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A Framework for Net Environmental Benefit Analysis for Remediation or Restoration of Contaminated Sites

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ABSTRACT / Net environmental benefits are gains in value of environmental services or other ecological properties attained by remediation or ecological restoration minus the value of adverse environmental effects caused by those actions. Net environmental benefit analysis (NEBA) is a methodology for comparing and ranking net environmental benefits associated with multiple management alternatives. A NEBA for chemically contaminated sites typically involves comparison of several management alternatives: (1) leaving contamination in place; (2) physically, chemically, or biologically remediating the site through traditional means; (3) improving ecological value through onsite and offsite restoration alternatives that do not directly focus on removal of chemical contamination; or (4) a combination of those alternatives. NEBA involves activities that are common to remedial alternatives analysis for state regulations and the Comprehensive Environmental Response, Compensation, and Liability Act, post-closure and corrective action permits under the Resource Conservation and Recovery Act, evaluation of generic types of response actions pertinent to the Oil Pollution Act, and land management actions that are negotiated with regulatory agencies in flexible regulatory environments (i.e., valuing environmental services or other ecological properties, assessing adverse impacts, and evaluating remediation or restoration options). This article presents a high-level framework for NEBA at contaminated sites with subframeworks for natural attenuation (the contaminated reference state), remediation, and ecological restoration alternatives. Primary information gaps related to NEBA include nonmonetary valuation methods, exposure–response models for all stressors, the temporal dynamics of ecological recovery, and optimal strategies for ecological restoration.

Net environmental benefit analysis (NEBA) is a methodology for identifying and comparing net environmental benefits of alternative management options, usually applied to contaminated sites. Net environmental benefits are the gains in the value of environmental services or other ecological properties attained by remediation or ecological restoration minus the value of adverse environmental effects caused by those actions. (Restoration, as defined here, refers to actions that directly improve environmental services or other ecological properties, onsite or offsite, in contrast to remediation, which focuses on chemical removal.) A NEBA for chemically contaminated sites typically involves the comparison of the following management alternatives: (1) leaving contamination in place, allowing natural attenuation; (2) removing or isolating contaminants through traditional remediation; (3) improving ecological value through onsite or offsite restoration that does not involve removing contaminants; or (4) a combination of those alternatives. An example of a combination of actions is the remediation of localized soil contamination combined with natural attenuation and the planting of trees. NEBA involves valuing environmental services or other properties, assessing adverse impacts, and evaluating remediation or restoration options. These activities are common to remedial alternatives analysis under state contaminated site regulations and the US Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); postclosure and corrective action permits under the Resource Conservation and Recovery Act (RCRA); evaluation of generic types of response actions pertinent to the US Oil Pollution Act (OPA); land-management actions that

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Table 1. Examples of ecological hazards posed by terrestrial remedial actions

Remedial action	Hazard
Microbial bioremediation and phytoremediation	Possibly increased bioavailability or toxicity of contaminants or products
	Devegetation due to tilling
	Decreased plant diversity and aqueous contamination due to fertilization
Excavation or isolation (capping) of soil	Destruction of vegetation
	Destruction of habitat and outmigration by vertebrates in excavated area
	Removal of nutrient-rich surface soil and associated micro-organisms and invertebrates
	Failure of soil ecosystem and vegetation to recover if nonindigenous fill soil is used
	Destruction of ecosystem at borrow pit where fill is obtained and at landfill where excavated soil is deposited
	Alarm and escape behavior of wildlife due to construction activity and noise
Burning of spills, soil incineration, or thermal desorption	Decrease in air quality and associated risk to wildlife or plants
	Destruction of aboveground vegetation and belowground seeds and root material from severe heat
	Destruction of soil organic matter and potential loss of productivity
	Change in chemistry of contaminants and soil, which might prevent emergence of new shoots
	Secondary fires, extending area of habitat destruction
	Outmigration by vertebrates in burned area
Most remedial actions	Destruction of vegetation and outmigration by vertebrates in areas where roads, parking areas, or laydown areas are developed, or foot traffic is frequent
	Reduction in biodiversity and wildlife forage from mowing of excavated area, cap, or landfarm to maintain lawn
	Decrease in air quality associated with increased truck traffic

are negotiated with regulatory agencies in flexible regulatory environments (e.g., many petroleum exploration and production sites in the United States, industrial impact areas in developing countries); and prioritization of contaminated sites for remediation (Powell 2002). However, NEBA has not been formalized in a manner analogous to the US Environmental Protection Agency (EPA) ecological risk assessment framework (EPA 1998), and land managers would benefit from such a NEBA framework. NEBA can be described as an extension of ecological risk assessment, which addresses benefits as well as risks, and integrates them.

Net environmental benefit analysis has the potential to help land managers avoid the possibility that the selected remedial or ecological restoration alternative will provide no net environmental benefit over natural attenuation of contaminants and ecological recovery. An alternative might provide no net environmental benefit because (1) the remedial or ecological restoration action is ineffective (does not substantially reduce adverse effects) or (2) the remediation alternative causes adverse environmental effects greater than the effects associated with the contamination. Potential hazards posed by remedial interventions are listed in Table 1. Similarly, NEBA has the potential to help land managers plan an ecological restoration alternative that provides a positive net environmental benefit over the hypothetical state that would have existed if contamination had not occurred. NEBA is recommended if any of the remedial or restoration alternatives potentially have significant negative ecological effects or minimal ecological benefits. For example, recent research suggests that dredging of sediments in a canal of the San Francisco Bay might not have provided net environmental benefits, as measured by dichloro-diphenyl-trichloroethane (DDT) and metabolite body burdens, and yet capping, more rigorous dredging, or an unevaluated restoration alternative might have provided an environmental benefit (Weston and others 2002). Finally, NEBA is needed when the multiple alternatives are beneficial, but the one with greatest net benefit is not apparent without formal analysis.

Few guidance documents emphasize the importance of comparing risks from various remedial and no-action alternatives (Suter and others 2000; Reagan 2000). Remediation is assumed to reduce risk. In Hungary, for example, the ranking of contaminated sites for remediation considers risk but not cost or benefit of particular remedial alternatives (Powell 2002). In the United States remedial goals are defined based on human health or ecological risks from the contaminants, but the remedial technologies are chosen based primarily on two engineering criteria: the ability to achieve those goals and cost-effectiveness. This focus on engineering

Table 2. Examples of NEBA

Example	Reference
Net environmental benefit (NEB) of excavation and rock-washing treatment technology versus natural attenuation and approved treatments, Exxon Valdez oil spill	NOAA (1990)
Quantification of wetland mitigation from petroleum pipeline construction	Nicolette and others (2001)
NEB of natural attenuation versus pump and treat technology versus air sparge/vapor extraction of volatile organic compounds in groundwater	Nicolette (CH2M HILL, confidential source)
NEB of dredging versus not dredging an estuary, with quantification of restoration needed to offset uncertainty in risk assessment	Rubin and others (2001)
NEB of seagrass and mangrove restoration, following undisclosed disturbance at John's Island, Palm Beach County, Florida[a]	Friant (Entrix, personal communication, 2002)
NEB of the use of dispersant following the grounding of the *Sea Empress* in Great Britain	Lunel and others (1997)

[a]In this example, net benefits were quantified, but not compared among multiple alternative types.

criteria rather than environmental goals tends to restrict the range of options considered.

Similarly, direct ecological restoration is not commonly considered in remedial alternatives [prior to compensatory restoration resulting from Natural Resource Damage Assessment (NRDA)], but examples of restoration alternatives at contaminated sites exist. Riparian zone planting of trees and shrubs has been performed in the CERCLA context at the NT-3 Tributary of Bear Creek at the Y-12 Plant in Oak Ridge, Tennessee (M. J. Peterson, Oak Ridge National Laboratory, personal communication, 2003). Similarly, a river was realigned and improved for fish habitat, with 8000 trees planted at the RCRA creosote-contaminated Union Pacific Railroad Laramie Tie Plant site in Wyoming, and a small creek was realigned and riparian habitat was restored in conjunction with a hydraulic containment structure for a chlorinated solvent release at Beale Air Force Base in California (T. Sale, Colorado State University, personal communication, 2003).

This article provides a framework for NEBA, demonstrates how benefits and residual adverse effects from natural attenuation, traditional remediation, and ecological restoration options can be compared systematically, and identifies key research needs. The emphasis of many examples is on petroleum contamination in terrestrial and wetland ecosystems, although the framework is equally applicable to a broad range of contaminants and to aquatic environments. A more detailed framework for NEBA is available as a report (Efroymson and others 2003).

Environmental management alternatives must also be considered in an economic context, but monetary cost issues are not included in this framework, which addresses net environmental benefits rather than net economic benefits. Similarly, human health risks and technical feasibility are typically treated externally to NEBA. However, these factors are expected to be integral to a remediation or restoration decision, and NEBA is only part of the analysis for that decision.

Precedents for NEBA

Several precedents for NEBA exist, but they provide little specific procedural or methodological guidance for the assessment of contaminated sites. The term NEBA is not commonly used in regulatory contexts. It was probably coined by agencies and industries evaluating options for marine oil spills, as in the report published by the US National Oceanic and Atmospheric Administration (NOAA) entitled "Excavation and rock washing treatment technology: Net environmental benefit analysis" (NOAA 1990). Although representatives of Exxon, NOAA, and the state of Alaska provided an analysis of the potential adverse impacts associated with the proposed remediation technology and estimated relative recovery periods, their report did not provide a framework or propose metrics for comparison of adverse effects and benefits from the alternative methods. The term NEBA is commonly associated with assessments of oil spill dispersants in marine environments (Fiocco and Lewis 1999; Lunel and others 1997). Additional applications of NEBA are listed in Table 2, although many reports are not publicly available because of their use in litigation proceedings, and, thus, many more NEBAs have been performed than those of which we are aware.

Although the NEBA terminology is not normally used in CERCLA remediation assessments, the concept is included in the guidance from the EPA Office of Emergency and Remedial Response (Luftig 1999). "Even though an ecological risk assessment may demonstrate that adverse ecological effects have occurred or are expected to occur, it may not be in the best interest of the overall environment to actively remediate the site...Although most receptors and habitats can recover from physical disturbances, risk managers should carefully weigh both the short- and long-term ecological effects of active remediation alternatives and passive alternatives when selecting a final response."

Similarly, the Great Lakes Water Quality Board recommends that "prior to embarking on sediment remediation, [one should] have developed some quantifiable expectation of result (ecological benefit) and a program to follow the predicted recovery" (Zarull and others 1999). Individual scientists have espoused NEBA-like concepts and methods (Principe 1995; Baker 1999) but have not provided a methodological framework.

At least three states endorse NEBA-related methodologies in environmental legislation. (1) The Texas Commission on Environmental Quality (TCEQ) (formerly the Texas Natural Resource Conservation Commission, TNRCC) recommends "Ecological Services Analysis" as an option for contaminated sites where chemical concentrations exceed ecologically protective concentration levels (PCLs) but not human health PCLs (TNRCC 2001). The potentially responsible party might propose compensatory ecological restoration after quantifying benefits and adverse effects associated with alternative remedial actions or natural attenuation. (2) The State of Florida Department of Environmental Protection (DEP) can enter into a voluntary "ecosystem management agreement" with regulated entities and other government entities if the DEP determines that "implementation of such agreement meets all applicable standards and criteria so that there is a net ecosystem benefit to the subject ecosystem more favorable than operation under applicable rules" and "implementation of the agreement will result in a reduction in overall risks to human health and the environment compared to activities conducted in the absence of the agreements" (State of Florida 2001). (3) Recent revisions to Washington State's Model Toxics Control Act include provisions for a "Disproportionate Cost Analysis" for the consideration of incremental benefits and costs in the selection of a remedial alternative. The comparison of benefits and costs may be quantitative or qualitative and need not be monetary (Washington State Department of Ecology 2001). In addition, New Jersey, Massachusetts, Louisiana, Arkansas, Connecticut, Alaska, Indiana, California, Pennsylvania, and Delaware have supported NEBA-type strategies for evaluating remedial alternatives.

Structure of NEBA Framework

A high-level framework for NEBA is depicted in Figure 1 and includes a planning phase for the analysis of alternatives, the characterization of the reference state, NEBA of alternatives (including characterizations of exposure and of effects, including recovery), comparison of NEBA results for multiple alternatives, and possible characterization of additional alternatives. Only ecological aspects of alternatives are included. Figure 1 also depicts other factors in decisions about contaminated sites that are external to the scope of NEBA described here, including cost, human health benefit, technical feasibility, and monitoring and efficacy assessment of the preferred alternative. Three subframeworks are presented: (1) characterization of the contaminated reference state or NEBA for natural attenuation (Figure 2), (2) NEBA for a remediation alternative (Figure 3), and (3) NEBA for an ecological restoration alternative (Figure 4). If an alternative involves multiple actions (e.g., removal of hot-spot contamination and grassland restoration), the assessor can draw on the work of Suter (1999) for recommendations concerning how to estimate combined effects. The trajectory of environmental services or other ecological properties that is the subject of the NEBA is depicted in Figure 5 and will be discussed at length in this article.

This detailed framework for NEBA does not preclude the use of more informal, NEBA-like approaches in regulatory negotiations. As in many other types of environmental assessment, the funds or time available for a NEBA might not allow the level of data collection that we recommend for estimating past, present, and future ecological states with confidence.

Planning Phase

The planning phase for a NEBA, which is comparable to the planning and problem formulation phases in risk assessment (EPA 1998), includes setting the goals of assessment, selecting a limited and feasible suite of alternative actions, defining the temporal and spatial scope of assessment, identifying contaminant and remediation stressors, selecting environmental services and other ecological entities, selecting metrics and methodologies for the comparison of alternatives, selecting measures of exposure and effects, selecting a reference state, establishing a link between stressors and services (conceptual model), and developing an analysis plan (Figure 1). A comparative assessment such as a NEBA should have a plan that encompasses all relevant, alternative actions.

Management and Assessment Goals

A common management goal for a site-specific NEBA might be to quantify net environmental benefits of remediation and ecological restoration alternatives

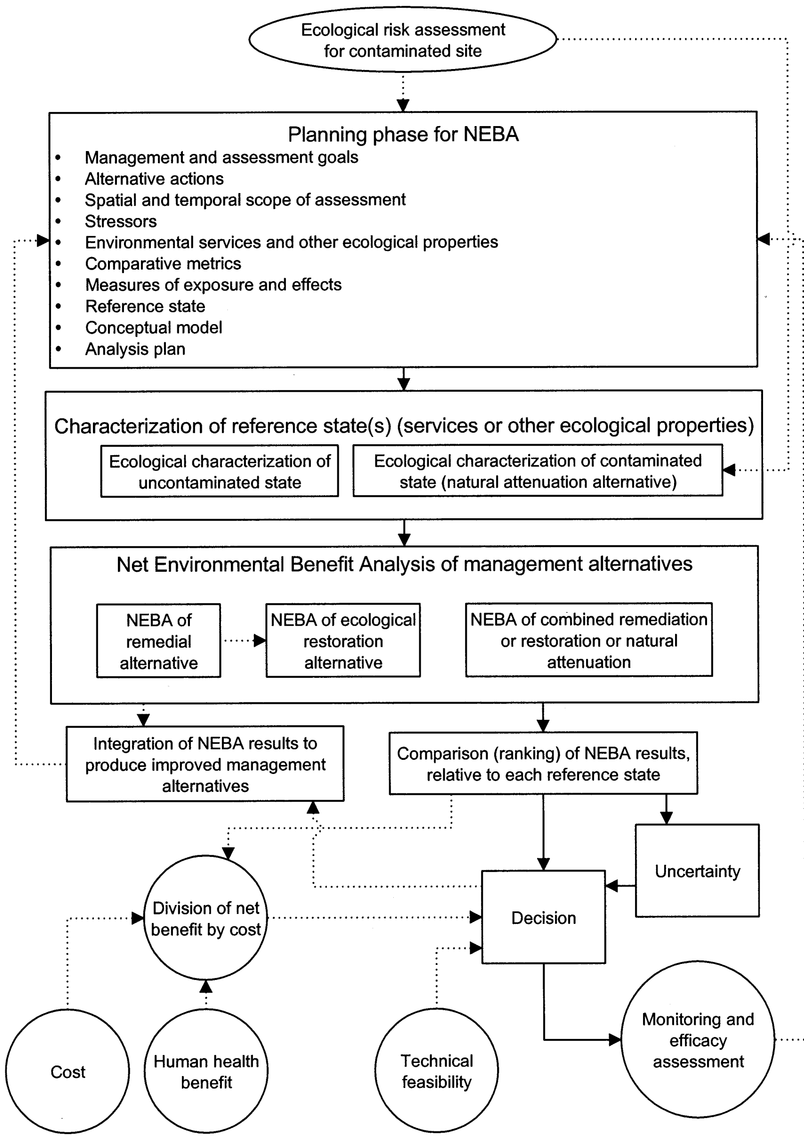

Figure 1. Framework for NEBA. Dashed arrows indicate optional connections between processes; boxes indicate processes within the NEBA framework; circles indicate processes outside of the NEBA framework. An ecological risk assessment can precede a NEBA and can constitute the ecological characterization of the contaminated state.

to support a cost–benefit analysis (CBA) of those alternatives. (Benefits in CBA do not necessarily need to be translated into monetary terms.) Ecological restoration onsite or offsite might be proposed for aesthetic purposes, to compensate for negative impacts of remediation (TNRCC 2001) to compensate for negative impacts of contamination (as in NRDA compensatory restoration), or as a substitute for economically or technically impracticable remediation, if restoration is consistent with applicable regulations. Even if restoration is proposed for aesthetic reasons, the environmental benefits might be pertinent to the decision. Although emergency response might necessitate decisions before a formal NEBA can be undertaken, NEBAs of generic treatment technologies are useful for contingency analyses prior to a spill (Lunel and Baker 1999; IPIECA 2000). Rules and regulations, scoping assessments, or ad hoc decisions by regulators might define the following: the environmental services or other properties of concern; the relative importance of past, present, and future adverse effects; the reference state for the analysis (contaminated or uncontaminated); acceptable or recommended analytical methodologies; preferred comparative methods; or preferred actions.

The NEBA-based remedial or restoration decisions are consistent with restoration goals under NRDA provisions of CERCLA, OPA, Clean Water Act, and state regulations. As a result of an NRDA, a responsible party could undertake compensatory restoration to offset the loss of environmental services and other resources

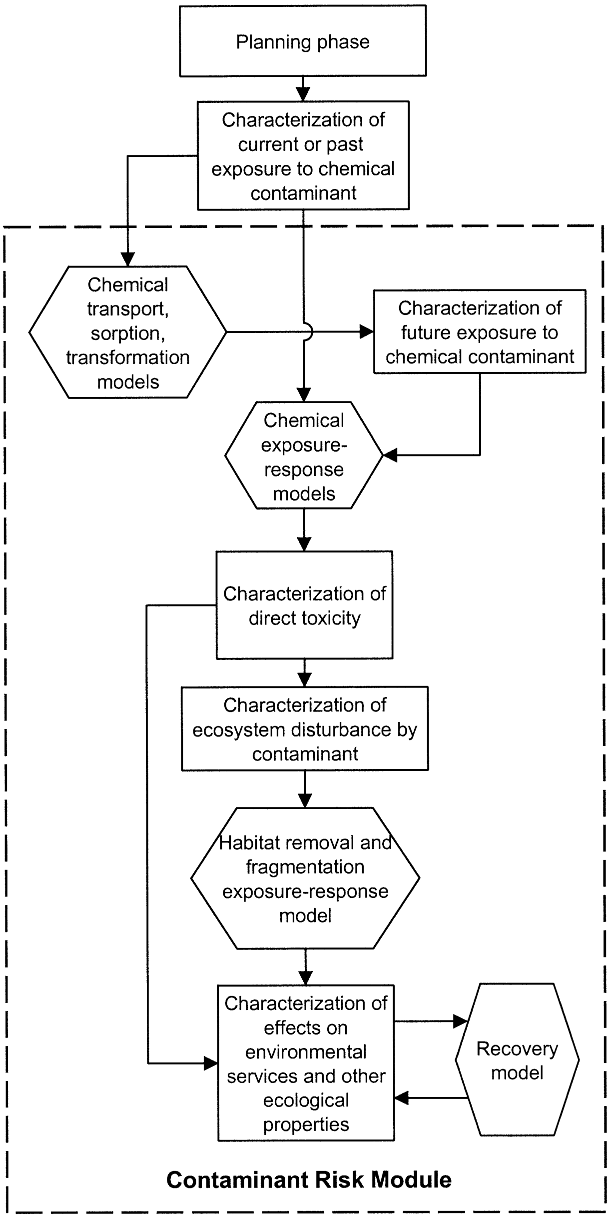

Figure 2. Characterization of the contaminated reference state or natural attenuation. The net environmental benefit of natural attenuation is zero for the reference state that represents contaminated conditions. Hexagons indicate models.

caused by contamination. The restoration could occur on the affected land or offsite, usually in the same ecosystem. In NRDA, the duration of injury is considered in the analysis, whereas in other regulatory frameworks, the analysis commences in the current time period. The level of required restoration would be minimized if remedial or restoration alternatives that were implemented prior to NRDA were chosen by maximizing net environmental benefits.

Alternative Actions

Alternative actions should be described in detail in the planning phase of a NEBA. As stated earlier, alternative actions are divided into three principal categories: natural attenuation, traditional remediation, ecological restoration, as well as combination of these. Natural attenuation is remediation through natural dilution and degradation processes. Natural attenuation might be proposed as the best alternative or part of the best alternative for meeting remedial goals if active remediation might be ineffective, cost-prohibitive, or damaging to the environment. Natural attenuation is nonintrusive and has no incremental remedial hazards, only those associated with the original contamination and its metabolites. Examples of traditional remedial technologies that reduce risks by removing contamination or actively reducing chemical concentrations in environmental media include excavation, incineration, burning, chemical remediation, microbial bioremediation, and phytoremediation. Excavation is the most common option for remediating contaminated soils if the scale of contamination does not make the cost prohibitive. Ecological restoration is the direct restoration of certain ecological entities or their habitats. Following NRDAs, ecological restoration might be proposed by potentially responsible parties to replace lost services or other ecological properties, in lieu of monetary compensation. The restoration might occur on the affected land or on other land, usually in the same ecosystem.

Spatial and Temporal Scope of Assessment

Because NEBA is a comparative analysis, all alternatives must have identical, broad spatial extents; that is, if ecological restoration is proposed 1 km from the area of contamination, the state of environmental services or other ecological properties at that location must be ascertained under the competing scenarios. TCEQ (TNRCC 2001) requires that ecological restoration occur in the "same ecosystem" as the injury from contamination. Offsite restoration and offsite contamination should be included within the spatial scope of the assessment.

The time-scale of a NEBA usually includes the duration of adverse effects and benefits combined with the longest construction and recovery period for the alternative actions. In contrast, assessments performed for TCEQ consider only prospective environmental services losses, from the date that site data were collected, unless an alternative time frame is negotiated with natural resource trustees (TNRCC 2001).

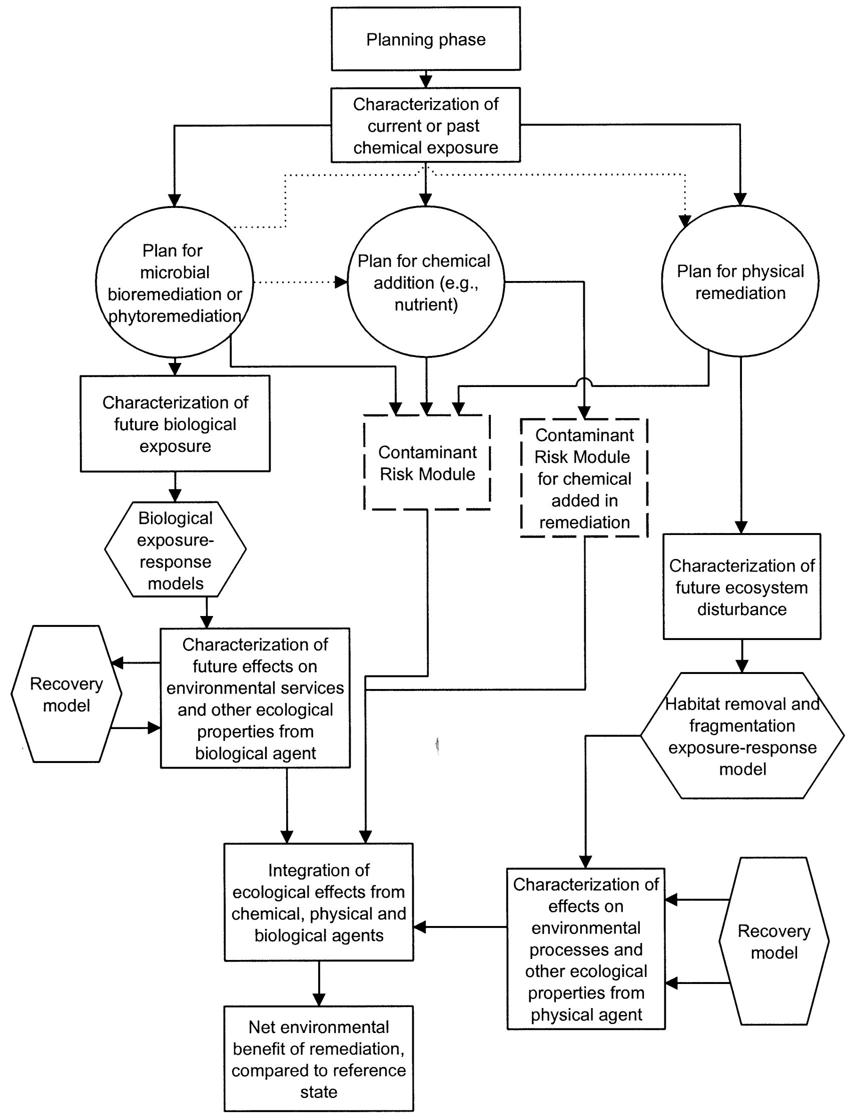

Figure 3. Framework for NEBA of remedial alternatives. Dashed arrows indicate optional connections between processes; boxes indicate processes within the NEBA framework; circles indicate processes outside of the NEBA framework; hexagons indicate models. Dashed borders on contaminant risk module boxes indicate that the processes in Figure 2 should be inserted here.

Stressors

Chemical contamination is a stressor that must be evaluated in all alternative scenarios. Traditional remediation imposes a wide range of potential stressors, including the physical stressor of excavation, tilling, or heat, the biological stressor of introduced micro organisms or plants, the residual chemical stressor, or added chelation agents, nitrate, or peroxide (Table 1). Physical stressors should always be evaluated when restoration is proposed at waste sites. Vehicle movement, grading, tilling, or trampling could constitute stressors in the process of restoring an ecosystem; the restoration might fail and result in physical disturbance; or the restoration of habitat for one population could decrease habitat for another.

Environmental Services and Other Ecological Properties

Net environmental benefit analyses usually evaluate environmental services that are provided by an area of land or wetland. Services are functions of ecosystems that might serve humans or other components of ecosystems, such as primary production, the provision of habitat for one or more populations, decomposition, and pollination (Daily and others, 1997). Services have been emphasized because (1) many that have human use value are more easily valued than other ecological properties, prior to a cost–benefit analysis of alternatives; (2) they are the subject of the Texas Commission on Environmental Quality's Ecological Services Analysis option for hazardous waste sites (TNRCC 2001); (3)

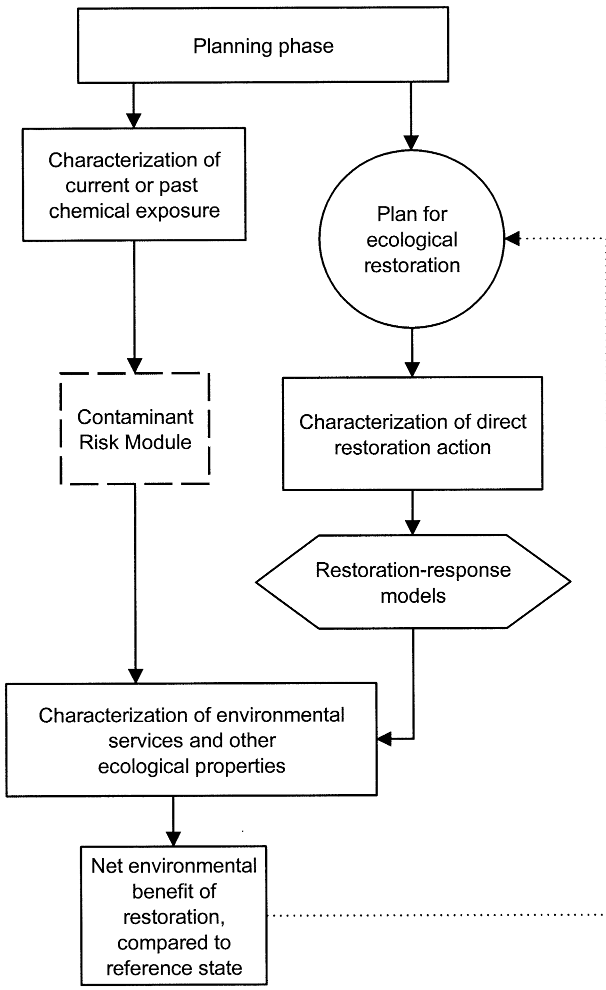

Figure 4. Framework for NEBA of ecological restoration. Dashed arrows indicate optional connections between processes; boxes indicate processes within the NEBA framework; circles indicate processes outside of the NEBA framework; hexagons indicate models.

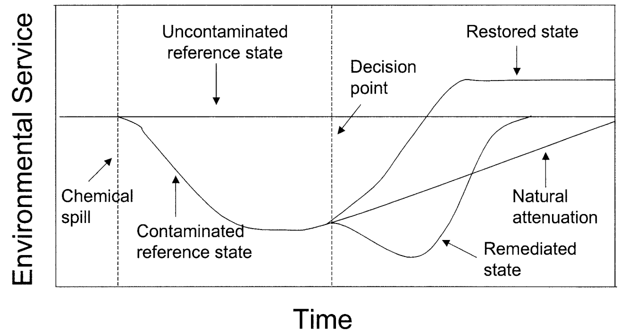

Figure 5. Hypothetical trajectory of assessment endpoint entity (service or other ecological property) with time, following a petroleum spill (contaminated reference state); conditions that would have been expected to prevail in the absence of the spill (uncontaminated reference state); expected trajectory of the remediated state; and expected trajectory of the restored state. Variability is not depicted.

they are often the subject of NRDAs, which might follow waste site remediation; and (4) the measurement of services might sometimes serve as a surrogate for measurements of multiple population or community properties.

The selection of services rather than population or community properties as focal entities of NEBA might appear to be inconsistent with CERCLA ecological risk assessments. Risk assessments associated with remedial investigations tend to emphasize multiple endpoint properties of organisms (e.g., mortality or fecundity) or populations (e.g., abundance or production) representing different trophic groups, whereas NEBAs typically emphasize environmental services and ecosystem value. However, services estimated or measured in NEBAs are sometimes quantities evaluated in an ecological risk assessment (e.g., production of a plant community, abundance of a food item, or area suitable for mating and nesting). In addition, the NEBA practitioner can choose other ecological properties as endpoints if they are consistent with the management goals of the assessment.

Environmental services or other ecological properties should be selected with all alternatives in mind. For example, if the habitat of a species of concern is adversely affected by one alternative action, the provision of that habitat should be evaluated under other alternatives, during the time and within the spatial extent of analysis.

Net environmental benefit analysis should assess multiple environmental services or other ecological properties to cover the full range of potentially significant losses and benefits. The number of services and properties analyzed might be reduced by choosing representative species or classes of services (e.g., retention of phosphorus as a representative nutrient). This practice is common in CERCLA assessments, which typically aggregate species based on the assumption that members of a taxonomic class have similar sensitivities and members of the same trophic group have similar exposures. In NEBA, because habitat loss must be considered, the members of a category of species must also have similar habitat requirements and home ranges.

Comparative metrics

Few methodologies or metrics exist to normalize impacts to allow either the subtraction of one type of adverse effect from another type of benefit of a single alternative or the comparison of unrelated net benefits of different alternatives. TCEQ states that "out-of-kind services can often be normalized such that they can be compared," although guidance on acceptable normalization methods is not provided (TNRCC 2001). Equivalencies between services could be valued using specified economic, ecological, or social equity criteria; they could be elicited as trade-offs from stakeholders or decision-makers (Lai 2001); or they may be established through regulatory negotiation in the planning phase of a NEBA. This latter means of determining equivalencies is often not transparent to many stakeholders.

Many valuation methods are available to estimate and to compare apparent dollar values of environmental services or other ecological properties, based on the desire to use or simply to preserve these services (Gregory 1999). The willingness to pay for or to accept a loss of services can be inferred from behavior or elicited in direct surveys, such as contingent valuation (NRC 1994). However, surveys that ask questions about specific trade-offs rather than about relative dollar values are more direct measures of the relative value of environmental services. The cost of replacing environmental services is also a useful estimate of their value.

Several principles of ecological valuation could be asserted to aid in NEBA comparisons: (1) A larger ecosystem fragment is more valuable than a smaller one of the same type. (2) A contiguous ecosystem is more valuable than a fragmented one of the same area. (3) An individual of a threatened species is more valued than a related individual of a nonthreatened species. (4) Populations at equivalent trophic levels might usually be considered of equivalent ecological value. (5) A community and the sum of its functions have equivalent value (e.g., vegetation and primary production; erosion control, provision of forage, etc.). (6) An irreversible, adverse environmental change is probably less acceptable than a reversible but otherwise comparable one. These principles are examples of relative values; others could be negotiated during a planning phase for NEBA. Some principles of ecological valuation would probably emerge from multiple uses of the valuation methods described above.

An established ecological valuation metric is the past available solar energy ("emergy") required to produce goods and services (Odum and Odum 2000). Thus, a deer population has a higher value per joule than their food. This metric could be correlated with the recovery time for these entities following ecosystem removal (e.g., via excavation). In one example, the cost of constructing and operating Mississippi River diversions to marshes were compared with benefits using an emergy analysis, whereby "natural and human contributions required to construct and operate two diversions were expressed in common units of solar energy" (Martin 2002). Suter and others (1995) propose the qualitative classification of ecological impacts as insignificant (*de minimis*), highly significant (*de manifestis*), or intermediate, and therefore requiring consideration of nonrisk factors prior to a remediation decision. For example, *de minimis* ecological effects could be defined as (1) "less than 20% reduction in the abundance or production of an endpoint population within suitable habitat within a unit area," (2) "loss of less than 20% of the species in an endpoint community in a unit area," or (3) "loss of less than 20% of the area of an endpoint community in a unit area."

A common methodology for scaling compensatory restoration in NRDA (NOAA 2000), which has also been used to compare remediation and ecological restoration alternatives for NEBAs at contaminated sites, is habitat equivalency analysis (HEA). A typical measurement unit for HEA analyses is the total service integrated over area and time, or service-hectare-year, discounted to present-day value. The mathematics of HEA are illustrated in Penn and Tomasi (2002) and Milon and Dodge (2001). This type of comparative metric is very useful if many environmental services are proportional to each other. For example, if grassland primary production is roughly proportional to litter decomposition and the provision of nesting or lekking (male display) sites for all bird species, then the single metric of primary production service-acre-years might be sufficient to compare net environmental benefits of remedial and restoration alternatives in the NEBA. In a more complex implementation of HEA, adverse effects that are not associated with ecosystem-level disturbance (e.g., direct mortality of birds from contact with oil spill) could be converted to habitat service metrics. Penn and Tomasi (2002) converted individual bird losses to the habitat area that would have produced the biomass, based on salt marsh production and inefficient energy exchange among trophic levels.

However, environmental services are not always proportional to each other. Strange and others (2002) found that the marsh service metrics of primary productivity, provision of habitat for the endangered light-footed clapper rail (*Rallus longirostris levipes*), provision of soil nitrogen, provision of benthic invertebrate prey for fish and shellfish, and secondary productivity proceeded along different recovery trajectories in a planned restoration. In general, the "marginal contribution" of a land area to the abundance of an endangered species is not well understood (Unsworth and Bishop 1994); thus, soil, plant, and other environmental services might not be proportional to each other. The breeding habitat area might differ from habitat area during nonreproductive phases. The area of habitat lost is not correlated with population survival (and not a suitable metric for population effects) when toxicity (not ecosystem area loss) reduces forage vegetation or prey, or bioaccumulation leads to toxicity. Moreover, the habitat might recover from contaminant or remediation stress more quickly than vertebrate populations colonize it; thus, there might be a lag between recovery periods of different services. Milon and Dodge (2001) note that HEA is most applicable to uniform landscapes with little difference in biological functions across the injured area; thus, they had to adjust basic HEA equations to account for different coral reef populations with unique area uses and recovery times. Therefore, relative net environmental benefits should usually be determined based on multiple services.

Ecological valuation methods should specify the species for which habitat is assessed. For example, rather than generic ecosystem equivalencies, species-specific habitat metrics, such as provision of suitable substrate for plants or provision of food for particular vertebrate species, could be evaluated across alternatives. In that way, the quality of the habitat might be quantified in terms of the number of individuals supported or the viability of the specified populations.

The NOAA (2000) notes that "landscape context affects whether the ecosystem will have the opportunity to supply many of the ecological and human services." Habitat requirements of populations of concern could include length of edge, connectivity of habitat, and minimum patch size required by the species. The total area of habitat that is a factor in the HEA comparative metric is not a surrogate for the distributions of habitat. For example, if a hectare of land is disturbed in the middle of a habitat corridor, the affected population is much larger than that which resides in the affected area. Similarly, if restoration occurs at a distance from the an affected ecosystem, the connectivity might be lost and the habitat value of the restored area might be less than that of the contaminated area prior to contamination.

The determination of net benefits of a single alternative and relative net benefits among alternatives will require a complex examination of human use, nonuse, and ecological value. Relative values of various ecosystem components should be made explicit in the planning phase of the NEBA. Differential weights could be attributed to different types of environmental services and other ecological properties if such an agreement is made during the planning phase. We suggest that these weights incorporate human values and are consistent with ecological importance and ecological correlations. Clearly, research is needed to improve valuation options for NEBA.

Measures of Exposure and Effects

Measures of exposure should be specified during the planning phase of the NEBA. These measures could be summaries of concentrations of chemical contaminants with particular area and depth profiles through time, with adjustments for the rates of natural attenuation (biodegradation and aging of chemicals) and the rates of contaminant removal or changes in bioavailability through remediation. The spatial distributions of habitat and disturbed areas are measures of exposure for wildlife population properties. Measurements of effects are statistical or arithmetic summaries used to estimate ecological services or other properties. These might be field observations, toxicity test results, or modeling results. Measures of effects might be adjusted through time by incorporating rates of ecological recovery.

Reference State

One of two potential reference states can be selected: (1) the contaminated reference state, equivalent to natural attenuation with ecological recovery, or (2) the uncontaminated reference state. Reference states are characterized by seasonal variability, meteorological variability, predator–prey cycles, and stressors not associated with the contamination or alternatives. Particular reference states might be mandated by regulations. In a CERCLA remedial investigation, the current, contaminated state of the environment is typically characterized in the baseline assessment, and if remediation is needed, assessment endpoint properties associated with proposed remedies are assessed and compared to the contaminated reference state in the CERCLA feasibility study (Sprenger and Charters 1997). In NRDA, a reference state (termed a baseline) consists of past, present, and future services that would have prevailed in the absence of disturbance (i.e., the uncontaminated reference state) (Figure 1). Although reference states are commonly called "baselines," that term is avoided in the following text because it has specific but differing meanings in the CERCLA remedial investigation and NRDA applications.

Conceptual Model

A conceptual model for an environmental assessment is a graphical representation of the relationships between the chemical or nonchemical stressor and the responses of environmental services or other ecological properties (Suter and others 2000). If there is no connection between a stressor and a service, then the link does not need to be represented in the NEBA. Contaminant exposure pathways should be considered for all alternatives in the NEBA. For this reason, the "contaminant risk" module that is detailed in Figure 2 is also included in Figures 3 and 4, the NEBAs for remediation and restoration. The conceptual model for NEBA of remediation alternatives includes stressor–service pathways for remedial technologies, such as the link between nutrients added in bioremediation and plant growth or diversity, or the link between excavation and vegetation cover (Figure 3). If multiple alternatives make use of a particular remedial technology, such as dredging of hot-spot contamination, this portion of the conceptual model should be depicted in all alternatives. If the effects of contaminants are indirect (i.e., if wildlife habitats or forage vegetation are directly affected by chemicals but not the animals), the connections between habitat or food and vertebrate population properties should be considered in the NEBA. Similarly, if the alternative calls for ecosystem restoration, the conceptual model should show how environmental services and other ecological properties could be influenced.

Analysis Plan

The analysis plan includes data collection, modeling, and logical analyses that are described or implicit in the NEBA framework. The plan should explain how exposure will be modeled, the exposure–response models that will be used, how evidence about exposure or effects will be weighed, how recovery will be modeled, how net environmental benefits of different alternatives will be compared, and how uncertainty will be treated and presented. The analysis plan should explain how predictions will be made forward and backward in time. The analysis plan should describe how sampling design decisions might influence the power to detect adverse effects relative to the reference state (Peterson and others 2001). The plan might describe NEBA results that would cause assessors to develop improved alternatives and to repeat the NEBA (Figure 1).

Characterization of Reference State

Net environmental benefit analysis involves the comparison of environmental services or other ecological properties of each alternative to those of a common reference state to determine net environmental benefit. A NEBA for one or more generic treatment technologies (e.g., use of dispersants) might be performed relative to a few potential reference states. If net environmental benefits of all alternatives are ranked relative to the contaminated reference state, the ranking relative to the uncontaminated reference state should not differ.

Environmental services and other properties that are associated with the uncontaminated state could sometimes be approximated by conditions at a neighboring, uncontaminated site or by conditions prior to the disturbance. However, models might be required to characterize the dynamics of reference services. Numerous environmental factors might act in concert with the contamination to alter environmental services following a chemical disturbance.

The characterization of the contaminated reference state could occur in the ecological risk assessment prior to a NEBA, as in CERCLA remedial investigations. In this analysis, current and future exposures are estimated, and exposure–response models are used to estimate adverse effects (Figure 2). In Figure 2, an indirect pathway whereby an ecosystem is disturbed and the areal disturbance results in adverse ecological effects is explicit. For example, oil and brine spills that occur at petroleum exploration and production sites often have little direct toxicity to vertebrates, but large-scale ecosystem removal could result in effects on these populations. The framework includes a recovery model for characterization of environmental services and other ecological properties associated with the future contaminated reference state (Figure 2).

NEBA of Single Alternatives

As stated earlier, the net environmental benefit of each alternative is the benefit minus the adverse effect of the alternative. If the net environmental benefit is positive (compared to the reference state), it is sometimes termed a credit; if it is negative, it is a debit. If the benefits are to different environmental services than the adverse effects, either both need to be expressed to the decision-maker or both should be normalized by a single metric, as described earlier.

The subframework for NEBA of natural attenuation compared to the uncontaminated reference state is presented in Figure 2. If the contaminated reference state is used in NEBA, the net environmental benefit of natural attenuation is zero, as these analyses are equivalent. The subframeworks for NEBA of remediation and ecological restoration are presented in Figures 3 and 4, respectively. Both subframeworks include the estimation of exposure, the use of exposure–response models, and the estimation of recovery.

Time-Integrated Analysis

An example of a result that might be expected from a NEBA for each service or other ecological property (or a weighted representation of a group of services) is presented in Figure 5. In this hypothetical example, following an oil spill, an environmental service or other ecological property is rapidly degraded. However, the depicted ecological property is expected to improve with time during natural attenuation of the contamination, followed by recovery (Figure 5). In Figure 5, the *y* axis might represent a single service or multiple services if a common metric is available. The level of the environmental service associated with the uncontaminated reference state is assumed to continue at approximately the prespill level. Although natural variability is expected, the environmental service or other ecological property in the uncontaminated reference state is generally considered to be a constant (Fonseca and others 2000). The proposed remedial alternative is expected to reduce the environmental service initially (as excavation would reduce vegetation production), but recovery is expected to be completed more rapidly than in natural attenuation (Figure 5). In the proposed ecological restoration alternative, restoration is achieved more rapidly than ecological recovery in the natural attenuation alternative, and the final level of the environmental service is greater than the prespill level.

The net environmental benefit of remediation, compared to the contaminated reference state, is the area under the environmental service curve for the remediated state minus the area under the environmental service curve for the contaminated reference state (Figure 5). Note that in this instance, the net environmental benefit is close to zero and might be less than zero. The net environmental benefit of restoration, compared to the contaminated reference state (natural attenuation plus recovery), is above zero (Figure 5). In NRDA practice, the target net environmental benefits of restoration might not be determined until after the injuries from chemical contamination are estimated, because restoration might be intended to offset exactly the injuries. The type of analysis shown in Figure 5 should be performed for each environmental service or other ecological property, for a service (e.g., primary production) that represents many other services, or for a weighted sum of all relevant environmental services.

Characterization of Exposure

If benefits and adverse effects associated with alternatives are not obvious, they could be determined through the use of exposure–response relationships. The characterization of exposure is the estimate of the magnitude of contact or cooccurrence of a stressor with an environmental service or other ecological property. An analysis of a proposed ecological restoration alternative could omit the characterization of exposure (Figure 4) if excavation, construction, tilling, trampling, or vehicle movement do not constitute significant stressors.

Present estimates of contaminant exposure could be determined by the measurement of chemical concentrations in soil or water, with an assumption about the statistical distribution of unmeasured contamination. Past and future contamination can be estimated with simulation models or, if data permit, statistical forecasting or hindcasting. For example, biodegradation could sometimes be modeled as a first-order process (Nedunuri and others 2000), or as an almost instantaneous (compared to the time scale of analysis) reduction to a constant concentration (Huesemann 1995). Factors controlling rates of biodegradation are discussed in Efroymson and others (2003). Although extensive and frequent biological surveys (with reference locations) might obviate the need for exposure analysis to estimate current effects of chemicals, the surveys would have to be accompanied by exposure measurements and modeling to estimate future effects. Chemical exposures change over time through leaching, volatilization, sorption, degradation, and transformation (Figure 2). Changes in bioavailability should be estimated, as they are predictors of effects.

Exposure–Response Relationships

Net environmental benefit analysis practitioners can determine the trajectory of environmental services or other ecological properties through time, either directly, or using estimates of exposure and one or more exposure– response models. However, continuous chemical and physical exposure–response relationships are rarely available for species or services in soil or water, and this is a major research gap for NEBA. Exposure– response thresholds (lowest observed adverse effects concentrations) or estimated EC_{50}'s (50th percentile effective concentrations) are commonly available for soil contamination, but the roles of soil type, receptor taxa, multiple chemicals, aging of chemicals, and acclimation to toxicity are not well understood. Moreover, the magnitude of the exceedence of a threshold does not reveal much about the magnitude of ecological property loss (e.g., the percentage of the community that is affected) or the probability of effect, unless the exposure–response relationship is known. In contrast, assessing the direct impacts of excavation might only require the spatial and temporal dimensions of soil ecosystem loss; thus, Figure 3 shows no exposure–response model for physical remediation.

In addition, chemical contaminants can act by disturbing ecosystems (Figure 2). Models that relate area and distribution of patches of disturbed vegetation and soil to vertebrate population density or probability of extinction (Efroymson and others 2004a) would be useful for estimating effects from these disturbed, contaminated areas (Figure 2), as well as effects from physical remedial alternatives (Figure 3), roads, and trampled areas. Models to estimate environmental services and other properties might include processes of primary production, colonization, succession, population demographics, bioenergetics, and predation.

Future effects from chemical contamination can be estimated for NEBA by field measurement or modeling to determine current ecological states, combined with (1) modeling of changes in exposure, followed by the use of toxicity and ecological relationships or (2) modeling of recovery, under the assumption that contamination is below toxic concentrations (Figure 2). Toxicity tests performed at multiple times can indicate the approximate rate of reduction of toxicity with time. For example, bioremediation treatment (tilling, fertilization, and liming) of a fuel-spill-contaminated soil led to the removal of phytotoxicity after 20 weeks (Wang and Bartha 1990). Marwood and others (1998) recommend a battery of toxicity tests to monitor bioremediation.

Recovery

Recovery is a key determinant of net environmental benefit but is difficult to quantify. Recovery typically refers to the colonization, growth, or succession of ecological entities, following the effective removal of the direct pressure of a stressor. Recovery defines the end of the NEBA analysis. As depicted in Figures 2 and 3, recovery modeling estimates the reduction over time of the effects of contamination or remedial actions. Guidance from the TCEQ notes that ″estimates of recovery time may come from literature, site-specific information, or other affected property investigations″ (TNRCC 2001). Certain services might not be measurable at the spatial scale of the action [e.g., small mammal populations in a restored, riparian wetland (Wike and others 2000)].

Mechanistic or empirical functions are typically used to estimate recovered environmental services or other ecological properties. Example times to recovery of ecological properties from petroleum and physical remediation exposures from a few investigations are summarized in Efroymson and others (2003). Recovery of vegetation from terrestrial petroleum spills tends to occur more rapidly than recovery from physical disturbance such as excavation and landfarming, but broadly applicable, predictive models will require additional research. Most data on recovery relate to aquatic rather than terrestrial ecosystems (Niemi and others 1990).

The error associated with the use of linear estimates of recovery depends on the duration of the recovery, relative to the timescale of the NEBA. In reality, the dynamics of recovery could be complex, for example, encompassing recovery from multiple processes, such as soil compaction, colonization, and succession of vegetation. Vasek and others (1975) suggest that the recovery of properties of scrub vegetation, such as composition and percentage of ground cover, would occur with sigmoidal temporal dynamics. The temporal dynamics of recovery could be estimated by monitoring during the assessment period and adjusted following the NEBA. The final level of recovered services could be highly uncertain.

Recovery models might apply to ecological restoration alternatives where secondary services or other ecological properties are restored as a consequence of the direct restoration goal. Restoration increases the rate of recovery of some services. In contrast, the recovery of one environmental service or other ecological property can impede restoration of another; for example, the maintenance of caps requires that deeply rooted vegetation and burrowing mammals be kept off a site (Suter and others 1993).

Comparison of Multiple Alternatives

Following the net environmental benefit calculation for individual alternatives, the net environmental benefits of each alternative are compared (Figure 1). As stated earlier, benefits and adverse effects of different types can sometimes be normalized by a single metric in the NEBA for single alternatives. Similarly, the net environmental benefits of multiple alternatives can be ranked in the NEBA only if normalizing metrics are available. If net environmental benefits of different alternatives are expressed in different units, the land managers or trustees can rank the alternatives subjectively. However, the ranking is likely to be more acceptable to stakeholders if relative values were established during the planning phase.

If alternatives are compared to the contaminated reference state, both remediation and restoration alternatives could have positive net environmental benefit. However, if alternatives are compared to the uncontaminated reference state and the analysis includes the period of past service losses, a contaminant removal alternative could ultimately provide the level of environmental services that were lost, but not compensate for past lost services or have a net environmental benefit.

If a single comparative metric is used in NEBA (e.g., primary production service-hectare-years), a single graph of environmental services through time for each alternative can depict the dynamics from which relative net environmental benefits of alternatives can be calculated (Figure 5). If multiple services or multiple, species-specific habitats are explicitly considered, then multiple analyses of environmental services through time should be performed and added or weighed, using the comparative valuation methods discussed earlier. The discount rate is incorporated into the estimate.

Challenges of Comparative Assessments

The challenges of conducting comparative assessments within the NEBA framework include using the few metrics available for relative valuation of alternatives or changes in benefits within a single alternative, as well as (1) assuring comparable conservatism among assessment results for individual alternative actions, (2) improving or making best use of inadequate exposure–response models to quantify the absolute magnitude of effect, (3) adapting qualitative results such as the weight-of-evidence from risk assessment to NEBA, and (4) adjusting valuation of past and future conditions to current value within an alternative.

Comparisons of ecological properties under remediation, natural attenuation, and restoration alternatives require assumptions of comparable conservatism. Ecological risk assessments commonly generate conservative estimates of exposure and effects, so estimates of contaminant effects generated independently of NEBA might be high. In typical ecological risk assessments, an organism is often assumed to be exposed to the maximum, measured concentration of a chemical across space and time, or an upper confidence limit on the mean of that concentration. Disturbed ecosystems are sometimes assumed to be entirely unavailable to biota, even when they are partially utilized. Ecotoxicological screening values tend to represent low values in the distribution of toxic thresholds and they are often based on tests in soils to which chemicals have been freshly added rather than toxicity of chemicals aged in the field (Efroymson and others 2004b). If effects of contaminants are estimated conservatively and effects of physical disturbance associated with remediation are estimated appropriately, then the NEBA might be biased against alternatives that incorporate natural attenuation and toward physical remediation, even if the latter choice generates lower net benefits. Tests of field soils or measurements of effects in the field should be relied on to the extent possible.

Assessors could be limited by the uncertainty of existing, empirical models and measurements. Assessors are much more confident in predicting the decrement in the biomass of plants where the surface soil has been excavated (i.e., no vegetation) than they are in predicting the percentage biomass decrement where a particular concentration of petroleum hydrocarbons or metals is found. Uncertainties in the NEBA should be presented qualitatively or quantitatively, as in ecological risk assessment (Warren-Hicks and Moore 1998). Uncertainty could make a NEBA comparison indeterminate if the uncertainty is much greater than the differences in net benefits among the alternatives.

The weight-of-evidence approach that is common in ecological risk assessment seldom results in a single value for magnitude of effect, because it is usually intended to aid an assessor in determining whether or not an effect is above the reference levels. It is difficult to compare net benefits across alternatives when our most quantitative ecological risk assessments are not very quantitative.

To compare present effects in one scenario to future effects in another, future effects can be discounted to the present value (NOAA 1999). The assessor should note that NEBA results are highly sensitive to the choice of discount rate (Milon and Dodge 2001).

Additional Considerations

Net environmental benefit analysis provides important information about relative environmental benefits and adverse effects of alternative actions to decision-makers, but NEBA does not make the decision. As shown in Figure 1, cost-effectiveness is also an important criterion for the decision, although it is outside of the NEBA framework. Essentially, the net benefit (including human health benefit), divided by monetary cost, results in an estimate of cost-effectiveness (Figure 1). Technical feasibility and human health risk will also inform decisions about the fate of contaminated sites, and sometimes a human health risk assessment might be required before NEBA is considered by regulatory agencies (TNRCC 2001). Decision models such as MultiAttribute Utility Theory can be used to make trade-offs between different and possibly conflicting objectives (Suslick and Furtado 2001), but these models require decision makers to assign weights to the objectives.

A NEBA can be performed iteratively as alternative actions are optimized, preferably before an action is implemented (Figure 1). Monitoring and efficacy assessment are external to the NEBA framework, but they can produce data supporting a decision to alter the preferred alternative and possibly to perform the NEBA again (Figure 1). The Great Lakes Water Quality Board recommends "that much greater emphasis be placed on post-project monitoring of effectiveness of sediment remediation" (Zarull and others 1999). Adaptive management can lead to effective redesign of restoration alternatives if they fail to meet their goals (Thorn 2000), especially if ecological properties have been well specified in the NEBA planning phase. As stated earlier, it is expected that decisions will be made using criteria in addition to the rankings that result from the NEBA.

Conclusions

This framework for NEBA should be useful when the balance of risks and benefits from remediation of a site is ambiguous. That ambiguity arises when the contaminated site retains significant ecological value, when the remedial actions are themselves environmentally damaging, when the ecological risks from the contaminants are relatively small, uncertain, or limited to a component of the ecosystem, and when remediation or restoration might fail. Even more than the EPA (1992) framework for ecological risk assessment, this framework for NEBA emphasizes the importance of completely framing the problem before proceeding to data collection and quantitative analyses. The additional planning elements include the definition of the comparative metrics and selection of the reference state. If the decision-maker and stakeholders can agree *a priori* on the comparative metrics and the standard for comparison, the results of the NEBA are likely to be acceptable, even if the assessment is qualitative or not supported by extensive reliable data and models. The heuristic nature of this planning process might also result in better environmental management by suggesting options for remediation and restoration that otherwise would not be considered. Research in several areas will increase the utility of the framework for NEBA: nonmonetary valuation metrics; nonconservative, quantitative exposure– response models; models of recovery; and strategies for ecological restoration. By focusing the assessment process of improving environmental conditions rather than simply reducing risks from chemical contamination, this framework for NEBA could result in greater environmental improvements at lower costs.

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