Should you measure the radon concentration in your home?

Phillip N. Price* Andrew Gelman†

January 23, 2004

1 Introduction

Radon, a naturally occurring radioactive element, was discovered in the year 1900, and high lung cancer rates among miners were recognized hundreds of years before that, but it wasn't until the 1950s that researchers accepted that exposure to radon decay products was one of the major causes of the very high lung cancer rate among miners. Risks to the general population weren't recognized until the early 1980s, when it was discovered that even homes can have high concentrations of radon—indeed, the airborne radioactivity in some (very rare) homes is higher than is allowed in uranium mines!

Once a risk from radon was recognized, the U.S. Environmental Protection Agency, and other organizations including the Department of Energy, launched research efforts to help assess risks and remediation options: what is the statistical and spatial distribution of indoor radon, what methods can be used to reduce radon concentrations in homes, what is the risk as a function of exposure, and so on. In this chapter, we summarize some of the data on radon distributions and some of the risk estimates, and then discuss how the available information can be used in a decision analysis to make recommendations on who should perform radon measuremnents or remediation. This chapter focuses on the decision analysis itself (originally discussed in Lin et al., 1999), and not on the statistical model, based on Bayesian hierarchical regression, that fed into the decision analysis. For more information about hierarchical regression, see Gelman et al. (2003, section 22.4).

2 The home radon problem

Radon is a naturally occurring radioactive gas produced by decay of the element radium, which is present in small quantities in rocks and soil. Since radon is a gas, it can flow through the soil and into homes. Radon's decay products, which are themselves radioactive, are known to cause lung

*Energy and Environment Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA. pnprice@lbl.gov

†Department of Statistics, Columbia University, New York, NY 10027 USA. gelman@stat.columbia.edu

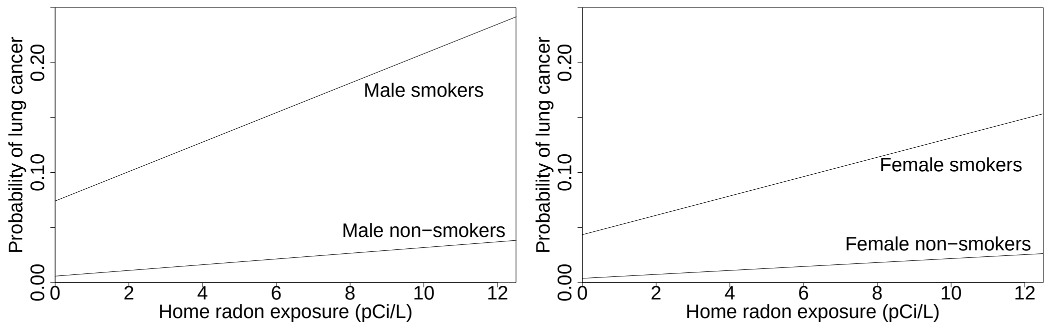

Figure 1: Lifetime added risk of lung cancer, as a function of average radon exposure in picoCuries per liter (pCi/L). The median and mean radon levels in ground-contact houses in the U.S. are 0.7 and 1.5 pCi/L, respectively (see Figure 3), and over 50,000 homes have levels above 20 pCi/L.

cancer if high concentrations are inhaled for a long time. When we speak of risk from radon, we really mean the risk from radon decay products.

What is the risk from radon? Studies have been carried out for uranium miners, many of whom had extended exposures at a high concentration of 20 picoCuries per liter, abbreviated 20 pCi/L, or more. Those studies, and others, suggest that life-long exposures of this magnitude increase the risk of lung cancer to about .06 for male non-smokers (from a risk of less than .006 for those not exposed to radon) and 0.32 for male smokers (from an unexposed risk of .07); estimates for women are comparable but slightly lower (National Research Council, 1998).

Figure 1 shows the estimated additional lifetime risk of lung cancer death for male and female smokers and nonsmokers, as a function of average radon exposure over 30 years, under the assumption that observed risks at the concentrations faced by uranium miners can be extrapolated linearly to lower concentrations that occur in homes (typically below 5 pCi/L). The miners were exposed to much higher radon concentrations than *typically* found in homes, but more than 50,000 of the U.S.'s 70 million houses have levels above 20 pCi/L; people who live in these houses receive a radiation dose that exceeds the occupational safety limit for uranium miners. For almost everyone else, the risk of lung cancer is much lower than for uranium miners, but there are millions of people facing this risk. Assuming the linear dose-response assumption is accurate, between 5,000 and 25,000 people die annually in the U.S. due to lung cancer caused by inhaling radon decay products in their homes, with most of these deaths being among smokers. The estimated number of annual deaths from radon far surpasses that from other chemical or radiological exposures. However, these estimates of radon deaths (including the uncertainties) are based on linear extrapolation, and there is no guarantee that the risk from radon is actually linear in exposure; the actual risk could be lower (or somewhat higher) than these estimates suggest.

3 The EPA's recommendations

The Environmental Protection Agency (EPA) recommends that all homeowners in the United States test for radon and, if the radon level exceeds a 4 picoCuries per liter (4 pCi/L) "action level," remediate the house to reduce the radon exposure to an acceptable level. Remediation costs about $2000, including maintenance and energy costs for operating the system. The action level was originally set based on the "annual living-area average" concentration in U.S. homes, which is the mean concentration in the living areas of a home, averaged over a year. However, the EPA's recommended testing methods don't measure the average concentration of the living areas of a home: the EPA recommends testing only on the lowest level of the home that is used as living space. Some state health departments, and many radon testing companies, recommend testing on the lowest level of the home that *can* be used as living space, rather than the lowest level that *is* used as living space, so in practice most homes are monitored in basements, whether or not the basement is frequently occupied. Testing on the lowest level of the home that is (or can be) used as living space almost always leads to a measurement that is higher than the living-area average radon concentration, since concentrations are typically highest on the lowest level of the home. The concentration in the basement is often two to three times higher than the concentration on the upper floors.

There are two types of inexpensive radon measuring devices; one measuring the average concentration over just a few days, the other averaging over several or many months. Unfortunately, a short-term measurement gives very little information about a home's long-term average concentration, which is believed to be the important parameter for radon risk: indoor radon concentrations vary substantially from day to day and from season to season, primarily due to changes in weather that affect the amount of soil gas that is drawn into the house.

The EPA recommends either a long-term test, or a short-term test plan that has two tiers: make a short-term test, and if the concentration exceeds 4 pCi/L then make another short-term test, taking the average of the two tests to see if remediation is recommended. In practice, relatively few people make long-term tests, and many people fail to follow the short-term protocol, especially when testing is performed as part of a real estate transaction and a rapid test is desired: the de facto testing plan for many homeowners who test for radon is to make a single short-term test on the lowest level of the home, and use that test as the basis for a decision. We will refer to this one-measurement decision plan as the "standard" plan even though it differs somewhat from the EPA's recommendation. Analyzing the EPA's actual recommended short-term testing plan would complicate our work without changing the results very much.

The standard decision plan has two notable features: first, the measurements on which it is based are biased (because they are taken on a low floor) and highly variable (because they are taken over only a few days) if interpreted as estimates of the average annual living area concentration; and second, the same testing procedure is recommended for all homes, even though some areas of the country and some types of homes tend to have much higher radon concentrations than others do.

Performing a single short-term test in every house in the country would cost nearly 2 billion dollars just for the measurements, and if those measurements are used to make remediation decisions based on the 4 pCi/L action level, many billion dollars more will be spent on remediations, most of them in homes that do not in fact have substantially elevated radon concentrations. We estimate that use of this decision plan in every house would cost $21 billion ($25 for each measurement and $2000 for each remediation) and save 55,000 lives over a thirty-year period. It is natural to wonder if we can do better using area- and house-specific information to develop an alternative decision plan.

4 Towards a better decision plan

Collecting and analyzing area- and house-specific information about radon risk is the key to finding optimal homeowner-specific recommendations about what action to take. This can be done through a formal decision analysis which considers the possible homeowner decisions (test, remediate, do nothing) as part of a statistical analysis. The decision analysis requires that we determine the predicted outcomes for each possible decision, namely how much money would be spent and how many people would die, including some measure of the uncertainty in these predictions. Including the uncertainty is crucial so that decisions take into account the full range of possible outcomes. One must also develop a quantitative measure of the desirability of each outcome. In this decision problem that amounts to attaching a dollar value to each live saved (or lost). We return to this important but hard question later. Based on the predicted outcomes and the relative desirability of each outcome, the decisions are analyzed to choose the one that has the best expected outcome.

5 Data and estimation of radon exposure

The first step in building a decision plan is to obtain information about the distribution of radon exposure across different homes in different regions of the country. There are several sources of residential radon data. In terms of the number of measurements, by far the largest data sets simply summarize all of the radon measurements performed by radon testing companies; often these are available by state, county, or even by zip code. Unfortunately, there are some serious problems with these data, most importantly that they overrepresent homes with high radon levels, and often include multiple measurements from such homes. High-radon homes are more likely to be included

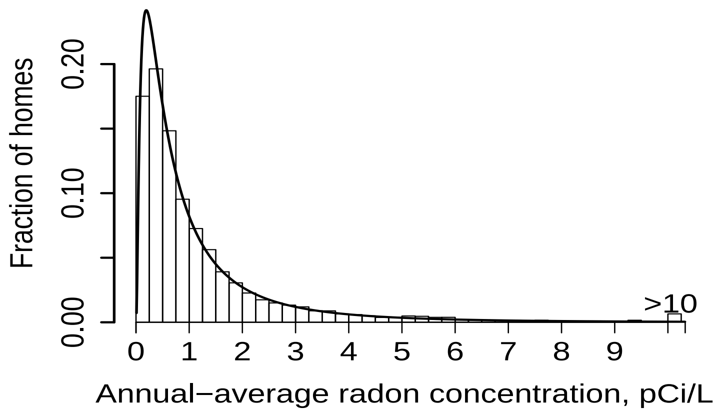

Figure 2: Distribution of average annual living area radon concentrations in U.S. residences; bin heights show fraction of homes in each bin, and the last bin shows the fraction of homes with concentrations exceeding 10 pCi/L. A superimposed curve shows a lognormal distribution with geometric mean (GM) of 0.67 pCi/L and geometric standard deviation (GSD) of 3.1; that is, the logarithms of the radon levels have mean log(0.67) and standard deviation log(3.1). The nationwide distribution is very close to lognormal.

because people who suspect their houses have high radon levels—perhaps because a neighbor has obtained a high measurement—are more likely to take measurements, and those who obtain a high measurement are more likely to measure again and this measurement will also be included in the database. Because of this large and unpredictable bias in "volunteer" data, we instead work with data collected by the government from random samples of houses. This is an illustration of the importance of using chance in the collection of data to avoid having systematic biases enter the data.

The EPA worked with most of the state health departments to perform radon testing in representative random samples of homes in each state. Taken together, these "EPA/State Residential Radon Surveys" contain about 55,000 radon measurements (Wirth, 1992). These are short-term measurements on the lowest level of the home but at least they use a standard protocol and are not subject to the selection bias (favoring high radon homes) that affects the commercial data.

Additionally, the EPA conducted a "National Residential Radon Survey," which measured annual living-area average concentrations (using long-term detectors on every floor of each home) in about 5700 homes across the country (Marcinowski et al., 1994). Figure 2 shows the distribution of annual living-area average radon concentrations as determined by that survey. It is common when working with quantities like concentrations, which are greater than or equal to zero, to work with the logarithm of the measurement. The logarithms tend to more readily allow the use of traditional statistical tools. For example, the logarithms of the radon levels follow a normal distribution

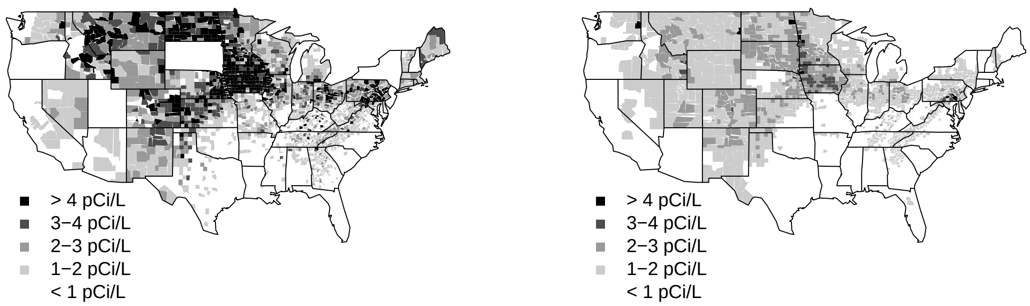

Figure 3: (a) Observed geometric mean indoor radon concentration by county, from the EPA/State Residential Radon Surveys. Measurements in these surveys are strongly biased estimates of annual-average living-area concentrations. Some states did not participate in these surveys but did collect data in different surveys; these data, using different measurement protocols, are not displayed but were used in our full analysis. (b) County geometric mean indoor radon concentration estimated from a hierarchical Bayes regression model, which corrects for systematic measurement biases, uses geologic and other information, and reduces small-sample variation, to predict long-term living-area concentrations.

with mean log(0.67) and standard deviation log(3.1); in standard terminology, the distribution is "lognormal" with a "geometric mean" (GM) of 0.67 pCi/L and a "geometric standard deviation" (GSD) of 3.1. Among other things, this implies that 6% of the homes have radon levels exceeding the EPA's threshold level of 4 pCi/L. To see this note that a radon level of 4 pCi/L is (log(4)-log(0.67))/log(3.1) = 1.58 standard deviations from the mean, and the probability that a sample from a standard normal distribution exceeds 1.58 is 6%.

The state radon surveys contain measurements in about 55,000 homes, and there are about 3000 counties in the U.S. The geometric mean measurements by county are shown in Figure 5a. Some of the counties were heavily sampled by the surveys, while others were missed altogether or included only a few houses. Radon concentrations vary a lot within a county, so a small number of measurements isn't enough to estimate accurately the distribution of radon concentrations within any given county. Also, as mentioned above, the measurement protocol for these surveys leads to measurements that are biased (because they are from the lowest level of the house only) and that are subject to a lot of variation (because they are short-term measurements).

The National and EPA/State survey data can be used to form a predictive model that allows us to draw inferences about the radon concentration in a house. For the moment we ignore the known weaknesses (bias, variability) of the state survey data. Our approach to learning about radon concentrations from the state survey data is to provide a statistical model linking the survey measurements to house and county factors (Price et al., 1996, and Price, 1997). This is a traditional survey inference approach, learning about the population from a limited number of sampled units.

We analyzed the radon data used a technique known as Bayesian hierarchical modeling (sometimes called "multilevel modeling"). The key idea underyling this method is that information about one data sampling unit (for example, a county) also tells you something about other units (other counties). For example, suppose we were to make a lot of radon measurements in 86 out of the 87 counties in Minnesota using the state survey protocol, and that we find that almost all of the counties have geometric mean concentrations in the range 2–5 pCi/L. Even with no samples at all from the missing county, we would think that it's very likely that its geometric mean would also be somewhere between 2 and 5 pCi/L. As this example illustrates, knowing the distribution of county geometric means can help in estimating the geometric mean for a specific county, even if that county is sparsely sampled or isn't sampled at all.

This concept can be applied even in more complicated cases that involve predictor variables. In our case, the state survey measurements are found to correlate with a number of home and county characteristics: the county's average surface radium concentration as measured with airborne detectors by the National Uranium Resource Evaluation; whether the home has a basement; the "geologic province" containing the county; and the county's heating degree-days (a measure of winter climate severity that is related to the convective forces that draw soil gas into homes). Even when all of these variables are taken into account, however, there remains considerable variation in radon concentrations, both within and between counties. Homes in some counties tend to have higher radon levels than expected given the county and home characteristics, while homes in other counties tend to have lower levels than expected. These tendencies are probably related to county characteristics that we have not measured or included in the study. We use a regression modeling approach to estimate the effects of all of the variables listed above on radon measurements, and we also include parameters to allow for the "county effects" that quantify the extent to which radon levels in a county are higher or lower than would be predicted from the other variables. We estimated the regression model separately in each of 10 regions of the U.S., yielding predictions (and uncertainties) of what every county's measured radon distribution would have been if they had all made very large numbers of measurements in the (biased) state surveys.

By comparing the state survey data to the national radon survey data it is possible to estimate the degree to which the state survey data are biased. This can be thought of as a calibration step, relating the biased state survey data to the more accurate annual living area average concentration from the national survey data. One way to think about this step is that we take the data from the national survey and compare each home's measurement to the prediction that would be made for that home using the regression model that was developed with the *state* survey data; if the national data differ systematically from the state survey prediction, we can figure out how to adust the prediction to remove the systematic error. (In practice the adjustment is done through a more sophisticated statistical model that looks at both data sources simultaneously (Price and Nero, 1996)). Once the bias is removed, we have a predicted radon distribution for almost every county in the United States; in some counties the distribution can be estimated rather precisely, but in the ones that were sparsely sampled the uncertainties are large. The estimated geometric mean living-area-average radon concentration in each county is displayed in Figure 5b.

We shall use these estimated distributions to make decision recommendations for homeowners living in each of the 3000 counties in the U.S., but first we must lay out the decision options and their costs and benefits.

6 Decision analysis, balancing dollars and lives

As with many public health decisions, radon measurement and remediation involves a balance between dollars and lives—or, more precisely, between resources spent on reducing radon risks and resources spent otherwise. Mathematically, the balance of dollars and lives is expressed as a *loss function* measuring the combined cost of measurements, remediation, and lives lost. For this problem a natural way to express the loss is to start with the cost of measurements and remediation (which are measured in dollars) and add to that a constant times the expected number of lives lost in the next thirty years (a reasonable guess at the time that a remediation system will be effective). The constant assigns a dollar value to saving a life. An approach for choosing a value for that parameter is described below.

Consider a home with an average living-area radon concentration of 4 pCi/L, which is the EPA's recommended "action level." Suppose the home has the average U.S. household mix of .30 male and .27 female smokers and 1.07 male and 1.16 female nonsmokers. (It may seem odd to consider a household containing fractional people but this allows us to discuss an average case that addresses all of the types of people of interest.) For such a household, a 4 pCi/L concentration represents an expected .02 radon-induced lung cancer deaths over a thirty-year period. Let C represent the dollar value of a life. If this household does nothing about radon, then the expected loss is $.02C$. Assume remediation costs about $2000 and reduces the average radon level to 2 pCi/L for thirty years (thus cutting the radon risk in half). For this household, the expected loss if remediation is performed is $\$2000 + .01C$. The fact that 4 pCi/L is the EPA's recommended action level means that this is the radon level for which the EPA thinks the above two expected losses are about the same. If true this would tell us that the value of saving a life is $C =$ \$200,000/life. Though \$200,000 can buy a lot, it is actually low compared to the value of life assumed in most public health decisions in rich countries; if the linear dose-response is true, then remediating your 4 pCi/L home for \$2000 is something we should consider a good investment! Setting the threshold at other levels yields different implicit values of a life. For example, a threshold of 20 pCi/L, as used by Canada, corresponds to only \$22,000 per life saved under our assumptions. The fact that such a low value is implied for a human life suggests that if the dose-response relationship is linear then the Canadian threshold is way too high and puts too many people at risk.

Using the same action level in every house will actually lead to a wide variation in the dollars spent per life saved: for a household with several inhabitants who smoke, reducing radon would save more lives than would the same reduction in a home with one, non-smoking, inhabitant. Conversely, if the trade-off between lives and dollars is the same for every *person*, as seems reasonable, then it is the action level that should vary among households. We assume that each household assigns the same dollar value (\$200,000 as implied by the EPA recommendation) to a life, compute the number of lives that would be saved by remediation based on the predicted or measured radon level and the composition of the household, and combine these estimates to calculate the expected loss with and without remediation. This allows the homeowner to select the strategy that minimizes the expected loss.

7 Advice for homeowners

We perform two separate decision analyses, one of them geared towards individuals (Should you measure the radon in your home?) and one geared towards public policy-makers such as the Environmental Protection Agency (Should we recommend that everyone in a particular county perform a measurement?).

The decision tree is shown in Figure 5. At the first stage a homeowner must choose between doing nothing, remediating immediately, or making a long-term measurement and then deciding whether to remediate or not. (A short-term measurement is also possible but turns out not to be the optimal decision for almost everyone.) The second stage of the decision tree covers the case where we measure first and then decide. Remediating has the highest cost in dollars but the lowest expected loss of life; doing nothing costs zero dollars but has the highest expected loss of life, and measurement potentially followed by remediation is somewhere in between in terms of dollars spent and lives saved. Our analysis chooses the decision option with the lowest expect loss (combining dollars spent and lives saved as described earlier). Remember that each household will make decisions based on the number of males/females and smokers/nonsmokers in the house, whereas we discussed only the

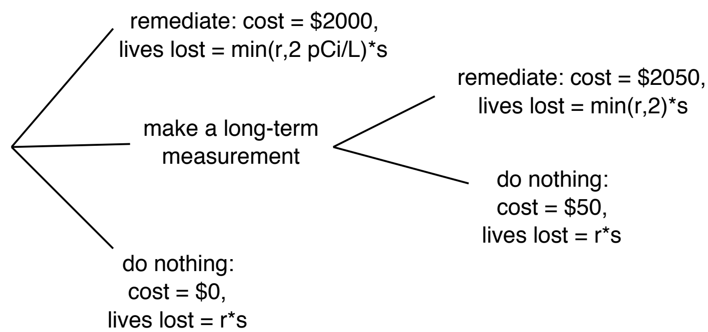

Figure 4: Decision tree for radon measurement and remediation. The first decision (whether to remediate, do nothing, or take a (long-term) measurement) depends on estimates from the county-level model displayed in Figure 5b. If a measurement is taken, the second decision depends on the value of the measurement. The expected loss of life depends on the radon concentration r, the post-remediation radon concentration (which we assume to be 2 pCi/L or r, whichever is lower), and on the risk per unit concentration for the household, which we call s. We assume that making a long-term measurement on each living area of the home costs $50.

average case earlier.

The decision tree must be evaluated from right to left, starting with the final decision. That is we first figure out what each homeowner should do if they do take a measurement. This is the only way to compare the measurement option to the other possible first stage decisions. In detail then we proceed as follows:

- We must decide whether the homeowner should remediate the house, given a measurement of the average living-area airborn radon concentration. We assume the homeowner would remediate if the home's indoor radon concentration exceeds a household-specific action level, where the action level is set by equating the expected loss (given the measured radon concentration and the makeup of the household) under remediation and under no action using the value of $200,000/life that is implicit in the EPA's current recommendation. There is a slight difference between remediating if the home's *long-term measurement* exceeds the action level and remediating if the home's *long-term average concentration* exceeds the action level, because even long-term measurements do not exactly match the personal exposure of the people in the home, but this is not crucial for the discussion here.

- Given the rule for the inner decision, the homeowner must decide whether to remediate im-

county, state	house	hhold	GM (pCi/L)	GSD	Pr(remed)	Expected cost ($)	Expected lives saved
Lebanon, Pa.	NB	avg	3.7	2.2	0.47	990	0.013
	BL	avg	6.4	2.2	0.74	1530	0.030
Montgomery, Md.	BNL	FS, MS	0.8	2.1	0.02	80	< 0.001
	BL	FS, MS	1.4	2.1	0.08	210	0.003
	BL	avg	1.4	2.1	0.08	210	0.001
Sacramento, Cal.	NB	avg	0.4	2.1	0.00	52	0.000
	BNL	avg	0.6	2.1	0.01	62	0.000
	BL	avg	0.8	2.1	0.02	84	0.000

Table 1: Estimated costs and benefits of making a long-term measurement and then deciding whether or not to perform remediation, for houses in a few different counties. House type can be B = Basement is a living area, BNL = Basement is not a living area, or NB = No basement. The variable `hhold` represents household makeup; in the table we consider the average household (.27 female smokers, .30 male smokers, 1.16 female nonsmokers, and 1.07 male nonsmokers) and a household with 1 female smoker (FS) and 1 male smoker (MS). The column labeled Pr(remed) shows the probability that remediation will be recommended if the "action level" is set at 4 pCi/L, independent of household composition. Expected lives saved are over a thirty-year period.

mediately, do nothing, or make a measurement, in the initial (outer) decision. The value of the measurement depends on the probability that it will affect the decision of whether to remediate, which is why we first had to evaluate the measurement/remediation decision.

The inputs to the decision problem for any household include the predicted radon concentration from our statistical model which is based on the county and the house type; the number of male and female nonsmokers; the costs of monitoring and remediation; and the value of C, the "dollar value of a life" (which mathematically determines, or is determined by, the radon concentration at which the owners would remediate). The inputs allows us to compute the expected cost of each action, including "do nothing" (which costs nothing and saves no lives). Table 1 shows the expected costs and benefits for one possible action: carry out a strategy of making a long-term living-area measurement and then deciding whether or not to perform remediation. The table shows the costs and benefits for different types of homes and households in several different counties.

For example, the first line of the table shows that for a home in Lebanon County, Pennsylvania—one of the highest-radon counties in the country—following this approach in a non-basement house will lead to a 47% chance of performing remediation. If remediation costs $2000 (including energy and maintenance costs for the system), then the expected total cost of following this plan is about $990, including the cost of measurements, and for a home with the national-average mix of female and male smokers and nonsmokers this plan is expected to save about .013 lives. Both the cost and the life savings presented in the table are for the entire decision plan: there's some chance that remediation will not be performed (because the radon measurement will not be high) and thus no expected lives will be saved, and some chance that remediation will be performed and there will be some expected life savings, and the values of expected dollar cost and of expected lives saved include both of these possibilities.

For a home in Lebanon County that has a basement that is used as living space, the expected cost is higher than for a non-basement house because there's even higher likelihood of remediating due to the higher expected radon concentration, but the number of lives saved is also much higher because of the larger radon reduction that would be provided by remediation. For such a home, using this decision plan has an expected dollar cost of $1530 but is expected to save almost .03 lives. That's quite a bargain: there aren't many other opportunities to have a 3% chance of saving a life for under $1600.

For a home in Sacramento, California—a low-radon county—the expected lives saved would be of the order of .0003 if this measurement plan if followed in an average house (rounded to .000 in the table). There's a 99% chance that the long-term living-area measurement will fall below the 4 pCi/L action level, and even if it does exceed the action level it is likely to do so by only a small amount (in contrast to the situation in Lebanon County, where many houses will be far above the action level). In Sacramento County, if the "value of a life" is set to $200,000 as implied by the 4 pCi/L action level under a linear dose-response relationship, making measurements in a non-basement house isn't worth the cost.

Montgomery County, Maryland, has a radon distribution that is fairly typical for the northern half of the continental U.S., with radon concentrations generally higher than in Sacramento but lower than in Lebanon County. Table 1 also shows the difference in risk for different households: even though an "average" household contains about 3 people, remediation would actually save more lives on average in a household consisting of two smokers because of their higher risk for a given exposure.

The analysis described above is the analysis that a homeowner might carry out, given only some basic information about a home's location and the makeup of the household. Additional information can be used as well, as long as the relationship to radon concentrations can be estimated. For example, suppose you have knowledge of a neighbor's measurement. Such information can be included to improve predictive distribution for the radon concentration in your house. Using information concerning the spatial correlation of radon—that is, the degree to which nearby homes have similar radon concentrations—we modified the decision analysis to incorporate information on measurements in nearby houses if they are available. You can try out the process at the web site `http://www.stat.columbia.edu/radon/` (Gelman and Price, 1999).

A public health official has a different decision problem to work on. Such a person would need

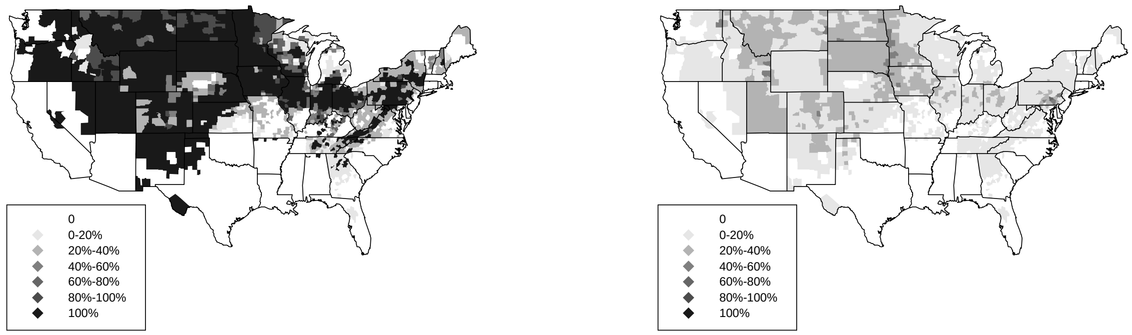

Figure 5: Maps showing (a) fraction of houses in each county for which measurement is recommended, given the perfect-information action level of $R_{\text{action}} = 4$ pCi/L; (b) expected fraction of houses in each county for which remediation will be recommended, once the measurement y has been taken. In some counties no measurements would be recommended; these counties do have some high-radon home, but for any individual home the odds of an elevated concentration are so low that it's not worth the paying for a measurement. Apparent discontinuities across the boundaries of Utah and South Carolina arise from irregularities in the radon measurements from the radon surveys conducted by those states, an issue we ignore here.

to see the effect of different public policies/recommendations on all of the homeowners they serve. Individual decisions can be combined to determine nationwide costs and benefits for various public policies that could be implemented at the county level. For example, the maps in Figure 7 display, for each county, the fraction of houses that would measure, and the estimated fraction of houses that would remediate, if the recommended decision strategy were followed everywhere with an action level of 4 pCi/L (and if we treat all households as if they have the country-average number of male and female smokers and non-smokers). About 26% of the 70 million ground-contact houses in the U.S. would monitor. The total monetary cost is estimated at $7.3 billion: $1 billion for measurement and $6.3 billion for remediation, and would be expected to save the lives of 49,000 smokers and 35,000 nonsmokers over a 30-year period. This compares quite favorably with the current strategy of having everyone make a remediation decision based on a short-term measurement: that plan would cost almost three times as much and save fewer lives.

8 Discussion

The standard dose-response model for radon—which we have used—is that risk is linear with dose even at low concentrations, but there's no strong evidence that this is true. The Canadian government assumes that the risk per dose is less at low doses and, consequently, they recommend remediation at 20 pCi/L rather than 4 pCi/L. Several studies have tried to estimate radon risk from concentrations below 10 pCi/L, but the studies aren't conclusive about even the presence of risk at, say, 4 pCi/L, much less the exact magnitude. Our analysis could of course be re-done using different risk-dose assumptions. and in the paper on which this chapter is based (Lin et al., 1999), we considered how the costs and benefits would change if there is a threshold below which there is no health effect. Of course, we could also keep the same dose-response assumptions but try different "action levels" (or different quantities for the "value of a life saved.")

Many people are uncomfortable with setting a dollar value for saving a life, and may even think it's immoral to do so, but actually, there's no avoiding it—if a expenditure of $\$D$ is considered worthwhile because because it will save N lives, then that implies a value per life. It is impossible to spend an infinite amount of money to reduce risks, so $\$D/N$ will always be finite. Nobody should be ashamed at choosing a dollar value, although there are plenty of other opportunities for shameful choices in risk-related decisions (a common one is failing to distinguish between *who* bears the costs and *who* reaps the benefits, but that's not an issue here, because the risks of radon exposure and the costs of remediation are borne by the same people). In our analysis we have set the "dollar value of saving a life" at a very low level, but this is the level that is implied by current radon policy and standard dose-response assumptions. Another value could be used instead, which would lead to different recommendations for which homes should be monitored for radon. The key is that whatever "value of a life saved" you select, you want to choose the optimal monitoring and remediation strategy for that value; otherwise, you're wasting lives by saving fewer people than you could for the same money.

Setting a radon policy involves many considerations other than those discussed here, including issues of practicality and politics that are very difficult to formalize (so we didn't try). What we have illustrated is how statistical methods can be used to help inform a difficult public health decision in which exposures are both spatially variable and have variable uncertainty. We have used a statistical model to estimate the distribution of home radon levels within U.S. counties using data from national and state radon surveys. The estimated radon distributions can be used for individual-level decisions and can be aggregated to test the costs and radon reductions if various radon policies are implemented. The individual decisions can be modified to take into account additional information such as available measurements on neighboring houses. Our calculations suggest that simple modifications to the EPA's monitoring recommendations could save more lives for less money than the current policy, assuming, of course, that people would actually follow the recommendations.

9 References

Carlin, B. P., and Louis, T. A. (2000). *Bayes and Empirical Bayes Methods for Data Analysis*, second edition. London: CRC Press.

Clemen, R. T. (1996). *Making Hard Decisions*, second edition. Belmont, Calif.: Duxbury Press.

Gelman, A., Carlin, J. B., Stern, H. S., and Rubin, D. B. (2003). *Bayesian Data Analysis*, second edition. London: CRC Press.

Gelman, A., and Price, P. N. (1999). Radon risk page. `http://www.stat.columbia.edu/radon/`.

Lin, C., Gelman, A., Price, P. N., and Krantz, D. H. (1999). Analysis of local decisions using hierarchical modeling, applied to home radon measurement and remediation (with discussion). *Statistical Science* **14**, 305–337.

Marcinowski, F., Lucas, R. M., and Yeager, W. M. (1994). National and regional distributions of airborne radon concentrations in U.S. homes. *Health Physics* **66**, 699–706.

National Research Council, Committee on the Biological Effects of Ionizing Radiation (BEIR VI) (1998). *Health Risks of Radon and Other Internally Deposited Alpha-Emitters.* Washington, D.C.: National Academy Press.

Price, P. N., Gelman, A., and Nero, A. V. (1996). Bayesian prediction of mean indoor radon concentrations for Minnesota counties. *Health Physics* **71**, 922–936.

Price, P. N., and Nero, A. V. (1996). Joint analysis of long- and short-term radon monitoring data from the Northern U.S. *Environment International* **22**, S699–S714.

Price, P. N. (1997). Predictions and maps of county mean indoor radon concentrations in the mid-Atlantic states. *Health Physics* **72**, 893–906.

Wirth, S. (1992). National Radon Database documentation: The EPA/State Residential Radon Surveys. Washington, D.C.: U.S. Environmental Protection Agency.