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The Precautionary Principle in Context: US and EU Scientists' Prescriptions for Policy in the Face of Uncertainty

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Objective. Our objective is to explain how scientists interpret less-than-certain scientific findings to inform policymakers' choices on controversial science policy issues. We focus on two particularly difficult policy cases concerning global climate change and low-dose radiation protection. *Methods.* Our method is to analyze data from a unique multination survey of scientists to analyze the ways their views about what is scientifically correct are translated into judgments about appropriate policy. The surveys asked scientists, randomly drawn from U.S. and E.U. subscribers to the journal *Science*, to indicate the "most likely" relationships between greenhouse gas emissions and average global temperatures and between radiation dose and incidence of cancer in humans. Follow-up questions asked for their judgments about appropriate policy targets for reductions in greenhouse gas emission and safety standards for radiation exposure. The data permit analysis of the relationships between scientific certainty and policy judgments in these two cases. *Results.* Our results shed light on when and how scientists reach precautionary policy conclusions, demonstrating that scientists' application of precaution is dependent on context. In the case of radiation protection, greater certainty is associated with less precaution. But with respect climate change, we found the opposite relationship. *Conclusions.* We conclude with a discussion of the implications for the role of scientists, and scientific advice, in the policy process.

Scientists are integral players in the translation of scientific knowledge into public policy. When policies concern risks and risk management, scientists may be called on to exercise judgment in extending less-than-certain scientific findings into policy recommendations (Revkin, 2004; Jasenoff, 1990; Salter, 1988; McGarity, 1979). The "trans-scientific" nature of the endeavor is particularly stark when the theoretical and empirical bases for the judgments are uncertain and contested. Of central importance is the role

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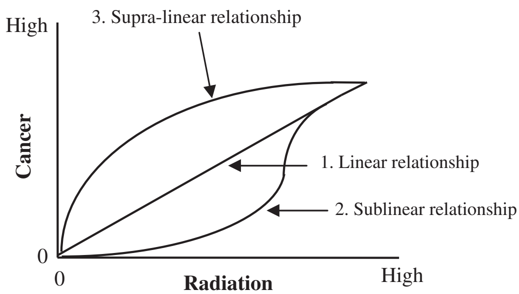
of what has become known as the "precautionary principle" in extending uncertain science to public policy. When extant scientific findings indicate that a hazard looms but it remains uncertain and contested, the precautionary principle holds that policy should act to minimize (or reduce) the risk (Foster et al., 2000; Raffensperger and Tickner, 1999; Goklany, 2001). Controversy can be particularly sharp when the effort to reduce the environmental or health risk may jeopardize other socially valued objectives such as employment and economic growth. This article explores the manner in which scientists make the extension from their beliefs about what is empirically correct to judgments about the assumptions that should underlie public policy and regulation.

We employ two cases in which scientists play a central role, current scientific findings are characterized by policy-significant uncertainty, and the stakes for tradeoffs of environmental risks and economic costs are substantial. The first case concerns the relationship of low-dose radiation exposure to cancer incidence in humans. The subject of enormous scientific effort by the National Academy of Science's Biological Effects of Ionizing Radiation (BEIR) Committees, the form of the dose-response relationship has large implications for setting standards for radiation protection, environmental remediation, and radioactive waste disposal (U.S. GAO, 2000; National Research Council, 2005). After decades of research, the seventh BEIR Committee concluded that, despite remaining uncertainty, the functional form of the dose-response relationship is best represented as linear, such that any increase in radiation exposure leads to a proportional increase in cancer incidence (National Research Council, 2005). One alternative and widely supported proposition is that the relationship is "sublinear," such that below some threshold level the effects of radiation are of no practical significance. Another alternative holds that the relationship is particularly responsive at the lowest doses, dubbed the supra-linear dose-response function. These possible relationships are depicted in Figure 1.

FIGURE 1

Hypothesized Radiation Dose-Response Relationships



According to the GAO, the implications of the contending functions for costs of environmental remediation at Department of Energy facilities could reach a trillion dollars (U.S. GAO, 1994, 2000). At the same time, uncertainty has resulted in different exposure standards at different federal agencies (U.S. GAO, 2000). Despite the recent BEIR report, prominent scientists continue to argue that the cumulative results of biological research support a sublinear dose-response function.[1]

The second case concerns the implications of carbon emissions for global climate change. Notwithstanding the near consensus among climate scientists that anthropogenic carbon emissions have resulted in significant changes in the composition of the atmosphere, with direct implications for trapping heat, uncertainty remains regarding the magnitude of the overall global temperature change and the distribution of such changes (Giles, 2002; Karl and Trenberth, 2003). Further uncertainty concerns the effects of possible future changes in levels of carbon emissions. But the stakes are enormous, with the range of possible effects from mild to catastrophic. At the same time, the potential economic costs of large-scale carbon reductions are massive and likely to prove to be politically costly. A substantial fraction of CO_2 emissions come from automobiles, and CO_2-emitting coal-fired generators produced over 50 percent of commercial electricity in the United States in 2002. The magnitude of the costs of reducing carbon emissions has become another locus of the policy debate, with policy preferences apparently influencing estimates of both proponents and opponents of policies to reduce emissions (Revkin, 2004).

How do scientists make the step from what they believe to be true about the effects of radiation exposure or carbon emissions to preferences for relevant safety standards and policy positions? Do scientists act to operationalize the precautionary principle in their recommendations? If so, how? Precaution can be taken to imply preference for a policy that presumes that the environmental or health consequences of the underlying phenomena will be as dire as can plausibly be supported by current scientific evidence, even if significant uncertainty remains. Do scientists assume, for purposes of making policy recommendations, the "worst-case" radiation dose-response function (supra-linear response) or the greatest plausible global temperature increase from carbon (or other greenhouse gas) emissions? In practice, of course, the application of caution may be more complicated (Sunstein, 2005). Presumably, some weight is given to avoiding economic, social, and other categories of loss. Moreover, in some cases, seeking to embed *too much* environmental or health precaution in policy might undermine the political feasibility of obtaining a desirable policy.

[1]See, for example, the keynote address given at the 2005 Health Physics Society Meeting by Ludwig Feinendegen, entitled "Low Doses of Ionizing Radiation: The Relationship Between Damage Induction and Biological Benefit Contradicts Validity of the LNT-Hypothesis." Available at ⟨http://hps.org/newsandevents/meetings/annual/50annual256.html⟩.

Precaution necessarily concerns the degree of certainty with which scientists can characterize the underlying natural phenomenon. As typically framed, the precautionary principle would hold that, ceteris paribus, the more certain the scientist is about the characteristic shape of the radiation dose-response relationship, the less need to opt for a precautionary shift in recommended policy. Put simply, there is less chance of underestimating the risk and hence less need to err on the side of caution. This is an important relationship, and it underlies the effort to advance scientific certainty through new research as a strategy to address issues such as radiation protection and global climate change. However, it raises an empirical question: Does the degree of certainty with which scientists understand these issues influence the introduction of precaution in their policy recommendations? In the absence of certainty, scientists might be expected to make decisions on the basis of an array of emotions, heuristics, and normative considerations, much the same as nonscientists do (Sniderman, Brody, and Tetlock, 1991; Zaller, 1992; Frank, 1988). By this logic, when we invest in scientific certainty it is in part because we ask scientists to narrow the "boundary conditions" for policies within which reasonable (but nonscientific) people can differ. Greater scientific certainty implies less need for precaution.

The precautionary principle is the subject of substantial debate and variation in application. John Graham, former Administrator of the Bush Administration's Office of Information and Regulatory Affairs in the Office of Management and Budget, has argued that there is "no such thing as a precautionary principle" (Graham, 2004; Wildavsky, 1995). Instead, Graham argues that scientists often exaggerate some risks, pointing to an array of recent scientifically unsupported health scares. Cass Sunstein observes that precaution with respect to one kind of risk may come at the price of increasing other risks (Sunstein, 2005). In the European Union, the concept of precaution has been explicitly employed in regulatory design (though the application has varied), while in the United States the reception has been less positive. An example that illustrates the policy differences that have emerged between the United States and the European Union is the high-profile trade dispute concerning genetically modified organisms. Thus it is reasonable to ask whether there are significant differences in the way that U.S. and European scientists engage in the exercise of precaution.

The Survey

A great deal has been written about how scientists make trans-scientific choices (Mukerji, 1989; Fischer, 1990), but to date relatively little systematic empirical research addresses these questions (Rothman and Lichter, 1985; Plutzer, Maney, and O'Connor, 1998; Slovic et al., 1995; Slovic and Peters, 1998; Slovic, 2000). Our data were obtained from a random sample of subscribers to the journal *Science* in the United States and Europe.

TABLE 1

Characteristics of U.S. and E.U. Scientist Samples

	U.S.	E.U.
For Entire Sample		
Percent Ph.D.	78.7	82.7
Average age (in years)	53.3	53.4
Percent male	79.8	87.0
Response rate	34.2	36.0
Sample size	865	1332
Average response lag (in days)	41.7	42.0
For Doctoral/Ph.D. Respondents from Physical, Biological, and Engineering Sciences		
Average age (in years)	54.1	53.2
Percent male	81.5	87.8
Sample size	633	1026
Fields of research (% shown)		
Agriculture, biology, medical sciences	70.8	68.5
Chemistry	11.8	11.7
Earth sciences	3.9	4.4
Engineering. math, computer science	8.4	6.6
Physics, astronomy	5.2	8.9
Type of organization (% shown)		
Private business/consultant (nonhealthcare)	18.7	11.8
Education and/or research	60.1	63.7
Government/nonprofit	7.6	4.4
Healthcare	13.6	20.0

A survey questionnaire was administered by mail in English, with the option of French, German, and Italian questionnaires for E.U. respondents.[2] The response rates were 34 percent in the United States and 36 percent in the European Union.[3]

The characteristics of the U.S. and E.U. samples are shown in Table 1. Of the original samples, 79 percent of the Americans and 83 percent of the Europeans had attained Ph.D. or equivalent degrees. To focus on those respondents most likely to reflect the behavior of scientists generally, we use the responses of these scientists in the analyses that follow. The characteristics of the Ph.D. scientist samples are shown in the lower panel of Table 1. Of particular significance is the distribution of fields of research, which would presumably have implications for the individual scientists' particular

[2]The European data collection was undertaken by Ronin Corporation. The U.S. data collection was managed under contract by the University of New Mexico's Institute for Public Policy.

[3]Telephone surveys of a random sample of nonrespondents were undertaken to determine whether responses to the survey were affected by systematic nonresponse bias. Respondents tended to be slightly older than nonrespondents (by about three years), but no statistically significant differences in responses to substantive items were found.

knowledge and certainty with respect to the issues evaluated here. We emphasize that this sample is of scientists generally (and subscribers to *Science* specifically)—not of experts in fields pertaining to the effects of radiation or global climate change. For that reason, the sample provides insight *into how scientifically trained professionals from a variety of scientific fields and positions would make policy judgments* in light of what they believe the best available science has to offer on these questions.

Radiation Dose Response

The survey questionnaire provided the dose-response functions illustrated in Figure 1, and respondents were asked: "Given your own knowledge of radiation effects on humans and other organisms, which of the above hypothesized relationships do you think is most likely correct?" A follow-up question asked: "On a scale where zero means not at all certain and ten means completely certain, how certain are you that the relationship you identified is correct?" And finally, to ascertain whether there was a precautionary policy shift, respondents were asked: "Which of these three hypothesized relationships do you think should be assumed for purposes of setting public safety standards for managing radioactive materials?" The exact question wording is provided in the Appendix, with the associated response distributions for the U.S. and E.U. samples.

What would precaution look like in responses to the radiation dose-response (D-R) questions? Based on the above discussion of precaution, we conjecture that "precautionary" choices would be those for which the safety standard is based on a D-R model that implies greater risk of cancer than does the model "most likely" to be correct. "Consistent" choices would be those for which the D-R that is believed the "most likely" one is also the one preferred for safety standard setting. Finally—and somewhat improbably—"risk accepting" choices would be those for which the policy is based on a D-R function that implies greater safety than would be warranted by the "most likely" function.

Table 2 shows the pattern of responses for the U.S. and E.U. samples. A substantial majority of both samples believed the sublinear curve to represent the most likely D-R function. Nearly half these scientists nevertheless opted for a precautionary shift to the linear or the supra-linear functions for standard setting. Approximately half the scientists in each sample were "consistent," preferring to employ the "most likely" D-R model as the basis for health standards. Only a very small fraction of the respondents were "risk accepting."

Global Climate Change

The climate change question provided a range of projected temperature changes inclusive of those from respected models (from −1 degree C to

TABLE 2

Observed Patterns of Precaution in the Radiation Dose-Response Debate (U.S.%/E.U.%)

		Preferred Dose-Response Function for Setting Regulatory Health Policy Standard			
		Sublinear	Linear	Supra-Linear	Don't Know
		33.4/30.3	32.8/28.8	21.5/27.4	12.4/13.6
Most likely dose-response function	Sublinear 66.9/62.0	32.5/28.7 Consistent	18.0/15.0 Precautionary	11.0/13.6 Very precautionary	5.6/5.2
	Linear 18.0/18.5	0.3/0.9 Risk accepting	12.9/12.0 Consistent	3.2/4.6 Precautionary	1.6/1.1
	Supra-linear 6.4/8.5	0.0/0.5 Risk accepting	0.2/0.3 Risk accepting	5.6/7.4 Consistent	0.6/0.3
	Don't know 8.7/11.0	0.6/0.2	1.8/1.5	1.6/1.9	4.6/7.0

+7), and asked: "Based on your knowledge of the climate change issue, please indicate the change in average global temperature you expect by the year 2100 if greenhouse gas emissions continue to increase proportional to growth in the world's population and economy." This was followed by a question concerning certainty: "Assuming greenhouse gas emissions continue to increase proportional to growth in the world's population and economy, on a scale where zero means not at all certain and ten means completely certain, how certain are you that average global temperatures will change as you expect?" Finally, to identify policy recommendations, we reminded the respondent that the target goal for temperature change "has critical environmental, economic, and political implications" and asked what base temperature change should be assumed for setting emission-reduction levels: "What goal for maximum allowable global temperature change by the year 2100 do you think should be used in negotiations to set international ceilings for greenhouse gas emissions?"

In the case of climate change, given uncertainty about how carbon emissions affect global temperatures, a precautionary policy stance would be to seek to limit carbon emissions (and other greenhouse gases) such that human-caused global average temperature increases would be minimized.[4] In its strongest form, precaution would seem to call for allowing no increase in temperature regardless of expected baseline change. A weaker form of precaution might call for setting a goal of temperature increase below the expected baseline change, but allowing some increase by 2100. This option would be a compromise, limiting but not disallowing the effect of carbon emissions. Allowing temperatures to rise to (or above) the expected baseline levels would be "risk accepting."

The responses to the global climate issue questions are shown in Table 3. Sizable majorities of both U.S. and European scientists expect a human-caused temperature increase of 1–4 degrees C by 2100. Very few expect no change, and over 20 percent expect an increase of 5 degrees or more. In response to the question about the target to use in emission goal setting, the U.S. and E.U. respondents differ only slightly: 13.7 percent of the EU scientists want the goal to be no increase, compared with 11.5 percent of the Americans. Equally similar, 66.4 percent of the Europeans want the target set at between a 1–2° C increase, compared to 64.7 percent of the Americans.

In the terms used here, only 11.5 percent and 13.7 percent of the respondents opted for "strong precaution" in the United States and the European Union, respectively. The percentage of Americans choosing the weaker form of precaution, limiting but allowing some warming, was 41.3

[4]Alternatively, precaution could be taken to imply setting a goal to move global temperatures downward by 2100. However, very few scientists in our samples (0.5 percent U.S. and 0.8 percent E.U.) opted to set carbon emission goals that would bring temperatures down by the year 2100.

TABLE 3

Observed Patterns of Precaution in the Global Climate Change Debate (U.S.%/E.U.%)

		Preferred Target Temperature for Negotiating International GHG Reductions				
		No Increase	1–2°C	3–4°C	5°C or More	Don't Know
	Total	11.5/13.7	64.7/66.4	12.4/11.7	3.8/1.9	7.7/6.3
Expected global temperature increase by 2100	No Increase 2.8/0.9	0.6/0.3 Strong precaution	1.3/0.4 Risk acceptant	0.2/0.0 Risk acceptant	0.5/0.1 Risk acceptant	0.3/0.1
	1–2°C 37.2/36.9	4.4/7.6 Strong precaution	27.2/24.9 Risk acceptant	2.8/1.7 Risk acceptant	0.6/0.4 Risk acceptant	2.2/2.4
	3–4°C 34.7/40.0	3.8/3.9 Strong precaution	23.9/29.1 Weak precaution	4.1/4.8 Risk acceptant	1.1/0.5 Risk acceptant	1.9/1.7
	5°C or more 23.1/20.1	2.7/1.9 Strong precaution	12.2/11.9 Weak precaution	5.2/5.3 Weak precaution	1.6/0.9 Risk acceptant	1.4/0.2
	Don't know 2.2/2.1	0.0/0.1	0.2/0.1	0.2/0.0	0.0/0.0	1.9/2.0

percent; the corresponding figure for the Europeans was 46.3 percent. Over a third of each group were risk acceptant, setting the goal at or above the baseline temperature change. Although the differences between the U.S. and E.U. scientists are statistically significant ($p = 0.026$), they are not substantively far apart.

The Role of Certainty

How does subjective certainty affect scientists' transition from what is perceived to be "most likely" to preferred policy options? For both the radiation dose-response and the expected global climate change items, respondents were asked to rate their level of certainty on a scale from 0 ("not at all certain") to 10 ("completely certain"). The means for the certainty scales for the two samples are remarkably close. For the radiation dose-response functions, average certainty was 5.68 ($SD = 2.80$) in the U.S. sample and 5.79 ($SD = 2.70$) in the E.U. sample. Respondents were slightly less certain about the expected base global temperature change—with scores of 5.24 (U.S., $SD = 2.69$) and 5.25 (E.U., $SD = 2.83$). In neither case are the mean differences statistically significant.

What is the expected role of certainty in precaution? As noted above, one expectation is that increased certainty will reduce precaution; greater certainty reduces the likelihood that risks have been understated, resulting in less reason to err on the side of caution. At the same time, we might expect other factors to play a significant role in leading scientists to opt for a precautionary stance. A substantial body of research suggests that scientists, no less than lay individuals, employ normative dispositions and broad beliefs in reaching conclusions about risk. In its most general form, the argument is that the concept of risk is concerned with values (the things that may be lost or gained) that, in turn, are grounded in larger normative frames of reference such as culture (Dake and Wildavsky, 1990; Douglas and Wildavsky, 1982), ideology (Plutzer, Maney, and O'Connor, 1998), and social experience as colored by gender, race, and social status (Slovic et al., 1995). Thus, an appropriate model of the role of certainty in precaution would include controls for these other factors.

To address these possible alternative explanations for precaution, we included measures of an array of beliefs and dispositions as controls in our analysis. In keeping with the broader literature, we include a measure of left-right political ideology (the question wording is included in the Appendix), in which respondents scale themselves from "strongly left/liberal" to "strongly right/conservative." Based on the findings in the literature, one would expect the left/liberal respondents to be more likely than those who label themselves "right/conservative" to opt for a precautionary policy stance. We also include a pair of measures each based on indices made up of three items that are intended to capture the respondents' preferences for egalitarian and hierarchical values. Egalitarians prefer social relations with few distinctions and roughly equal distributions of wealth and power. For egalitarians, the most alarming risks are those stemming from the abuse of power by concentrated and unresponsive authority (government and corporations). By contrast, hierarchs prefer greater structure and distinction in society, with deference to those in authority. Priority is given to threats to order and security. We would hypothesize that those with egalitarian leanings would be more precautionary, while hierarch leanings would be associated with a greater willingness to accept the extant body of science on the issue and set policy accordingly (Douglas and Wildavsky, 1982; Dake and Wildavsky, 1990; Dake, 1991).

A disposition more directly linked to precaution concerns norms governing societal allocation of risk. As a general perspective, one might prefer a society in which risk is avoided where possible, and no risks are imposed on individuals without consent. On the other extreme, one might embrace risk as good and even necessary for societal development, wherein imposing some risks in return for larger social gains is permissible, and compensation for imposed risks is a fair means for society to prosper. We use a set of four questions to develop a risk index, with full question wording included in the Appendix. The scale values (0 to 7) indicate the degree to which respondents believe that imposing risks is both necessary and permissible, with higher values meaning greater acceptance of that position. We expect a higher score to be associated with less precautionary decisions in our two cases. In addition, because of its direct relevance to the environmental issues at hand, we include a measure of the degree to which the respondent perceives the overall state of the environment to be at risk. Our expectation is that the greater the sense that the environment is in peril (a higher score), the more prone the respondent will be to take a precautionary position. Finally, because gender has been found to be robustly associated with risk perceptions, we include a binary gender variable (1 = male) as a control variable (Finucane et al., 2000; Barke, Jenkins-Smith, and Slovic, 1997). The mean values for each of the disposition items for the U.S. and E.U. samples are shown in Table 4.

Modeling Precaution

To test hypotheses concerning the effects of certainty while controlling for the array of normative dispositions on precaution in the case of radiation exposure, our approach is to model the shift made from the D-R function perceived to be correct to the one preferred for regulatory standard setting. Because a substantial majority (71 percent of those who identified a D-R function) believed the sublinear model was "most likely" to be correct, we focus on the decision of this group to opt for a sublinear, linear, or supralinear function as the basis for standard setting. We use a multinomial logit

TABLE 4

Explanatory Variables for Belief and Attitudinal Analyses Mean Values and Differences by Sample

	U.S. Sample	E.U. Sample	Difference (Significance)
Left-right ideology	3.41	3.59	– 0.181 (0.007)
Egalitarianism	4.20	4.96	– 0.754 (<0.000)
Hierarchy	3.22	3.38	– 0.159 (0.009)
Societal risk allocation index	3.62	3.68	– 0.061 (0.341)
General environmental threat	6.65	6.65	0.006 (0.953)

NOTE: Scales and individual questions are shown in the Appendix.

model, as this approach makes the least demanding assumptions about the underlying functional form of the model. For each of these variables and the certainty measures, we included an interaction term that permitted the relationship to differ for the U.S. and E.U. samples. Although all variables were included in the initial model, those controls that failed to reach statistical significance were dropped from the final analysis. The model results are shown in Table 5.

TABLE 5

Explaining Precaution in the Radiation Dose-Response Case (Multinomial Logistic Regression Model)

	Coefficient	Std. Error	Z	$P>\|z\|$
Shift to Linear				
DR certainty	– 0.1460677	0.0345743	– 4.22	0.000
Env. threat	0.0484457	0.0402865	1.20	0.229
Risk index	– 0.0008795	0.0716617	– 0.01	0.990
Risk index-E.U.	– 0.0018582	0.0403063	– 0.05	0.963
Hierarchy	– 0.2825261	0.1174318	– 2.41	0.016
Male	– 0.4820284	0.2266939	– 2.13	0.033
Constant	0.4070379	0.4880618	0.83	0.404
Shift to Supra-Linear				
DR certainty	– 0.2425642	0.0377011	– 6.43	0.000
Env. threat	0.1446576	0.0480916	3.01	0.003
Risk index	– 0.4685608	0.0854824	– 5.48	0.000
Risk index-E.U.	0.1360581	0.0521183	2.61	0.009
Hierarchy	– 0.2911347	0.1328293	– 2.19	0.028
Male	– 0.5594834	0.2425993	– 2.31	0.021
Constant	1.509648	0.5506723	2.74	0.006
Diagnostics				
Sample size	LR χ^2	Prob $> \chi^2$	Pseudo-R^2	Log likelihood
918	129.94	0.0000	0.07	– 882.188

In our initial estimates, political ideology and all the U.S./E.U. interaction terms but one were insignificant and therefore dropped from the model. The top panel of Table 5 shows the final estimated logit coefficients for the odds of choosing the linear D-R function, rather than the sublinear, given that the sublinear was believed to be the one most likely to hold in nature. The estimated coefficient for certainty is both negative and statistically significant. As expected, the greater the level of subjective certainty, the less likely it is that a respondent who believes that the sublinear model is empirically correct will shift to the linear D-R function for standard setting. Other factors are of significance as well. The higher the score on the hierarch scale, the less likely the shift. Men are less likely to shift than women.

The lower panel shows the comparable coefficients for the odds of choosing the supra-linear function, given that the sublinear was believed to be the most likely to be correct. Again, the greater the certainty, the less likely is the precautionary shift. Also of significance is the sense of environmental threat, for which a greater perceived threat increases the odds of the precautionary shift. The risk index also comes into play, for which a higher score results in lower odds of the precautionary shift. The interaction term for the risk index is significant, indicating that the effect of the index is smaller for the European respondents (though it remains independently significant). Males, once again, were less likely to exercise precaution.

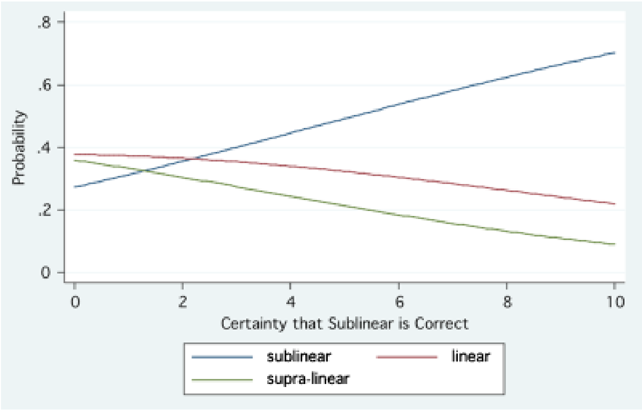
The effect of certainty was as expected: the greater the level of certainty, the lower the probability that a scientist would opt to shift to a more precautionary D-R function for purposes of standard setting. The magnitude of the effect of certainty was calculated using the logit results, holding all variables except certainty at their mean.[5] Differences between the U.S. and E.U. scientists were slight, and the average estimated relationship for all Ph.D. scientists is shown in Figure 2.

Modeling the effect of certainty on precaution for the global climate change case was handled differently. The dependent variable was the temperature increase that the respondent chose as the target for limiting greenhouse gas emissions. Respondents who did not expect temperatures to rise were excluded from the analysis because setting greenhouse gas emissions limits would not make much sense for this group (1.66 percent of the sample). We explicitly controlled for the expected baseline global temperature increase. Precautionary scientists, then, are those who opted for setting the emissions goals to keep temperature change at a minimum. Subjective certainty is the independent variable, and the dispositions and belief variables were included as controls. We employed an ordinary least squares

[5]Results using ordinal probit models were entirely consistent with the results reported here. In addition, focusing on those scientists who believe the linear model is correct, a logit model finds that certainty significantly reduces the likelihood of the precautionary choice of the supra-linear model as the basis for standard setting. The model results are available from the authors.

FIGURE 2

Preferred D-R Function for Safety Standard by Level of Certainty that Sublinear D-R is Correct



regression model, using robust standard errors. Again, controls that failed to reach statistical significance were dropped from the final model. The results are shown in Table 6.

First note the effect of the expected baseline temperature change. The higher the expected temperature growth, the higher was the respondent's preferred goal for setting emissions standards. The estimate is that for each one-degree increase in the expected baseline temperature, the average emissions goal is raised to allow for a net increase of only 0.25 degrees. This "slippage" indicates that those who expect large baseline temperature increases would (on average) not opt to impose emissions standards that would fully offset the increase. This might be interpreted as a degree of pessimism concerning prospects for action to decrease emissions.[6]

The effects of certainty are not as expected. Recall our general conjecture that greater certainty would lead to *reductions* in the need to err on the side of caution. The estimated coefficient for certainty is significant, but in this case greater certainty is associated with a preference for more stringent restrictions on greenhouse gas emissions. Greater certainty militates in the direction of greater risk aversion. The effect is modest but significant: an increase over the full range of the certainty scale (from 0 to 10) is estimated to result in a decrease in the goal of about a third of a degree C.

[6]We respecified the model, using a polynomial expression to permit a nonlinear relationship between expected increases and the goal. The estimated coefficient was not statistically significant, indicating that the relationship is essentially linear.

TABLE 6

Explaining Precaution in the Greenhouse Gas Emission Case (Robust Regression Model)

	Coefficient	Robust Std. Error	*t* Stat	$P>\|t\|$
GCC expected	0.2537291	0.0312681	8.11	0.000
GCC certainty	– 0.032525	0.0150956	– 2.15	0.031
Risk index	0.0582949	0.0244479	2.38	0.017
Environ. threat	– 0.1181842	0.0195911	– 6.03	0.000
Egalitarian	– 0.0788129	0.0336957	– 2.34	0.019
Hierarchy	0.0891643	0.0313737	2.84	0.005
E.U. scientist	– 0.0832962	0.0752456	– 1.11	0.269
Constant	1.694891	0.2381242	7.12	0.000
Diagnostics				
Sample size	*F* statistic	Prob > *F*	R^2	Root MSE
1,305	20.72	0.0000	0.12	1.205

The control measures had the expected signs. A higher score on the risk index was associated with a more permissive emissions standard, as was a higher score on the hierarch index. Thus a willingness to impose risks on members of society for other societal gains, and placing greater value in authority and order, are associated with less environmental precaution. Having a perception that general environmental risks are dire, and an egalitarian outlook, was associated with a lower (more precautionary) temperature-change goal. Once the other variables were accounted for, there was no difference between U.S. and E.U. scientists (as indicated by the statistically insignificant estimate for the E.U. SCIENTIST variable).

Discussion

Our interest has been to explore how scientists operationalize precaution when faced with uncertainty pertaining to controversial environmental issues. Using recent survey data collected from samples of U.S. and European readers of *Science* magazine and who hold a Ph.D. (or equivalent degree), we have been able to explore important aspects of scientists' translation of what they believe to be true to what they prefer to employ as standards for policy for two significant environmental issues. For both issue areas, significant fractions (30–40 percent) could reasonably be classified as precautionary. Differences between the U.S. and Europe samples in these patterns were consistently modest, indicating that—at least within the broader scientific community—precaution is not treated differently across the Atlantic.

Given that a frequent response to environmental controversy is to invest in science in an attempt to reduce uncertainties, we were particularly interested in evaluating the effect of variation in subjective certainty on the exercise of precaution. We found certainty to work in opposite directions in our two cases. For radiation protection, given that most of our scientist respondents believe the sublinear model to best represent the effects of low doses of radiation on humans, certainty served to reduce precaution. The effect of certainty was *relatively* large, when compared with the effects of the kinds of dispositions used to explain risk perceptions in the broader social science literature. For the global climate change issue, however, greater certainty is associated with more demanding carbon emissions standards. In this case, most of our scientist respondents believe that temperature increases will be significant, and greater certainty therefore appears to justify calls for more stringent goals for emissions reductions.

In light of these findings, what can one make of the proposition that increased certainty will decrease the propensity of scientists to exercise the precautionary principle? In the case of climate change, we found that greater uncertainty about expected global temperature change is associated with preference for a less stringent baseline for negotiating international greenhouse gas limits. This finding suggests a central flaw in the argument that increased certainty reduces the propensity to exercise precaution: increased scientific certainty can increase understood risks as readily as it can decrease them.

Perhaps the prevalence of high-visibility cases in which popular perceptions of risk exceed those of scientific experts (e.g., risks from radiation exposure, genetically modified organisms, or electromagnetic field emissions) has led to a general expectation that increased certainty will allow us to reduce the need for precaution in public policy. As our climate change case illustrates, this need not be true. Indeed, given that new discoveries can uncover and sharpen knowledge of threats as well as debunk them, we would expect scientists to update risks relative to the current baseline understanding in Bayesian fashion. The current baseline—grounded as much in public perceptions and extant policies as it is in science—is as likely to understate threats in light of new findings as it is to overstate them. Thus increased scientific certainty can cut two ways. This is as one should expect and—we think—it validates the general strategy for investing in science to increase understanding of threats to society and the environment.

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Appendix: Question Wording and Responses

Values shown are for the U.S. and E.U. samples *including only Ph.D. respondents*; where shown, the *p* values indicate statistical significance of the differences in means between the U.S. and E.U. samples.

Ideology—U.S. Version: On a scale of political ideology, individuals can be arranged from strongly liberal (referred to as strongly "left" in Europe) to strongly conservative (referred to as strongly "right" in Europe). Which of the following best describes your own political views? Using the options listed below, please check the one box that best characterizes your own political views.

	Strongly Liberal	Liberal	Slightly Liberal	Middle of the Road	Slightly Conservative	Conservative	Strongly Conservative	
%	1	2	3	4	5	6	7	Mean
U.S. 02	6.2	27.6	22.8	17.4	14.8	10.5	0.6	3.41

Ideology—E.U. Version: On a scale of political ideology, individuals can be arranged from strongly *left* (referred to as strongly "liberal" in the U.S.) to strongly *right* (referred to as strongly "conservative" in the U.S.). Which of the following best describes your own political views? Using the options listed below, please check the *one* box that best characterizes your own political views.

%	Strongly Left	Left	Slightly Left	Middle of the Road	Slightly Right	Right	Strongly Right	
%	1	2	3	4	5	6	7	Mean
E.U. 02	1.8	19.2	28.7	25.2	18.5	6.3	0.2	3.59

General Environmental Threat: On a scale where zero means the natural environment is *not at all threatened*, and ten means the world is on the brink of *environmental disaster*, how do you assess the current state of the natural environment?

	Not at All Threatened										Brink of Environmental Disaster		
%	0	1	2	3	4	5	6	7	8	9	10	Mean	p Value
U.S. 02	0.5	1.0	3.5	4.4	3.3	10.4	18.5	21.7	22.0	10.6	5.2	6.65	
E.U. 02	0.2	1.6	2.7	5.4	4.4	9.9	14.8	23.8	21.1	9.1	6.0	6.65	0.9530

Please respond to the following set of statements on a scale where one means strongly *disagree*, and seven means strongly *agree*.

Egalitarian Item 1: What society needs is a fairness revolution to make the distribution of goods more equal.

	Strongly Disagree						Strongly Agree		
%	1	2	3	4	5	6	7	Mean	p Value
U.S. 02	12.8	16.3	14.3	16.5	20.1	11.6	8.4	3.83	
E.U. 02	4.8	8.9	12.1	15.3	22.9	21.1	15.8	4.67	<0.0001

Egalitarian Item 2: Society works best if power is shared equally.

	Strongly Disagree						Strongly Agree		
%	1	2	3	4	5	6	7	Mean	p Value
U.S. 02	4.2	9.2	16.3	16.9	20.2	22.9	10.3	4.50	
E.U. 02	1.3	8.0	10.4	12.5	20.2	27.6	19.9	5.05	<0.0001

Egalitarian Item 3: It is our responsibility to reduce the differences in income between the rich and the poor.

%	Strongly Disagree 1	2	3	4	5	6	Strongly Agree 7	Mean	*p* Value
U.S. 02	8.4	13.6	11.9	14.6	23.5	17.6	10.4	4.26	
E.U. 02	2.4	6.1	7.4	12.7	24.1	25.7	21.7	5.14	< 0.0001

Hierarchy Item 1: The best way to get ahead in life is to work hard and do what you are told to do.

%	Strongly Disagree 1	2	3	4	5	6	Strongly Agree 7	Mean	*p* Value
U.S. 02	13.3	18.4	16.9	23.6	16.8	7.7	3.4	3.49	
E.U. 02	13.0	20.1	15.8	20.0	14.8	10.0	6.4	3.59	0.2471

Hierarchy Item 2: Society is in trouble because people do not obey those in authority.

%	Strongly Disagree 1	2	3	4	5	6	Strongly Agree 7	Mean	*p* Value
U.S. 02	30.5	34.0	14.5	11.2	7.0	2.2	0.6	2.40	
E.U. 02	23.2	36.6	14.6	14.0	8.3	2.8	0.6	2.58	0.0078

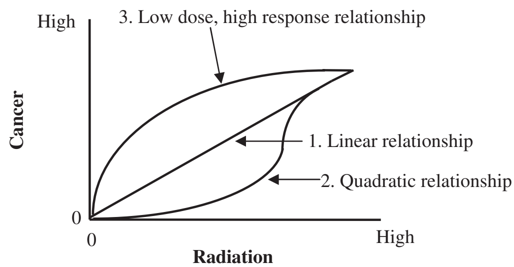
Hierarchy Item 3: Society would be much better off if we imposed strict and swift punishment on those who break the rules.

%	Strongly Disagree 1	2	3	4	5	6	Strongly Agree 7	Mean	*p* Value
U.S. 02	7.6	18.6	19.5	18.3	19.2	11.6	5.2	3.79	
E.U. 02	6.6	16.7	16.5	20.2	22.0	12.9	5.1	3.93	0.0726

Radiation Dose-Response Items: Studies of the relationship between radiation dose and incidence of cancer have had to rely on incomplete data. In particular, data on the low dose effects are statistically inconclusive. Several possible kinds of relationships have been hypothesized:

a. A *linear* relationship in which the low-dose effects of radiation are assumed to be proportional to high-dose effects
b. A *quadratic* relationship in which the effects of radiation at low doses are minimal below some threshold
c. A *low-dose, high response* relationship in which the effects of radiation are assumed to be proportionally higher at the low dose ranges

These possible relationships are illustrated in the following graph:



Most Likely D-R Function: Given your own knowledge of radiation effects on humans and other organisms, which of the above hypothesized relationships do you think is most likely correct?

%	1: Linear	2: Quadratic	3: Low-Dose, High Response	4: Do Not Know
U.S. 02	18.0	66.9	6.4	8.7
E.U. 02	18.5	62.0	8.5	11.0

D-R Certainty: On a scale where zero means *not at all* certain, and ten means *completely* certain, how certain are you that the relationship you identified is correct? (included only if U/E4_28 = 1, 2, or 3)

	Not at All Certain										Completely Certain		
%	0	1	2	3	4	5	6	7	8	9	10	Mean	*p* Value
U.S. 02	6.0	4.7	7.7	6.9	4.7	11.3	11.9	16.5	15.2	7.7	7.4	5.68	
E.U. 02	6.2	3.0	6.4	7.4	3.3	13.9	12.0	16.7	16.8	8.7	5.7	5.79	0.4534

DR Standard: Which of these three hypothesized relationships do you think should be assumed for purposes of setting public safety standards for managing radioactive materials?

%	1: Linear	2: Quadratic	3: Low-Dose, High Response	4: Do Not Know
U.S. 02	32.8	33.4	21.5	12.4
E.U. 02	28.8	30.3	27.4	13.6

Global Climate Change Items: Scientific inquiry into the effects of greenhouse gas emissions on global climate change has produced a range of projections of the expected average global temperature change over the next century. For reference, the scale below includes the range from the Hadley model and the Canadian Climate Model estimating the global temperature change by the year 2100 due to human-caused greenhouse gas emissions.

GCC Expected: Based on your knowledge of the climate change issue, please indicate the change in average global temperature you expect by the year ***2100*** if greenhouse gas emissions continue to increase proportional to growth in the world's population and economy.

%	DK	0°C	+1°C	+2°C	+3°C	+4°C	+5°C	+6°C	+7°C	Mean	p Value
U.S.	2.2	2.8	11.2	26.1	18.7	16.0	15.7	3.6	3.8	3.17	
E.U.	2.1	0.9	9.9	27.0	24.9	15.1	13.7	3.5	2.9	3.15	0.8388

GCC Certainty: Assuming greenhouse gas emissions continue to increase proportional to growth in the world's population and economy, on a scale where zero means *not at all* certain, and ten means *completely* certain, how certain are you that average global temperatures will change as you expect?

	Not at All Certain										Completely Certain		
%	0	1	2	3	4	5	6	7	8	9	10	Mean	p Value
U.S.	8.3	3.8	8.8	8.6	4.9	12.7	12.6	16.7	14.5	5.6	3.5	5.24	
E.U.	8.0	5.7	8.8	9.2	4.1	10.4	11.9	15.2	16.7	5.7	4.3	5.25	0.9751

GCC Target: The magnitude and urgency of greenhouse gas reductions are related to expected temperature changes. Setting a goal for acceptable temperature change has critical environmental, economic, and political implications. If the goal is set too high, many countries will not cooperate; if the goal is set too low, it may not adequately protect our environment. What *goal* for maximum allowable global temperature change by the year ***2100*** do you think should be used in negotiations to set international ceilings for greenhouse gas emissions?

%	DK	<1°C	−1°C	0°C	+1°C	+2°C	+3°C	+4°C	+5°C	+6°C	+7°C	>7°C	Mean	*p* Value
U.S.	7.7	0.2	0.3	11.0	30.1	34.5	9.7	2.7	3.0	0.3	0.2	0.3	1.69	
E.U.	6.3	0.4	0.4	13.0	37.0	29.2	9.2	2.5	1.1	0.2	0.3	0.3	1.53	0.0260

Societal Risk Allocation Index Items: There is disagreement over whether and to what degree it is acceptable for government to impose risks on individuals without their consent. On a scale where one means you strongly *disagree*, and seven means you strongly *agree*, please respond to the following statements.

Risk Index Item 1: When the risk is very small, it is acceptable for the government to impose that risk on individuals without their consent.

	Strongly Disagree						Strongly Agree		
%	1	2	3	4	5	6	7	Mean	*p* Value
U.S.	20.9	21.7	12.7	10.9	16.6	13.8	3.5	3.36	
E.U.	18.3	19.4	11.3	11.9	18.8	15.1	5.2	3.60	0.0139

Risk Index Item 2: Even if the potential benefits to society are very large, it is wrong for the government to impose risks on individuals without their consent.

	Strongly Disagree						Strongly Agree		
%	1	2	3	4	5	6	7	Mean	*p* Value
U.S. 02	7.0	15.4	15.6	9.9	12.6	18.6	21.0	4.45	
E.U. 02	6.6	16.2	14.4	11.2	12.2	21.1	18.3	4.43	0.7885

Risk Index Item 3: It is acceptable for the government to impose risks without consent if the individuals harmed by the policy are compensated for their losses.

	Strongly Disagree						Strongly Agree		
%	1	2	3	4	5	6	7	Mean	*p* Value
U.S. 02	34.7	25.4	11.5	12.6	9.1	4.9	1.9	2.58	
E.U. 02	29.5	27.5	12.2	13.5	10.3	4.9	2.2	2.71	0.1290

Risk Index Item 4: For society as a whole to survive and prosper, it is necessary that risks and sacrifices be accepted by citizens.

	Strongly Disagree						Strongly Agree		
%	1	2	3	4	5	6	7	Mean	*p* Value
U.S. 02	3.3	7.0	4.6	16.0	25.5	26.6	17.0	5.01	
E.U. 02	5.5	8.3	6.7	13.0	24.1	27.8	14.7	4.84	0.0400

Age: How old are you?

	Mean
AAAS/U.S. 02	54.1
AAAS/E.U. 02	53.2

Sex: Are you female or male?

%	0 = Female	1 = Male
AAAS/U.S. 02	18.5	81.5
AAAS/E.U. 02	12.2	87.8

Field of Expertise: From the following list of science categories, please mark the *one* category that *most closely* describes your area of greatest expertise.

%	United States	European Union
1(a) Agriculture, Biological, or Medical Sciences	70.8	68.5
2(b) Chemistry	11.8	11.7
3(c) Earth Sciences	3.9	4.4
4(d) Engineering	4.9	4.9
5(e) Mathematics and Computer Sciences	3.5	1.7
6(f) Physics and Astronomy	5.2	8.9

Type of Employing Organization: Please indicate which one of the following sectors most accurately describes your current professional affiliation.

(If retired or unemployed, please indicate the one sector that most accurately describes your previous professional affiliation.)

%	United States	European Union
1 Business or Industry (other than healthcare)	16.5	9.0
2 Education or Research	60.1	63.7
3 Government	5.2	2.7
4 Non-Profit Organizations	2.4	1.7
5 Independent Consulting	2.2	2.8
6 Healthcare	13.6	20.0