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LAND APPLICATION OF SEWAGE SLUDGE: AN APPLICATION OF MULTIPLE OBJECTIVE METHODS

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Decisions are currently being made on the problem of disposing of Metropolitan Boston's sewage sludge. The decision process has focused on only a narrowly defined version of a single goal (cost) and this in part accounts for a bias against the disposal alternative of application on agricultural land. Provided below is an analysis which explicitly considers several goals and which ultimately views land application in a more favorable light.

Sludge is presently treated at two plants located on islands in Boston Harbor. The sludge is then pumped through submerged outfalls into the outer harbor. Recently, Region I of the Environmental Protection Agency has ruled that by 1981 municipalities must phase out the practice of disposing of sewage sludge in streams, rivers, and oceans. As a result, contracts have been let (initially to Havens and Emerson [1974], then Ecol. Science, Inc. [1976], and currently ERT, Inc. [1977]) to consulting firms to recommend alternative approaches for disposing of Metropolitan Boston's sludge. The first two efforts recommended incineration modes, while the third which is not yet completed appears to offer rather ambiguous results -- no alternative emerges as clearly the best.

The first two efforts have been severely criticized on a number of counts. These include a failure to account for uncertainty and sequential aspects of the decision process and to explicitly incorporate objectives such as environmental impacts and risk into the analysis. The third effort was commissioned in part with these shortcomings in mind. While it is an

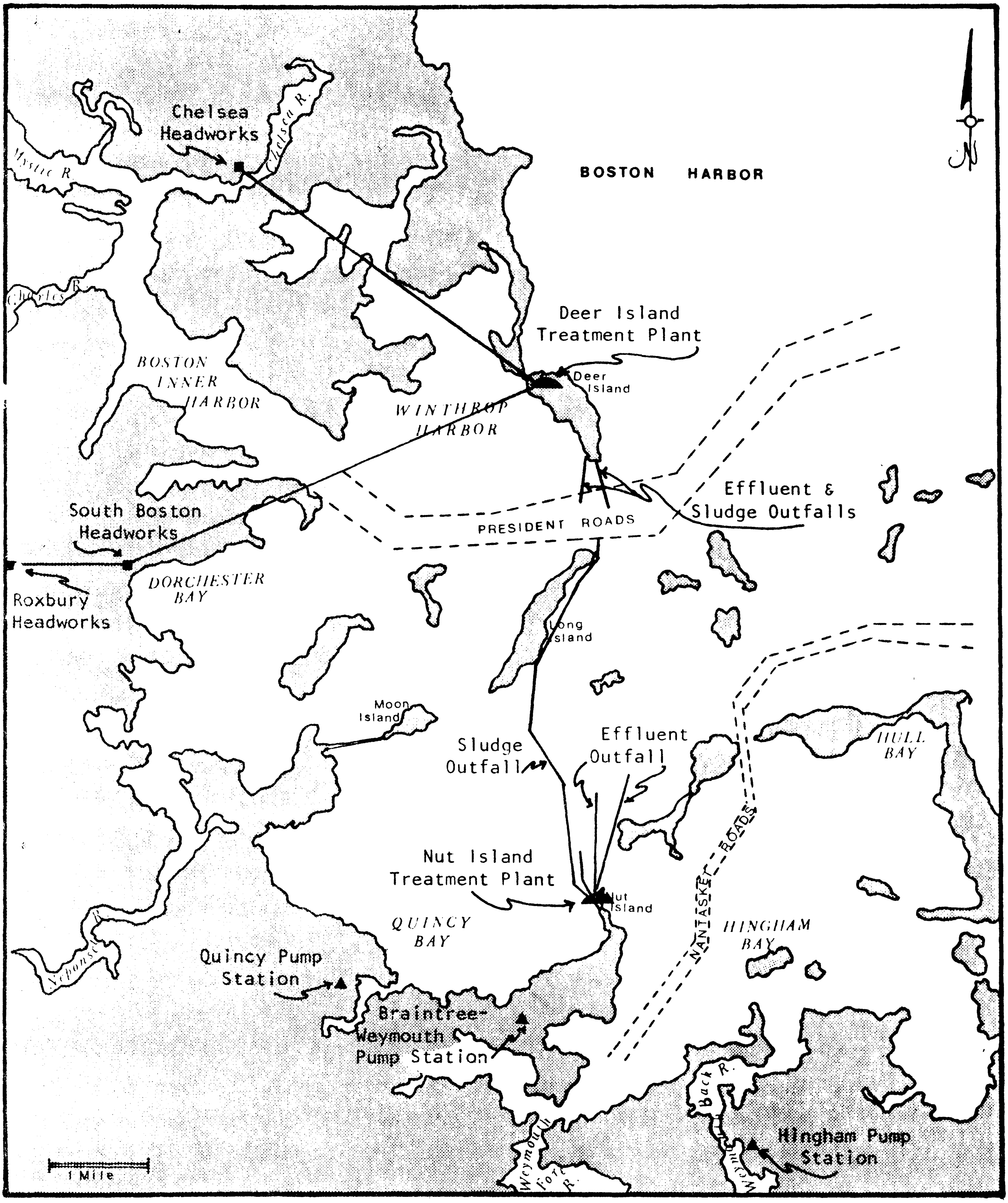

Figure 1: Greater Boston Study Area

improvement over its predecessors, this effort falls short as well. These issues are addressed in the application reported below. The multiple objective application is described in the next section and the results are set out in the final part.

APPLICATION

The first part of the application below is the basic two-period multiple objective model. The solution of this model for the set of noninferior solutions employs the constraint method of the class of generating techniques (see Cohon and Marks [1975]). The second part adds a sequential dimension.

<u>Two-Period Formulation</u>: Since secondary treatment of sludge will be required in the future and will result in a three-fold expansion in total sludge output, we employ a two-period framework -- denoting these as Phase I and Phase II.

The decision variables (x_{ijt}) will then represent quantities of sludge (tons per year) allocated to a particular disposal alternative (i) produced from either the Deer Island (j=1) or the Nut Island (j=2) treatment plant in Phase I (t=1) or Phase II (t=2). Except for the time dimension, the decision variables are summarized in Table 1.

The model can be expressed as:

(1) Maximize

$$NEB = \sum_{i=1}^{9} \sum_{j=1}^{2} \sum_{t=1}^{2} \left[b_{it}\, x_{ijt} - \gamma_{it}\, x_{ijt}\, \mathrm{EXP}\ (-\ \delta_{it}\, x_{ijt}) \right]$$

$$- x_{p_1} \left[595{,}180 + 3.01 \sum_{\substack{i=1 \\ i \neq 3,5}}^{6} x_{i21} \right] \qquad - x_{p_2} \left[761{,}820 + 1.02 \sum_{\substack{i=1 \\ i \neq 3,5}}^{6} x_{i22} \right]$$

subject to

$$(2)\quad EI = \sum_{i=1}^{9} \sum_{j=1}^{2} \sum_{t=1}^{2} EXP\left(\alpha_{it} - \frac{\beta_{it}}{x_{ijt}}\right) + 10 \sum_{t=1}^{2} x_{p_t} \le L_2$$

$$(3)\quad VAR = \sum_{i=1}^{9} \sum_{j=1}^{2} \sum_{t=1}^{2} c_{it}\, x_{ijt}^{d_{it}} + 2 \sum_{t=1}^{2} x_{p_t} \le L_3$$

and

$$(4)\quad \sum_{\substack{i=1\\ i\neq 3,5}}^{6} \sum_{j=1}^{2} x_{ij1} - x_{p_1}\, 16,600 \le 27,000$$

$$(5)\quad \sum_{\substack{i=1\\ i\neq 3,5}}^{6} \sum_{j=1}^{2} x_{ij2} - x_{p_2}\, 63,000 \le 86,500$$

$$(6)\quad \sum_{i=1}^{9} x_{i11} = 27,000$$

$$(7)\quad \sum_{i=1}^{9} x_{i21} = 16,600$$

$$(8)\quad \sum_{i=1}^{9} x_{i12} = 86,500$$

$$(9)\quad \sum_{i=1}^{9} x_{i22} = 63,000$$

$$(10)\quad \sum_{i=1}^{2} \sum_{j=1}^{2} x_{ij2} \le 128,200$$

$$(11)\quad \sum_{j=1}^{2} x_{3j2} \le 82,100$$

$$(12)\quad \sum_{j=1}^{2} x_{7j2} \le 43,600$$

$$(13)\quad x_{p_1} + x_{p_2} \le 1.0$$

$$(14)\quad x_{ijt} \ge 0 \qquad \forall i,j,t$$

where

$$x_{p_1} = \begin{cases} 1; \text{ if } \displaystyle\sum_{\substack{i=1\\ i\neq 3,5}}^{6} \sum_{j=1}^{2} x_{ij1} > 27,000 \\ 0; \text{ otherwise} \end{cases}$$

$$x_{p_2} = \begin{cases} 1; \text{ if } \displaystyle\sum_{\substack{i=1\\ i\neq 3,5}}^{6} \sum_{j=1}^{2} x_{ij2} > 86,500 \\ 0; \text{ otherwise} \end{cases}$$

Table 1

Decision Variables (x_{ij})

Variable*	Variable Description
x_{11}, x_{12}	Incineration of Deer I. sludge, Nut I. sludge
x_{21}, x_{22}	Pyrolysis of Deer I. sludge, Nut I. sludge
x_{31}, x_{32}	Coincineration of Deer I. sludge, Nut I. sludge
x_{41}, x_{42}	Ocean discharging of Deer I. sludge, Nut I. sludge
x_{51}, x_{52}	Ocean barging of Deer I. sludge, Nut I. sludge
x_{61}, x_{62}	Composting of Deer I. sludge, Nut I. sludge
x_{71}, x_{72}	Landfilling of Deer I. sludge, Nut I. sludge
X_{81}, x_{82}	Land application on private sites of Dear I. sludge, Nut I. sludge
x_{91}, x_{92}	Land application on MDC sites of Deer I. sludge, Nut I. sludge

*All x_{ij} are measured in tons per year of dry sludge.

Equation (1) denotes the net economic benefit objective to be maximized. The constrained objectives of environmental impact and variability with upper bounds of L_2 and L_3 are represented by equations (2) and (3). Equation (4) requires that a pipeline be constructed to transport sludge from Nut Island to Deer Island, when the quantity of sludge allocated to either the incineration, pyrolysis, ocean discharge or composting alternatives exceeds that amount produced by the Deer Island facility in Phase I. Similarly, equation (5) requires that a pipeline be constructed in period two, if the amount of sludge allocated to the above alternatives exceeds the Phase II Deer Island output. Equations (6), (7), (8) and (9) are the availability constraints, which require that the sludge produced from both treatment plants in Phase I and Phase II be allocated to some disposal mode. For instance, equation (9) requires that the sludge produced by Nut Island in Phase II be allocated to some disposal mode(s). Equations (10), (11), and (12) restrict the scale of the incineration, pyrolysis, coincineration and the landfill alternatives in accordance with either environmental regulations or physical capacity limitations. Finally, equation (13) is a binary constraint that prevents the pipeline from entering more than once in the model, and equation (14) is the usual nonegativity restriction.

The model is solved (determining the nondominated set) by parametrically varying the upper bounds of the constrained objectives as described in Cohon and Marks [1975]. The data and estimated parameters for this model are available upon request.

Sequential Decision Model: The previous formulation considered multiple conflicting objectives. In addition, the set of non-inferior solutions reported in the next section was winnowed by a committee of decision-makers in arriving at a most preferred or compromise solution. However, this and the previous investigations have assumed that the parameters are known with certainty. Of course, they are not.

The major uncertainty for the combustion modes, is whether the technology would operate as planned. For the land disposal modes, the risks pertain to application standards and to whether significant markets exist for sludge and compost. For the ocean modes there is a possibility that federal regulations may change which would permit utilization of these low cost disposal options. This model incorporates this risk explicitly using a sequential decision model cast in a Bayesian decision theoretic form, which emphasizes the expected net economic benefits objective.

EMPIRICAL RESULTS

Two-Period Formulation: The nondominated solutions to the multiple objective formulation are provided in Table 2. Again, the decision variables (x_{ijt}) represent allocations of sludge (tons of dry sludge per year) from either the Deer Island (j=1) or Nut Island (j=2) treatment plant to the nine disposal alternatives (i=1, ..., 9) in Phase I (t=1) and Phase II (t=2). Twenty distinct nondominated solutions were generated by the algorithm. The incineration and the pyrolysis alternatives were completely dominated by the others -- each of the others appeared in at least one non-inferior solution. Ocean barging, landfilling, and land application appeared in solutions most often.

A committee was then formed to evaluate these results. The experiment was constructed in accordance with modern social choice theory (available upon request). In the interests of space, we simply report that solution 9 was selected as a best compromise solution. This solution landfills the entire sludge output in Phase I and applies it all on private agricultural land in Phase II. This analysis is further refined below.

Sequential Model: While parameters are assumed known above, in reality there is a high level of uncertainty. This risk is probably greater with the combustion modes than it is with the ocean and land alternatives. This higher risk is primarily a result of the high capital intensity which would make costly a change-over to another mode of disposal if they should prove unsatisfactory.

Therefore, a useful question in this regard would be to analyze the effect of delay upon the combustion alternatives particularly the

Table 2
Two-Period Formulation - Nondominated Solutions*

Phase	Solution Number	x_{11}	x_{12}	x_{21}	x_{22}	x_{31}	x_{32}	x_{41}	x_{42}	x_{51}	x_{52}	x_{61}	x_{62}	x_{71}	x_{72}	x_{81}	x_{32}	x_{91}	x_{92}
I (t=1)	1					5,668				5,668		8,284		8,720		7,848		7,412	
	2					5,668				6,104				15,260		8,720		7,848	
	3					5,668				6,540				13,516		9,592		8,284	
	4					4,796				6,540				14,824		9,592		7,848	
	5									5,668				25,288		6,976		5,668	
	6									4,796				33,572		5,232			
	7									4,360				39,240					
	8									3,924				39,676					
	9													43,600					
	10									6,540				22,236		8,284		6,540	
	11					43,600													
	12									5,232				33,136		5,232			
	13													43,600					
	14									4,360				39,240					
	15									4,796						38,804			
	16															43,600			
	17									4,796						38,804			
	18															43,600			
	19									43,600									
	20							43,600											
II (t=2)	1						1,794		20,930		20,930				34,385		29,900		25,415
	2										1,790				113,620		17,940		
	3								23,920		25,415				35,880		37,375		26,910
	4										14,950						134,550		
	5										14,950						134,550		
	6										13,455						136,045		
	7										13,455						136,045		
	8																149,500		
	9																149,500		
	10										149,500								
	11										149,500								
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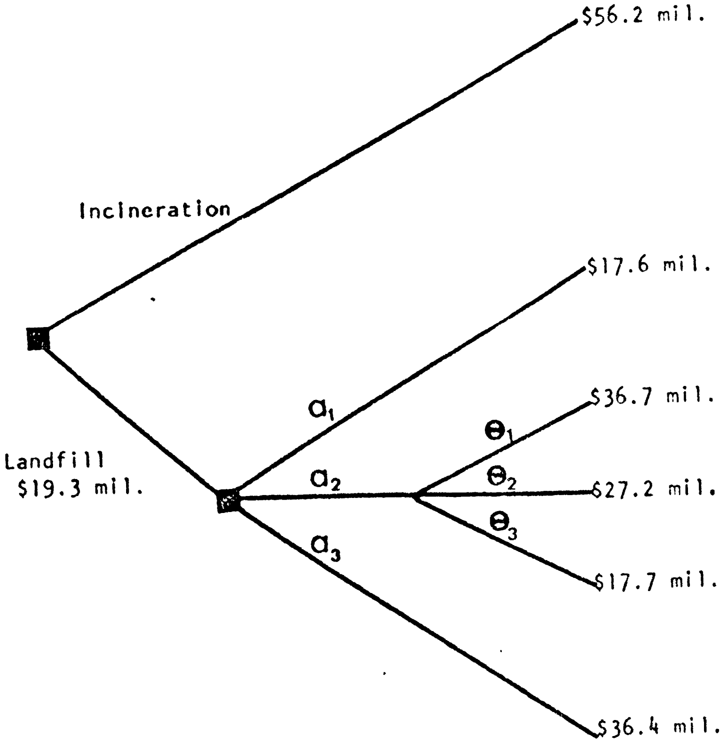
	17								149,500										
	18								149,500										
	19								149,500										
	20								149,500										

*Values are measured in tons per year of dry sludge.

incineration mode. That is, one could actively learn during the delay period about the performance factors associated with sludge incineration, as well as acquire more knowledge about the land application of sludges and the environmental hazards associated with ocean disposal. Since the results of the previous two models emphasize the overwhelming dominance of the landfill mode as a short-run solution, in effect, the question of delay has already been answered. If the results had been suggestive of the construction of combustive facilities a sequential formulation would have been more compelling. Nevertheless, a rudimentary sequential model can provide useful insights.

The simplified decision tree in Figure 2 is used to depict the sequential decision problem. At the first decision point there are two

Figure 2
Sludge Decision Tree



possible actions -- construct incinerators immediately or delay and utilize the landfill mode during the interim. For the "incineration now" action, the outcome is regarded as a point estimate of \$56.2 million in present value of costs over a 25 year period. For the five years of landfill the point estimate of present value of cost over the period is \$19.3 million. These values have been computed from the net economic benefit estimates in the Phase I model.

Assuming that the decision to delay has been made, the decision-makers are faced with a second decision point for five years hence. At this point there are three alternative actions. First, with further environmental studies during the delay period, ocean disposal (a_1) may become an acceptable alternative which could result in significant cost savings. The outcome of this action is approximately \$17.6 million in present value of costs over a 20 year period. However, this action is by no means certain -- in fact, it has a very low probability of occurrence. ERT [1977] has suggested a conservative estimate of 0.02. The second action (a_2) at this decision point is to use sludge as a soil conditioner and fertilizer in a land application mode. Figure 2 depicts possible outcomes for this action (corresponding with states of nature θ_1, θ_2, θ_3) having present value costs of \$36.7, \$27.2, and \$17.7 million and probabilities of occurrence set at $\theta_1 = 0.20$, $\theta_2 = 0.60$, and $\theta_3 = 0.20$, respectively. The third and final action (a_3) is to construct incinerators with a point estimate of present value of costs over the remaining 20 year life of \$36.4 million.

To analyze the implications from the decision tree several comparisons are made in Table 3. First, C_1 is defined as the point estimate of

Table 3

Sequential Decision Comparisons

Consequence	Outcome
C_1 - implement incineration now	\$56.2 million
C_2 - landfill for 5 years with land application afterward	\$46.5 million
C_3 - land fill for 5 years with outcome based on sequential without incineration action (a_3)	\$44.2 million
C_4 - landfill for 5 years with outcome based on full sequential implications	\$47.1 million

the present value of costs over 25 years for the alternative to initiate incineration in the first decision period. The value C_2 is the point estimate of the present value of costs over 25 years for the alternative of using the landfill mode for 5 years followed by land application, where the decision is "cast in concrete" in the sense that the learning which may occur over the 5 year delay period is not admissible. Since C_1 exceeds C_2 by \$9.7 million, the delay alternative would be chosen even without the benefits of delay (learning benefits).

In order to isolate the expected benefits attributable to the delay and learning (reduced costs of wrong decisions), the expected net present value of the delay alternative (C_3) is calculated, where a_1 has probability 0.02, a_2 has probability of $\theta_3 = 0.20$ and probability of θ_2 (the point estimate) of 0.80. That is, a_3 and a_2 with state of nature θ_1 are removed from Figure 3 to maintain correspondence with C_2. Clearly, if a_1 is feasible at the end of 5 years, that alternative will be chosen.

If not, action a_2 would be taken with one of two outcomes depending upon whether θ_3 or θ_2 is obtained. This expected present value of the delay alternative is \$44.2 million; i.e., $P(a_1)(17.6) + P(\theta_3|\overline{a}_1)(17.7) + P(\theta_2|\overline{a}_1, \overline{\theta}_3)$ 27.2, where $P(a_1) = 0.02$, $P(\theta_3|\overline{a}_1) = 0.196$ and $P(\theta_2|\overline{a}_1, \overline{\theta}_3) = 1 - (0.02 - 0.196) = 0.784$ and $\overline{\theta}_1$ is the complement state of nature. Thus, the expected value of delay is the difference between C_2 and C_3 or \$2.3 million. Presumably, this is the expected value of the information that could be collected during the delay period.

The comparisons between C_2 and C_3 are based upon formulations made unrealistically simple and are computed for comparability reasons only. A more realistic approach would be to compute the outcome for C_4 which uses the full sequential implications. This outcome is \$47.1 million and is computed as follows: $P(a_1)(17.6) + P(\theta_3|\overline{a}_1)(17.7) + P(\theta_2|\overline{a}_1, \overline{\theta}_3)(27.2) + P(a_3)(36.4)$, where $P(a_1) = 0.02$, $P(\theta_3|\overline{a}_1) = 0.02(1-0.02) = 0.196$, $P(\theta_2|\overline{a}_1, \overline{\theta}_3) = 0.60(1-0.02)(1-0.80) = 0.47$, and $P(a_3) = 1-(0.02 + 0.196 + 0.47) = 0.314$. Under action a_1, state of nature θ_1 was excluded because it is dominated by the incineration action (a_3). Unfortunately, C_4 is not strictly comparable to C_1, unless some modifications are added to C_1, i.e., introduce an array of outcomes. Nevertheless, it does provide a more realistic calculation of expected cost of the delay alternative. One final comment; if the "incineration now" action had an outcome of, say, \$45 million, then the full consequences of the sequential decision tree could have been explored. That is, while the point estimates based on current information only suggest "incineration now" to be optimal in a cost sense, the value of avoiding wrong decisions is sufficient to make the delay alternative superior.

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