loss of quantity or quality of existing species' habitat? [20, Q53]	5.614 (5.322–5.906)
8. Which management approaches to fisheries are most effective at mitigating the impacts of fish extraction and fishing gear on non-target species and their habitats? [20, Q49]	5.300 (5.012–5.588)
9. How can aquaculture and open water farming be developed so that impacts on coastal and aquatic habitats are minimized? [18, Q04)	5.227 (4.900–5.554)
10. How will northern coastal ecosystems respond to changes in climate and industrial activity as a reduction in ice cover increases human access to those ecosystems? [7, Q21]	5.064 (4.701–5.427)
11. What are the effects of changes in human patterns of seafood consumption on biodiversity, and how are such human patterns of consumption shaped by education programs, financial incentives, and other policy instruments? [20, Q84]	5.014 (4.674–5.354)
12. What are the comparative impacts of newly emerging types of renewable energy, such as wave energy, on coastal ecosystems and species? [21, Q66]	4.668 (4.299–5.037)
13. How will key fishery species be affected by changes to nursery grounds as coastal ecosystems undergo re-organization? [17, Q16]	4.517 (4.258–4.776)
14. How far should we go with managed realignment of coasts in order to adapt to sea-level rise? [15, Q11]	4.220 (3.866–4.574)
15. How do aquatic conservation policies directly or indirectly affect human health? [7, Q30]	4.086 (3.744–4.428)
16. Within and outside of marine protected areas, how do the abundances and distributions of species with different life histories respond to establishment of those areas? [16, Q39]	3.969 (3.701–4.237)
17. What are the impacts of alternative configurations of, and management strategies for, aquatic reserves on human well-being? [7, Q17]	3.573 (3.289–3.857)
18. What are the cumulative demographic and genetic effects of harvest on target and non-target aquatic populations and species? [7, Q09]	2.787 (2.562–3.012)
19. How important are caged fishes as reservoirs of parasites and pathogens that have detrimental effects on wild populations? [21, Q25]	2.141 (1.913–2.369)
20. How do transboundary migrations of aquatic animals affect efforts to manage populations of those species? (7, Q10]	2.113 (1.927–2.299)

[a] Source and question numbers in brackets; some questions edited slightly to emphasize aquatic focus.
[b] Score=mean probability (%) of being chosen as most important research question (with 95% confidence intervals in parentheses). Note that with 20 questions, the probability of being chosen at random would be 5.0%.

respondents according to their research priorities (Table 3). Note that several lower priority research questions proved the most useful for quantifying heterogeneity in scientists' orientation. That is, scientists' research orientation was best explained by divergent priorities they held for a combination of questions ranked relatively lowly at the aggregate level rather than differences in opinion over research questions that were regarded as being highly salient in aggregate.

For discussion purposes, it is useful to label the LC clusters. For instance, respondents in the second cluster, LC02, put a much higher than average priority emphasis on questions 1 (integrated upland-coastal management), 15 (human health impacts), and 17 (MPA effects on human well-being), while putting a lower than average emphasis on questions 13 (nursery grounds for fisheries), 16 (MPA biological effects), 19 (caged fish impacts on wild stocks), and 20 (transboundary species management). Clearly members of this *human oriented* cluster viewed social- and human-oriented issues as high research priorities relative to ecological issues. In contrast, members of LC05, a *marine ecology oriented* cluster, had virtually opposite research priorities compared to LC02 (Fig. 2). LC05 members scored higher than average on questions 13 and 16, and lower than average for questions 1, 2 (ocean acidification), 12 (renewable energy), 15, and 17.

Similarly, respondents in cluster LC03 prioritized questions 1, 12, 15, and 17, but ranked the global issues of coral reefs and northern development as low priorities. As such, they could be labeled as a *regional human oriented* cluster. Cluster LC04, a *global environment oriented* group, on the other hand, exhibited nearly opposite priorities with coral reefs, saltwater intrusion and opening of northern waters (all issues with strong climate change connections) as their highest priorities, but with human health and MPA effects on humans receiving little emphasis (Fig. 3).

Of the remaining latent class clusters, LC01, a *coastal resource oriented* cluster, prioritized broad resource extraction and human uses of the coastal zone with little emphasis on marine conservation or fisheries. Respondents in LC06, a *regional conservation oriented* group, ranked species-oriented questions as most important and resource industry and global ecological issues as less important. Cluster LC07 members, a *coral reef oriented* cluster, ranked coral reefs at the top of their priority list, species-oriented management issues at the bottom, and put relatively low emphasis on human health and Marine Protected Area (MPA) impacts. Finally, LC08, a *temperate species oriented* cluster, ranked aquaculture impacts and transboundary species migration as highest, and integrated management and coral reefs as lowest priorities.

3.1.3. *Predictors of heterogeneous research priorities*

The second stage of the analysis identified manifest variables – research questions – that were strongly associated with an unobservable latent variable, research orientation. In the third stage of the analysis, mutually exclusive demographically or professionally based segments that were predictive of posterior LC membership probabilities were identified. In other words, particular types of scientists that had particular patterns of research orientation were identified. Latent class cluster membership was most strongly differentiated by scientists' disciplinary training (χ^2=75.37, df=21, $p<0.001$) (Table 4). Research priorities among scientists from the largest segment (agricultural and aquaculture scientists, n=24; biologists, n=193; NGO and government non-scientists [for whom we did not ask disciplinary background], n=63), were statistically similar. This group could subsequently be differentiated by gender (χ^2=14.66, df=7, p=0.040).

Applied scientists and engineers (n=59) were segmented into one group while health professionals (n=8) and social scientists (n=45) were combined in a common segment; neither of these groups could be further segmented based on the additional

Table 3
Mean probability (%) of questions retained in latent class analysis being chosen as most important research question overall, and for each of eight latent class clusters individually.

Cluster	Overall	LC01 Coastal resource	LC02 Human	LC03 Regional human	LC04 Global	LC05 Marine ecology	LC06 Regional systems	LC07 Coral reef	LC08 Temperate species
Orientation size (%)	100.00	15.19	15.08	13.83	13.79	12.94	11.18	10.12	7.89
Q01. How do policy, legal, or institutional arrangements shape the effectiveness of integrated management for terrestrial watersheds and adjacent coastal environments?	7.57	6.88	**11.67**	**9.46**	7.07	*4.40*	8.90	7.52	*1.86*
Q03. How will coastal aquifers and groundwater resources respond to sea level rise through effects such as saltwater intrusion, and how can freshwater quality be maintained under these conditions?	7.08	**10.16**	7.40	5.03	**9.88**	*4.85*	*4.28*	8.61	5.04
Q05. Which management actions are most effective for ensuring the long-term survival of coral reefs in response to the combined impacts of climate change and other existing stressors?	6.68	5.33	6.20	*4.03*	**8.60**	8.04	7.65	**8.81**	*5.19*
Q10. How will northern coastal ecosystems respond to changes in climate and industrial activity as a reduction in ice cover increases human access to those ecosystems?	5.06	**7.09**	2.96	*2.20*	**7.72**	6.58	*0.60*	7.07	6.86
Q12. What are the comparative impacts of newly emerging types of renewable energy, such as wave energy, on coastal ecosystems and species?	4.67	**7.05**	4.46	**6.17**	5.46	*1.80*	*0.88*	5.07	5.85
Q13. How will key fishery species be affected by changes to nursery grounds as coastal ecosystems undergo re-organization?	4.52	3.33	*2.95*	3.75	4.88	**7.90**	**5.83**	*2.93*	5.22
Q15. How do aquatic conservation policies directly or indirectly affect human health?	4.09	5.77	**7.30**	**7.18**	*0.63*	*0.34*	2.67	3.24	4.53
Q16. Within and outside of marine protected areas, how do the abundances and distributions of species with different life histories respond to establishment of those areas?	3.97	*1.65*	*1.66*	4.29	2.37	**6.63**	**6.52**	4.62	6.33
Q17. What are the impacts of alternative configurations of, and management strategies for, aquatic reserves on human well-being?	3.57	1.98	**6.12**	**7.95**	*0.58*	*1.06*	5.00	2.49	2.85
Q19. How important are caged fishes as reservoirs of parasites and pathogens that have detrimental effects on wild populations?	2.14	**4.03**	*0.37*	3.12	0.55	2.84	1.19	*0.41*	**5.27**
Q20. How do transboundary migrations of aquatic animals affect efforts to manage populations of those species?	2.11	1.02	*0.52*	2.04	1.71	3.72	**4.03**	*0.99*	**4.08**

Bold and *italic* indicates the 2 latent classes with the highest and lowest probabilities, respectively, for each question.

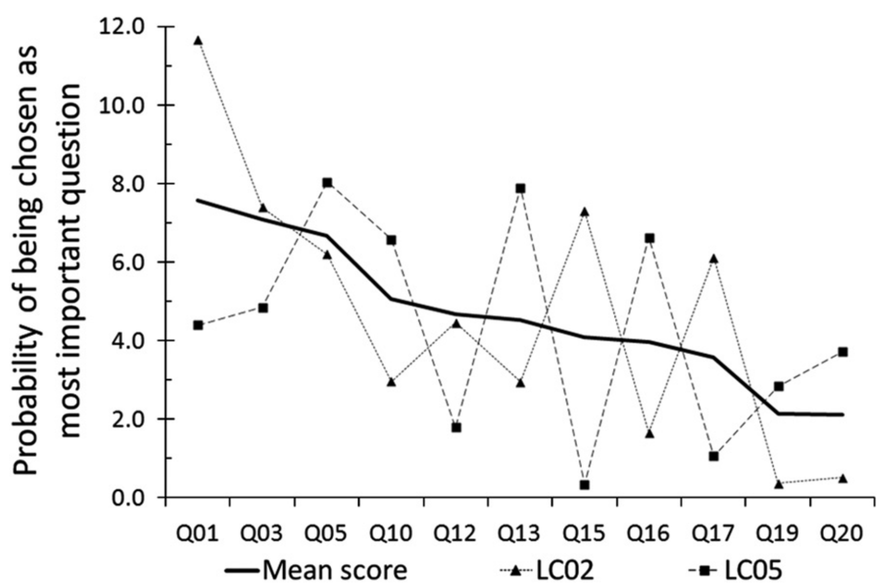

Fig. 2. Variability in research priority between latent classes 02 (human oriented) and 05 (marine ecology oriented).

demographic or professional characteristics. The fourth branch in the segmentation included scientists from the physical sciences and mathematics ($n=54$) and respondents that specified other disciplinary options ($n=143$, virtually all of whom were from various physical sciences). It cleaved at the second level ($\chi^2=33.21$, $df=7$, $p<0.001$) by root likelihood categories, where category 1 contained the lowest scores (mean$=0.383$), indicating that respondents likely prioritized on key research questions only and responded somewhat randomly for others. Note that region of residence, age, education, sector of employment, length of employment, and number of publications scientists had authored were not significant predictors of LC membership patterns in any analyses.

Table 4 shows the percentage of respondents from each segment in each LC cluster, and an index score and ranking for the segment. Index scores gave ranking for a segment in relation to the sample as a whole. For example 19.1% of male scientists in agricultural and biological sciences were *marine ecology* oriented

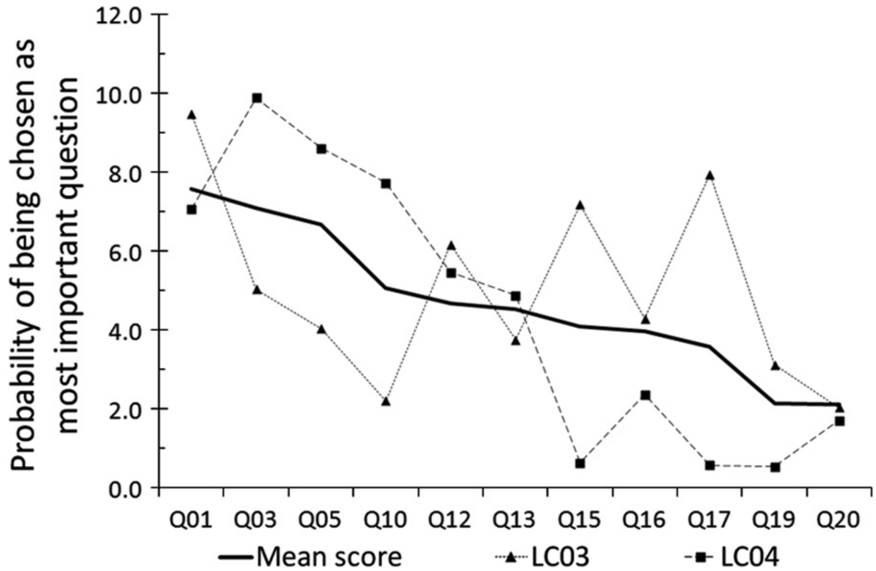

Fig. 3. Variability in research priority between latent classes 03 (regional human oriented) and 04 (global environment oriented).

Table 4
Significant predictors of sample segments that vary in their patterns of research orientation.

	Sample segment					
	S01 Female natural scientists	S02 Male natural scientists	S03 Applied scientists	S04 Social scientists	S05 Physical scientists (less consistent)	S06 Physical scientists (more consistent)
Segment Size						
n	104	176	59	53	54	146
% of total sample	17.6	29.7	10.0	9.0	9.1	24.7
Demographics						
Discipline[b]	1,2,9	1,2,9	3	4,7	5,6,8	5,6,8
Gender	Female	Male	–	–	–	–
Fit (likelihood ratio)[c]	–	–	–	–	1	2–4
Membership orientation						
LC01. Coastal resource (%)	17.9	9.1	**26.3**	8.9	20.0	16.7
Index (rank)	117 (3)	60 (5)	**173 (1)**	59 (6)	132 (2)	110 (4)
LC02. Human (%)	8.5	11.2	11.6	**41.1**	11.4	17.8
Index (rank)	56 (6)	74 (5)	77 (3)	**273 (1)**	76 (4)	118 (2)
LC03. Regional human (%)	9.1	14.3	23.9	13.3	**30.4**	6.7
Index (rank)	66 (5)	103 (3)	173 (2)	96 (4)	**220 (1)**	48 (6)
LC04. Global environment (%)	18.5	11.0	4.8	11.4	9.1	**20.1**
Index (rank)	134 (2)	79 (4)	35 (6)	83 (3)	66 (5)	**146 (1)**
LC05. Marine ecology (%)	17.7	**19.1**[a]	8.9	5.1	2.0	10.6
Index (rank)	137 (2)	**148 (1)**	69 (4)	39 (5)	15 (6)	82 (3)
LC06. Reg. conservation (%)	7.1	**17.3**	14.8	9.7	4.6	8.2
Index (rank)	63 (5)	**155 (1)**	133 (2)	86 (3)	41 (6)	73 (4)
LC07. Coral reef (%)	9.5	7.0	7.6	6.8	8.7	**17.0**
Index (rank)	93 (2)	70 (5)	75 (4)	68 (6)	86 (3)	**168 (1)**
LC08. Temperate species (%)	11.8	11.0	2.1	3.7	**13.8**	3.0
Index (rank)	150 (2)	140 (3)	26 (6)	48 (4)	**175 (1)**	38 (5)

[a] **Bold** indicates segment with the highest index scores.
[b] 1, agriculture or aquaculture (n=24); 2, biological sciences (n=193); 3, engineering and applied sciences (n=59); 4, health professions (n=8); 5, law (n=3); 6, physical sciences and mathematics (n=54); 7, social sciences (n=45); 8, other (n=143); 9, NGO/government non-scientists (n=63).
[c] 1, mean root likelihood (RL)=383.4; 2, mean RL=484.4; 3, mean RL=540.0; and 4, mean RL=613.7.

(segment 2) versus 12.9% of the overall sample, giving an index score of 148 (=19.1/12.9). That is, male ecologists were 48% more likely than average to hold marine ecology oriented research priorities.

3.1.4. *Proposed additions for high-priority coastal research question lists*

Respondents submitted an additional 340 substitute research questions as potential substitutes they had ranked lowest. Eighteen of the proposed replacements were virtually the same as existing questions, 93 shared common themes or were relatively close extensions of existing questions, and 174 were only marginally related to existing questions or were not addressed at all in the original big question exercises. Additionally, 55 questions were very broad in nature; many had been identified in prior exercises but the 20 coastal questions selected for this study were too narrowly focused to have included them all. Of the 174 questions that were much different than the existing questions, important themes included coastal processes and management,

Table 5
Examples of newly submitted research questions and themes.

Theme	Example questions
Coastal processes and management	• How well do we understand the physical processes of coastline responses to long-term sea level change and short term climatic variability? • How do anthropogenic activities affect the biogeochemical cycling of biogenic elements in coastal seawaters? • How can human settlement design and planning decisions surrounding human settlement location in the coastal zone increase resilience to environmental change? • What are the cumulative effects of coastal development to the ecosystem? • What are the effects of sea level rise and other stressors on terrestrial coastal communities such as coastal barrens, grasslands and headlands? • How important is carbon sequestration in coastal and ocean ecosystems?
Contaminants	• Which are the most toxic anthropogenic contaminants to the marine organisms and how can we prevent them from reaching the marine environment? • How the climate change will affect remobilization of past deposits of contaminants in the coastal zone? • How are pollutants distributed in coastal water bodies and what is their fate (including all the compartments and the trophic web)? • How should coastal human communities and fisheries policies respond to potential or existing nuclear power-plant radiation discharge such as that which has recently occurred at Fukishima, Japan?
Spatial planning	• Can marine spatial planning really allow for partitioning marine areas for multiple uses without impact on fisheries and habitat? • How can we predict positions of coastlines at various stages of progression and integrate with urban planners to better manage redevelopment and pre-emptive restoration of present coastal communities?
Monitoring	• How important are knowledge and monitoring of benthic components for evaluating the quality status of coastal waters? • What are the human and institutional capacity needs and means to develop these capacities to improve marine and coastal environmental management? • What is the full range of indicators of coastal ecosystem condition and health, and can managers and researchers identify key drivers of change?
Governance	• How will regional politics and conflicts affect water resources and marine environment? • How effective are international environmental agreements on combating the over-exploitation of fishery resources? • How must maritime trade be regulated to minimize the entry of invasive alien species? • How can existing research findings on almost all of the questions be more effectively communicated to people who vote for decision makers?
Mineral resource extraction	• What are the long-term effects of oil spill disasters like the one in the Gulf of Mexico? • How can sea floor raw materials (energy and minerals) be exploited with minimum effects on marine habitats?
Social	• How do aquatic conservation policies directly or indirectly affect human happiness? • What can be the role of women in the rebuilding of coastal ecosystems in the world? • How can we increase equity to empower communities to better cope with changes to coastal regions?

contaminants, spatial planning, monitoring, governance, resource extraction, and social issues. Table 5 shows a selection of important research questions that the coastal scientists identified (see Supplementary Information).

4. Discussion

4.1. Aggregate research priorities

At the aggregate level, respondents in this global sample of coastal scientists assigned highest priority to research questions broadly related to environmental change and lowest priority to specific management measures for aquatic species. The top priority was on the effectiveness of integrated upland and coastal management. This is clearly an important issue globally given the degree to which upland catchments have undergone extensive development and changes in hydrological regimes [5,10,31], and the extent to which development and urbanization have occurred within the coastal zone [3,14]. The next four top priorities related to global environmental change and included research supporting the assessment and management of ocean acidification, saltwater intrusion resulting from sea level rise, the effects of sea level rise on human communities, and coral reef ecosystems.

Although all research questions in the survey had already been vetted and ascertained to be important in prior exercises, those questions focusing on the cumulative effects of harvesting aquatic species, transfer of disease from farmed to wild fish, and the management of transboundary species were viewed as relatively unimportant to many survey respondents. Because prior exercises were largely focused on the conservation of biological diversity [16,17,19–21], this ordering is not surprising given a sample frame that included coastal scientists from all disciplines. The new questions that were submitted in this survey (Table 5) particularly emphasized the importance of coastal processes and contaminants, both topics that were largely outside the scope of the original exercises. It is clear that questions from the new themes identified in this survey need to be considered in robust coastal research prioritization efforts.

Beyond the influence of disciplinary background on research orientation, it is also important to note the lack of influence that other covariates had in this analysis. Perhaps of most interest was the lack of significance of region of residence on research priorities or orientation. Another study on global conservation priorities [32] found that there were strong regional differences between conservation scientists (largely ecologists and social scientists), with scientists from Africa, Asia, and Europe having one pattern of research orientation and those from Australia, New Zealand, and the Pacific Islands, North America, and Latin America and the Caribbean having another. The findings of this survey suggest that disciplinary perspectives on research priorities are relatively homogenous globally and disciplinarity has much more influence on research orientation than, for example, East–West or North–South geographic divisions or gender.

4.2. Implications of heterogeneous research priorities

4.2.1. Conflicting science advice

There was significant heterogeneity in research orientation within the sample. Of the covariates tested, disciplinary background was the single best predictor of research orientation. While it should not be surprising, for instance, that social scientists were most likely to prioritize human-oriented research questions, it is crucial for decision-makers to understand the orientation of science advice they receive. Because disciplinary lenses can legitimatize alternative knowledge claims, discussions about competing values must be transparent in the environmental problem solving process [33]. This quantification of disciplinary-based values may help policy makers better understand science advice and make more balanced and informed decisions about coastal management.

An example of how results from this study could be used to build understanding about advice from various types of scientists is useful to illustrate. Take, for example, the debate regarding MPAs for managing species and protecting aquatic ecosystems e.g., [34,35]. If policy-makers are getting advice from scientists in clusters 5 (marine ecology orientation) or 8 (temperate species orientation), the priorities they receive would focus much more on biological outcomes relative to human-oriented outcomes. If science advice was sought from scientists in clusters 2 (human orientation) or 3 (regional human orientation), the recommended priorities would be more focused on MPA-induced impacts on human well-being. If, however, policy-makers received advice on coastal science priorities from scientists in cluster 1 (coastal resource orientation), neither ecological nor human dimensions of MPA research would figure highly. An interesting corollary is that it may be possible to develop testable research hypotheses regarding the source of advice for observed policy positions. In a quasi-Bayesian spirit, one might hypothesize, for instance, that where MPAs were a 'non-issue' for coastal policy-makers that the likelihood was high that policy makers relied heavily on science advice from scientists belonging to clusters 1 or 4 (global orientation).

4.2.2. Encouraging cooperative cross-disciplinary collaboration

This research has clearly shown that disciplinary research priorities vary strongly among coastal scientists. Collaboration across disciplines is, however, necessary for effective coastal management. At its simplest, 'multidisciplinary' research is the lowest level of disciplinary integration, where teams work separately from disciplinary bases with a view of addressing a common problem [36]. At an intermediate level, 'interdisciplinary' researchers work jointly, with more collaboration between disciplines, but still with a clearly delineated disciplinary base. At its most complex, 'transdisciplinary' researchers not only collaborate but also develop a shared conceptual framework drawn from each of their disciplines according to the needs of the problem being addressed.

Efforts to encourage disciplinary collaboration can, however, remain persistently rigid [37,38]. Numerous explanations have been put forward to explain researchers' 'silo' mentality [39]. Those working within one discipline share common epistemologies (theories of knowledge), methodologies (the methods, principles, and rules for generating knowledge), and phenomenology (ideas and understanding of the world), which can be opaque and intimidating to those from other disciplines. At a social level, the conceptual and physical separation of disciplines within the academic system can promote an 'in group' mentality [40], as well as the development of obstructive prejudices between practitioners of different disciplines [41]. Institutional barriers may also encourage the separation of the natural and social sciences, for example through the separation of funding bodies and publication outlets [42].

Numerous recommendations have been made for overcoming disciplinary barriers. Fay et al. [40] emphasized the importance of 'group' cohesion via personal or professional interactions, and the creation of high-level goals shared and supported by the project or community. Co-location can be important for breaking down personal barriers [43], as cross-disciplinary collaboration can take researchers out of their day-to-day organization and into real world applications of their work. In addition, the short-term nature of some collaboration provides a freedom and tractability which has been shown to lead to more successful disciplinary collaboration [44]. Practitioners from all disciplines need training for cross-disciplinary collaboration at the academic level and for crossing the gap to the policy sphere [45,46] and to develop shared understandings of relevant disciplinary vocabularies [47]. Institutional innovations to encourage interdisciplinary or transdisciplinary research may also be needed. For example, over the longer term funders and universities may need to explicitly

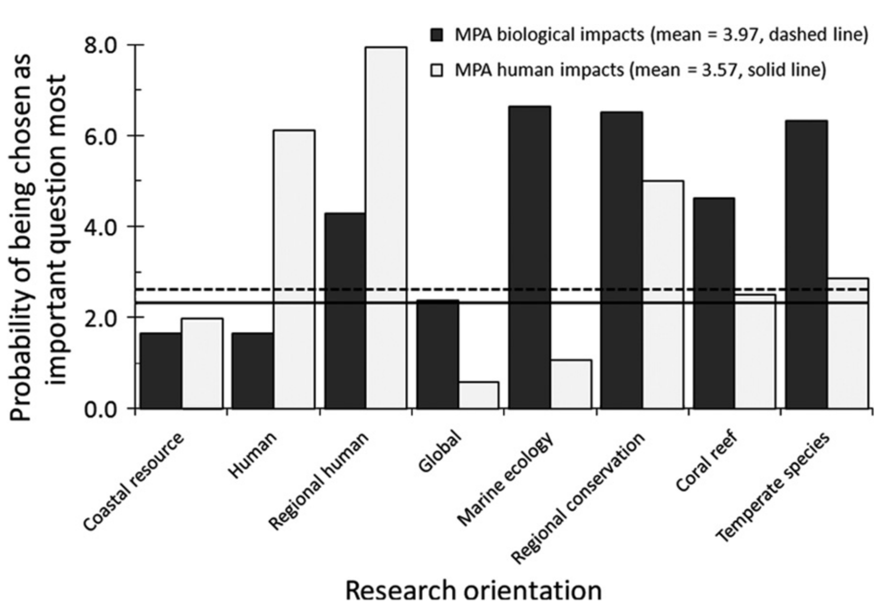

Fig. 4. Different emphases on the biological (Q 16) and human impacts (Q17) of Marine Protected Areas (MPAs) among eight latent classes that vary in research orientation.

recognize and reward cross-disciplinary publications as being as desirable for performance review purposes as publications in top but narrow disciplinary journals.

It could be possible to use information such as that in Fig. 4 to inform the feasibility of assembling balanced cross-disciplinary research teams to address complex coastal research. Returning to the MPA example, it is evident that clusters 2 and 3, and clusters 5 through 8 have research orientations strongly prioritizing human and ecological outcomes, respectively. A research team comprised only of scientists from clusters 2 and 5 might have such fundamental differences in perspectives that successful implementation of inter- or trans-disciplinary research could be a challenge. Note that clusters 1 (coastal resources) and 6 (regional conservation) weigh MPA outcomes relatively evenly, albeit at below and above average levels, respectively. From a cross-disciplinary research perspective, it could make sense to engage scientists from both those clusters to balance the disparate views of human and ecologically oriented scientists.

In general, the level of collaborative research intensity that teams engage in can affect both benefits and costs of that collaboration e.g., [48,49]. For the MPA example, a multidisciplinary approach to science advice would involve scientists from each discipline giving independent advice on MPAs to policy-makers, who may then rely on internal science advisors to interpret potentially conflicting views. The possibility exists for policy-makers to simply pick and choose science advice that meshes well with their political agenda [7]. Interdisciplinary teams require more coordination and intra-team communication, increasing the costs of cross-disciplinary coastal research. Transdisciplinary research, which may require that scientists undertake extensive learning outside their core discipline and develop new ways to communicate their methodologies and findings, and increases research costs further. In combination, the differences in research orientation that coastal scientists' hold suggest that future research on collaboration across disciplines may benefit from taking a transaction cost approach [50], matching the nature of the research challenge with the approach for which research competencies are brought to bear in the most cost-effective manner [see [51] for a discussion of transaction costs in an MPA context]. For some coastal research challenges it may make sense to undertake relatively 'cheap' multidisciplinary research if the long-term benefits of full integration are potentially low, while for other challenges it may be desirable to invest heavily upfront to build transdisciplinary research capacity, engaging researchers from across the research orientation clusters, because of the potential for high long-term returns.

4.3. Broadening participation in research prioritization processes

This survey proved useful as a tool for broadening participation in the research prioritization process started with various 'big question' exercises. The ecology oriented exercises conducted over the past several years [16,17,19–21] have identified many important coastal research questions but clearly missed important coastal research questions related to contaminants, changes in upland development and hydrological regimes, and physical

Table A1
Summary of latent class model diagnostics.

Model	Clusters	LL	BIC (LL)	AIC (LL)	AIC3 (LL)	CAIC (LL)	Number Parameters	Error	# Significant BVRs ($\chi^2>3.84$)	Entropy R^2
A1 - all indicators in model	1	−32,743.2	65,741.7	65,566.3	65,606.3	65,781.7	40			1.0000
A2	2	−31,699.2	63,915.5	63,560.4	63,641.4	63,996.5	81	0.0336	109	0.8828
A3	3	−31,224.1	63,227.0	62,692.2	62,814.2	63,349.0	122	0.0366	92	0.9103
A4	4	−30,829.5	62,699.6	61,985.1	62,148.1	62,862.6	163	0.0473	78	0.9117
A5	5	−30,571.5	62,445.3	61,551.1	61,755.1	62,649.3	204	0.0523	72	0.9162
A6	6	−30,306.6	62,177.2	61,103.3	61,348.3	62,422.2	245	0.0513	58	0.9260
A7	7	−30,279.2	62,384.0	61,130.3	61,416.3	62,670.0	286	0.0509	38	0.9248
A8 – BIC minimizing [local minimum for AIC/AIC3]	8	−29,923.2	***61,933.7***	60,500.3	60,827.3	62,260.7	327	0.0547	31	0.9284
A9	9	−29,904.4	62,158.0	60,544.9	60,912.9	62,526.0	368	0.0509	21	0.9364
A10	10	−29,752.1	62,115.0	60,322.1	60,731.1	62,524.0	409	0.0471	23	0.9427
A11 – AIC/AIC3 still declining	11	−29,645.6	62,163.8	60,191.2	60,641.2	62,613.8	450	0.0503	12	0.9408
A8 – lowest BIC for refinement	8	−29,923.2	61,933.7	60,500.3	60,827.3	62,260.7	327	0.0547	31	0.9284
A8b – drop Q8, BVR $\chi^2=27.1$	8	−28,483.7	58,952.6	57,589.3	57,900.3	59,263.6	311	0.0443	20	0.9412
A8c – drop Q18, BVR $\chi^2=17.7$	8	−27,121.9	56,126.9	54,833.8	55,128.8	56,421.9	295	0.0706	21	0.9104
A8d – drop Q13, BVR $\chi^2=13.9$	8	−25,287.0	52,355.0	51,132.0	51,411.0	52,634.0	279	0.0573	14	0.9259
A8e – drop Q20, BVR $\chi^2=11.4$	8	−23,719.3	49,117.5	47,964.6	48,227.6	49,380.5	263	0.0533	10	0.9280
A8f – drop Q11, BVR $\chi^2=9.4$	8	−22,305.1	46,187.0	45,104.3	45,351.3	46,434.0	247	0.0725	10	0.9022
A8g – drop Q03, BVR $\chi^2=7.54$	8	−20,570.0	42,614.6	41,602.1	41,833.1	42,845.6	231	0.0670	6	0.9084
A8h – drop Q01, BVR $\chi^2=10.4$	8	−18,978.7	39,329.8	38,387.3	38,602.3	39,544.8	215	0.0644	6	0.9154
A8i – drop Q07, BVR $\chi^2=5.7$	8	−17,247.1	35,764.5	34,892.2	35,091.2	35,963.5	199	0.0658	3	0.9113
A8j – drop Q09, BVR $\chi^2=4.5$	8	−16,103.4	33,374.9	32,572.7	32,755.7	33,557.9	183	0.0812	0	0.8905
B1 – reduced indicator set (A8j)	1	−17,811.0	35,762.4	35,666.0	35,688.0	35,784.4	22			1.0000
B2	2	−17,240.6	34,768.4	34,571.1	34,616.1	34,813.4	45	0.0281	35	0.8856
B3	3	−16,828.0	34,090.0	33,792.0	33,860.0	34,158.0	68	0.0553	34	0.8714
B4	4	−16,583.5	33,748.0	33,349.1	33,440.1	33,839.0	91	0.0597	17	0.8861
B5	5	−16,446.3	33,620.4	33,120.7	33,234.7	33,734.4	114	0.0681	7	0.8848
B6	6	−16,307.5	33,489.6	32,889.1	33,026.1	33,626.6	137	0.0784	10	0.8816
B7 – minimum BIC, 2 BVRs	7	−16174.1	***33,369.7***	32,668.3	32,828.3	33,529.7	160	0.0811	2	0.8871
B8 – no significant BVRs	8	−16,130.2	33,428.5	32,626.3	32,809.3	33,611.5	183	0.0942	0	0.8791
B9	9	−16,045.8	33,406.6	32,503.6	32,709.6	33,612.6	206	0.0763	1	0.9029
B10	10	−15,965.4	33,392.5	32,388.7	32,617.7	33,621.5	229	0.0981	0	0.8822
B8 FINAL	8	−16,130.2	33,428.5	32,626.3	32,809.3	33,611.5	183	0.0942	0	0.8791

Notes: **Bold** and *italic* indicates minimum BIC for model run; BVR, bivariate residual; LL, log likelihood; BIC, Bayesian information criterion; AIC, Akaike information criterion; CIAC, consistent Akaike information criterion.

processes in estuaries and coastal zones. These topics were not the focus of prior exercises, but current results demonstrate that research challenges within the coastal zone should not be dealt with in isolation. The survey results suggested that the big question exercises may, rather than simply being exercises that produce static lists of research questions, be used for syntheses that identify and prioritize research questions through iterative processes. These types of initiatives could support broader needs of the international research community, such as the identification and prioritization of coastal adoption options [31]. With a thorough prioritization by international coastal scientists, the list of 20 key research questions should be much more valuable for coastal policy-makers and may help open new opportunities for further science-policy dialog on critical coastal issues. A logical follow-up to this research would be to conduct further surveys that incorporate questions from the new themes identified here and specifically targets coastal policy-makers in different parts of the world.

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Appendix A

See Table A1.

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2012.09.004.

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