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Science and practice of phytoremediation for soils and groundwater: a comprehensive review

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This comprehensive review will synthesize the state-of-the-science and state-of-the-practice for phytoremediation of various contaminants in soils and groundwater using *Phytoremediation: Transformation and Control of Contaminants* (Wiley, 2003) and a few more recent seminal publications as a basis. The review will highlight the fundamental knowledge of plant metabolism or rhizo-microbial degradation of organic contaminants, and the practice of using plants to accumulate or transform contaminants. The soil and ground water contaminants for which phytoremediation is known to be effective include, petroleum hydrocarbons, polyaromatic hydrocarbons, cyanide, phenols, polychlorinated biphenyls, chlorinated and other halogenated aliphatic compounds, nitroaromatic and other explosive chemicals, some metals, and some metalloids. This synthesis will focus on the fundamental investigations of plant proteomics and genetics, especially the work of COST 837 and other European investigators. In general, European research and development has taken a different approach from the more practical investigations in North America. The synthesis of the more fundamental European advances, with the American and Canadian field and laboratory advances and some contributions from Australia, Japan, and a few other countries, defines the nascent field of phytoremediation. The term phytoremediation was only coined in 1991, but has experienced tremendous growth because of the outstanding science basis that has developed early and that has been expanding continuously with COST 837 predominately. A U.S. innovation that has fueled early applications is that almost all teams consistent of scientists and engineers. The engineering communities have embraced more scientific approaches to apply existing vegetative practices in waste and resource management—applications of wetlands, vegetative control of erosion, land farming with plants, development of riparian buffers, agroeconomic ap-

proaches, and silvaculture. For this reason, most phytoremediation practices are not new; we are simply developing scientific bases for the application of existing vegetative practices, dating back almost 600 years in the case of land farming in Europe.

Nevertheless, funding for fundamental work is of constant concern worldwide—we run the real risk of stagnating growth of the field due to a lack of fundamental discoveries to fuel rapid development of science bases for applications. Differences in protection of intellectual properties in the European Union and the U.S. that control commercialization and development may explain why the different complementary developments have occurred. Another reason for the rapid growth of phytoremediation is the early use of biotechnology precedents and patterns for commercialization. This more scientific approach makes the use of advances in plant and mammalian biochemistry, proteomic, and genetics feasible to spur the phenomenal growth of the field. This makes phytoremediation research somewhat consistent with medical, pharmaceutical, nutrition, and veterinary research to name a few. Furthermore, many teams are embracing an ecological engineering approach that guides research on the basis of developing low-cost, self-engineering communities for more sustainable clean up and even pollution prevention. Nevertheless, a few critical fields like ecology and botany and have not sufficiently embraced phytoremediation. Thus, there are not only continental and national differences in research approaches, some disciplinary indifference remains that may influence the limited funding of fundamental investigations.