IMPROVING TOOLS AND METHODS FOR ECOLOGICAL RISK ASSESSMENT AT PETROLEUM-CONTAMINATED SITES

R. A. Efroymson and W. W. Hargrove

INTRODUCTION

This project, FEAC319, began in May of 2000 with support from the U. S. Department of Energy (Fossil Energy Program, National Petroleum Technology Office, Tulsa, OK; Nancy Comstock and Kathy Stirling, Project Managers). The project is intended to provide risk assessment tools and methods to the Petroleum Environmental Research Forum (PERF) project 99-13, "Expanding the Science Basis of Risk." Although the kickoff meeting for this project was planned for 1999, it did not occur until February of 2001. ChevronTexaco, ExxonMobil, BP, Unocal, and the Canadian Association of Petroleum Producers have contracts in place with PERF, in addition to Proprietary Agreements with Lawrence Berkeley National Laboratory and Oak Ridge National Laboratory. FEAC319 has four ongoing tasks: (1) to develop a framework for Net Environmental Benefit Analysis, (2) to develop plant uptake models for chemical contaminants that are found at downstream sites, (3) to develop or to evaluate spatial analysis models and tools for risk assessment of vegetation and wildlife, and (4) to finalize a review of soil ecotoxicity values for petroleum mixtures in soil.

The justification for this work is that remedial activities at refinery or other downstream locations may be more expensive than necessary for at lease three reasons. First, models for estimating ecological exposure are not readily available, so excessively conservative estimates of exposure and risk are sometimes made. Second, certain remedial actions such as soil removal and the associated destruction of habitat may result in greater risk to ecological populations or processes than the continued presence of the original, aged contamination. Third, certain ecological functions may be replaced by on-site or off-site restoration.

Net Environmental Benefit Analysis (NEBA). NEBA attempts to answer the question: what type and scope of remediation, restoration, or natural attenuation of chemicals in environmental media would cause the least damage or most benefit to the value of habitat, local populations, and valued ecological functions? NEBA involves calculating a net environmental benefit of remediation or ecological restoration, compared to natural attenuation (no action) or another regulatory baseline. Remedial alternatives include traditional methods such as excavation, and less invasive options, such as microbial bioremediation (nutrient additions and tilling), phytoremediation, natural attenuation, wetland enhancement, and planting of native species. The recolonization of areas damaged by contamination, excavation or tilling may depend on the extent of fragmentation of a landscape.

The term "NEBA" was probably coined by agencies and industries evaluating options for marine oil spills. A report was published by the National Oceanographic and Atmospheric Administration (NOAA) in 1990 entitled *Excavation and rock washing treatment technology: net environmental benefit analysis*. In that study a group of scientists and engineers comprised of Exxon, NOAA, and State of Alaska scientists evaluated the environmental tradeoffs associated with excavating and washing hydrocarbon-contaminated sediments that were deeply buried along parts of the Alaskan shoreline affected by the Exxon Valdez oil spill. Several precedents for NEBA exist, but they provide little, specific methodological guidance for the assessment of contaminated sites. These range from federal and state government examples (e.g., Texas Commission on Environmental Quality) to industry examples. A framework for Net Environmental Benefit Analysis, analogous to the EPA framework for ecological risk assessment, has not been developed prior to the effort under this project.

Plant uptake models. A primary gap in any ecological risk assessment for terrestrial wildlife is in the quantification of chemical concentrations in wildlife foods. It is advisable to measure these concentrations at a site of concern. However, because funding or seasonal constraints may limit the number and type of measurements that may be made at a site, it is useful to have models available to estimate contaminant concentrations in plant materials and invertebrates, based on concentrations in soil, soil characteristics, and taxonomic characteristics. Elements and compounds of concern at downstream petroleum sites include: polycyclic aromatic hydrocarbons, lead, nickel, selenium, mercury, and vanadium. Published soil-plant uptake factors tend to overestimate bioaccumulation and risk when concentrations of elements in soil are high and to underestimate uptake at lower concentrations. In addition, soil and/or plant characteristics have not previously been incorporated into uptake models.

Spatial modeling. The exposure of ecological receptors to chemical contaminants has spatial dimensions. Wildlife exposure models include dietary uptake but rarely the habitat and movement preferences that also determine exposure. Refineries, landfarms, or pipelines may be located at the center of a single habitat type (e.g., grassland), in which case the sizes of the habitat patches are important, or between remnant patches habitat. The most efficient corridors for establishing connectivity between habitat remnants is unknown, and if these could be established, optimal restoration plans could be developed. Spatial modeling adds to the realism of estimates of ecological exposure, so that fewer conservative assumptions may be used in risk assessments.

Ecotoxicity values. Ecotoxicity benchmarks for petroleum mixtures (i.e., concentrations in soil that are associated with a particular level of ecological effect) can be used to help determine which impacted sites might require an ecological risk assessment. Several studies of the ecotoxicity of petroleum in soils have been conducted in the past decade, including toxicity tests of plants, soil invertebrates, and other organisms in field-contaminated and laboratory-contaminated soils. This information has not previously been assembled. Such a review is a necessary precursor to determining research gaps and ultimately selecting concentrations of petroleum hydrocarbons that may be used as screening levels for ecological risk assessments at petroleum exploration and production sites, refinery sites, pipeline locations, or other petroleum-mixture-contaminated locations.

It is assumed that improved methods for ecological risk assessment should lower costs of remediation by decreasing the need for conservative assumptions in estimates of ecological exposure.

DISCUSSION OF CURRENT ACTIVITIES

Net Environmental Benefit Analysis. Net Environmental Benefit Analysis (NEBA) provides a methodology for revealing and comparing benefits and risks of alternative management options. NEBA of chemically contaminated sites has been defined as the comparison of risks and benefits associated with any pair of three principal alternatives, as well as combinations of these: (1) leaving contamination in place; (2) physically, chemically, or biologically remediating the environment through traditional means; and (3) improving ecological value through on-site and off-site restoration alternatives that do not directly focus on removal of chemical contamination. The focus of this task has been on the development of a framework for NEBA; petroleum industry representatives indicated that such a framework would provide a useful product. We completed a report in January 2003, Efroymson, R.A., J.P. Nicolette, and G.W. Suter II. 2003a. *A Framework for Net Environmental Benefit Analysis for Remediation or Restoration of Petroleum-contaminated Sites*. ORNL/TM-2003/17. Oak Ridge National Laboratory, Oak Ridge, TN. In December of 2002, we submitted a manuscript to the peer-reviewed journal *Environmental Management*, which is currently in press: Efroymson, R.A., J.P. Nicolette, and G.W. Suter II. 2004. *A framework for Net Environmental Benefit Analysis for remediation or restoration of contaminated sites.*

We have chosen to adopt risk assessment terminology to describe the NEBA framework to facilitate the use of NEBA by risk assessors. The NEBA framework described here has a single problem formulation stage to define the management goals of the assessment, the assessment endpoint entities, the stressors of interest, temporal and spatial scales of analysis, and the plan for comparison between alternatives, including proposed, comparative metrics for ecological states. Parallel characterizations of exposure for each alternative include chemical concentration dynamics (e.g., estimates of rate, extent, and metabolites of biodegradation) and changes in bioavailability. Parallel characterizations of effects (benefits and risks) for the alternatives include the dynamics of ecological recovery, as well as direct restoration dynamics. NEBA, by definition, includes a final step of comparing ecological states among alternatives. The high-level framework for NEBA is depicted in the flow chart in Figure 1. Additional flow charts for NEBAs of individual alternatives (natural attenuation, remediation, ecological restoration) are depicted in the report on NEBA cited above.

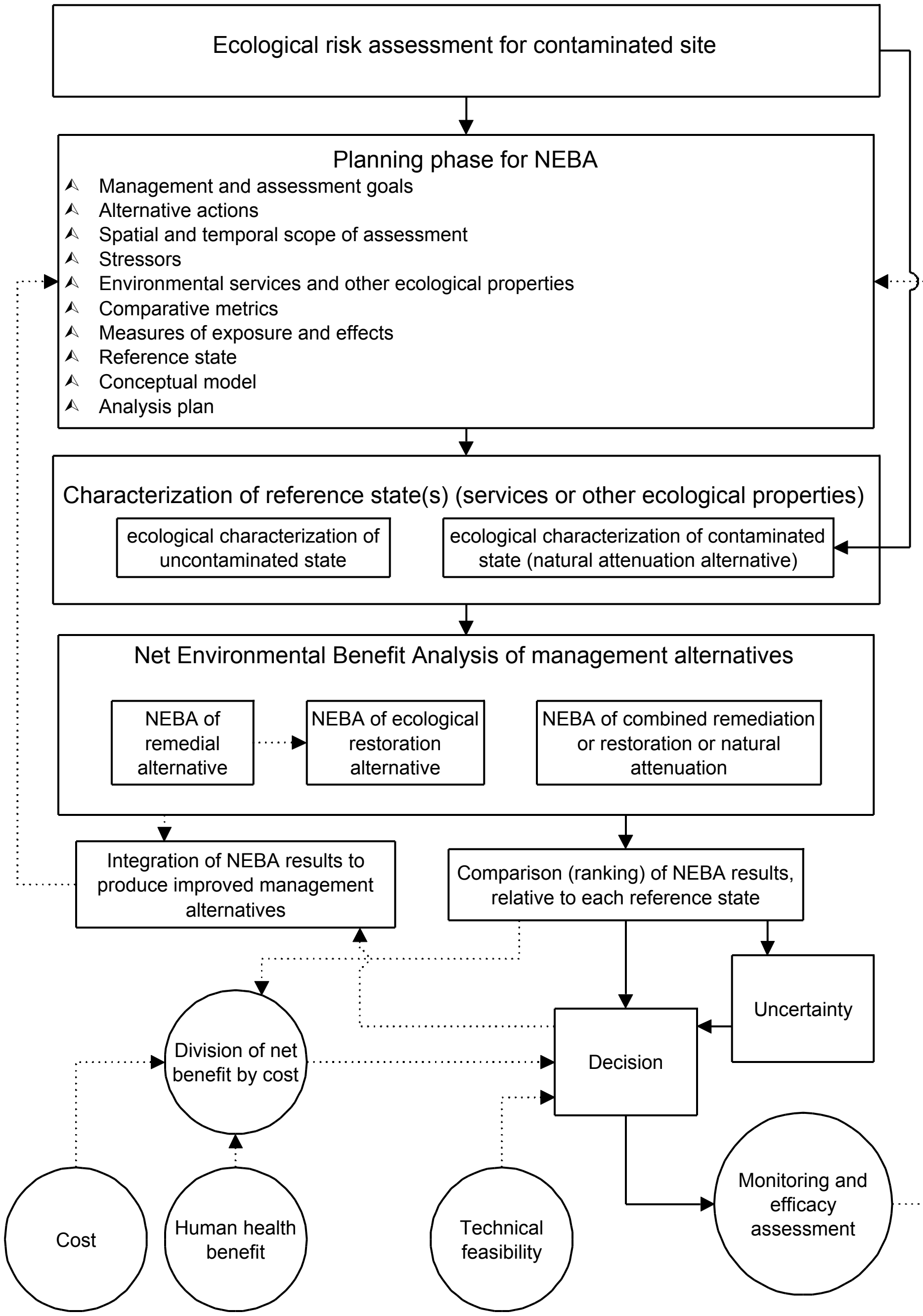

Fig. 1. Framework for Net Environmental Benefit Analysis for contaminated sites. Dashed lines indicate optional processes; circles indicates processes outside of NEBA framework.

Plant uptake models. To evaluate the relationship between the contaminant concentration in soil and plants, single-variable and multiple regressions were performed. Earlier in this project, regression models were developed for 1) vanadium in soil and soil characteristics; 2) lead in soil, one common co-contaminant (cadmium), and three soil characteristics (i.e., pH, percent organic matter, and cation exchange capacity); and 3) selenium in soil and three soil characteristics (i.e., pH, percent organic matter, and cation exchange capacity). Regression models derived for various types of plants were compared. Work on this task was suspended this year after the investigator left ORNL. A final report on summarizing accmplishments will be sent to the DOE National Petroleum Technology Office.

Spatial analysis tools and models. The Pathway Analysis Through Habitat (PATH) tool was developed to identify and map corridors of animal movement across maps of land cover categories (e.g., roads, grass, industry, etc.) or more specific features (e.g., structures or land farms). Applications of the tool to the petroleum industry lie in the identification of key areas for ecological restoration; spill remediation; wildlife barrier construction; or avoidance areas for road, pipeline or refinery facility development. Corridors are the "roadways" most commonly used by animals as they travel through an area. Corridors represent frequent movement paths among discrete patches of suitable habitat in a diverse matrix of land cover categories. Despite its importance, the idea of landscape corridors remains largely conceptual. No analytical tool has existed which could examine a real-world map, quantify landscape connectance, and identify wildlife corridors. The tool simulates virtual animals, termed "walkers," which are imbued with the movement characteristics and habitat preferences of particular animal species.

Three types of results are generated for each analyzed map: (1) the collective "footprints" of all walkers successfully dispersing, summed to map corridors; (2) a matrix of pair-wise rates of transfer from each patch to each other patch in the map; and (3) a set of importance values for each patch in the landscape, in terms of the addition that patch makes to overall connectivity across the map. The absence of corridors may represent barriers to movement, and absolute barriers are explicitly included in the modeling process. The transfer matrix indicates whether particular patches of habitat are population “sources” or “sinks,” which indicates the overall effect of this patch on the demography of the animal population.

The patch importance values are an important potential result of the tool. We calculate a connectivity index for the map with the patch present, then conceptually remove the patch and recalculate map-wide connectivity to compute an importance value for each patch in the map. Patches with high importance could be protected or preferentially remediated; patches with low importance would be more favorable for industrial growth and development. In the case of an invasive species, the sense of the importance values would reverse. Patches important for connecting movements of a weedy species could be made inhospitable for the invader. In addition, the tool could lead to mitigation measures, such as the identification of key areas for habitat restoration or barrier construction.

The code is written in parallel to allow the analysis of very large maps or maps with large numbers of habitat patches. The tool has been tested with several artificial maps; that is, corridors are predicted where they would be expected. The tool has also been used to identify corridors in three realistic landscapes. An example is depicted in Figure 2. The corridor analysis tool, PATH, is summarized in a manuscript that was submitted to the journal *Landscape Ecology*, and is currently in review. Hargrove, W.W., Hoffman, F.M., and Efroymson, R.A. 2004. A practical map-analysis tool for detecting dispersal corridors.

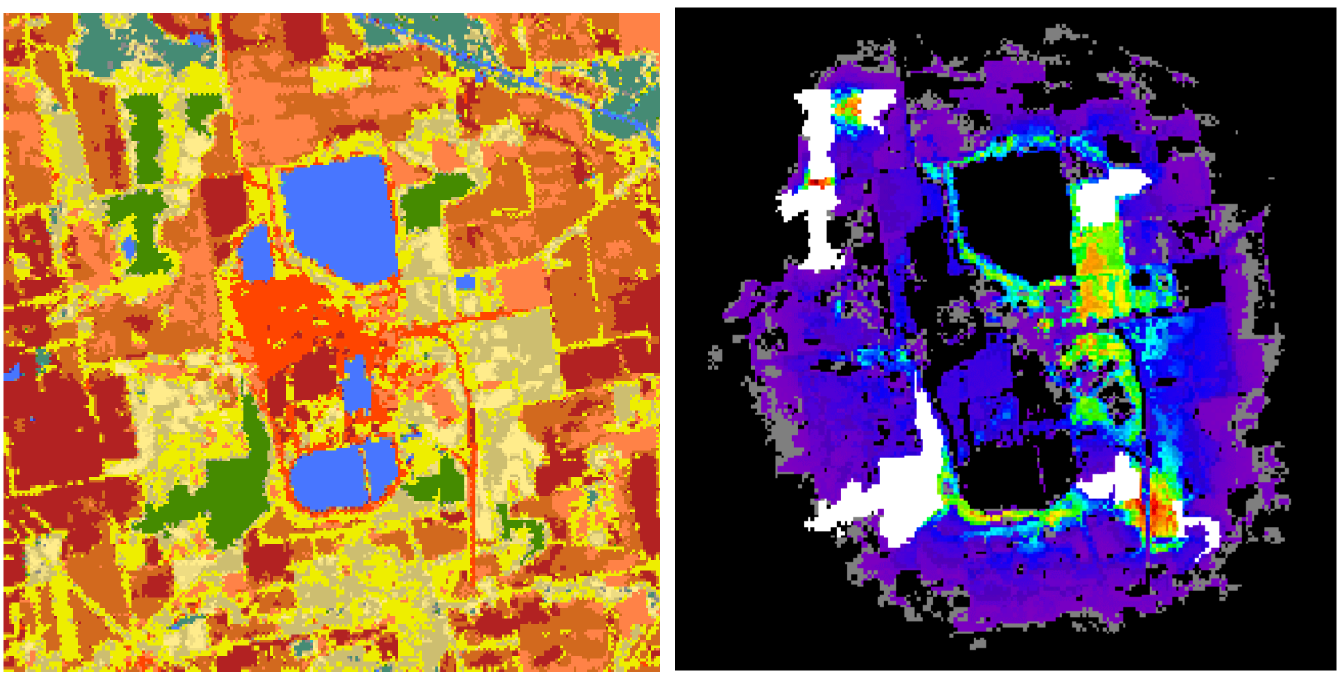

Fig. 2. (left) Patches of habitat at a gravel pit operations site, with forest remnants depicted in green-black, and ponds in blue. (right) Output of PATH showing the forest remnants in white, strong corridors in red, moderate corridors in green or yellow, and poor corridors in blue.

Ecotoxicity benchmarks. Project funds were used to revise a journal article on ecotoxicity benchmarks for plants and soil invertebrates that was originally written under FEAC303 "Biological quality of soils containing hydrocarbons and efficacy of ecological risk reduction by bioremediation alternatives." The article was accepted by *Environ. Toxicol. Chem.* but withdrawn after results were presented at a PERF 99-01 meeting in October 2000 and received substantial review comments from petroleum industry representatives. The article was revised in June of 2001 and again in November of 2001 and November of 2002, based on additional petroleum industry comments. The paper has become a review of existing ecotoxicity values and guidance to regulatory agencies and others regarding recommended considerations in the derivation of soil ecotoxicity benchmarks. The new version of the paper was recently published, Efroymson, R. A., B. E. Sample, and M. J. Peterson. 2004. Ecotoxicity test data for total petroleum hydrocarbons in soil: plants and soil-dwelling invertebrates. *Hum. Ecol. Risk Assess.* 10:207-231.

Data on the toxicity of total petroleum hydrocarbons (TPH) to plants and soil invertebrates were reviewed for possible application to benchmark development. Toxicity data included Lowest Observed Adverse Effects Concentrations (LOAECs); estimated 25th percentile effective concentrations (EC25s), EC20s, and median lethal concentrations (LC50s); effective concentrations that caused greater than a 20% level of effect; and No Observed Adverse Effects Concentrations (NOAECs). The variabilities in petroleum material, chemical analytical methodology, age of hydrocarbon-soil contact, nutrient amendment, and measured effects levels did not permit much aggregation of the data. Tenth, twenty-fifth, and fiftieth percentiles of toxicity and no-effects data were presented for unaggregated results. Some toxicity values for plants exposed to various refined petroleum mixtures in soil were below the 10000 mg/kg TPH level that is sometimes recommended as a protective criterion for plants exposed to crude oil waste. Toxicity to invertebrates often occurred at concentrations of TPH lower than those associated with toxicity to plants. Lighter mixtures generally were associated with lower ranges of effects concentrations than heavier mixtures such as heavy crude oil. Existing toxicity data were not sufficient to establish broadly applicable TPH ecotoxicity screening values with much confidence, even for specific mixtures.

The following guidance was suggested for regulatory entities or other interested parties that are considering establishing screening benchmarks for ecotoxicity:

1. A party with interest in developing screening benchmarks must consider what entities to protect.
2. A user of the toxicity data should have two levels of protection in mind: (1) an approximate response level and (2) a percentile that represents the acceptable percentile of the community that may exhibit the response.
3. A decision should be made about which analytical data to use. Considerations include the accuracy and availability of data obtained using various methodologies.
4. The regulatory agency or other interested party should decide whether toxicity data for TPH or petroleum fractions are most useful (and available) for estimating toxicity of aged mixtures in soil.
5. Screening benchmarks should be established with detection limits in mind.

6. Regulatory agencies and other interested stakeholders should strongly consider collecting new ecotoxicity data for petroleum hydrocarbons in soil.
7. Given the paucity of existing ecotoxicity data for TPH, a well-conducted field survey may currently be a more useful screening tool than a benchmark comparison.

General. An article was completed for a British petroleum business journal that summarizes these and related efforts to improve ecological risk assessment. The article will be published on July 30, 2004. Efroymson, R. A. 2004. Improving tools for ecological risk assessment at petroleum-contaminated sites. *Business Briefing: Exploration & Production: The Oil & Gas Review 2004.* World Markets Research Centre, Ltd.