Policymakers' and Scientists' Ranks of Research Priorities for Resource-Management Policy

MURRAY A. RUDD AND ERICA FLEISHMAN

Recent collaboration between decisionmakers and scientists in the United States yielded 40 research questions that reflected the needs of those with jurisdiction over natural resources. We surveyed managers, policymakers and their advisers, and scientists to rank the questions with respect to their applicability to policy. The 602 respondents included 194 policymakers, 70 government scientists, and 228 academic scientists. A question on the water supply necessary to sustain human populations and ecosystem resilience was ranked as having the greatest potential, if it were answered, to increase the effectiveness of policies related to natural resource management in the United States. Research priorities differed significantly among the respondents. However, no simple science–policy divide was evident. Priorities did not differ between academics and government employees or between scientists (academic and government) and policymakers. Our results suggest that participatory exercises can establish priorities to guide funders of research and researchers who aim to inform policy.

Keywords: research prioritization, policymaking, conservation, environmental management

Development, population growth, resource extraction, and climate change increasingly challenge resource management. Building the knowledge base to address these challenges effectively requires collaboration among scientists from different disciplines and among scientists and diverse information users in the public, private, and nonprofit sectors (Sutherland et al. 2011, Hackmann and St. Clair 2012, Pahl-Wostl et al. 2013).

Collaborations intended to guide knowledge development relevant for different spatial scales and on various topics are reflected in the recent identification of high-priority research questions in conservation science (Sutherland et al. 2009, Fleishman et al. 2011, Rudd et al. 2011), agriculture (Pretty et al. 2010), environmental management (Boxall et al. 2012), and environmental policy (Sutherland et al. 2012). In most cases, the lists of candidate questions were compiled from a broad solicitation and then reduced by an iterative process of voting and discussion (Sutherland et al. 2011). Although, in each study, 20, 40, or 100 research questions were identified, in only two were the questions explicitly prioritized: a study of Swiss conservation practitioners' research needs (Braunisch et al. 2012) and a synthesis of coastal research questions drawn from seven priority-setting exercises (Rudd and Lawton 2013).

There are compelling reasons for which it may be useful to rank research questions. First, understanding research priorities can help direct funding and scientific effort toward the questions of greatest relevance to policy. Second, ranking makes it possible to test whether research priorities differ between groups (e.g., policymakers and scientists). If priorities differ greatly, it may be worthwhile to target communications and outreach with the intent of aligning research with public and political priorities or to build public and political awareness about topics that scientists view as crucial (Rudd 2011, Sutherland et al. 2011). Third, engaging individuals not involved in the original question-identification process may broaden the debate over research priorities, identify new questions at different organizational levels, and increase the legitimacy of the research prioritization process.

Forty questions to guide research on the management of natural resources in the United States (table 1) were identified through an open, inclusive process of personal interviews with decisionmakers; broad solicitation of research needs from resource managers, policymakers, advisers to policymakers (henceforth, we collectively refer to these three groups as *policymakers*), and scientists; and an intensive workshop that included science-oriented individuals with jurisdiction over natural resources (Fleishman et al. 2011). The broad solicitation yielded contributions from more than 375 individuals affiliated with a minimum of 109 different academic, governmental, philanthropic, and private organizations.

BioScience 64: 219–228.
doi:10.1093/biosci/bit035 Advance Access publication 5 February 2014

Table 1. Percentage of respondents who ranked each of the 40 research questions as the most or least likely to increase the effectiveness of policies related to the management of natural resources in the United States and the mean likelihood that each question would be ranked as the most important (highest).

		Ranked as the most likely		Ranked as the least likely		Likelihood of highest ranking	
Rank	**Question**	***n***	**%**	***n***	**%**	**%**	**95% quasi-CI**
1	What quantity and quality of surface and groundwater will be necessary to sustain US human populations and ecosystem resilience during the next 100 years? [Q01]	831	85.9	136	14.1	5.3	5.1–5.5
2	What are reliable and scientifically defensible metrics for quantifying the benefits that humans receive from ecosystems and trade-offs among those benefits? [Q19]	685	78.2	191	21.8	4.5	4.3–4.7
3	How will coastal ecosystems and human communities be affected by sea-level rise, storm surge, erosion, the intrusion of saltwater, and changes in the amount and variability of precipitation? [Q37]	603	79.3	157	20.7	4.3	4.1–4.5
4	How do different strategies for managing forests, grasslands, and agricultural systems affect carbon storage, ecosystem resilience, and other desired benefits? [Q04]	574	78.2	160	21.8	4.2	4.0–4.3
5[a]	What are the potential effects on ecosystems of developing new sources of renewable and nonrenewable energy? [Q08]	573	78.6	156	21.4	4.1	4.0–4.3
6	How do different agricultural practices and technologies affect water availability and quality? [Q06]	577	77.8	165	22.2	4.1	3.9–4.2
7	What are reliable scientific metrics for detecting chronic, long-term changes in ecosystems? [Q21]	575	73.2	211	26.8	3.9	3.7–4.1
8	What are the ecological and economic effects of different methods of restoring forests, wetlands, and streams? [Q07]	526	75.3	173	24.7	3.8	3.7–4.0
9	How will ecosystems be affected by the changes in species composition that are likely to result from changes in land use and climate? [Q26]	487	71.4	195	28.6	3.4	3.3–3.6
10	How do different systems of natural resource governance affect capacity for adaptive management and maintenance of ecosystem resilience? [Q17]	478	62.9	282	37.1	3.2	3.0–3.4
11	How does the configuration of land cover and land use affect the response of ecosystems to climate change? [Q22]	420	67.0	207	33.0	3.1	3.0–3.2
12	How do demographic and cultural shifts in the human population of the United States shape conservation values, attitudes, and behaviors? [Q12]	450	52.6	405	47.4	2.9	2.6–3.0
13	How do shifts in agricultural subsidies, commodity prices, and markets affect the location and rate of conversion of natural ecosystems to agricultural uses? [Q15]	422	54.9	346	45.1	2.8	2.7–3.0
14	How will changes in land use and climate affect the severity of infrequent, spatially extensive disturbance events? [Q23]	391	58.4	278	41.6	2.8	2.6–2.9
15	What are the ecological characteristics of populations and species most likely to persist in the face of changes in land use and climate? [Q27]	368	55.8	292	44.2	2.6	2.4–2.7
16	How do alternative ways of managing fisheries affect marine ecosystems and coastal human communities? [Q38]	348	55.2	282	44.8	2.6	2.4–2.7
17	What are the ecological, social, and economic costs and benefits of different mechanisms of conservation financing? [Q16]	392	49.8	395	50.2	2.5	2.4–2.7
18	How do the economic costs and benefits associated with provision of ecosystem services vary spatially, temporally, and among social groups? [Q20]	378	51.9	351	48.1	2.5	2.3–2.6
19	At what threshold values of abiotic or biotic attributes do ecosystems change abruptly in response to species extirpations or species introductions? [Q25]	359	51.5	338	48.5	2.4	2.3–2.6
20	What ecological and economic changes will result from ocean acidification? [Q36]	320	46.2	373	53.8	2.4	2.2–2.6
21	How will changes in land use and climate affect the effectiveness of terrestrial and marine protected areas? [Q40]	317	52.4	288	47.6	2.3	2.2–2.4
22	What are the relative ecological effects of increasing the intensity versus spatial extent of agricultural and timber production? [Q05]	313	50.6	306	49.4	2.3	2.1–2.4
23	How do different strategies for growing and harvesting biomass or biofuel affect ecosystems and associated social and economic systems? [Q03]	295	47.5	326	52.5	2.2	2.1–2.4
24	How will changes in land use and climate affect ecologically and economically important mutualistic relationships among species? [Q29]	313	50.1	312	49.9	2.1	2.0–2.2
25[a]	What are the aggregate effects on ecosystems of current-use and emerging toxicants? [Q11]	272	42.0	375	58.0	2.1	1.9–2.2
26	Within and outside the United States, what are the ecological and economic effects of programs implemented under the Conservation Title of the Farm Bill? [Q14]	291	37.2	492	62.8	2.0	1.9–2.2

Table 1. Continued.

Rank	Question	Ranked as the most likely		Ranked as the least likely		Likelihood of highest ranking	
		n	%	*n*	%	%	95% quasi-CI
27[a]	How will changes in the Arctic's climate affect ecosystems in the Arctic and elsewhere in the United States? [Q34]	251	39.4	386	60.6	1.9	1.7–2.0
28	How will changes in land use and climate affect factors that facilitate the spread of nonnative species? [Q31]	237	39.2	368	60.8	1.8	1.7–1.9
29	What attributes of ecosystems facilitate prediction of impending transitions among alternative states? [Q24]	273	37.0	465	63.0	1.8	1.6–2.0
30[a]	How do population dynamics respond to the independent and interactive effects of multiple stressors? [Q09]	275	39.4	423	60.6	1.8	1.7–1.9
31	How do the social and economic impacts of US conservation policies vary spatially, temporally, and among social groups? [Q13]	260	32.8	532	67.2	1.7	1.6–1.9
32	What factors affect the ability of native species to move through and persist within human-dominated landscapes? [Q28]	248	37.3	417	62.7	1.7	1.6–1.8
33	How do different types of cross-jurisdictional governance systems affect ecosystems? [Q18]	274	31.9	585	68.1	1.7	1.5–1.8
34	How do different strategies for ecosystem management across the gradient of development intensities affect human health in urban areas? [Q02]	225	32.9	458	67.1	1.5	1.4–1.6
35[a]	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? [Q39]	195	30.8	439	69.2	1.5	1.3–1.6
36[a]	How is the productivity of soil in a given region affected by different policies and stressors? [Q10]	197	25.5	577	74.5	1.3	1.2–1.4
37	How will changing levels of human activity in the Arctic that are enabled by climate change affect Arctic ecosystems? [Q35]	143	21.2	533	78.8	1.1	1.0–1.2
38	How will changes in land use and climate affect the prevalence and rates of transmission of diseases among non-domesticated animals? [Q30]	131	19.5	542	80.5	0.9	0.8–1.0
39[a]	What are the attributes of species that will require ongoing human intervention to persist outside captivity? [Q32]	104	12.0	766	88.0	0.6	0.5–0.7
40	How does domestic propagation of species affect the supply of, demand for, and persistence of these species in the wild? [Q33]	77	9.1	765	90.9	0.5	0.4–0.6

Note: The question numbers from Fleishman and colleagues (2011) are in brackets. Abbreviations: %, percentage; CI, confidence interval; *n*, number of rankings. [a]This question was retained in the latent-class cluster analysis.

Our objectives here were to obtain policymakers' and scientists' rankings of the full set of research questions with respect to the questions' ability, if they were answered, to increase the effectiveness of policies related to the management of natural resources in the United States over the next 5–10 years (henceforth, *most applicable to policy*)—the original intent of identifying the questions (Fleishman et al. 2011)—and to test whether research orientations (i.e., research preferences or ranking patterns) differed between the two groups. The alignment of orientations would suggest considerable enthusiasm and potential for research to meet the needs of policymakers. Alternatively, increased engagement between policymakers and scientists on topics for which priorities were not aligned may increase the probability of those topics' being addressed by both communities.

Ranking process

We used best–worst scaling (BWS; Flynn et al. 2007) to rank the 40 research questions (Fleishman et al. 2011). We repeatedly asked the respondents to choose the questions that they viewed as the most and least applicable to policy from randomly selected subsets of 4 of the 40 questions. The respondents were provided with a link to the 40 questions and supporting details for each, in which terms were defined and examples were presented (Fleishman et al. 2011). The BWS method allowed us to rank all 40 questions in relative order of priority for each respondent and to subsequently test whether research orientations varied among respondents with different professional or demographic characteristics (e.g., Rudd and Lawton 2013). BWS scaling reduces or eliminates *anchoring biases*, the tendency of a given respondent to place all items near either the center or the extremes of a rating scale, and *survey inattentiveness*, the tendency of respondents to, for example, simply rate all items as *very important*. BWS thus makes respondents' priorities more comparable across sectors, disciplines, regions, or even cultures (Auger et al. 2007).

Survey instrument. We administered a three-part, Internet-based survey (supplement S1). Before the survey began, we introduced its purpose and presented information about confidentiality. In the first part, we requested information on demographic and professional variables, including the respondent's age, gender, state of residence, highest degree conferred, years of experience in resource management or research, sector or organization of primary employment or professional engagement, and type of professional position. The second part of the survey consisted of a set of 24 BWS ranking comparisons. We also allowed each respondent to propose a maximum of three new research questions to replace those that he or she ranked as least applicable to policy. The respondents were invited to provide explanations of why they proposed the new questions.

In the third part of the survey, we asked the policymakers about their awareness of the types of research being conducted on the management of natural resources in the United States and the importance of different sources of information on research in natural and social science for decisionmakers within their organization. We also asked the policymakers for their comments on how scientists could make their research more applicable to policy, could better communicate their research findings, or could improve the credibility of their research. We asked the scientists about their awareness of the types of information needed by policymakers to manage natural resources in the United States and their perceived reasons for which science may not be applied to the formulation and implementation of environmental policy. All of the respondents were able to provide general comments on research priorities and on the survey.

Sample. We developed the sample of policymakers by searching online for employee directories of federal and state agencies with potential jurisdiction over natural resources. We contacted individuals whose job titles suggested that they had policy, management, or research responsibilities and whose direct e-mail addresses were publicly available. We followed a similar procedure for major national and international environmental nongovernmental organizations based in the United States and included these individuals in the sample of policymakers.

Given the number of researchers based at academic institutions in the United States, we developed our sample of scientists by contacting heads of relevant departments (e.g., ecology, wildlife biology, fisheries, environmental science, environmental studies) at universities in the 50 states and the District of Columbia.

We asked all of the individuals that we contacted to forward the survey to colleagues within their organizations. This is not an ideal way to distribute surveys, because it is impossible to determine how many individuals received the survey and to calculate the response rates. However, given that our principal goal was to compare research priorities among policymakers and scientists, this approach had the highest likelihood of reaching a high number of representatives of both groups.

Data analysis

We used a two-tailed Mann–Whitney U test to assess whether the policymakers' self-reported levels of awareness of the types of research being conducted on the management of natural resources in the United States differed from the scientists' self-reported levels of awareness of the types of scientific information needed by policymakers.

Our analysis of rankings had three steps (Rudd and Lawton 2013). First, we used a multinomial logit model and hierarchical Bayesian models (MaxDiff, version 8, Sawtooth Software, Orem, Utah, with its hierarchical Bayesian default settings of 20,000 iterations for burn in; 10,000 iterations to calculate coefficients; a prior covariance matrix of 2; and 5 degrees of freedom) to rank each of the 40 questions on the basis of its mean likelihood of being ranked as the most applicable to policy in all of the respondents' BWS comparisons. Mean scores, which represent the likelihood of a given research question's being ranked as the most applicable to policy and sum to 100, were calculated for each research question. A question with a mean score of 4 (i.e., it has a 4% likelihood of being ranked as the most applicable to policy) could therefore be interpreted as twice as important to the respondents as a question with a mean score of 2. With 40 questions, the mean likelihood of being ranked as the most applicable to policy would be 2.5 if the choices were made randomly. We report the upper and lower 95% quasi-confidence bounds for the scores. Computing standard errors (SE) on the basis of point estimates is inconsistent with the Bayesian tradition, and one cannot infer statistical differences in rank from these bounds. Nevertheless, the bounds (computed by estimating the SE for each item on the basis of the respondents' point estimates and adding ±1.96 SE to the mean) are useful to illustrate where gaps in rank occur.

Second, we used latent-class cluster analysis (Vermunt and Magidson 2002, Magidson and Vermunt 2004) to identify different patterns of research orientation or to group individuals on the basis of their research priorities within the sample. Latent-class clustering minimizes within-cluster variation while maximizing between-cluster variation (Hagenaars 1988, Vermunt and Magidson 2002). The choice of the number of clusters is commonly guided by a suite of diagnostic indicators (Wedel and Kamakura 2000, Scarpa and Thiene 2005, Hynes et al. 2008, Morey et al. 2008). To identify the models best supported by the data, we used the Bayesian information criterion (BIC; $-2\text{LL} + (\log N)(n_{\text{par}})$, where N is the sample size, LL is the log-likelihood, and n_{par} is the number of model parameters). The BIC penalizes models as the number of parameters increases but typically suggests that fewer latent classes be retained in a final model than do alternative information criteria (Hynes et al. 2008). Because no single diagnostic measure definitively identifies the latent-class model best supported by the data, the choice of a final latent-class model "must also account for [the] significance of parameter estimates and be tempered by the analyst's own judgment on the meaningfulness of the parameter signs" (Scarpa and Thiene 2005, p. 435). In our latent-class cluster analysis, the BIC provided an indicator of whether it was justifiable to select, for example, a five-cluster rather than a six-cluster model.

Latent-class models generally assume that observed variables are independent within clusters (the *local independence assumption*; Vermunt and Magidson 2002). That is, unobserved latent variables are assumed to account completely for observed relations between observed indicator variables (Hagenaars 1998). Correlated response errors and omitted variables may, however, produce relations among indicator variables in addition to those produced by the unobserved latent variables. To test whether our observed indicator variables—the 40 research questions—were locally independent, we used the bivariate residual Pearson χ^2 statistic. When interactions between the indicators were significant (i.e., $\chi^2(1) > 3.84$, $p < .05$, indicating that the local independence assumption was violated), we sequentially deleted the research questions with the greatest number of violations from the latent-class cluster analysis until no significant bivariate residual coefficients remained. We used Latent GOLD (version 4.0, Statistical Innovations, Belmont, Massachusetts) to estimate all latent-class cluster models. Posterior latent-class membership probabilities from the latent-class cluster analyses were used as response variables in the subsequent segmentation. For example, an individual might have .75, .20, and .05 probability of belonging to latent-class clusters A, B, and C, respectively.

Third, we used Bonferroni-adjusted chi-squared tests to examine whether research orientations differed among the respondents with respect to their affiliated organizational classes (e.g., academia, government) and between the policymakers and the scientists. We also tested whether the research orientations differed as a function of other demographic or professional variables (e.g., age, gender, education level, disciplinary training, years of career experience). The response variables for our tests were the posterior probabilities of each respondent belonging to each latent class. We used chi-squared automatic interaction detection software (SI-CHAID version 4.0, Statistical Innovations, Belmont, Massachusetts) to systematically test all of the possible combinations of covariates and to identify those combinations for which the research orientations were statistically different.

We (i.e., each of the present authors) used our judgment to classify new research questions submitted by the respondents as either aligned with one or more of the original 40 questions or as introducing a new theme. We then compared our independent classifications, discussed discrepancies, and adjusted our classifications as was needed to reach consensus.

We received 602 completed surveys between 7 October 2011 and 14 April 2012. Another 884 respondents partially completed the survey. Seventy-eight individuals opted out of the survey after viewing its objectives because they did not have professional interests in the management of or research on natural resources in the United States ($n = 53$) or because they did not wish to participate ($n = 25$). We restricted our analyses to data from the 602 completed surveys.

The ages of the respondents varied from approximately 30 to approximately 70 years. About 34% of the respondents were female. At least one respondent lived in each of the 50 states and the District of Columbia. A majority of the respondents (52%) held a doctoral degree. Most (77%) had more than 10 years of experience in resource management or research. A total of 264 respondents (44%) were primarily employed by or engaged with governmental organizations: 125 (21%) with federal departments, 131 (22%) with state-level organizations, and 8 with other levels of government. Seventy of 256 state and federal government employees identified themselves as scientists. Of the remaining 186 respondents from federal and state governments (31% of the full sample), 100 were managers, 17 were senior executives, 13 were science advisers, and 56 held other positions; this is our *policymaker* group. A total of 228 scientists from academia completed the survey (209 faculty and staff members; 19 students). A further 60 respondents (10%) were from nongovernmental organizations, 18 (3%) from private sector consulting firms, and 32 (5%) from other organizations. The full demographic data are presented in supplement S2.

The academic scientists' self-reported level of awareness of the types of scientific information needed by policymakers was significantly greater than the policymakers' self-reported level of awareness of research on the management of natural resources (supplement S3). The policymakers' mean rankings of the importance to individuals within their organization of different sources of information on research in natural and social science are presented in supplement S4.

Survey responses

Of the original 40 questions, *What quantity and quality of surface and groundwater will be necessary to sustain US human populations and ecosystem resilience during the next 100 years?* had a significantly greater probability than any other of being ranked as the most applicable to policy (table 1). The questions that were ranked 2–8 constituted a distinctive group of second-highest-priority questions (their 95% quasi-confidence bounds did not overlap those for the questions ranked 1 and 9). These questions were focused on metrics for assessing trade-offs among the benefits that humans receive from ecosystems, the effects of sea-level rise, managing land for carbon storage and ecosystem resilience, the effects of energy development, the effects of agriculture on water, metrics for detecting long-term ecological change, and the ecological and economic effects of ecosystem restoration.

The questions ranked 9–14 had a likelihood greater than the mean of being ranked as the most applicable to policy. The questions ranked 15–21 had a likelihood no greater or less than the mean of being ranked as the most applicable

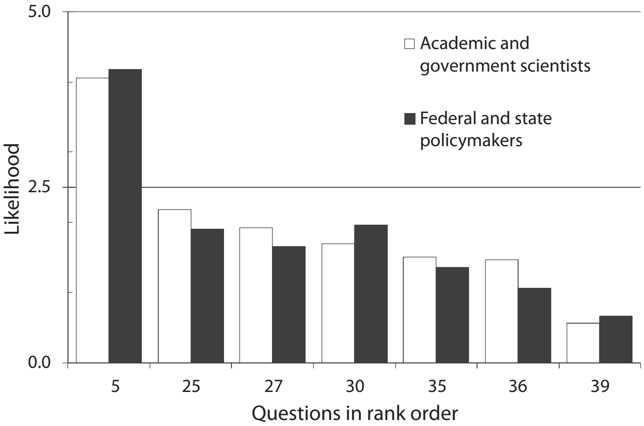

Figure 1. Research orientations (the likelihood, expressed as a percentage, of ranking a given question as the most likely to increase the effectiveness of policies related to the management of natural resources in the United States) of academic and government scientists (n = 279) and federal and state policymakers (n = 193).

to policy. The questions ranked 22–36 had a likelihood significantly less than the mean of being ranked as the most applicable to policy. The questions ranked 37–40 addressed the effects of human activity enabled by climate change in the Arctic, the epidemiology of wild animals, the attributes of wild animals that are reliant on human intervention, and the domestic propagation of wild species.

Differences in research orientation among sectors

Here, we summarize our principal results. We examine the latent-class clusters in more detail below. We did not find significant differences in research orientation among the respondents with respect to their affiliated organizational class (academia, n = 209; government, n = 263; other organizations, n = 130; $\chi^2(14) = 15.24$, $p = .36$). Nor did we detect a significant difference in research orientation when we pooled the responses of government and academic scientists (n = 279) and tested whether their rankings differed from those of the other respondents (n = 323) ($\chi^2(14) = 15.43$, $p = .35$). The difference in research orientations between the government and academic scientists (n = 279) and the federal and state policymakers (n = 186) (figure 1) was not statistically significant ($\chi^2(7) = 11.83$, $p = .11$). No other demographic or professional covariate was significantly associated with latent-class membership and, therefore, research orientation (age, $\chi^2(35) = 41.25$, $p = .22$; gender, $\chi^2(7) = 4.86$, $p = .68$; education level, $\chi^2(21) = 14.48$, $p = .85$; years of career experience, $\chi^2(49) = 52.69$, $p = .33$).

Additional research questions

The respondents submitted 193 new research questions as potential replacements for the existing 40 questions that they had ranked as the least applicable to policy, often with an accompanying rationale (supplement S5). Of these, we agreed that 60 questions were not aligned with the original 40 (box 1, supplement S6). A further 95 questions were reworded versions of the existing 40 questions (supplement S7), whereas the remaining 38 were either extremely broad or were framed as statements rather than as questions.

Heterogeneity in research orientation

Recall that a latent class includes individuals whose research priorities are similar to each other's and different from those of the individuals in other classes. We found that different research orientations were defined by a relatively small proportion of research questions, most of which were of low priority.

When all 40 research questions were included in the analysis, we initially identified seven classes of distinct research

Box 1. Examples of new research questions submitted by individual respondents as replacements for low-ranked questions.

Given projected increases in temperature and changes in precipitation patterns, how will the agricultural capacity of the United States change due to effects of projected climate change?

How will air quality impact human health given projected changes in climate?

How do we effectively communicate science about complex systems to the public and policymakers?

What are the aggregate effects on ecosystems of current use and emerging bio-engineered or genetically altered species?

What factors shape human values toward natural resources and the application of those values to natural resource policy decisions?

What natural resource management practices share the broadest support among groups with distinct personal and political ideologies?

How do human population dynamics and health respond to the independent and interactive effects of multiple ecologic stressors?

How will changes in land use and climate affect the prevalence and rates of transmission of diseases among humans?

What are the economic and environmental benefits of reconnecting rivers with their floodplains in areas that have been leveed?

What are reliable metrics for balancing energy, food, and biodiversity production from ocean algal afforestation ecosystems?

Is the cultivation/transplantation of species facing extinction viable?

Table 2. The research questions whose rankings defined latent classes differing in research orientation.

Rank	Question	Full sample (N = 602)	Latent class 1 (n = 114)	2 (n = 109)	3 (n = 65)	4 (n = 73)	5 (n = 72)	6 (n = 65)	7 (n = 53)	8 (n = 51)
05	What are the potential effects on ecosystems of developing new sources of renewable and nonrenewable energy? [Q08]	4.14	4.83*a	4.54*a	2.92*b	4.72*a	4.45	3.27*b	3.68	3.97
25	What are the aggregate effects on ecosystems of current-use and emerging toxicants? [Q11]	2.06	2.29	3.11*a	3.18*a	0.91*b	0.59*b	0.56*b	2.63*a	2.58*a
27	How will changes in the Arctic's climate affect ecosystems in the Arctic and elsewhere in the United States? [Q34]	1.87	1.66	2.75*a	3.21*a	2.21	0.56*b	0.77*b	0.48*b	2.67*a
30	How do population dynamics respond to the independent and interactive effects of multiple stressors? [Q09]	1.79	0.68*b	0.76*b	2.04	2.49*a	0.88*b	3.59*a	2.90*a	2.56*a
35	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? [Q39]	1.46	0.33*b	2.15*a	2.49*a	0.63*b	0.63*b	2.20*a	0.83*b	2.89*a
36	How is the productivity of soil in a given region affected by different policies and stressors? [Q10]	1.31	2.21*a	0.66*b	2.72*a	0.38*b	0.89*b	0.35*b	2.87*a	0.15*b
39	What are the attributes of species that will require ongoing human intervention to persist outside captivity? [Q32]	0.61	0.07*b	0.22*b	1.20*a	0.31*b	0.11*b	2.14*a	0.46*b	1.01*a

Note: The question number from Fleishman and colleagues (2011) is in brackets. [a]Higher than the mean. [b]Lower than the mean. $^{*}p \leq .05$.

priorities (i.e., a model with seven latent classes had the lowest BIC). However, the rankings of many pairs of questions were closely correlated (i.e., there were many significant bivariate residual coefficients). We sequentially deleted 33 research questions from the latent-class cluster analysis, which resulted in no remaining significant bivariate residual coefficients. We then ran a second set of models with the remaining seven questions and up to 12 latent classes. The model that minimized the BIC (our final model) identified eight classes of distinct research priorities (supplement S8).

Seven of the 40 questions provided information about differences in research orientation among the eight latent classes (table 2). Of those seven questions, six were ranked at priority 25 or lower. To illustrate how research orientation varied among the latent classes, the rankings of the respondents in latent classes 3 (n = 65) and 4 (n = 73) deviated substantially both from the mean likelihoods and from each other for four questions (figure 2a). The rankings of the respondents in latent classes 5 (n = 72) and 8 (n = 51) also illustrated different patterns of research priorities (figure 2b).

Latent class 1 included 114 respondents. Their ranks of questions on the effects of renewable energy and the effects of policies and stressors on soil productivity as the most applicable to policy were higher than the mean likelihood ranking (table 2). They ranked lower than the mean likelihood ranking questions on the responses of population dynamics to multiple stressors (original question Q09, which was ranked 30), the responses of species with different life histories to the establishment of marine protected areas (MPAs) (Q39), and species persistence outside captivity (Q32). The respondents from latent class 1 provided the greatest proportion of comments that we received (114 respondents provided 91 comments) and emphasized the need for scientists to conduct research useful to policymakers and to present the results of that research clearly. Detailed verbatim comments on how scientists can make their research more applicable for policy, can better communicate their research findings, or can improve the credibility of their research are available in supplement S9.

The respondents from latent class 2 (n = 109) ranked higher than the mean likelihood ranking questions on the effects of energy development (Q08), emerging toxicants (Q11), Arctic climate change (Q34), and the ecological effects of MPAs on species (Q39). Their rankings were lower than the mean likelihood ranking for the remaining three questions (Q09, Q10, Q32), and their comments were not distinctive.

The respondents from latent class 3 gave high ranks to questions about toxicants (Q11), Arctic climate change (Q34), MPAs (Q39), soil productivity (Q10), and species persistence outside captivity (Q32); they ranked the question on the effects of energy development on ecosystems (Q08) lower than the mean. They contributed a relatively

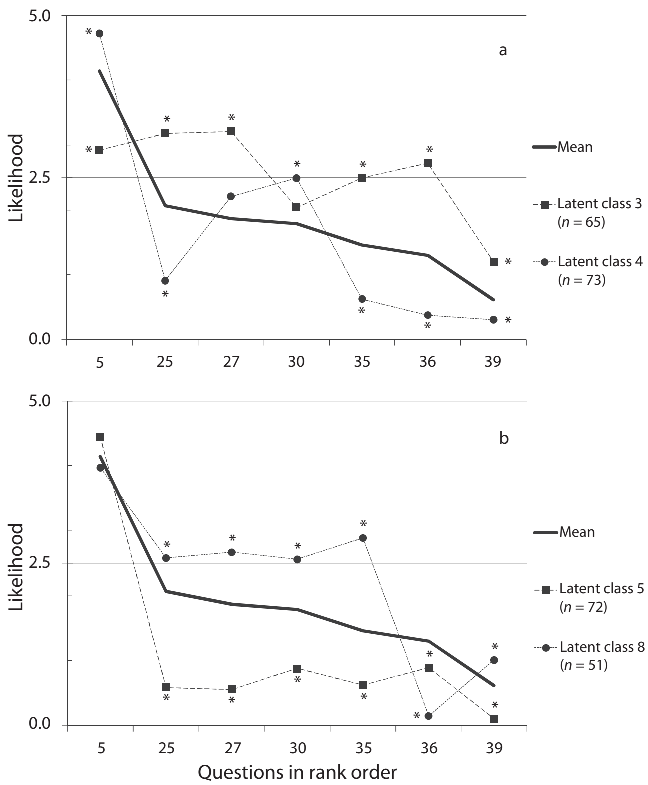

Figure 2. Differences in research orientations (the likelihood, expressed as a percentage, of ranking a given question as the most likely to increase the effectiveness of policies related to the management of natural resources in the United States) among the respondents from selected latent classes. ***$^{*}p \leq .05$.***

high proportion of comments on barriers to the application of research (7 of 35 comments submitted on that topic were from latent class 3), the perceived dichotomy between economic growth and environmental quality (3 of 8 comments on that topic were from latent class 3), and the perceived effectiveness of ecosystem management (10 of 32 comments on that topic were from latent class 3).

The respondents from latent class 4 could not be clearly characterized on the basis of their rankings. They assigned relatively high ranks to the questions about energy development (Q08), Arctic climate change (Q34), and the responses of populations to multiple stressors (Q09) and relatively low ranks to all of the others, and they contributed few comments that distinguished them from respondents in the other latent classes.

The only question that the respondents in latent class 5 gave a rank higher than the mean likelihood was on the effects of energy development (Q08). In their comments, they emphasized the applicability to policy of questions related to the relative capacity of different types of governance to manage resources (7 of 34 comments), the role of social capital in management (10 of 33 comments), and the effectiveness of cross-disciplinary research in informing solutions to environmental challenges (9 of 27 comments). One respondent, for instance, said, "[the] problems we are facing are fundamentally social, yet most of the questions focus on biophysical sciences and economics" (ID678). Another emphasized that it was crucial to "get the science to middle management… [and to] help make connections between universities and state and federal agencies" (ID1546).

The respondents in latent class 6 gave ranks greater than the mean likelihood ranking to the questions on the responses of populations to multiple stressors (Q09), the ecological effects of MPAs (Q39), and species persistence without human intervention (Q32), and their comments ranged widely in perspective. The respondents from latent class 7 gave toxicants (Q11), the responses of populations to multiple stressors (Q09), and soil productivity (Q10) ranks greater than the mean likelihood ranking and gave Arctic climate change (Q34) and the establishment of MPAs (Q39) ranks lower than the mean likelihood ranking. They provided 17 comments. The respondents in latent class 8 gave high ranks to questions on the responses of populations to multiple stressors (Q09), Arctic climate change (Q34), and species persistence outside captivity (Q32). They submitted new questions on governance (5 of 34 new submissions on that topic) and ecosystem management (4 of 32 submissions). One respondent strongly questioned the human–nature cleavage of modern environmental management: "For… Native Americans and other groups, it is inherently offensive to consider ecological services as benefits to be obtained when human beings have no separate origination apart from the environment. It is analogous to a child or parent speaking of a family member as a commodity, like a sack of grain" (ID1291).

Conclusions

Numerous research–management partnerships in the United States, such as regional landscape conservation cooperatives and climate science centers, are intended to identify and meet the information needs of government resource agencies. The launches of collaborative initiatives have often been followed by assessments of national or regional science priorities. The lists of science needs or priorities are typically compiled on the basis of surveys and are intended to inform the development of research agendas and the allocation of funds. However, the extent to which the design and administration of these surveys are informed by quantitative social science varies considerably, as does the extent to which survey responses represent the priorities of policymakers.

To generate the original 40 questions (Fleishman et al. 2011), we used an established method (that presented in Sutherland et al. 2011) to solicit 531 policy-relevant research questions from 375 individuals affiliated with 109 organizations. The questions were culled to 40 by 25 well-informed staff members of or collaborators with government agencies, nonprofit organizations, trade associations, and similar groups. Here, we applied rigorous methods to gauge whether policymakers and scientists concurred on the relative ranks of those 40 questions. Given the significant alignment, we hope that the ranked set of questions will inform strategic planning by research–management partnerships with limited time and resources to conduct their own rigorous needs assessments.

In this case, demographic and professional covariates were not significantly associated with research orientation. Nevertheless, we believe that the method is feasible and highly applicable to the objective classification of science needs on the basis of organizational affiliation or attributes associated with management or regulatory jurisdiction, such as ecosystems, taxonomic groups, the size of the area of jurisdiction, or dominant environmental changes.

Research priorities. Of the original 40 research questions, *What quantity and quality of surface and groundwater will be necessary to sustain US human populations and ecosystem resilience during the next 100 years?* was more than twice as likely as the mean and over 10 times as likely as the lowest-ranked question to be ranked by our sample of policymakers and scientists as the most likely, if it were answered, to increase the effectiveness of policies related to the management of natural resources in the United States over the next 5–10 years. The other water-related question, *How do different agricultural practices and technologies affect water availability and quality?* was ranked sixth. Our data were collected before the peak of the 2012 US drought (*http://droughtmonitor.unl.edu*), so the salience of questions on water supply may have even increased.

The other 13 questions with a likelihood significantly greater than the mean likelihood of being ranked as the most applicable to policy addressed diverse topics that were sometimes superficially similar to those questions ranked as less applicable to policy. For example, the question *How will coastal ecosystems and human communities be affected by sea-level rise, storm surge, erosion, the intrusion of saltwater, and changes in the amount and variability of precipitation?* was ranked third, whereas *What ecological and economic changes will result from ocean acidification?* was ranked 20th. One expert on ocean acidification recently stated that “other stressors associated with the climate change, such as temperature changes, wind and wave climate changes, incidence of severe storms, [and] hypoxia” are more likely to affect coral reefs than are trends in pH (Gattuso et al. 2013, p. 733). The former question is focused on coastal systems that may change considerably in response to even one storm event in the United States. Although ocean acidification will affect the coastal United States, discussion of acidification in the resource-management community is largely focused on coral reefs around the world (Gattuso et al. 2013). The relatively low priority for research on ocean acidification in this survey of US residents diverged from that of 592 coastal scientists from 91 countries. The latter group ranked the same question on ocean acidification as the second-highest priority for coastal research (Rudd and Lawton 2013).

Similarly, *How do different strategies for managing forests, grasslands, and agricultural systems affect carbon storage, ecosystem resilience, and other desired benefits?* was ranked fourth, whereas *What are the relative ecological effects of increasing the intensity versus spatial extent of agricultural and timber production?* was ranked 22nd. This rank may suggest that carbon sequestration is perceived as more applicable to policy than are the general ecological effects of resource production. For example, California’s Global Warming Solutions Act of 2006 (Assembly Bill 32) requires reductions in carbon dioxide emissions that will be achieved, in part, by carbon sequestration. The wording of the questions may also be a factor if questions directly addressing management were prioritized over obviously ecological questions. Most of the questions ranked among the least applicable to policy were not aligned with the jurisdictions of most of the policymakers in US resource agencies (e.g., the establishment of governance systems, which might be determined by Congress rather than by resource agencies) or emphasized ecological inquiry that may be of interest to a subset of policymakers. For example, responses of species with different life histories to the establishment of marine protected areas may be of limited interest to policymakers primarily responsible for terrestrial ecosystems or marine fisheries.

Research orientation. In our sample, research orientation was highly heterogeneous, and the strong differences among the latent classes were driven by the respondents’ prioritizations of questions ranked relatively low with respect to their perceived ability, if they were answered, to inform policy. Demographic or professional factors did not explain the variation in research orientation. The difference in research orientation between the government policymakers and the pooled government and academic scientists was not statistically significant. That research orientations differ between scientists, whether in academia or government, and policymakers is often taken for granted (e.g., Lawton 2007). In our sample, however, there was no significant divergence of research orientation between the scientists and the policymakers.

There are two main possible reasons for the lack of significant differences in research orientation. First, our sampling method may have allowed for self-selection by the respondents, such that only scientists and policymakers with strong and aligned views on research priorities responded to the survey. However, given the diversity of disciplines and institutional affiliations represented by the respondents, we think that a major self-selection bias that aligned the scientists’ priorities with those of the policymakers is unlikely.

A second possibility is that the original exercise achieved its goal of identifying questions that the scientists and the policymakers agreed were highly applicable to policy. With one exception, the questions ranked 24th and higher did not affect differences in research orientations. The scientists and the policymakers within the latent classes had similar research orientations, and there appeared to be relatively broad agreement among the scientists and policymakers on research priorities. However, research priorities differed significantly among individuals, and the reasons for that remain unclear. A full analysis of the qualitative responses to our survey is beyond the scope of this article, but we are now conducting a follow-up survey with scientists and policymakers from various latent classes to further explore underlying factors that drive latent-class membership and, therefore, patterns of research priorities. We are hopeful that an in-depth probe of personal and professional beliefs and experience with the successful use of science in natural resource management and policymaking may shed further light on why research orientation differed among the survey respondents and on the underlying factors that may explain those differences.

Acknowledgments

This work was supported in part by Kresge Foundation grant no. 239855 to the University of California, Santa Barbara (to EF). We thank Nathalie Kopytko for assistance with the sample construction and Ricky Lawton for assisting with the organization of the respondents' comments. Thanks to David E. Blockstein, John A. Hall, Michael B. Mascia, and three anonymous reviewers for comments that improved the manuscript. We are grateful for the patience and participation of all of the survey respondents.

Supplemental material

The supplemental material is available online at *http://bioscience.oxfordjournals.org/lookup/suppl/doi:10.1093/biosci/bit035/-/DC1*.

References cited

Auger P, Devinney TM, Louviere JJ. 2007. Using best–worst scaling methodology to investigate consumer ethical beliefs across countries. Journal of Business Ethics 70: 299–326.

Boxall ABA, et al. 2012. Pharmaceuticals and personal care products in the environment: What are the big questions? Environmental Health Perspectives 120: 1221–1229.

Braunisch V, Home R, Pellet J, Arlettaz R. 2012. Conservation science relevant to action: A research agenda identified and prioritized by practitioners. Biological Conservation 153: 201–210.

Fleishman E, et al. 2011. Top 40 priorities for science to inform US conservation and management policy. BioScience 61: 290–300.

Flynn TN, Louviere JJ, Peters TJ, Coast J. 2007. Best–worst scaling: What it can do for health care research and how to do it. Journal of Health Economics 26: 171–189.

Gattuso J-P, Mach KJ, Morgan G. 2013. Ocean acidification and its impacts: An expert survey. Climatic Change 117: 725–738.

Hackmann H, St. Clair AL. 2012. Transformative Cornerstones of Social Science Research for Global Change. International Social Science Council.

Hagenaars JA. 1988. Latent structure models with direct effects between indicators: Local dependence models. Sociological Methods and Research 16: 379–405.

Hynes S, Hanley N, Scarpa R. 2008. Effects on welfare measures of alternative means of accounting for preference heterogeneity in recreational demand models. American Journal of Agricultural Economics 90: 1011–1027.

Lawton JH. 2007. Ecology, politics and policy. Journal of Applied Ecology 44: 465–474.

Magidson J, Vermunt JK. 2004. Latent class models. Pages 175–198 in Kaplan D, ed. The Sage Handbook of Quantitative Methodology for the Social Sciences. Sage.

Morey E, Thiene M, De Salvo M, Signorello G. 2008. Using attitudinal data to identify latent classes that vary in their preference for landscape preservation. Ecological Economics 68: 536–546.

Pahl-Wostl C, Giupponi C, Richards K, Binder C, de Sherbinin A, Sprinz D, Toonen T, van Bers C. 2013. Transition towards a new global change science: Requirements for methodologies, methods, data and knowledge. Environmental Science and Policy 28: 36–47.

Pretty J, et al. 2010. The top 100 questions of importance to the future of global agriculture. International Journal of Agricultural Sustainability 8: 219–236.

Rudd MA. 2011. How research-prioritization exercises affect conservation policy. Conservation Biology 25: 860–866.

Rudd MA, Lawton RN. 2013. Scientists' prioritization of global coastal research questions. Marine Policy 39: 101–111.

Rudd MA, et al. 2011. Generation of priority research questions to inform conservation policy and management at a national level. Conservation Biology 25: 476–484.

Scarpa R, Thiene M. 2005. Destination choice models for rock climbing in the Northeastern Alps: A latent-class approach based on intensity of preferences. Land Economics 81: 426–444.

Sutherland WJ, et al. 2009. One hundred questions of importance to the conservation of global biological diversity. Conservation Biology 23: 557–567.

Sutherland WJ, Fleishman E, Mascia MB, Pretty J, Rudd MA. 2011. Methods for collaboratively identifying research priorities and emerging issues in science and policy. Methods in Ecology and Evolution 2: 238–247.

Sutherland WJ, et al. 2012. A collaboratively-derived science-policy research agenda. PLOS ONE 7 (art. e31824).

Vermunt JK, Magidson J. 2002. Latent class cluster analysis. Pages 89–106 in Hagenaars JA, McCutcheon AL, eds. Applied Latent Class Analysis. Cambridge University Press.

Wedel M, Kamakura W. 2000. Market Segmentation: Conceptual and Methodological Foundations, 2nd ed. Kluwer Academic.

Murray A. Rudd is a senior lecturer in the Environment Department at the University of York, in the United Kingdom. His research is focused on conservation social science and the environmental science–policy interface. Erica Fleishman (efleishman@ucdavis.edu) is a researcher at the University of California, Davis. Her work is focused on the integration of science with management and policy in the western United States.