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INCORPORATING PROJECT UNCERTAINTY IN NOVEL ENVIRONMENTAL BIOTECHNOLOGIES: ILLUSTRATED USING PHYTOREMEDIATION

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ABSTRACT

Pollution of the environment by metals and organic contaminants is an intractable global problem, with cleanup costs running into billions of dollars using current engineering technologies. The availability of alternative, cheap and effective technologies would significantly improve the prospects of cleaning-up metal contaminated sites. Phytoremediation has been proposed as an economical and 'green' method of exploiting plants to extract or degrade the contaminants in the soil. To date, the majority of phytoremediation efforts have been directed at leaping the biological, biochemical and agronomic hurdles to deliver a working technology, with scant attention to the economic outlook other than simple estimates of the cost advantages of phytoremediation over other techniques. In this paper we use a deterministic actuarial model to show that uncertainty in project success (the possibility that full clean up may not be realized) may significantly increase the perceived costs of remediation works for decision-makers.

KEYWORDS: Biotechnology, project risk, soil contaminants, Environmental remediation, Industrial crop technologies

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1. INTRODUCTION

Pollution of soils with metals, metalloids and organic contaminants is a serious problem in the United States and globally. Under the source-pathway-receptor model of risk assessment, the failure to clean up contaminated sites (source) leads to risk of harm to plants, animals, humans and natural resources such as water (receptors) via significant pollutant linkages (pathways). For example, the contaminants may impact groundwater or surface water on site, or may be directly toxic to plants, animals and humans. Additional concerns are raised when the contaminants migrate from the site in groundwater, run-off and dusts, or enter the food chain.

Globally, all countries have sites contaminated with metals and organic contaminants. In the developed world there is the often legal, obligation that the 'polluter pays' for clean up. There can also be some financial provisioning by government to remediate, or at least stabilize, significant contaminated sites where a polluter cannot pay or be identified for some reason. For example, in 1980 the United States Congress established the Superfund Program to locate, investigate, and clean up the most contaminated sites nationwide (USEPA 2002). Currently, there are approximately 1200

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sites[4] on the US EPA's priority clean up list. Resources For The Future estimate that the Superfund will cost US tax payers between US$14 billion and US$16.4 billion over the next 10 years (Probst et al. 2001). In many developing countries, however, clean-up funds are likely to be inadequate or nonexistent. Moreover, the local people are more likely to be in contact with the contaminants than in the developed world, due to reliance on subsistence agriculture or the inadequate provision or unaffordable costs of services such as clean drinking water.

The availability of alternative cheap and effective technologies would significantly improve the prospects of cleaning-up contaminated sites, particularly where financial provisioning is poor. Phytoremediation, has been championed as a potentially economical and 'green' method of removing contaminants from the soil, which does not require significant engineering works. For metal contamination, metal-accumulating plants can be used to 'harvest' contaminant metals from soils – "phytoextraction". For petroleum hydrocarbons, pesticides and chlorinated solvents contamination, the biological and biochemical mechanisms of plants and associated bacteria are exploited to degrade organic contaminants *in situ* eventually reducing the organic compounds to water, CO_2 and mineral salts – "phytodegradation". And, for metalloid contamination such as selenium and mercury, plants can be exploited to either accumulate the metalloids or to convert them volatile organic forms, which are released to the atmosphere – "phytovolatilization". For detailed reviews of the general principles and biological mechanisms of phytoremediation see, for example, Leeson and Alleman 1999; Raskin and Ensley 1999; Terry and Banuelos, 2000; McCutcheon and Schnoor 2003; Tsao 2003. Note that phytoremediation using plants in wetlands, water filtering systems or

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[4] http://oaspub.epa.gov/oerrpage/basicqry

evapotranspirative covers are not considered in this paper; for technological information the reader is directed to, for example to Kadlec and Knight (1996); Weand and Hauser (1997); Campbell and Ogden (1999); Batty (2003).

Much of the optimism surrounding the different phytoremediation strategies is based on the belief that they might offer significant cost advantages over engineering-intensive remediation solutions such as ‘dig and dump’, soil washing or heat treatment. Phytoremediation strategies are also perceived to have the added benefit that they might be more sustainable and “environmentally-friendly” because the contaminated soil is treated rather than disposed of by landfill. Despite the potential positives of phytoremediation, the primary considerations for stakeholders needing to treat contaminated land are the (1) likelihood of success (i.e., meeting regulatory criteria for contaminants), (2) the time taken to achieve success, and (3) the cost effectiveness[5] of the solution.

To date, most effort has been invested in conquering the technical, agronomic and biological challenges involved in delivering phytoremediation as a working technology (improving success) and speeding up the rate at which phytoremediation occurs[6] (time to achieve success), which go some way to addressing the first and second of a site stakeholder’s concerns. While phytoremediation may appear initially to be cost effective there has been scant attention to third concern, the economic outlook, other than simple estimates of how much cheaper phytoremediation might be compared to other technologies. Most analyses of the cost effectiveness of phytoremediation solely

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[5] Cost effectiveness refers to the ability of a technology to remediate a site at a lower cost per hectare than an alternative technology.

[6] Phytoremediation can take several years to achieve success (e.g., for metals see Zhao et al., 2003). Note that in the case of high concentrations of contaminants, or where the contaminants are beneath the rooting zone of plants, success might never be achievable using phytoremediation. The considerations for testing feasibility of phytoremediation for a particular set of contaminant conditions are not explored in this article.

compare ‘estimates’ of accounting costs of ‘dig and dump’ projects against phytoremediation works, where phytoremediation is costed as an agricultural concern (e.g. Glass 1999). There are two crucial omissions in such analyses. Firstly, they rarely consider costs in terms of a realistic bill-of-quantities for each remediation technique, which would include overheads, management and salaries on top of the engineering costs. Secondly, the cost estimate models ignore the effect of uncertainty on management decision-making[7], which will increase the perceived cost of works.

In this article we consider uncertainty[8] in project outcomes. Managing uncertainty is a key factor in economic decision-making, and can be incorporated in economic management models using expected utility theory[9]. The same principles of uncertainty should be considered in the assessment of environmental technologies, including phytoremediation, bioremediation, physical treatment systems or soil disposal. We have developed a simple management decision model that explicitly incorporates the effect of uncertainty on management decisions. The purpose of the model is to demonstrate the effect that uncertainty has on perceived cost. Managing uncertainty will be the next big hurdle for phytoremediation as a commercial product now that the biological and agronomic techniques are being perfected. This type of information will be vital to support Best Practicable Environmental Option (BPEO)[10] desk studies, which precede the design of a remediation strategy.

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[7] Refers to the process where by management arrives at a decision. This includes approaches such as risk analysis and cost benefit analysis (www.sra.org).

[8] Uncertainty arises from a number of sources and includes inherently random processes and natural variation. Uncertainty also includes our lack of knowledge of situations which may be deterministic and not necessary inherently random. In this situation lack of knowledge leads uncertainty over what will occur. Phytoremediation projects exhibit both types of uncertainty described.

[9] For example see Hare and McCutcheon (1991) for a practical implementation or Mas-Colell *et al*. (1995) for a theoretical development.

[10] http://www.ehsni.gov.uk/pubs/publications/BPEOCurrentStatusFeb2005.pdf

2. MODEL DEVELOPMENT

Typically remediation investment decisions are based on a combination of the net present value of profits (NPV), the payback period t, and the probability of success p. The Net Present Value is thus the sum of the discounted stream of annual net benefits. Net Present Value requires subtracting all the costs necessary to bring the project into existence and an estimate of future benefits. The NPV is discounted at the hurdle rate of return, which is simply the rate of interest applied to discount the stream of net benefits. The hurdle rate represents an existing benchmark rate of interest usually the rate of return demand for projects calculated on the proportion of debt and equity used to finance the project. If the NPV is greater than zero, then the project is accepted. Usually these parameters are subject to constraints, which will be dependent on both business and regulatory pressures. For example, management may require that the NPV of profits be positive, the payback period be less than three years and that the project have at least a 90 percent chance of success, or, if the regulator is involved, achieving 100 percent success might be required for compliance. The payback period is the time taken to return any initial capital investment. A short payback period ensures that capital is freed within a reasonable period of time as opposed to being tied up for many years. The NPV of profits measures the discounted value of future profits using a rate of return required for the project.

Consider a simple model for comparing phytoremediation of a contaminated site with an engineering method of remediation. For the purposes of demonstration it does not matter whether this is phytoremediation of metals, metalloids or organics contaminated soil. The engineered remediation technique could be ‘dig and dump’, heat treatment, soil washing etc, so, for the purposes of demonstration, let us call the engineered remediation, RemedY. In the model, it is assumed that profits are generated from the sale of the decontaminated land (benefits), for example, from real estate sales that occur at the end of the remediation period. It can also be assumed that no initial financial strain occurs because companies considering the use of phytoremediation pay a technology fee as part of the cost of using the technology. Therefore we assume that there is no significant initial capital outlay in addition to buying the seed and paying a technology fee[11]. The implication of this assumption is that the payback period can be ignored. This is a common assumption for this kind of work (Hare and McCutcheon 1991).

Further if it is assumed that using pytoremediation is 100 percent successful then the net present value of profit is given by:

$$NPV_p = \frac{P_s}{(1+i)^N} - \sum_{t=1}^{N} \frac{c_t}{(1+i)^{t-1}} \qquad (1)$$

where c_t is the cost of phytoremediation each year, i is the discount rate (usually the hurdle rate of return), N is the project time horizon, and P_s is the expected net value from the sale of the land (i.e. net profit after sale costs), which is assumed to be a constant but in reality is a random variable. This equation is a standard business model for estimating *NPV* of profit (Hare and McCutcheon 1991).

If it is assumed that phytoremediation is unsuccessful then the net present value of profit is given by:

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[11] In reality sites are often prepared by adding chemicals to the soil. The cost depends on the type of preparation required. For example sulfur added to lower soil pH is relatively cost effective and thus insignificant compared to the overall cost of phytoremediation; however, chelates can be quite expensive.

$$NPV_{pd} = \frac{P_s}{(1+i)^{N+1}} - \sum_{t=1}^{N} \frac{c_t}{(1+i)^{t-1}} - \frac{c_d}{(1+i)^N} \tag{2}$$

where c_d is the additional cost associated with undertaking RemedY in year *N* (after phytoremediation failed) to meet the regulatory clean up needs for the site. The profit is also assumed to be delayed by an additional year.

If we included our estimates of the success of the project (probability of success *p* and the probability of failure *1-p*), then the model is given by the expected net present value (*EV*) of profits (combining (1) and (2))

$$EV_p = NPV_p p + NPV_{pd}(1-p) \tag{3}$$

which gives

$$EV_p = \left(\frac{P_s}{(1+i)^N} - \sum_{t=1}^{N} \frac{c_t}{(1+i)^{t-1}} \right) p + \left(\frac{P_s}{(1+i)^N} - \sum_{t=1}^{N} \frac{c_t}{(1+i)^{t-1}} - \frac{c_d}{(1+i)^N} \right)(1-p). \tag{4}$$

For decision-making (4) should be compared with the *EV* of profits from RemedY given by

$$EV_d = \left(\frac{P_s}{(1+i)} - c_d \right) \tag{5}$$

Comparing (4) and (5) it is necessary for $EV_p \geq EV_d$ if phytoremediation is going to be the preferred technology or

$$EV_p = \left(\frac{P_s}{(1+i)^N} - \sum_{t=1}^{N} \frac{c_t}{(1+i)^{t-1}} \right) p + \left(\frac{P_s}{(1+i)^N} - \sum_{t=1}^{N} \frac{c_t}{(1+i)^{t-1}} - \frac{c_d}{(1+i)^N} \right)(1-p) \geq \left(\frac{P_s}{(1+i)} - c_d \right)$$

simplifying

$$\sum_{t=1}^{N}\frac{c_t}{(1+i)^{t-1}} \leq \frac{c_d(1+i)^N - c_d + pc_d}{(1+i)^N} + \frac{P_s\left(1-(1+i)^{N-1}\right)}{(1+i)^N} \tag{6}$$

The right hand side of (6) is linear in *p* and forms an upper bound on the cost of phytoremediation.

3. RESULTS

'Real' values could be inserted into the model developed above to illustrate the effect of uncertainty on the cost comparison of phytoremediation and RemedY. However, obtaining actual cost and profit data for illustrative purposes is not easy because off-the-shelf phytoremediation products are not available and there are significant site-specific and pollutant-specific tailoring of the bill-of-quantities required for remediation projects, including assumptions about the person-hours required for each program of works. Moreover, assumptions on the potential use and consequent value of the land are required, which will drive the remediation cost a stakeholder is willing to forfeit and the timescale for return on the investment. For example, values for farmland vary from a few hundred dollars per hectare in the least populated states to a many thousand dollars per hectare in the most populated states (USDA 2002). For the purposes of this article, some arbitrary values thought to be representative of real-world values have been chosen to illustrate the impact of uncertainty on the cost of phytoremediation projects. The primary assumption we have made, based on public perception of phytoremediation, is that RemedY is several-fold more expensive per hectare than phytoremediation.

Using the set of generic values in Table 1, profits and costs can be combined to illustrate the effect of different scenarios. Five cases were investigated: (a) a base case, (b) high property prices, (c) high phytoremediation costs, (d) low RemedY costs, and (e) short phytoremediation times.

Table 1--Parameter values used for the scenario analysis.

Parameter	Scenario (a) Base case	Scenario (b) High property price	Scenario (c) High phytoremediation cost	Scenario (d) Cheap RemedY[§]	Scenario (e) Fast phytoremediation	Description
P_s (Profit per hectare)	1000 USD/ha	2000 USD/ha	1000 USD/ha	1000 USD/ha	1000 USD/ha	Profit per hectare from land sales. Prices vary from place to place. The value was chosen for illustrative purposes (USDA 2002).
c_t †	45 USD/ha	45 USD/ha	90 USD/ha	45 USD/ha	45 USD/ha	A range of values is cited in Glass 1999. 40 USD was chosen for illustrative purposes from this range.
c_d ‡	900 USD/ha	900 USD/ha	900 USD/ha	450 USD/ha	900 USD/ha	Cost of 'dig and dump'
I	0.05	0.05	0.05	0.05	0.05	Discount rate.
N	10 years	10 years	10 years	10 years	5 years	Project Term

§ RemedY costs per hectare based on clean up of the top 50 cm of soil, which would be the equivalent depth to which phytoremediation is typically possible (i.e., rooting depth).

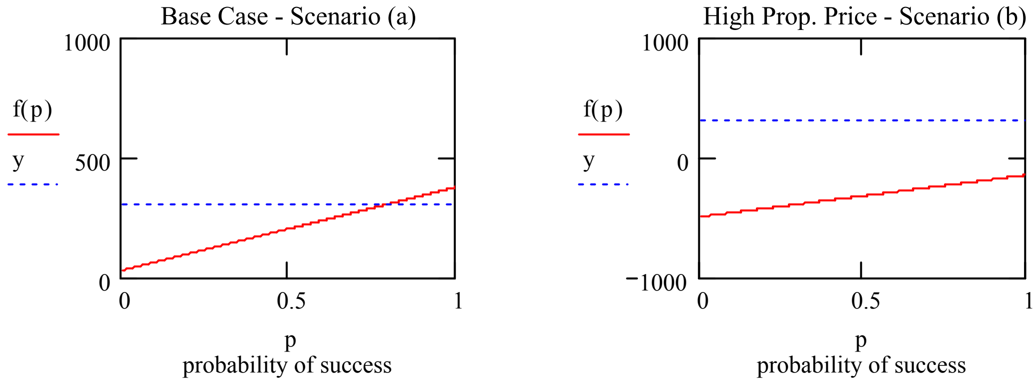
† Cost of phytoremediation is given a surrogate cost value 45 USD/ha in the base case model. Expensive phytoremediation is represented by a value of 90 USD/ha, i.e., a doubling in phytoremediation cost.

‡ Cost of the engineering technology 'RemedY' is given a surrogate cost of 900 USD/ha, i.e., this is 20 times more costly than phytoremediation per hectare; In the cheap engineered technology scenario, the cost of RemedY is set at 450 USD/ha, i.e., half halving the cost of this technology, but is still 10 times more expensive than phytoremediation.

Scenario (a), the base case using ‘typical’ costs for the model parameters, is provided in all of the subsequent figures for comparison.

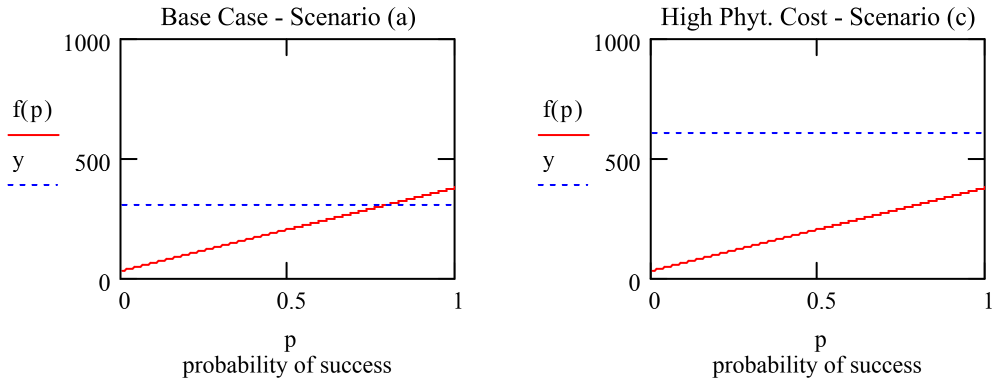
Scenario (b) – High land value. Increasing property prices may have a significant impact on the remediation strategy used, even when phytoremediation is guaranteed to succeed. In areas with valuable commercial or residential land, RemedY may provide faster realization of profits and, in terms of the net present value of profits, this may be preferred. For example if property prices double over the prices assumed in the base case then RemedY appears to be the better strategy given the assumptions of the model (Figure 1).

Figure 1--Comparing scenarios (a) and (b) i.e. the effect of a doubling of property prices on the viability of using phytoremediation. The red line f(p) represents the right hand side of Equation 6 and the blue line y represents the left hand side of Equation 6. For phytoremediation to be economically viable y ≤ f(p). The graph on the left hand side shows that phytoremediation is viable for probabilities of success above approximately 0.7. The graph on the right hand side shows that phytoremediation is not viable with a doubling in property prices when compared to the base case (left hand side graph).



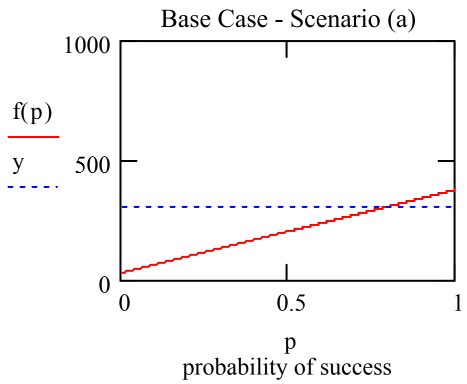
Scenario (c) – Phytoremediation costs increase relative to RemedY. If phytoremediation becomes more expensive then it is important that the project has a greater chance of success because there is a higher cost associated with failure. A doubling of the phytoremediation cost was sufficient to make phytoremediation unviable (Figure 2).

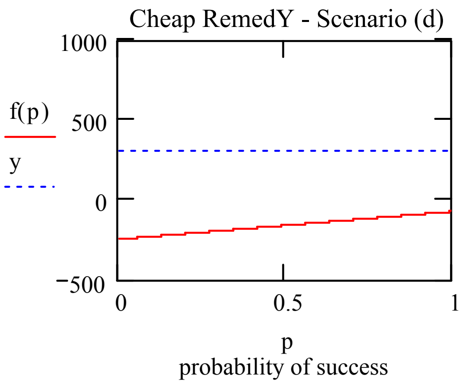
Figure 2--The graph on the right hand side shows the effect of increasing the cost of phytoremediation projects. The red line f(p) represents the right hand side of Equation 6 and the blue line y represents the left hand side of Equation 6. For phytoremediation to be viable y ≤ f(p). Doubling the cost of Phytoremediation results in Phytoremediation projects becoming unviable compared to the Base Case.



Scenario (d) – RemedY costs decrease relative to phytoremediation. If RemedY becomes more affordable then phytoremediation becomes less attractive as a strategy. Under scenario d, if RemedY costs are halved over the base case then phytoremediation becomes unviable (Figure 3).

Figure 3--The graph on the right hand side shows the effect of decreasing RemedY costs. The red line f(p) represents the right hand side and the blue line y represents the left hand side of Equation 6 respectively. For phytoremediation to be viable y ≤ f(p). Phytoremediation projects never become viable if the RemedY cost is halved compared to the base case (left hand side graph).

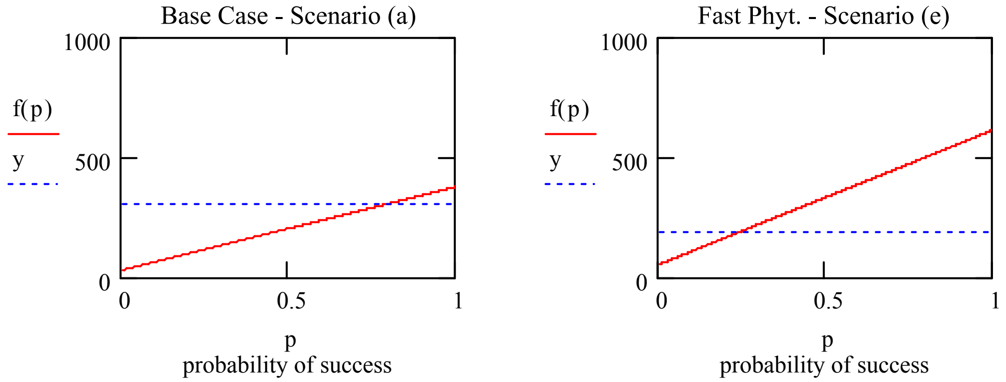




Such situations might not arise in developed countries if, for example, RemedY were dig-and-dump, because the increasing cost of landfilling of contaminated spoil would tip the financial balance towards other in situ treatment technologies. Indeed, in the United Kingdom, the recent Landfill Directive (July 2004) and associated changes to waste acceptance criteria have dramatically reduced the number of landfills that will take contaminated waste from around 200 down to around 11. In consequence, the cost of landfilling contaminated soil has risen from £100 per tonne (~US$180) to £150 per tonne, and is continuing to rise.

Scenario (e) – Phytoremediation technology develops such that operation time is reduced. The time taken to reduce contamination to levels below regulatory reference levels is an important driver in deciding which strategy should be used. If phytoremediation technology is improved such that the time frame for successful remediation is reduced, then this will work in favor of applying cheaper phytoremediation technologies. This occurs because, if failure occurs, the receipt of profit is not delayed too long. For example, halving the remediation term implies that a phytoremediation project will become viable if the probability of success is approximately 0.25 compared to approximately 0.7 in the base case (Figure 4).

Figure 4--The graph on the right hand side shows the effect of decreasing the remediation time for phytoremediation. The red line f(p) represents the right hand side and the blue line y represents the left hand side of Equation 6 respectively. For phytoremediation to be viable y ≤ f(p). Phytoremediation projects become viable if the probability of success is approximately 0.25 compared to approximately 0.7 in the base case (left hand side graph).



Many pilot studies of phytoremediation have found that it can take from a few to many hundreds of crops to successfully remediate a metal contaminated site using plants (e.g., Zhao et al., 2003). Clean-up times of longer then a few (3) years are likely to be unacceptable to stakeholders and regulators alike, unless special conditions for the site are granted.

4. DISCUSSION

The availability of a cheap alternative technology to conventional highly engineered methods of contaminated land remediation would save industry and taxpayers many millions of dollars. Phytoremediation has been proposed as a potentially cheap biotechnology for cleaning up soils contaminated with moderate levels of metals or organic pollutants, particularly where the pollution is distributed over a very large area. Phytoremediation is sold as having the added benefit of retaining the physical and biological integrity of the soil. Research has advanced the effectiveness of phytoremediation and has enhanced understanding of the situations where phytoremediation is most likely to be viable alternative to other remediation technologies.

Further research into the real cost of phytoremediation is critical to making meaningful cost comparisons with alternative technologies in BPEO assessments. In particular, fiscal management decisions about technology for a particular situation must consider both the likely success of the remediation (i.e., Will the land be acceptably clean at the end of a defined time period?) and management's confidence in this estimate.

To illustrate the vital impact of remediation success on the economic benefits flowing from the remediation, we presented a simple Net Present Value assessment incorporating remediation success with the differential costs of two technologies and the financial benefits of releasing real-estate. A number of simple assumptions underlie cost/success analysis of phytoremediation against a generic 'other' remediation technology RemedY. In particular, a deterministic expected value model was used to explore the effect of project success p on the cost comparison [realistically the variable p can be viewed as having a significant random component and in more sophisticated models should be incorporated as a probabilistic parameter together with uncertainty in prices and the likelihood of success of alternatives]. The results of our model illustrate the impact that variation in p may have on the decision to use phytoremediation without directly quantifying the extent of the uncertainty. This is shown graphically by plotting the decision variables against p (Figures 1, 2, 3, and 4).

This simple deterministic approach allows us to begin to understand the relationship between probability of remediation success, the comparative project cost, and how these are affected by market changes such as the value and need for real estate (Figures 1 and 4) or the relative costs of the different technologies (Figures 2 and 3). The model results are plausible. If property prices are high then there is a time advantage to remediating the site now, i.e. using a guaranteed technology such as ‘dig and dump’ that totally removes the contaminants quickly (Figure 2). However, this result depends on the period over which the phytoremediation project would need to be conducted to achieve the same success. Short phytoremediation terms may favor phytoremediation over other technologies (Figure 4) because of the potential cost advantages of phytoremediation, which is likely to be a cheaper technology.

Clearly, the cost differential between the technologies will have an effect on technology selection despite the potential difference in their success. As the relative cost of each technology changes the more ‘risky’ technology (phytoremediation), in terms of success, is increasingly favored as its cost advantage is increased over RemedY (Figures 2 and 3). It is interesting to note that when calibrating the model, obtaining realistic costs for both phytoremediation and other technologies such as ‘dig and dump’ was problematic. Even ignoring the cost for staff, plant and project management that vary dramatically between projects, the typical rates for phytoremediation per meter cube of soil are not available. Similarly, taking dig and dump as the example and ignoring the cost for staff, plant and project management, the rates for landfill vary considerably from state to state and from location to location, and are heavily dependent on the nature, concentration and mixture of contaminants in the soil. Landfill rates could be as low as $2 US per ton to more than $150 US per ton for household waste. Disposal costs for hazardous materials would be expected to be more expensive and may incur additional costs for haulage to landfills that are licensed to take hazardous waste. This will certainly drive the adoption of in situ remediation technologies. Further work is clearly needed in this area to calibrate realistic cost assessment models, or to tailor them to a particular region or even to a particular site.

Various extensions of model include incorporating situations where the primary goal of remediation is the environmental cleanup of a site. Such projects my not rely on land sales to generate profits and environmental valuation approaches such as contingent valuations may be required to quantify the benefits associated with a cleanup. In such situations the model would more realistically include an additional parameter to reflect that cleanup may only be partially effective and, depending on the circumstances, this may be an acceptable result. Stochastic extensions of the model would more realistically reflect the extent and variation of parameters. The probability of success p and the cost of remediation c_t could be treated as random variables with a normal and lognormal distribution, respectively. This would allow a more comprehensive exploration of the effect of uncertainty on decisions.

To conclude, the model presented in this article illustrates that the probability of remediation success, and the time taken to achieve that success, are major influencing factors in the decision to use phytoremediation, not just overall cost comparisons with alternate technologies. The deterministic model clearly demonstrates how stakeholders assessing remediation options for a contaminated site would consider the cost of works, likelihood of remediation success and other market drivers. The model presented here is the cornerstone for the development of stochastic models that incorporates realistic assessments of the uncertainty associated with the variable p, the success of the remediation. Modeling of uncertainty will be a key complement to models assessing the viability of phytoremediation from the scientific and agronomic standpoint, such as the Phytoextraction Simulator model developed by Phytomine Ltd in New Zealand. Indeed, Phytoextraction Simulator does include economic factors such as profit from metal recovery, cost of inaction and an estimate of the cost of an alternative technology. Future probabilistic models that take into account, for a certain site, both the suitability of each remediation technology plus the uncertainty of success will provide vital support to feasibility studies for the different remediation technologies and BPEO assessments. Therefore analysis is required to decide what factors are likely to influence phytoremediation so that the probability of success can be quantified and incorporated into management decision making.

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