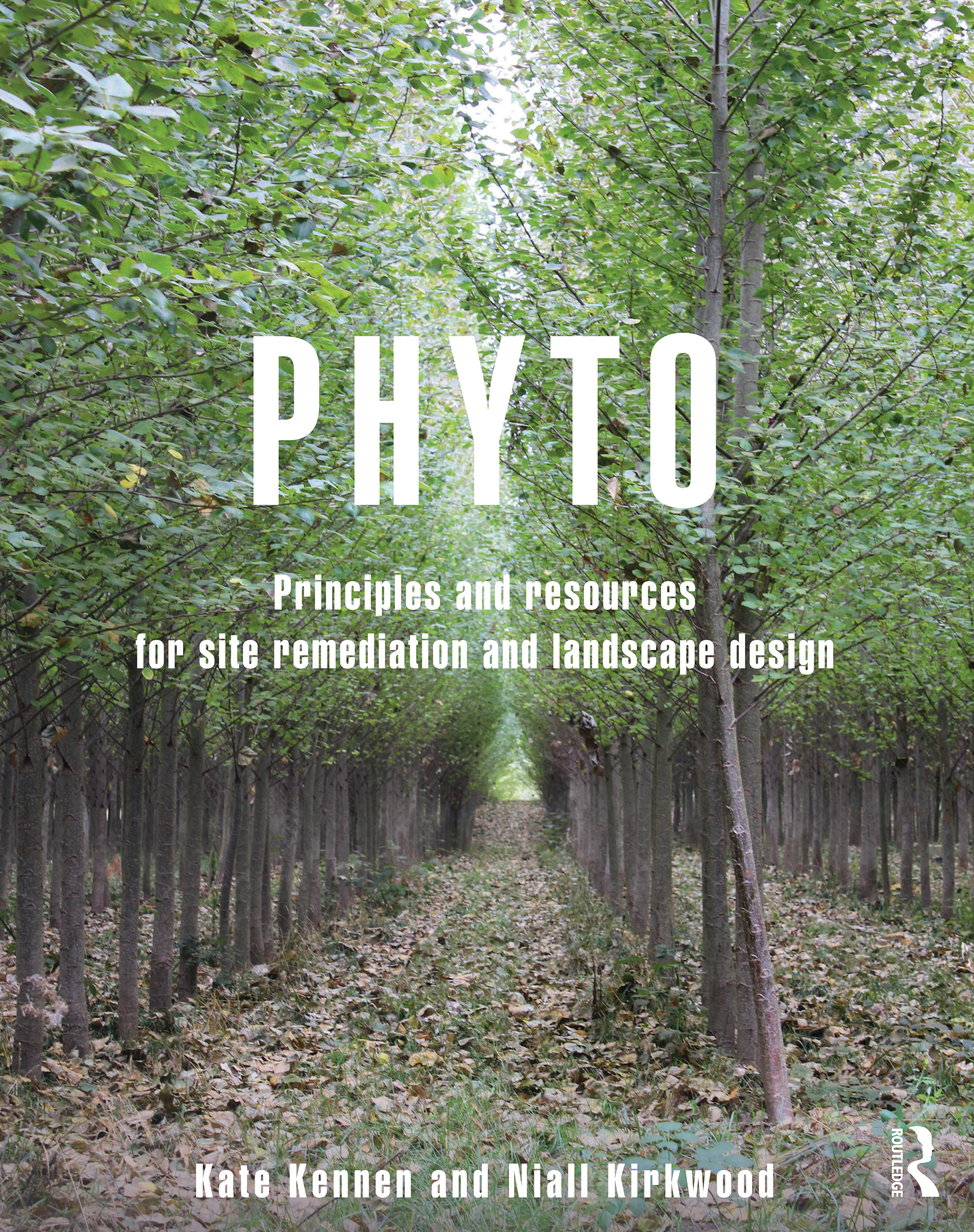

PHYTO

Principles and resources for site remediation and landscape design

Kate Kennen and Niall Kirkwood

Phyto

Principles and resources for site remediation and landscape design

Phyto presents the concepts of phytoremediation and phytotechnology in one comprehensive guide, illustrating when plants can be considered for the uptake, removal or mitigation of on-site pollutants. Current scientific case studies are covered, highlighting the advantages and limitations of plant-based cleanup. Typical contaminant groups found in the built environment are explained, and plant lists for mitigation of specific contaminants are included where applicable.

This is the first book to address the benefits of phytotechnologies from a design point of view, taking complex scientific terms and translating the research into an easy-to-understand reference book for those involved in creating planting solutions. Typically, phytotechnology planting techniques are currently employed post-site contamination to help clean up already contaminated soil by taking advantage of the positive effects that plants can have upon harmful toxins and chemicals. This book presents a new concept to create projective planting designs with preventative phytotechnology abilities, 'phytobuffering' where future pollution may be expected for particular site programs.

Filled with tables, photographs and detailed drawings, Kennen and Kirkwood guide the reader through the process of selecting plants for their aesthetic and environmental qualities, combined with their contaminant-removal benefits.

KATE KENNEN is a landscape architect, and the founder and president of Offshoots, Inc., a Boston, Massachusetts landscape architecture practice focused on productive planting techniques and phytotechnology consulting. Offshoots has won numerous awards for projects integrating plantings to clean up polluted sites. Having spent her childhood at her family's garden centre in central Massachusetts, Kate is well versed in the plants of the Northeast. She completed her undergraduate studies in Landscape Architecture at Cornell University, and received her master's degree in Landscape

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NIALL KIRKWOOD is a landscape architect, technologist and Professor at the Harvard University Graduate School of Design, where he has taught since 1992. He teaches, carries out research and publishes on a range of topics related to landscape architectural design, the built environment and the sustainable reuse of land including urban regeneration, landfill reuse, environmental site technologies and international site development. His publications include *Manufactured Sites: Rethinking the Post-Industrial Landscape* (Routledge), *Principles of Brownfield Regeneration* (Island Press) also published in Korean and Chinese translations, *Weathering and Durability in Landscape Architecture* (Wiley) and *The Art of Landscape Detail* (Wiley). Professor Kirkwood is a Fellow of the American Society of Landscape Architects and in addition is the Gerard O'Hare Visiting Professor, University of Ulster, Belfast, Northern Ireland, Distinguished Visiting Professor, Korea University, Seoul and Visiting Professor, Tsinghua University, Beijing, China.

In two words: "Beyond comprehensive". *Phyto* is by far the most comprehensive compilation of phytotechnologies out there. It truly goes beyond by tying together this broad set of plant technologies for cleaning the environment with the necessary form and functionality of landscape design. As an advocate and trainer in phytotechnologies, I especially appreciate the illustrative graphics and easy-to-understand descriptions that clearly convey the science, engineering, design, and planning to the technical and artisan alike.

– David Tsao, Ph.D, BP Corporation North America, Inc.

Phyto is a fantastic resource, not just to landscape architects but also to engineers and scientists as well. As phytoremediation developed, advancement efforts focused on the biochemical science of the processes, and while the field was cognizant of 'ancillary benefits' valuation was not considered, mostly due to lacking knowledge and resources. *Phyto* brings the social and physical science into a common meeting place, and provides much needed discussion, fantastic visualizations and cross cultural presentation of plant-based technologies that can be incorporated into our urban spaces to serve both public health and the quality of life itself.

– Joel G. Burken, Missouri University of Science and Technology

This book closes a very important gap between phytotechnologies and practice. Through creative design, the authors succeed in translating a comprehensive subject matter into accessible information. A special merit is that the book predicts vegetation strategies becoming an anticipatory tool in the hands of the landscape architect in advance of potential future contamination preventing human exposure to soil, water and air contamination.

– Jaco Vangronsveld, Centre for Environmental Sciences of Hasselt University, Belgium

Phyto

Principles and resources for site remediation and landscape design

Kate Kennen
and Niall Kirkwood

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Contents

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Therefore this book project would not have been possible without the advice, knowledge and general encouragement provided by a wide range of colleagues, friends and experts in the design, planning and engineering fields and scientific community. This includes active collaboration over a number of years between the authors and a wide group of phytotechnology scientists, landscape architects, ecologists, environmental engineers and federal regulators, and current and former graduate students in landscape architecture and urban design. In particular we would like to acknowledge the significant role played in the evolution of this book by Dr. Jason White of the Connecticut Agricultural Experiment Station, President of the International Phytotechnology Society and Managing Editor of the *International Journal of Phytoremediation*, Steven Rock of the US Environmental Protection Agency (EPA), Dr. Lee Newman, SUNY College of Environmental Science and Forestry, Immediate Past President of the International Phytotechnology Society and Co-Editor in Chief of the *International Journal of Phytoremediation*, Dr. Joel G. Burken, Missouri University of Science and Technology, Environmental Research Center, Dr. David Tsao of BP Corporation North America, Inc., and Dr. Jaco Vangronsveld, University of Hasselt Center for Environmental Sciences, Belgium. In addition, many other scientists and consultants contributed significantly to the text, case studies, research, review and editing, and the names and addresses of these individuals are included in the list of contributors.

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Preface

> Toxic trees, virus-bearing vines, plants from outer space that eat poisons for lunch, then snack on young adults. B-movies from the 1950s vividly portrayed freakish vegetation to scare their audiences. In the last reel, mankind destroys the mutant greenery through the ingenuity of the scientist hero…. But recent eye-grabbing headlines – "Lead-eating mustard plants," "Pint sized plants pack a punch in fight against heavy metals," and "Pollution-purging poplars" – seem to have brought B-movies to life and unsettled our comfortable view of vegetation as benign and green. However, these seemingly freakish plants are in fact our good friends.
>
> (Kirkwood, 2002)

The excitement and expectations of the B-movie "toxic trees" and "virus-bearing vines" are vividly brought to light in the developing field of phytotechnology, or 'phyto' for short. The more sensational aspects of this vegetation are tempered by the scientific basis and practical uses of plants in confronting pollutants in the contemporary environment. However, we can still continue to be entranced by both the processes taking place inside the plants, roots and surrounding soils and the good work plants can carry out on our behalf.

Phytotechnology applications have the capacity to play a significant role in transforming contaminated urban land, providing a more sustainable choice for remediation when combined with short- and long-term land planning. In some cases, plants can take up, break down or hold pollutants in place. However, the science that lies behind phytotechnology has been found by the authors to be challenging to comprehend for the non-specialist reader, and therefore difficult to implement. The ambition of this book is to bridge the critical science and engineering associated with phytotechnology site applications and its creative design use in the field.

I Background

This publication is the first targeted towards the spatial design, form, structure and aesthetics of this technology, rather than simply the science behind it. The authors' intent is to translate current research and field studies carried out by scientists into a format useful for the design practitioner in addressing site pollutants. Chapters 1–3 of the book delve into the science and regulatory issues around phytotechnology, including the nature of particular site contaminants and field case studies. Chapters 4–6 focus on projecting the potential environmental, spatial, cultural and aesthetic qualities of these productive vegetation types matched to site programs and specific contaminants.

The content of the book utilizes diagrams to illustrate a basic understanding of how the science related to phytotechnology functions, when it may work in site applications and when it does not. The great majority of the background information has been collected from individuals, institutions or agencies who have undertaken research or site installations. Detailed information on the relevant plant species for potential contaminants commonly found on sites is included. Additional diagrams and charts illustrate typical contaminants present on various types of programmatic sites (for example gas stations, road corridors, railroad corridors). Innovative plant combinations involving treatment solutions for these site programs provide practical design ideas where aesthetics and social functions have also been considered. Preventative planting palettes for certain site programs, such as railway corridors, dry cleaners, parks and urban homes are also created, thus allowing landscape design to propose vegetation strategies in advance of future potential contamination. In this way phytotechnologies become projective, anticipatory and a creative tool for the landscape architect and site owner to create landscape amenities for the citizens and communities in which these sites occur.

The origins of this book lie in two areas. First, noting the increase in urban landscape reclamation projects and environmental engineering practices, particularly on brownfield and contaminated land, there is an increasing need for clear guidance for landscape site design applications of plant-based remediation, in anticipation of further non-remediation-based planting installations. Second is the desire on the part of the authors to build on the earlier scientific research work of pioneers in the phytotechnology field and make their work and other current research work comprehensible and therefore usable to a larger range of stakeholders and participants. The book is the outcome of continuous study over the last 15 years by the authors, around the challenges, opportunities and techniques of phytotechnology and the activities of plant selection, landscape design and monitoring to reclaim post-industrial land and landscapes.

II Book structure

The structure of the book is as follows.

Chapter 1 provides an overview of phytotechnologies and their current application in the environment and their anticipated future use. This includes coverage of the definition and evolution of the subject, discussion of the legal framework in which they are used, review of their efficacy and finally an outline of potential innovative applications.

Chapter 2 reviews the fundamentals of the scientific processes involved in phytotechnology remediation and provides a summary of these processes. The activities of soil enhancement and plant cultivation are also addressed.

Chapter 3 offers the reader a survey of the groupings of contaminants commonly addressed by phytotechnology approaches and plant selection. These are related to the following chapter on planting typologies and application to polluted sites.

Chapter 4 outlines the interrelationship of specific contaminants with specific planting types, illustrating 18 different phytotechnology planting typologies.

Chapter 5 applies the phytotechnology planting types developed in Chapter 4 to a range of 16 commonly found land-use programs such as gas stations, road corridors, military sites and agricultural uses.

Chapter 6 is a listing of additional resources for those interested in following up on specific areas of the phytotechnology field.

Through an understanding of new research on phytotechnology vegetation and the potential opportunities and, conversely, limitations of their application, the reader will comprehend the range of topics that engage with this emerging technology. These topics taken together constitute the core knowledge of phytotechnology. The authors strongly support the notion that they will form a new core subject within the study and practice of landscape architecture and land regeneration in the future.

III Why the book is needed

This book is unique among publications on phytotechnology, as it links the scientific basis of the topic with its application in the planning and design fields. This involves addressing the reality of contemporary sites and their former and current programs, and the range of contaminants that are likely to be found. The need to remediate particular chemicals in soils and groundwater using plants is connected with neighborhood and community health and sustainability. In the authors' estimation, there exists a large gap between the publications and journals covering the scientific research, including laboratory experiments and field testing, and its general understanding and subsequent application on current brownfield sites.

One scientific journal, *The International Journal of Phytoremediation*, and several research-based books listed in the bibliography which are edited collections of research papers have been published on the subject of phytotechnologies. However, all of these publications are presentations of research and field studies, and the information presented is scientific, text-based and difficult to decipher by the landscape design professional. *Phyto* is different from these publications. This book is first and foremost a design-based guide utilizing simple charts and diagrams to clearly explain the science. Lists of potentially applicable plant species are provided. Plants hardy and suited for the northeast US climate are emphasized but the introduced design typologies and overall site strategies can be applied globally.

In addition five further issues for why this book is needed can be identified.

A Issue one: the contaminated environment

Major urban centers of population continue to lose industrial and manufacturing companies, and the land that supported them is left vacant with the contaminants and former infrastructure. This has created numerous abandoned, derelict and contaminated sites of varying sizes within communities, many of them located next to community amenities such as playgrounds, schools, recreational fields, daycares and senior centers. One of the central priorities of city planning initiatives is the urban reclamation and regeneration of inner city land such as degraded river edges, railroad yards, ports, harbors and piers that are central to the revitalization of city districts and neighborhoods. There is a growing need for innovative, sustainable, low-cost methods to address the remaining contamination of soils, groundwater, sediments and surface water over a wide range of site locations.

B Issue two: the productive use of contaminated land

With concerns for sustainable planning and quality of life entering public discourse and the diminishing amount of available urban sites for development, there is a need to regenerate the middle-scale and smaller sites found within the city fabric. Driving the cleanup of polluted sites is the desire for higher and best use of the land, for economic development opportunities and community facilities. Of interest to the landscape architect is how phytotechnology can inform more progressive and creative planning and design work to achieve these productive uses, and conversely, to what extent new programs and uses can direct the regeneration of these sites through phytotechnologies. In addition, the potential for phytotechnologies to produce an economic product such as biomass for energy, paper or wood products while also cleaning sites is of primary interest.

C Issue three: available information on phytotechnologies

Current information available on phytotechnology is very widely dispersed and varied, appearing in a range of media including books, magazines, websites and technical manuals. Research presented may be contradictory, and it is difficult to determine which research is the most current. In addition, test projects and field applications have generally occurred on inaccessible places in remote locations out of the public eye, such as Department of Defense sites or large-scale industrial or resource extraction lands (Stoops, 2014). This easy-to-read handbook targeted at the design and landscape professions summarizes the wealth of research and field case studies produced in recent years. It not only includes case studies that have worked, but describes many misconceptions in the field where phytotechnologies likely are not very effective.

D Issue four: design, performance and landscape architecture

There has been a changing mood in the development of landscape sites where functional ecologies, community, public health, urban design and sustainable development concerns are a driving force in addition to aesthetic factors. More recent projective design approaches have included the consideration of what the landscape can 'do' in addition to the human programs layered on sites. Phytotechnologies can enhance the landscape functionality of green corridors, vegetation patches, new woodlands, hedgerows, urban agriculture and wetlands.

E Issue five: future projections of domestic site contamination

Homeowners have an increased awareness of site contamination issues in gardens, yards and surrounding house properties through local reporting on the concerns of existing site urban fill, past pesticide use, leaking oil tanks and lead poisoning of children through playing in the polluted soil of home gardens and yards. Enough research now exists to apply phytotechnology concepts at a residential scale. This strategy is based on the need to make communities more livable for residents and to provide safer landscapes for all citizens – but particularly for children and seniors – and a healthier approach to community resources such as playgrounds, schools, pocket parks and homes in the neighborhood.

IV Audience for the book

Phyto is conceived as a practical and easy-to-use handbook for college-level instruction and in continuing education programs, and as a reference for design professionals and those in the horticultural and construction industries. It also is envisioned as contributing to the advancement of discussion in the design and planning fields about the way designers conceive and construct phyto landscape design work in a variety of site conditions. The following are examples of who might read it and how the authors expect it to be used.

A Landscape architecture and other design students

As a textbook or guide for planting design and site remediation for landscape architecture, landscape planning, urban design and site design students in a plants or technology class or in a planning and design studio.

B Landscape architects, other design and engineering practitioners

In the professional offices of landscape architecture, site engineering, environmental engineering and ecological engineering consultants as a reference for planting design and remediation for urban sites.

C Urban designers and planners

In the private, professional and municipal offices of planners, urban designers and municipal employees to assist in the initial planning and research on sustainable cleanup alternatives for brownfield site projects with polluted soils and groundwater.

D Horticultural industry

For plant growers, nurserymen and members of the horticultural community as a handbook of some plant varieties able to be grown and available to the phytoremediation industry.

E Landscape construction companies

As a reference guide for landscape and engineering construction companies involved in the implementation and maintenance of the landscape, from project, site supervision and procurement managers to plant installation job captains and field workers.

F Organic land care associations

As a reference guide in order to instruct industry professionals and community planners, groups and educators in a range of productive planting techniques for urban and ex-urban sites.

The subject of phytotechnology brings together the disciplines, professional worlds and knowledge of landscape design, science, engineering, horticulture, site planning and cultural and social programs, whether through initiatives such as land regeneration, urban gardens, energy creation, greening of local neighborhoods, new recreational venues or local stormwater management action, and often including intensive local community interest and involvement. Even as the “seemingly freakish plants” identified in the opening quote appear to be independently and single-handedly tackling the polluted lands that dot the current environment of communities, they are actually there as a result of a larger multidisciplinary effort carried out by concerned teams of scientists, engineers, government officials, academic researchers and independent research groups, design and planning professionals in private practice and community volunteers. Community organizers, local planning offices, members of government agencies and non-profit environmental groups are all critical players in the implementation of these technologies.

It is the authors’ intention firstly that this book should guide all of these players to an understanding of the potential of phytoremediation-based design and of the promise of these “freakish plants” not only to remediate sites but to act within a pre-emptive approach to address the future evolution of these sites. Secondly, that residents and community members will be able to access and enjoy a new range of landscape spaces and outdoor planted places that are indeed healthier, less polluted and full of lessons about the power of natural processes of remediation. Through the art and science of phytotechnologies and on an increasing range of design sites, landscape architecture will possess a swift and sure means of touching the greater world and creating a more ecologically sustainable, resilient and responsive means to shape the future constructed environment.

Foreword

Steve Rock

People have deliberately grown plants to alter their environment for at least millennia. The Roman roads were lined with poplar trees both to provide shade and to keep the roads' foundations dry by consuming water along the edges, thus making the roads last longer.

The broadest definition of phytotechnologies includes any plantings that enhance the environmental goals for the planet. The field has grown from narrow beginnings to widespread applications and has moved from hopeful but ultimately unfounded expectations to a mature set of techniques and technologies that are commonly accepted as a part of the environmental cleanup toolbox.

Even before the field was named, people have been using plants to enhance their work. In the 1930s bioprospecting was used as a way to predict the presence of minerals subsurface. Prospectors, particularly in newly opened lands of Siberia, discovered that they could search for plants that grew only in areas rich in certain minerals. It was noted that some plants were reliable indicators of minerals and that leaves and twigs could contain quantities of metals much higher than those in others of the same type in other locations.

In the 1970s several research groups began systematically studying and classifying the relationship between metals and plants, and found some plants growing in metal-rich soils to have extraordinary properties. Three researchers in particular, Drs. R. R. Brooks, R. D. Reeves, and A. J. M. Baker and their teams, crisscrossed the globe finding and cataloging plants that grew on metal-rich soils and took up unusual quantities of those metals. Some plants were found to take up more metals than normal plants and eventually were named as accumulators and hyperaccumulators.

Increasing general environmental awareness at the time spurred traditional agricultural research to study the effects of environmental contaminants on food-production crops, particularly the uptake of potentially harmful heavy metals. The practice of using biosolids from sewage sludge as fertilizer brought rural crop plants into contact with all the industrial pollutants that were flushed down urban drains. It was found that some contaminants did move into some crop plants. One USDA researcher, Dr. Rufus Chaney, suggested that while planting metals excluders might help to protect the food supply, it might also be possible to clean soil by raising crops that extract and accumulate metal which could be harvested not for food but for remediation.

Also in the 1970s the new field of bioremediation was exploring how to use microbes to attempt environmental cleanup of degradable contaminants. Research began into whether and how much plants enhanced the microbial degradation of pesticides and petroleum products. It was soon clear that planted systems did remediate certain contaminants sooner, deeper, and in some cases more completely than microbial systems alone.

Such fundamental research continued into the 1980s, attracting attention from university research teams, government agencies, and private industry. The new-found national and international environmental awareness of the time and the creation and passage of foundational environmental legislation such as the Clean Water Act and the CERCLA (Superfund) led to increased funding into many possible remediation strategies. Municipalities and corporations were under pressure to reduce the discharge of toxins into the air and water, and onto the land. Cleaning of historical contamination became a new and large industry. Consulting and contracting companies sprang up everywhere, industrial and commercial enterprises started in-house remediation divisions, and government agencies were started or became larger. It is no wonder that by the late 1980s some people were turning their thoughts to commercializing this new process of using plants for remediation.

The earliest definitions of phytoremediation in the 1990s in publications and presentations refer to environmental protection via metal uptake by plants. Terms and definitions quickly proliferated as firms tried to distinguish and differentiate themselves and their processes. Phyto hyphen anything became a way to classify increasingly specific uses of planted systems. Phyto-degradation, -extraction, -enhanced bioremediation, etc. were used to describe and differentiate aspects of the field. Other terms like rhizofiltration and hydraulic control were invented and used in specific circumstances. Phytotechnologies to this day is an umbrella term that aims to encompass all uses of plants for environmental goals.

The 1990s were a time of proliferation of patents as well as companies and invented words. Some patents were for inventions, some for techniques, and some for practices that had been widely used but never patented.

One successful phyto-based patent was introduced when Edd Gatliff patented a TreeWell system that in part uses a downhole sleeve and air tube to induce and enable tree roots to penetrate deeper than they would naturally. The system allows trees to be targeted at a particular depth below ground surface and to tap into contaminated groundwater while bypassing clean water-bearing layers. This innovation combines several known and novel techniques and devices, and allows remediation to depths and in places otherwise unobtainable.

Other patents were not so specific and had a chilling effect on the deployment of the some remediation practices. The numbers of on-site applications and field experiments fell at the end of the decade, in part due to legal concerns over patents and in part because expectations caught up with reality.

It was widely hoped that phytoremediation would solve the problem of widespread low-level contamination of heavy metals in soil. Many heavy metals of concern, and particularly lead, persist in soils for many decades from spills, dumping, or atmospheric deposition. Large areas of land have soil that poses a risk to residents and workers but there are few tools that are economical, non-invasive, and effective. Phytoremediation for metals (phytoextraction) was hoped to be all those things and quite literally a green technology into the bargain.

There are some plants that will naturally accumulate some metals under some circumstances. These natural accumulators are often small, grow slowly, and are difficult to cultivate outside of their native and often narrow range. It was hoped and claimed that some plants that grew faster, larger, and using standard agricultural equipment and practices could be induced to take up enough metal to clean soil. Unfortunately, induced phytoextraction of metals has several flaws that have to date proved insurmountable. These include the fact that the most widely used technique relies on chemically altering the contaminant to become much more soluble than in its natural state. This more soluble metal is then more likely to be taken up by the planted phytoextraction crop; the soluble metal is also more likely to be washed away into surface water and groundwater, where it poses an even greater risk than when it was bound into the soil, which is both morally and regulatorily unacceptable.

There were a number of highly publicized demonstration projects with optimistic reports and enticing pictures. Phytoremediation entered the public lexicon via popular articles, usually featuring a picture of a field of sunflowers. After a few careful experiments it was determined that indeed the plants could be induced to take up quantities of metal that could lead to a respectable cleanup in a matter of years, but that the need to prevent the escape of the mobilized metals would prevent the process from ever becoming economically feasible.

First the industrial boosters repurposed their staff and resources. Then the contractors and consultants changed their focus. Phytoextraction remains a popular academic topic of study in the search for the plant that might naturally extract and accumulate enough contaminant to be an effective tool, or to find a safe way to induce uptake. There have been some attempts at genetic modification. Currently, phytoextraction of metals has not lived up to its early promise, and despite continued academic and public interest is not a mainstream tool in the remediation toolkit.

However, at the same time that phytoextraction of metals was enjoying a lot of press, discussion, and also some failures, other phytotechnologies to mitigate contaminated groundwater plumes and treat organic pollutants such as petroleum and solvents were quietly maturing and taking their place in the toolkit. One of the processes that plants do naturally and quite well is move water. This has been used widely and effectively in landfill covers to prevent precipitation penetration, and in subsurface applications to control contaminated groundwater plumes, and in phytoforensics, where plants are used to track subsurface contaminants.

It was soon shown that planted cover systems for landfills are generally as effective as conventional covers in many parts of the US. Like all plant-based systems, the actual effectiveness will be a function of location. A nationwide field study from 1999 to 2011 showed how to determine equivalency for landfill cover systems. Now that there are hundreds of plant-based covers in place and enough more on engineering firms' drawing boards, such covers are no longer considered experimental or innovative and regulatory approval is regularly given.

Planting trees not only to control water but also to enhance bioremediation of organics and light solvents is also common enough to be included in many cleanup plans. Although most metals do not move easily into plants, several other organic contaminants of interest are soluble enough to move or translocate into plants, where they are often degraded, without the need for harvesting the plants.

This ability of plants in general and trees in particular to take soluble contaminants from groundwater has allowed an interesting and potentially very useful technique called phytoforensics. Since 2000 Drs. Don Vroblesky, James Landmeyer, and Joel Burken have pioneered and refined the techniques needed to remove tree cores and analyze the chemical content of the sap. Side-by-side studies have shown that phytoforensics can reveal the origin and direction of groundwater contamination with as great accuracy as and considerably less expense and disruption than conventional testing and monitoring-well drilling.

No discussion of phytotechnologies is complete without including wetlands. In use for cleaning wastewater since at least the 1880s, wetland technology continues to be developed and improved. Many large environmental firms have some capacity to size, specify, and install constructed wetlands to treat industrial or municipal outflow. It is one of the most robust and frequently applied uses of planted systems to achieve such diverse environmental goals as organics degradation, metals sequestration, and wildlife habitat creation – often at the same time.

Since the first meetings to discuss these topics, like the "Beneficial Effects of Vegetation in Contaminated Soil" meeting hosted by Kansas State University in 1992, to the now annual conferences of the International Phytotechnology Society, researchers, consultants, regulators, and contractors meet and talk about the what works and what does not. The field has undergone a tremendous shift from fringe idea, to highly touted silver bullet, to the current state of reasonable expectations for successful application on a local site-by-site basis.

Phytotechnologists, landscape architects, and site designers share an overlapping toolbox with plants, soils, and water as the pieces to build the constructs we are called upon to create. Often a site will employ both sets of professionals – one to clean the canvas and one to provide the finishing touches once the site's structures are complete. This book provides a means to bridge those task areas so the means to remediate a site may be part of the final landscape site design. Each profession has a specific and distinct vocabulary, as is appropriate for fields that come from widely different origins and have individual project goals and deadlines. This book will help to overcome that language gap, for the landscape architecture community and for any scientists and engineers who want to understand this design discipline.

Planting any given vegetation is neither difficult nor complex, but planting for a particular outcome that sometimes won't be realized until years or decades later requires experience, and patience. Practitioners in both fields recognize the need for time on a plant scale, although the site owners and regulators sometimes don't share that view.

In conclusion, the future of phytotechnology and its application to a wide number of sites and over a range of timescales is still evolving. Designers and scientists working in collaboration can help create the correct environments to advance the range and type of plants to be used, as well as create phased projects that can begin to demonstrate the value of phytotechnologies over time.

Ultimately, phytotechnology is about using specifically selected plants, installation techniques, and creative design approaches to rethink the landscapes of the post-industrial age. It is less about simply the beauty of plants, less about gratuitous site planning and design and the creation of individual design ideas; rather, it is to focus through design on plant characteristics to sequester, take up or break down contaminants in soils and groundwater. The purpose is to understand and include the margins of scientific research and invention to employ broader boundaries, where plant-based remediation can be used for improvement and renewal, and to plan beyond the short term for a longer vision for the contemporary environments of cities, towns and communities.

Icons

Contaminants

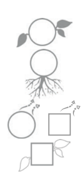
Organic contaminants

- Petroleum
- Chlorinated solvents
- Explosives
- Pesticides
- Persistent Organic Pollutants (POPs)

Inorganic contaminants

- Nutrients
- Metals
- Salts
- Radionuclides

Organic and inorganic mechanisms



- Phytodegradation
- Rhizodegradation
- Phytovolatilization
- Phytometabolism

 Phytoextraction

 Phytohydraulics

 Phytostabilization/Phytosequestration

 Rhizofiltration

Abbreviations

Abbreviation	Icon for contaminant	Name	Description
Al	■	Aluminum	Inorganic metal(loid) associated with metals mining, production and smelting.
As	■	Arsenic	Inorganic metal(loid) commonly found in pesticides and pressure-treated lumber and naturally occurring in high concentrations in some soils and groundwater.
B	■	Boron	Inorganic metal(loid) commonly associated with glass manufacturing, pesticide use and leather tanning.
BOD		Biochemical Oxygen Demand	Biochemical oxygen demand or BOD is the amount of dissolved oxygen needed in a body of water to break down organic material present. It is used to gauge the organic quality of the water.
BTEX	●	Benzene, Toluene, Ethyl benzene, and Xylene	Volatile organic compounds (VOCs) found in petroleum products.
Cd	■	Cadmium	Inorganic metal commonly contaminating agricultural fields and derived from soil amendments and mining and smelting activities.
Ce	■	Cesium	Inorganic radionuclide associated with nuclear energy production and military activities.
CERCLA		Comprehensive Environmental Response, Compensation and Liability Act	Commonly known as 'Superfund', this was a Federal US Law enacted in 1980 that established a trust fund used by the government to clean up contaminated sites on the National Priorities List (NPL).
Co	■	Cobalt	Inorganic metal commonly used as a colorant in glass and ceramic production, as well as alloy and aircraft manufacturing.
CO		Carbon monoxide	Toxic gas created by automobiles and the incomplete combustion of hydrocarbon fuels; component of air pollution.
CO_2		Carbon dioxide	Component of air pollution, greenhouse gas.
Cr	■	Chromium	Inorganic metal commonly associated with the electroplating, automotive and tannery industries as well as the production of pressure-treated lumber.

Abbreviation	Icon for contaminant	Name	Description
Cu	■	Copper	Inorganic metal commonly used in metals, pipe and wire production, pesticides and fungicides.
DDT, DDE	●	Dichlorodiphenyltrichloroethane, Dichlorodiphenyldichloroethylene	Highly toxic persistent organic compound used as a pesticide and banned in the US since 1972. DDE is a common toxic breakdown product of DDT.
EDTA		Ethylene Diamine Tetra-acetic Acid	Chemical added (chelant) to make pollutants more bioavailable to plants for uptake.
EG		Ethylene Glycol	Organic compound commonly used in de-icing fluids.
EPA		Environmental Protection Agency	Federal government regulatory agency in the United States responsible for enforcing laws pertaining to the natural environment and regulating the cleanup of contaminated sites.
Carbon tet Halon 104 Freon 1	●	Carbon tetrachloride	Organic chlorinated solvent compound denser than water. Used as a refrigerant, fire suppressant, industrial degreaser and in the cleaning industry.
DNAPL		Dense Non-Aqueous Phase Liquid	Oily type of pollution that lies beneath water.
DRO	●	Diesel Range Organics	Organic compounds typically found in diesel fuel.
F	■	Fluorine	Inorganic metal associated with phosphate fertilizer production as well as smelting, coal-fired power plants and mining.
Fe	■	Iron	Inorganic metal widely found and usually not considered a contaminant except when in high concentrations in water.
GRO	●	Gasoline Range Organics	Organic compounds typically found in gasoline.
Hg	■	Mercury	Inorganic metal associated with coal-burning power plants, metals and paint manufacturing.
HMX	●	1,3,5,7-tetranitro-1,3,5,7-tetrazocane	Explosive organic compound, commonly associated with military uses.
LNAPL		Light Non-Aqueous Phase Liquid	Oily type of pollution that floats on water.
Log K_{ow}		Octanol-Water Partition Coefficient	A dimensionless constant which provides a measure of how an organic compound will partition between an organic phase and water.
LSP		Licensed Site Professional	An engineer, environmental scientist, or geoscientist licensed by the State, who is qualified to assess contamination and conduct cleanups.
LUST(s)		Leaking Underground Storage Tank(s)	Tanks found below ground that are typically leaking fuel. Common on former and current industrial sites and old gas stations.
Mn	■	Manganese	Inorganic metal, widely found and usually not considered a contaminant except when in high concentrations in water.
Mo	■	Molybdenum	Inorganic metal most often associated with mining operations.
MTBE	●	Methyl Tertiary Butyl Ether	Organic compound that is an additive to gasoline. Can exist in both liquid and gas phases.
N	■	Nitrogen	Essential inorganic nutrient needed for plant growth that can become an environmental pollutant from agricultural activities and wastewater.
NASA		The National Aeronautics and Space Administration	The agency of the United States government that is responsible for the nation's civilian space program and for aeronautics and aerospace research.

Abbreviation	Icon for contaminant	Name	Description
Ni		Nickel	Inorganic metal commonly generated from mining and battery-production operations.
NO_x/NO_2		Nitrogen oxides	Component of air pollution (smog and acid rain) created by fossil fuel combustion and automobile engines.
NPL		National Priorities List	List of national priorities among the known releases or threatened releases of hazardous substances, pollutants or contaminants throughout the United States. The NPL is intended primarily to guide the EPA in determining which sites warrant further investigation (US EPA, 2014).
O_3		Ozone	Component of air pollution created by reactions between VOCs and nitrogen oxides as they are exposed to sunlight.
P		Phosphorus	Essential inorganic nutrient needed for plant growth associated with agricultural activities and roadways.
PAHs		Polycyclic Aromatic Hydrocarbons	Class of petroleum organic hydrocarbons that contain difficult-to-break-down benzene ring structures. Associated with fuel spills, coal processing or petroleum manufacturing.
Pb		Lead	Persistent inorganic metal causing widespread contamination in urban areas. Formerly added to paint and gasoline until the 1970s.
PCE/Perc		Perchloroethylene, Tetrachloroethene	Organic chlorinated solvent compound denser than water. Commonly associated with dry-cleaning or metal-working facilities.
PCBs		Polychlorinated Biphenyls	A class of persistent organic pollutants banned in the US since 1979 that do not break down easily. Associated with many types of manufacturing or industrial processes.
PG		Propylene glycol	Organic compound commonly used in de-icing fluids.
Phyto		Phytotechnologies	Abbreviation for phytotechnologies.
PM (2.5)		Particulate matter (small)	Small liquid and solid particles found in the air. Very harmful to human respiratory systems.
PM (10)		Particulate matter (large)	Larger liquid and solid particles found in the air.
POPs		Persistent Organic Pollutant(s)	A group of 24 toxic organic contaminants that do not break down in the environment and exist for a very long time.
RAO		Response Action Outcome	A classification given to a site to designate the level to which significant risks or substantial hazards have been mitigated at the conclusion of remedial action.
RDX		Cyclo-Trimethylene-Trinitramine, 1,3,5-Trinitroperhydro-1,3,5-Triazine	Explosive organic compound commonly associated with military uses.
Se		Selenium	Inorganic metal(loid) naturally occurring in high concentrations in some soils and groundwater.
SO_x/SO_2		Sulfur oxides	Component of air pollution (smog and acid rain) created by fossil fuel combustion and automobile engines.
Sr		Strontium	Inorganic radionuclide associated with nuclear energy production and military activities.
$T/^3H$		Tritium	Inorganic radioactive isotope of hydrogen associated with military activities.

Abbreviation	Icon for contaminant	Name	Description
TCE		Trichloroethylene	Organic chlorinated solvent compound, denser than water. Commonly associated with dry-cleaning or metal-working facilities.
TNT		Trinitrotoluene	Explosive organic compound commonly associated with military bases and some mining activities.
TPH		Total Petroleum Hydrocarbons	A combined measure of all the organic hydrocarbon compounds (can be hundreds) found in a petroleum sample at a given site.
TSS		Total Suspended Solids	A measurement of the amount of particles suspended in water. As TSS increases, a water body begins to lose its ability to support a diversity of aquatic life.
U		Uranium	Inorganic radionuclide associated with nuclear energy production and nuclear energy.
VC		Vinyl chloride, chloroethene	Organic chlorinated solvent compound used to produce PVC (polymer polyvinyl chloride), a type of popular plastic.
VOC		Volatile Organic Compounds	Synthetic organic chemical capable of becoming vapor at relatively low temperatures.
Z		Zinc	Inorganic metal commonly associated with mining, smelting and industrial operations.

1: Phytotechnology and the contemporary environment: an overview

In this chapter, the key background issues and design topics surrounding plant-based remediation are introduced and an overview of the potential use of phytotechnologies in site design work is given. Chapter 1 also includes the current definition of the term phytotechnologies, and outlines the opportunities and constraints of vegetation-based remediation. Previous and current research on the subject is described and an outline of the legal framework in which phytotechnologies are used is provided. Finally, potential innovative applications are summarized as well as projected areas of future scientific and field research.

I What is phytotechnology?

The authors have proposed a broader definition of phytotechnology than is currently available, so as to engage and integrate this work with contemporary site design practices:

> Phytotechnology is the use of vegetation to remediate, contain or prevent contaminants in soils, sediments and groundwater, and/or add nutrients, porosity and organic matter. It is also a set of planning, engineering and design tools and cultural practices that can assist landscape architects, site designers, engineers and environmental planners in working on current and future individual sites, the urban fabric and regional landscapes.
>
> Definition by Kirkwood and Kennen as an expansion of previous definitions (Rock, 2000; ITRC, 2009)

The major focus of phytotechnology in this book is on the plant-based remediation of soils and groundwater. Planted systems for stormwater and wastewater treatment are already commonly integrated in landscape design practice, therefore the book will only briefly address these topics. This work will also touch on air pollution as it relates to the natural ability of plants to bioaccumulate or degrade airborne pollutants or render them less harmful. Phytotechnology implements on-site scientific and engineering solutions to

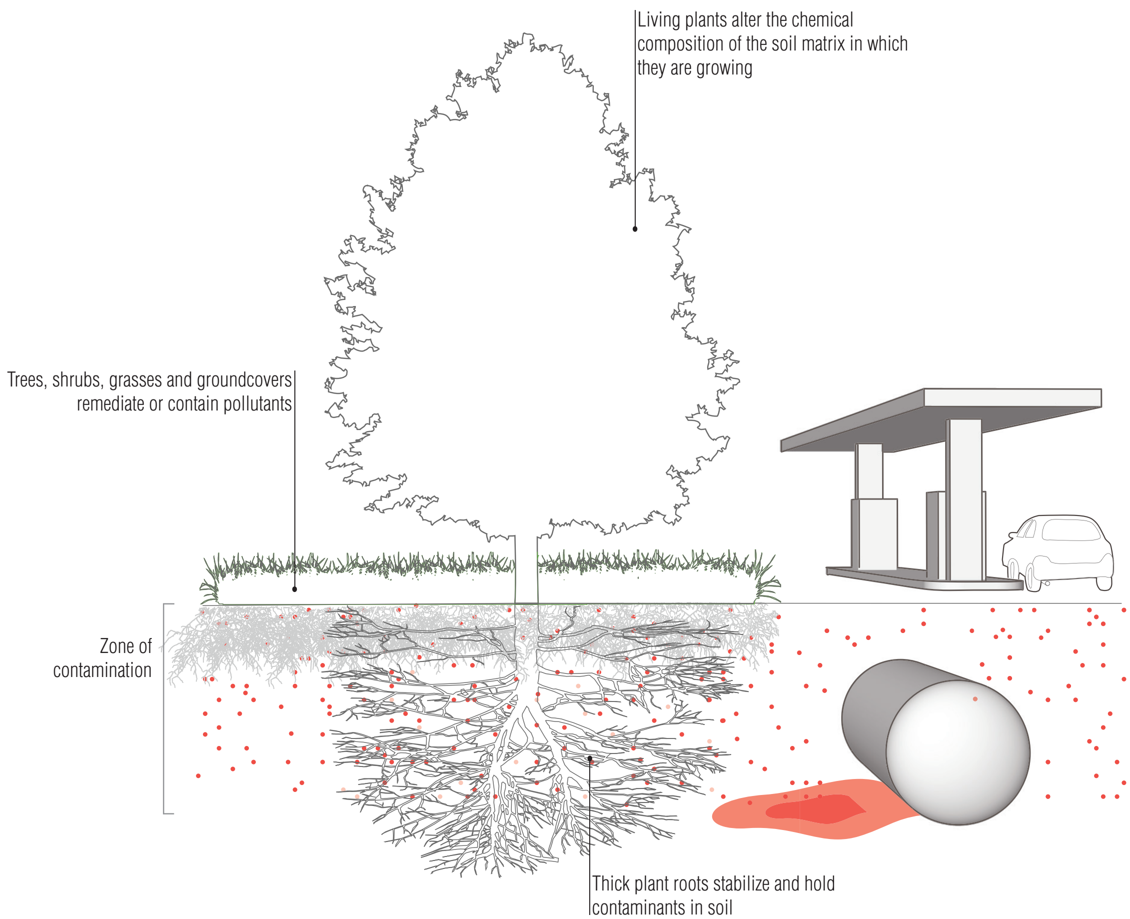


Figure 1.1 Phytotechnologies

contaminants found predominantly in soils and groundwater, via introduced vegetation that is targeted to be self-sustaining and integrated in the site design.

Following the above definition, the background to the term phytotechnology, and in particular its evolution over recent years, is worth describing. Confusion can result from a slight difference between the terms 'phytoremediation,' which is more traditionally used in scientific papers, and 'phytotechnology,' which is seen more in recent literature. Instances are not uncommon where the two terms have been used interchangeably, leading to further confusion about the subject.

II The difference between phytotechnologies and phytoremediation

The term phytoremediation, or remediation by plants, simply describes the degradation and/or removal of a particular contaminant on a polluted site by a specific plant or group of plants. However, in addition to the degradation and/or removal of contaminants, phytotechnology also includes techniques such as the stabilization of pollutants within the surrounding soil or root structure of a plant and the pre-emptive installation of plant-based approaches so as to treat a pollutant or mitigate an ecological problem before it actually occurs. Stabilization utilizing plants does not actually remediate or break down the pollutants but renders them immobile in the soil, thus allowing no further contact to take place between the occupants of the site and subsurface contamination. In addition, the term phytotechnology may also include prophylactic advance plantings on a site that can help prevent contamination that could arise in the future from site activities. Where phytoremediation is typically known to focus on upland plantings for soil and groundwater cleanup, phytotechnology includes all plant-based pollution-remediation and prevention systems, including constructed wetlands, bioswales, green roofs, green walls and planted landfill caps. Taking an even broader view, parks, community gardens and greenways often have phytotechnology components designed into these landscapes, such as protective riparian buffers and vegetated filter strips, where introduced vegetation addresses a range of environmental constraints and pollution control.

Phytotechnologies are based on ecological principles and consider the natural systems as an integral component of human and societal interventions. It is this that makes the use of phytotechnologies integral with evolving landscape architectural design practices. For the remainder of the book the term phytotechnology will be used to describe the comprehensive application of plants on contaminated land and its relationship to the field of landscape architecture and site design.

III Why do we need phytotechnologies?

Recently ‘greenfield development’ or building on formerly undeveloped or agricultural land has tended to overshadow the reclamation, regeneration and reuse of polluted brownfields. In particular, sites that by virtue of past industrial uses are today contaminated, environmentally disturbed, ecologically threadbare and perceived as economically and socially dysfunctional need remediation to become habitable again.

A The brownfield problem and the need for cost-effective solutions

The class of site known as ‘brownfield’ is universal and gaining more attention. The term is not only found across every part of the country, but in almost every nation and across each continent. The sites are often the most contentious type, politically, ecologically, culturally, economically and aesthetically. They include those with leaking or obsolete underground oil storage tanks, such as gas stations, former industrial sites and former manufactured-gas plants. They also include landfills in varying stages of use from active to closure, railroad corridors, burial grounds and Department of Defense (DOD) military lands. Twenty percent of all real estate transfers in the United States are brownfield sites (Sattler et al., 2010), with the current value of these lands in 2010 in the range of US$2 trillion. The US Environmental Protection Agency (US EPA) estimates there are approximately 450,000–600,000 identified sites located across the country, although this number has been considered unrealistically low (US Accounting Office, 1992). More than 16% of global land areas, equivalent to about 52 million hectares, are impacted by soil pollution worldwide (Anjum, 2013). All these sites, whether large or small, nationally or internationally, need a wider range of cost-effective solutions to clean up or mitigate the risks from soils, groundwater, sediments and existing infrastructure of canals, pools, lagoons and buildings found there.

Remediation technologies are, however, very costly, preventing cleanup of contaminated brownfield sites. The majority of traditional remediation approaches are expensive and energy intensive in their approach to quickly correcting an environmental problem that was decades in the making. Among the remediation methods that are under review by regulatory agencies are phytotechnologies, used either singly or in combination with other industry methods such as removing or capping of polluted soils, and mechanical pumping and treatment of groundwater plumes. The cost-effectiveness of phytotechnologies versus traditional remediation-industry approaches is often a significant advantage and the long-term energy required is often less, since phytotechnologies typically do not require mechanical pumping systems, utility power or much supporting infrastructure and equipment. Plant-based cleanup methods can be as little as 3% of the cost of traditional cleanup costs. Examples provided by author David Glass in his reports (Glass, 1999) demonstrate that phytotechnologies are significantly cheaper than the remediation-industry standard methods. For example, pump-and-treat for groundwater, or incineration of polluted soils, are cheaper by a factor of up to one to thirty; and more specialized methods such as thermal desorption, by a factor of one to ten; soil washing, by a factor of one to four; and bioremediation, by a factor of one to two. These figures, however, do not take into account differences based on individual existing site conditions, location and externalities caused by pollutant types and intensity, climate and human factors, such as the needs for ongoing monitoring, maintenance and site security.

The above-mentioned extent of contaminated sites is based on those already discovered, inventoried and being addressed in some fashion in either the short or long term. There still remains the larger number of landscapes and sites that are in private ownership and currently occupied by industry and manufacturing and that can still produce site pollutants or will be occupied in the future with all the potential for further site contamination. The scale of industrial activities and the number of individual sites may be never ending, with attendant levels of pollution. The potential for plant-based remediation to contribute to the larger cleanup work will increasingly include the design professional, by providing a new set of tools for site regeneration and a source of continual new project work.

B The limitations of conventional remediation practice

Conventional industry remediation practices, such as the 'pump-and-treat' (cleaning polluted groundwater through extraction, filtration and recharge methods) and 'dig-and-haul' (where polluted soils, as the name suggests, are dug up and shipped off site), are not only expensive but are single-outcome technologies and have limited site-design potential beyond treatment. Additionally, these traditional remediation approaches are often extremely invasive and disruptive and, by destroying the microenvironment, even leave the soil infertile and unsuitable for agricultural and horticultural uses.

C The build-up of everyday pollutants

The pollution potential of ubiquitous everyday landscapes and installations such as roadways, septic systems and lawn-care applications has recently come to the forefront as a concern. The build-up of contaminants not only affects the surrounding natural resources of an area but also puts a major strain on the local and, in some cases, regional ecosystems. This is due either to prior ignorance of the persistent effects of contamination in the environment, by lack of long-term vision, or to carelessness on the part of local and municipal governments in first legislating for and then administering the overview of environmental regulations. There is a critical need to prevent daily releases of small amounts of pollutants from these widespread land uses.

IV Opportunities and constraints

In phytotechnology the natural properties and mechanisms of living plants are used to accomplish defined environmental outcomes, especially the reduction of chemicals in soils and groundwater. The diversity of available plants also gives versatility to the application of phytotechnology across a range of landscape locations and types. However, many site conditions and pollution situations render phytotechnologies ‘not viable’ for implementation. A review of the opportunities and constraints for using these technologies is provided below.

A Opportunities

The advantages of the application of phytotechnologies are as follows.

- Plant-based systems are natural, passive, solar energy-driven methods of addressing the cleanup and regeneration of several types of pollution-impacted landscapes.
- The process leaves the soil intact, even improved, unlike other, more invasive methods of site remediation used by the industry, such as removal and disposal, soil washing and thermal desorption.
- Phytotechnologies have the potential to treat a wide range of organic contaminants in the soil and groundwater in low to moderately contaminated sites. However, there are also many cases where phytotechnologies are not applicable. Very specific plant and soil interactions must be considered and monitored for their effectiveness, as detailed in Chapters 2 and 3.
- The use of phytotechnology in a variety of landscape-restoration and environmental installations is attractive to scientists, engineers and designers. These include hybrid technologies combining chemical, physical and other biological processes with plant-based methods.
- Vegetation-based remediation, when applicable, has been found to be less expensive in comparison with other, more conventional, industry-based technologies and approaches.
- Public acceptance is considered high, particularly if the site is located close to or within residential neighborhoods, as phytotechnology is a natural, low-energy, visually and aesthetically pleasing remediation technology.
- The application of phytotechnologies can be integrated into other vegetation and landform design strategies and programs proposed for the site. The expansion of the range of natural cleanup technologies at the disposal of the landscape architect during the planning and design of post-industrial sites can be a starting point for design.

- Pollution prevention: Plantings can prevent the spread of future pollution releases and the further environmental degradation of urban land and waterways.
- Indicator species: Vegetal indicators of ecosystem health can be integrated into monitoring and assessment strategies for sites.

1 Ancillary potential benefits

Ancillary potential benefits from phytotechnology applications include such factors as community use, educational use and habitat creation.

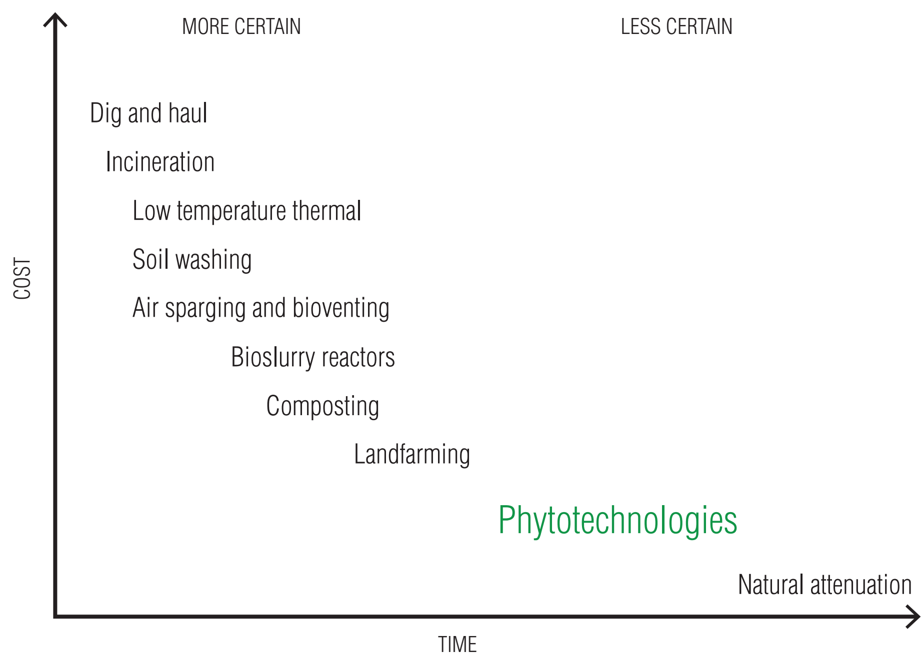
- Community use: The involvement of stakeholders and adjoining neighborhoods can offer opportunities to engage local communities with phytotechnology installations and to provide an additional amenity in areas where green space is limited. This can lead to informal policing and security for the site as well as greater community involvement in the planning and design stages.
- Educational use: Closely related to community use is the potential role for phytotechnology installations in providing an outdoor classroom experience for local students at all levels. In addition, they can be a living-experiment setting for non-students and students alike that can educate residents about the dangers of post-industrial land, polluted soils and groundwater and the natural techniques that are available to provide remedies for the contamination.
- Habitat creation: The introduction of vegetation as a natural remediation technique increases the amount and variety of habitat on a formerly polluted and abandoned site. If this is carefully considered during the design process, phytotechnology applications can increase the canopy cover, nesting sites and potential food available to wildlife without exposing animals to toxicity.
- Biomass production: Remediation plantings may also be harvested and utilized for the production of biomass and energy sources, creating an economic product that may have the potential to offset remediation costs.
- Climate change: Long-term phyto sites can assist in creating microclimates, mitigating climate change and controlling environmental disease.
- Benefit to agricultural systems: New installations of plants on marginalized land can support nutrient cycles, crop pollination and long-term improvement of soils.

B Constraints

The disadvantages of the application of phytotechnologies include the following.

- Many contaminants cannot be remediated with phytotechnologies, or soil/climate conditions are not favorable for their application. In addition, some soils may be too toxic or infertile for any plants to be grown. Contaminant and plant interaction details are provided in Chapter 3.
- The process is limited to relatively shallow contamination sites and is dependent on the adaptability and climate zone of the plants that can be used.
- In some cases, plants may need to be harvested and disposed of as a waste to remove a pollutant; this can be costly and energy intensive.

- Contaminants stored by plants could potentially be released through either transpiration or uncontrolled incineration of harvested plant materials. In addition, when pollutants are taken into plant stems and leaves, a risk of exposure may be created. Humans, animals or insects could consume or be exposed to plants that have stored pollutants, although this is typically not a significant risk factor.
- Once plantings are installed, ongoing maintenance operations may be costly and must take account of adequate drainage, watering, testing and protection for the introduced planting.
- Monitoring may be required and soil- and groundwater-testing practices may be costly or inaccurate.
- The elongated timescale of the phytotechnology installation may preclude its use in short-term site-regeneration projects. Many phytotechnologies take at least 5 years or more to reach maturity and some could be designed as legacy projects, with lifespans of 50 years or more. They require a long-term commitment to management and maintenance by the site owner, as the process is dependent on a plant's ability to grow and thrive in an environment that is not always ideal for normal plant growth.
- Natural systems are variable, and weather, browsing by animals, disease and insect infestations can be devastating or produce unanticipated results.
- Suitable plant stock may not be available from local growers or may require installation during specific seasons of the year.



Compared to other remediation options, phytotechnologies can provide a significant cost savings when feasible, but requires longer treatment time frames. In addition, there is some degree of performance uncertainty in all plant-based systems.
Source: Graphic redrawn from original provided by (Reynolds, 2011)

Figure 1.2 Phytotechnologies Cost Benefits vs Treatment Time

- A lack of understanding of the science, and implementation without the participation of experienced researchers, engineers and scientists, can lead to many improperly designed and implemented projects.
- In more temperate climates the systems may become inactive or much less active in the winter months, and they may not be usable at all in more extreme environments such as are found in Alaska or the Arctic region.
- Current legal, regulatory and economic conditions surrounding remediation using plants may be difficult to navigate. Regulators may not be aware of potential phytotechnology opportunities, and extensive precedent research and explanation may be required.

V The current state of phytotechnologies

A Market share

In the remediation industry, phytotechnologies still account for less than 1% of the market share of remediation techniques carried out (Pilon-Smits, 2005). The lagging use of phytotechnologies is a result of several factors, including

- an inadequate amount of core and applied research and field testing, mostly due to a lack of research funding sources, which have been dwindling in the US since 2001
- consequently diminishing support from federal, state and local regulators
- lack of a proven track record, due to variability in field experiments and lack of metrics of success for novel technologies that do not map well to the traditional metrics of assessment and monitoring for older technologies
- general uncertainty inherent in natural and biological systems
- insufficient available information on systems that do work, preventing their integration into engineering and design practices
- typically, within environmental engineering firms responsible for the design of remediation systems, a lack of staff versed in agronomics or plants, and greater reliability placed in traditional engineering practices, since plant-based systems are not their area of expertise and indeed may be more uncertain
- typically, greater monitoring costs and a longer time frame for remediation.

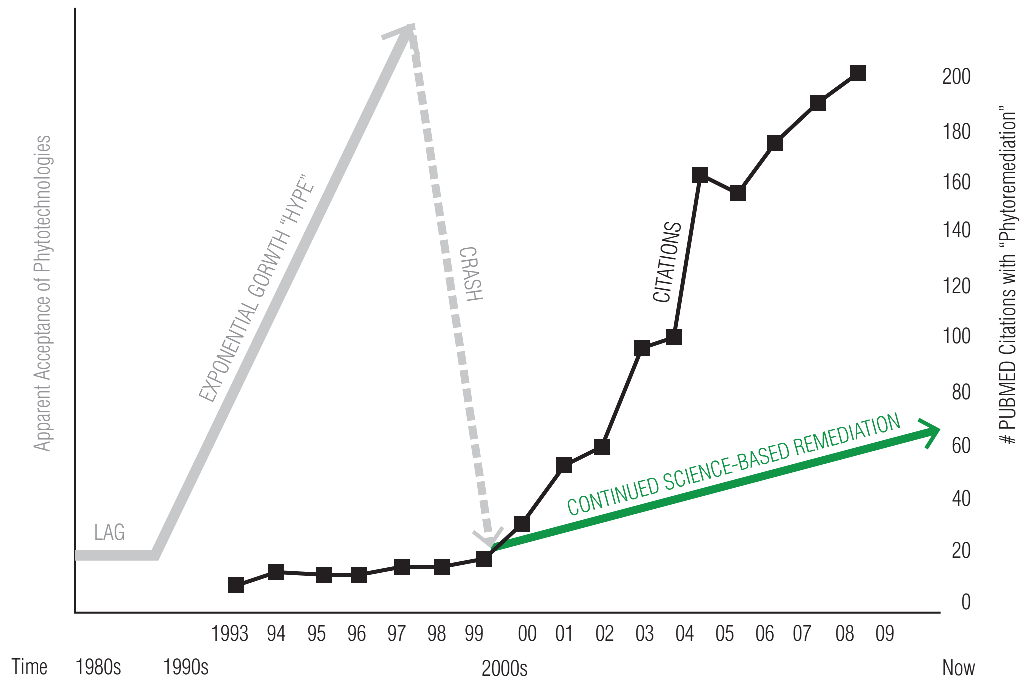
B Perceptions

In addition, there is some dissent both in the sciences and in the field of landscape architecture that either criticizes phytotechnologies as ineffective and not worthy of the community's attention and resources or, alternately, hypes phytotechnologies as the 'silver bullet' for pollutants. The truth lies somewhere in the middle, as some good opportunities certainly exist where phytotechnologies can be applied and there are also many cases where they are not feasible and should be avoided. Typically, misinterpretations arise when old or outdated studies are referenced and utilized, which commonly happens when web-based research is re-referenced over and over again and is not updated for years on end. In addition, many practitioners are not aware of the highly specific plant and soil-based interactions required in phytotechnologies, and applicability and success are extremely site and contaminant specific. Field studies where the environmental conditions, plant and toxins were mismatched and the goal was not reached can harm the reputation of the entire field (US EPA, 2002). Additionally, short-term projects and lab and greenhouse studies may produce successful results that do not effectively translate into field applications, where weather patterns, pests, competition and poor project management are common failure modes that are absent in greenhouse or laboratory studies. Longer time frames than are the norm in conventional methods are often needed for plant treatments to reach performance metrics and remediation goals, but these are not available, due to academic schedules or grant-funding rules. For all these reasons, misinformation surrounding plant applications and the capability of site remedies can quickly spread and generate unjustified preconceptions about phyto.

C History

As described in the Foreword to this book, the field of phytotechnologies in the US was generally named and formally established in the 1980s. In the 1990s a large number of phytotechnology greenhouse and lab experiments were published, leading to a belief in the applicability of plant-based cleanup approaches to a broad range of pollutants in groundwater and soils and site contexts. In addition, a number of plants found to ‘hyperaccumulate’ metals were discovered during the same time period, and speculation arose that these plants could potentially be used for the remediation of metals-contaminated sites. Unfortunately, this generated a lot of excitement and, in a ‘boom and bust’ scenario, advocates of the science overestimated and oversold the technology (White and Newman, 2011). Its performance was mixed, however, and failures in the field outnumbered successes because implementation in the field occurred before the science had been substantiated in the laboratory (White and Newman, 2011). Uptake and remediation of lead by sunflowers, for example, was hailed as an exemplar without the biology and mechanisms being fully understood. When actually applied on real-world sites, it was found that this previously ‘hyped’ technology was unsuccessful at field scale. Interestingly, sunflowers for lead remediation continued to appear in landscape architecture renderings as a phytoremediation application well past 2010, even though they essentially failed in field trials in the late 1990s.

As has been documented by Dr. Alan Baker and Dr. Charles Reynolds, among others, this led in the late 1990s to what was termed an “unmasking phase,” where the unjustified claims led to a crash of the phytotechnology field both in credibility and in funding (Reynolds, 2013). This is commonly termed the “Trough of Disillusionment” that follows the “Peak of Expectations” for new technologies (Burken, 2014). Since then, a very slow but steady flow of scientific research work has been carried out, with growing acceptance by a more cautious and prudent remediation industry and regulatory authorities. Although the concept of phytotechnology is simple, research is slow, complicated and does not map well to the need for quick site remediation. Nonetheless, in many cases phytoremediation still may be the most suitable alternative, compared to the very abrupt, disruptive and expensive process of soil removal and physical extraction of contaminants.

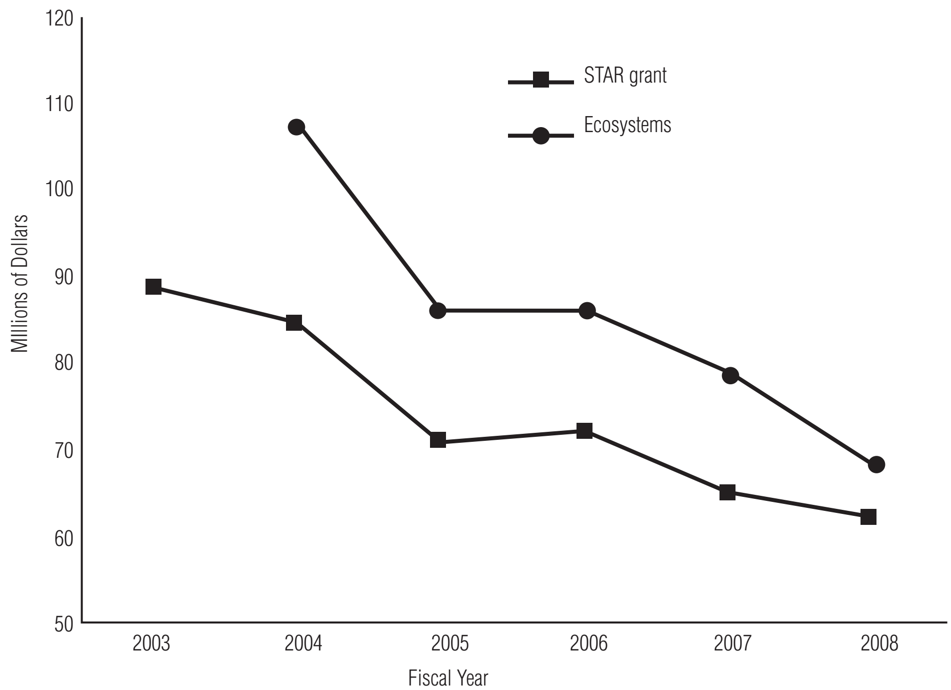


In the early 1990s, the phytotechnology field was just beginning and there was a huge surge in interest that led to overspeculation and 'hype'. Failures in on-site projects outnumbered successes since implementation in the field occurred before the science was substantiated in the laboratory (White and Newman, 2011). The field of phytotechnologies is slowly rebuilding its reputation based on projects rooted in science rather than speculation. Source of Graph: Redrawn from (Reynolds, 2012) (Baker, 2013)

Figure 1.3 Perceived History of Phytotechnologies

D Research funding

For the field of phytotechnology to advance, research funding must be available so that academic institutions can apply for grants to conduct experiments and field trials. In the 1990s, environmental research funding was prevalent. The US EPA was actively funding and participating in phytoremediation projects, and large government departments such as the Department of Energy, Department of Defense, US Army and the US Department of Agriculture (USDA) were sponsoring projects to further phytoremediation research. However, the failed field trials conducted in the late 1990s tarnished the reputation of the phytoremediation field and, with the onset of the Bush administration in 2001, remediation of government-contaminated land was no longer a political priority; government-sponsored environmental research funding in the US started dwindling. In 2005, the Bush administration started cutting the EPA's budget by about 4% per year (Schnoor, 2007). Two important research-funding programs administered by the EPA (the Ecosystem Services Research program and Science To Achieve Results grant funding) have been reduced by millions of dollars in recent years (Schnoor, 2007). The US EPA Hazardous Substances Research Center was eliminated entirely (Burken, 2014). Unfortunately, even under more recent administrations, the EPA's budget has continued to be cut, due to the economic recession and congressional calls for spending cuts (Davenport, 2013). Since 2004, the funding for the EPA's Office of Research and Development has declined by 28.5%, and the



Two important research funding programs administered by the EPA, the research budget for Ecosystems and Science To Achieve Results (STAR) grant funding have been reduced by millions of dollars since 2004 (Schnoor, 2007). This has contributed to a difficult financial environment for phytotechnology scientists looking to fund research work.

Figure 1.4 Environmental Protection Agency's Research Budget

Ecosystem Services Research program has declined by 58% (AIBS, 2013). The current research funding climate for phytotechnologies at the publication date of this book is poor. Funding exists for plant-based biofuels and nano-particles research, so many of the former institutions focused on phyto research have now shifted to those areas or other funded areas of interest. Many formerly active researchers from the1990s are no longer actively conducting research in the phyto field. With the engagement of landscape architects and other professions, hopefully, interest in the field will reemerge and government agencies again will reprioritize appropriate funding for this important area of science.

E Current research

The current state of phytotechnologies research and application includes laboratory, field testing and small-scale site experiments carried out by several US and international institutions and industries. In addition, some US government departments such as the US Geological Survey (USGS), US Military and National Aeronautics and Space Administration (NASA) continue to conduct field trials. A list of sample projects follows in Chapter 3.

The development of phytotechnologies has been aided by growing interest in the subject from a variety of sources, including those planners and engineers focused on sustainable development, city greening and community urban agriculture. There still remain, however, a number of outstanding issues to be overcome.

With the reuse of polluted sites on the rise, and redevelopment a critical component in sustainably moving forward, the potential of utilizing plants to cleanse soil on site is more economically and environmentally attractive than removing contaminated soils off site. Developers, municipalities and site planners are actively looking for alternatives to traditional remediation; however, they do not always have the resources to understand when phytotechnologies might be an option for them. To this end, the International Phytotechnology Society (IPS), a non-profit worldwide professional society with members in Europe, Africa, India, Asia and North America, is leading the development of the core scientific research with guidance from the US EPA. In this way the earlier mistakes of the late 1990s and the 'unmasking period' can be avoided.

VI Legal and regulatory framework

A Remediation projects

Contaminants that may be found on sites are well documented and their properties understood and exposures regulated. The legal and cleanup process in the US is rigorous and the strict legal framework for remediation work must be adhered to in the redevelopment of brownfield sites. Within a regulatory framework there initially arise a number of key questions regarding the use of phytotechnologies as a remediation method.

- What regulatory program is the site designer working with?
- Who are the stakeholders and professionals involved?
- What is the implementation process?
- Where does any waste or biomass produced go?
- What are the overall risk and long-term project goals?

Irrespective of the federal, state or local cleanup program that covers the project site, the extent of effort, the requirements of management and bureaucracy and the final result of remediation should all be the same. The program will depend on whether the project is involved with permitting a discharge or cleaning up a site of pollutants and whether there is a single contaminant or a 'cocktail' of contaminants in a range of media such as soils, sediments and groundwater. A number of the cleanup programs arise from the following:

- Federal Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) 1980, commonly known as 'Superfund'
- Federal Resource Conservation and Recovery Act (RCRA) 1976
- Federal Toxic Substances Control Act 1976
- State Resource Conservation and Recovery Act (RCRA)
- State Site Cleanup
- State Solid Waste

Landscape and redevelopment sites may involve a single entity or a number of these programs in an overlapping fashion. The major difference between the programs is that the federal ones are generally larger, more complex and therefore slower, according to the site conditions. The state programs are smaller, simpler and faster, involving semi-privatized Licensed Site Professionals programs to move project cleanups along in a timely manner, while the federal programs contain specialized programs for leaking underground storage tanks (LUSTs), brownfields, landfills and RCRA Corrective Action, which can produce another layer of complexity and management.

Cleanup of site contamination using phytotechnologies is generally 'risk based', that is, site specific and chemical specific using risk-management techniques based on the future end-uses for the site. The goal is for the site to pose 'no significant risk of harm' to health, safety, public welfare and the environment. Such cleanup can be accomplished by meeting generic cleanup standards and employing a site-specific risk-assessment method tied to end-use, usually referred to as Risk-Based Corrective Action. For example, whether the site will become a park, as opposed to housing, or will remain a light industrial complex will determine the levels of cleanup required.

The stakeholders involved in this work include the following:

- regulators
- other government entities such as planning boards
- the principal responsible parties for the pollution
- development agencies or developers for the site
- landscape architects and site designers and engineers
- future owners and occupants of the site, if known
- adjacent site owners, stakeholders and occupants

The cleanup process works using phytotechnology in five phases.

- Phase 1: Preliminary assessment of Site (Phase 1 Site Assessment)
- Phase 2: Comprehensive site assessment (Phase 2 Site Assessment)
- Phase 3: Assessment and remedial alternatives*
- Phase 4: Implementation of phytotechnology remediation
- Phase 5: Operation and maintenance of phytotechnology installation

* *Note*: In this phase an assessment of alternative remediation methods and techniques is carried out. The assumption is that phytotechnology will be selected as one of the appropriate remedies on the site, and may often be used in a treatment train with other remediation methods. For example, hot spots may first be excavated and removed or chemicals may be injected to encourage contaminant breakdown before the phytotechnology planting is installed. Often, during this phase phytotechnologies may be found not to be applicable on a site. The selection of the remedy is based on the following:

- overall protection of human health and the environment
- long-term reliability and effectiveness
- the ability to be carried out on site

- cost
- attainment of risk-based goals, such as reduction of toxicity, mobility or volume of contamination
- compliance with all federal and state applicable or relevant and appropriate requirements.

Stated more simply, will phytotechnology meet the remedial goals, is it technically reasonable, is the cost reasonable, does it fit with reuse plans and timetables and will it do the job and provide certainty? When the remediation project is completed, a 'Response Action Outcome' or a 'letter of no further action' is issued, or a site delisting from the National Priorities List (NPL) can take place for a CERCLA site, documenting that cleanup requirements have been met.

Impediments to the use of phytotechnologies on a range of sites include: regulatory uncertainty and delays; liability risk in relation to the general public; stigma; and perception of risk by local stakeholders and adjacent landowners attached to sites with phytotechnology remediation approaches and proposals. Among the issues raised by their use are the use of species within the same genera and monocultures, genetically engineered cultivars, ownership, storage, distribution and risk of commercial exploitation. In particular, the following issues have arisen.

- Bioaccumulation: When certain contaminants are present on a site, the opportunity exists for the accumulation of contaminants in the biomass of plants and the potential for toxicity and food-chain transfer. The bioaccumulation of pollutants can create a perception of risk to adjacent communities and stakeholders, particularly in residential neighborhoods. This perception may not be based on scientific data that may be currently available; rather, it may be based on values related to deeply held convictions within the community.
- Contaminated biomass collection: Stakeholders are often significantly concerned about the possible accumulation of contaminants in the biomass of the plants and the future disposal of contaminated biomass off site through landfilling or incineration. Close control of site operations may be required, including the collection of biomass from off the ground, such as leaf litter, fallen bark and branches, and the complete harvesting of plants on a defined schedule.
- Waste disposal: What becomes of the waste generated during remediation, such as vegetation harvested and disposed of as part of the removal process? There are three types of waste: solid, remediation and hazardous; two of these, remediation and hazardous, are relevant to phytotechnologies. In many cases, plants may completely degrade contaminants and they need not be harvested from sites. However, in some cases plant material that has absorbed inorganic contaminants such as metals into roots, shoots and leaves may be classified as hazardous waste for the purposes of disposal. Remediation waste covers those materials from a phytotechnology installation that are not hazardous but still exceed reportable concentrations and come from a listed site.

B Pollution-prevention projects

Phytotechnologies have always been considered a tool for site remediation; however, it has been seen that phytotechnologies can be also utilized as a preventative measure rather than solely as a remediation or post-remediation tool. An example of this is the early use of phyto-buffering, where plants are grown to contain anticipated spills or plumes that might occur below ground at some time in the future. This moves the application of phytotechnologies away from the laws and regulatory frameworks surrounding remediation activities and the control of waste, and towards a horticultural and planning-related set of concerns.

Preventative phytotechnology planting strategies fall under the normal set of planning and local engineering regulations regarding site works, as would any other type of landscape installation. This is similar to the introduction and use of bioswales on a site as a landscape element to divert, capture and cleanse stormwater runoff in a parking lot. The design and installation of phytotechnology buffers can be based on anticipated pollution events.

VII Designer checklist for phytotechnology

A detailed phytotechnology project checklist and decision tree has been developed by Dr. David Tsao and the Interstate Technology and Regulatory Council in the free document, PHYTO 3 (available for download at: www.itrcweb.org). This document details a logical, step-by-step process and series of questions to ask so as to determine if phytotechnologies may be a viable approach on a particular property. The authors refer you to this reference for a detailed project guidance document (ITRC, 2009). However, in order to give the landscape architect every chance of success in executing a phytotechnology installation, a listing of the main items that a practitioner should know before starting follows below.

A Preplanning phase

1 Defining a 'phytotechnology project vision'

Establish a project vision for demonstration, experimental or full-installation sites, to include short-term issues relating to the cleanup or longer-term sustainable goals for the land and its surrounding environments.

2 Site selection

While sites are selected by virtue of their previous or future uses, local knowledge about sites from local municipalities and the community can help to determine priority issues in terms of suitable access points, circulation and adjacency concerns.

3 Data collection to be carried out prior to phytotechnology design

- Soil sampling and environmental testing
- Subgrade and groundwater conditions
- Existing vegetation and wildlife
- Microclimate and weather
- Existing utilities and water supply
- Site boundaries for access and security
- Storage of equipment for maintenance and testing

4 Economic values

Identify loan and grant programs (if available) to assist in both testing and remediation activities.

5 Partnerships with local stakeholders

Consider organization and outreach for educational enrichment, maintenance and public acceptance.

6 Phytoremediation education

Expose clients and stakeholders to the considerable applications of technology, capital and labor at work in the transformation of polluted sites through phytotechnologies. This could involve on-site documentation of remediation and redevelopment processes; interviews and tours with engineers involved in a cleanup; development of individual and group media and arts projects; creation of an interactive technology curriculum that can be used by other communities facing severe environmental threats; and establishment of a project website that gathers the resources and research developed through the project and makes them available to other communities, educators, municipal leaders and environmental professionals nationally and internationally.

B Phytoremediation design and protocol phase

1 On-site remediation

Develop protocols regarding access, security protection, environmental engineering-site practices, supply of plant stock, irrigation/water supply, installation techniques, monitoring and tabulation of results, documentation of site installation and ongoing maintenance. This should be done in conjunction with an experienced phytotechnology expert and may involve several different types of engineers and scientific consultants, including agronomists and hydrologists, biologists, chemists, micro-horticulturalists, foresters, ecologists and civil and environmental engineers.

2 Environmental opportunities

- Consider habitat creation
- Animal shelters/microclimate
- Other productive landscape or biomass opportunities

C Implementation phase

1 Establishment of installation protocols

Once the landscape architect has agreed on a solution for the phytotechnology application an installation protocol needs to be developed. Close work with soils specialists, agronomists, forestry practitioners and maintenance operators will be required.

D Post-implementation phase

1 Maintenance and ongoing operations

- Security of installation area
- Graphics and warning signage for installation area
- Regular weeding, watering and management of area
- Ongoing monitoring and repeating as required

2 Publication of results: best practice workbook or manual

3 Disposal of vegetation material (if required)

4 Reoccupation of phytotechnology site area

VIII Innovative applications

A Integration into daily design practice

As has been mentioned above, phytotechnology planting techniques are currently employed *post* site contamination, to help clean up and remove already contaminated soil or groundwater for some form of reuse or reclamation. Where future pollution may be expected from particular site programs such as gas stations or industrial manufacturing sites, there is potential for planting approaches such as vegetation buffers with preventative phytotechnology abilities. Current phytotechnology plantings are typically of one plant species (monocultures) installed in a field application. Plant combinations can be considered to both treat toxins and create aesthetic and functional compositions. The overall goal is to expand awareness of phytotechnology so that it is not only employed to remediate contaminants that already exist, but proactively used in everyday landscapes. The creation of productive landscapes is the ultimate objective, with plantings that not only have aesthetic functions but also enhance environmental and human health conditions.

B Biomass production

Cultivation of short-rotation willow and poplar coppice was introduced after the oil crisis of the 1970s, with the intention of replacing fossil fuels with new energy sources. Extensive research to identify fast-growing species that could be grown intensively for use in energy production suggested that willows grown in coppice systems were the most suitable. Nutrient utilization and stand management were seen to be more cost efficient for willow than for other woody species, and short-rotation willow coppice proved to be a sustainable way of producing fuels that were carbon dioxide neutral, since burning of the biomass would release into the atmosphere the carbon dioxide that the plants had taken from the air. Willows in short-rotation coppice systems are currently grown, consisting mainly of different clones and hybrids that have been specifically bred for this purpose. In the initial phase, approximately 15,000 cuttings per hectare are planted in double rows, to facilitate future weeding,

Willow (*Salix)* biomass crops resprouting in the spring after being harvested the previous winter. This willow is about a month old above ground on a four-year-old root system (Volk, SUNY ESF, 2014).

Field of four-year-old willow biomass crops just prior to being harvested in the late fall (Volk, SUNY ESF, 2014).

Four-year-old willow biomass crops being harvested with a New Holland forage harvester and coppice header. This system cuts and chips the willow biomass in a single pass (Volk, SUNY ESF, 2014).

Figure 1.5 Willow Biomass/Coppice Planting and Harvesting

fertilization and harvesting. The willows are harvested every three to five years, during winter when the soil is frozen, using specially designed machines. After harvest, the plants coppice vigorously, and replanting is therefore not necessary. The estimated economic lifespan of a short-rotation willow coppice stand is 20 to 25 years.

In recent years other fast-growing species have been used for biomass ethanol production, including grasses such as *Miscanthus* and *Panicum* as well as corn. Poplars may also be cultivated for energy production, including for production of wood pellets. Additional uses for poplars include cardboard and hardwood production.

Recently, many phytotechnology sites have been proposed where willows, poplars or other biomass-production species are simultaneously cleaning soils or groundwater while producing these economic products. This is often an attractive proposition, since utilizing marginal land frees up quality agricultural land that might otherwise have been used for this purpose.

C Economic development

Phytotechnology installations provide opportunities for workforce development in a specialized market. More recently, workers in the general construction industry have retrained in the remediation and reclamation work that is connected to post-industrial sites. Funding for this was provided by the US EPA Brownfield Program, and more opportunities and higher compensation are available to workers in the large number of brownfield lands.

D Carbon sequestration

Poplars are among the fastest-growing tree species in North America and are a central tree used in phytotechnology. They are capable of accumulating enormous amounts of wood and biomass in a relatively short period of time. With selection of appropriate varieties and proper care in site projects, poplars sequester enormous amounts of carbon dioxide in a short period of time. Research on this topic includes screening and selecting poplar clones for growth, and understanding processes of below-ground carbon movement and storage. A future hope is to establish a basis on which poplar trees and other plant species used in phytotechnology projects can be credited for the amount of carbon their plantations are accumulating and to document the chain of custody for a variety of products made from poplars.

E Plant sentinels

In some cases, phytotechnology plants may have potential to serve as detectors for environmental contaminants via aerial and satellite photography with remote sensing. When plants take up certain contaminants, changes in their chemical structure can occur that may have the potential to be read through sensing equipment.

F Phytoforensics

As plants collect water and nutrients from the subsurface, they also collect pollutant molecules and atoms. Developed from the work of Dr. Don Vroblesky of USGS and Dr. Joel Burken of Missouri S&T, phytoforensics uses existing on-site plants – most commonly trees – to identify and delineate subsurface contaminants. This primary sampling method inserts a thin probe (increment borer) horizontally into the trunk to collect cores of trunk tissues (i.e. xylem) that can be analyzed in the laboratory for the presence of pollutants in the tree. The amount of contaminants in the tree correlates to the amount of contaminants to which the roots are exposed. Tree cores that show elevated contamination can point to hot spots below the surface of the ground and provide clues as to the original source of contamination and current spatial extent of pollution. Tapping into available trees in an area that is suspected to be contaminated can help engineers to better and more rapidly delineate contaminants in the subsurface. Traditional groundwater sampling requires the use of heavy equipment to drill into the ground and the creation of sampling wells to draw water from the site. Individual wells can take days to install and months to sample. Phytoforensics is fast and inexpensive (compared to traditional well-testing techniques) and can quickly provide field information about the underlying conditions (Burken, 2013).

The process may involve either coring trunks of trees to gather small samples or inserting sampling devices into the trees in the field. A thin filament called a solid-phase microextraction fiber, or SPME, can detect traces of chemicals at minute levels, right at the tree, down to parts per trillion for many

Core samples of trees are taken with a standard arborist's tree coring device and brought back to the lab in vials for analysis. The samples are analyzed to determine if contaminants are present in the tree (Burken, 2014).

Figure 1.6 Phytoforensics Sampling Tools

compounds (Sheehan et al., 2012). Field portable analysis is beneficial, providing results for the level of contamination in the tree in real time. The use of field gas chromatography mass-spectrometers (GC-MS) has proven to be effective (Limmer et al., 2014), but the instrumentation is expensive to operate. Novel methods to provide similar analysis at less cost are under development.

In Sedalia, MO, for example, well drilling and testing for the solvents trichloroethylene (TCE) and perchloroethylene (PCE) near an abandoned section of railroad took 12 years and placed 40 traditional engineering sampling wells. Working with the environmental consulting firm Foth Engineering, Burken and a team of students spent one day at the site and took 114 tree samples. Their work more accurately determined the extent and locations of contamination, for a fraction of the cost (Burken et al., 2009). In Rolla, MO, Burken's students have used phytoforensics to determine the extent of contamination from the Busy Bee Laundry, which is adjacent to Schuman Park and just two blocks from Missouri S&T and the building where the phytoforensic research was initiated. By testing trees in Schuman Park, the Missouri S&T team determined that solvents from the dry-cleaning operation had seeped into the groundwater of the park, but not at levels hazardous to human health. The USGS is working with the city of Rolla and with funding from the National Science Foundation to remediate the area by planting additional trees to extract the contaminants from the groundwater. The project is expected to remove the contaminants at increased rates and decrease any potential release into Frisco Lake. By deploying a new technique whereby a probe is left in the plant and a small measuring device is brought to the tree, concentrations of pollutants were able to be easily assessed in the trees over a period of years. This project validates the concept of monitoring phytotechnologies through novel plant sampling, versus traditional, expensive groundwater sampling.

Recently, funding from the US Army's Leonard Wood Institute helped to develop new approaches to current phytoforensics methods in order to analyze more water-soluble and nonvolatile compounds. The current methods detect molecules as gases, but explosives constitute a different contaminant type that requires detection as liquid. A method for collecting aqueous samples was developed to aid the military in detecting areas where explosives may have leaked or been spilled on military bases. The method is also being used for perchlorate and several other nonvolatile compounds not previously tested in phytoforensic methods. Through these new efforts and findings, researchers can now detect the presence of trace amounts of explosives, in addition to chlorinated solvents, petroleum, and other organic volatiles.

Recent breakthroughs in the field have included directional analysis of the plume from the coring of a single tree (Limmer, 2013), advances in solid-phase sampler development (Shetty, 2014), real-time/in-field GC-MS analysis and long-term monitoring advances (Limmer, 2014). In addition to detecting the presence of individual contaminants from the soils and groundwater, trees can also be used to detect the timing of contaminant releases into the ground through analysis of the differential concentration of some elements in the growth rings of the tree, termed dendrochemistry (Balouet, 2012). Phytoforensics has been accepted by the USGS as a reliable testing and monitoring technology, and a technology transfer document for more information is available and listed in Chapter 6.

In the future, it may become commonplace to use the existing trees on a site to determine the location of contaminant plumes below the surface and then to monitor the efficacy of phytotechnologies. Monitoring of phytotechnology impacts may have great benefit in gaining acceptance from regulators and site owners who need proof of efficacy in order to validate claims of remediation and pollutant removal rates. Advanced methods in phytoforensics and phytomonitoring mean that contaminants can be detected more rapidly and treated at far lower costs, using a method that offers multiple ecological benefits along with pollutant attenuation.

IX Conclusions

In conclusion, the major barrier to utilizing phytotechnologies in the field remains the lack of complete knowledge about: the process; accepted metrics of monitoring and success; molecular genetics; and biochemical mechanisms of adaptive tolerance in plants to organic and inorganic contaminants. This requires both laboratory and field tests to continue to address contaminant types matched with plant species and to follow remedial treatments over prolonged periods. Research in phytotechnologies has enhanced our understanding in the fields of plant and soil sciences; however, more effective and commercially feasible techniques are still required.

To advance the field, the following needs to happen:

- clearly distinguish those sites, phytotechnology processes and techniques that have been studied the most, and identify those with the best opportunities for potential success
- improve communication and cooperation with the private commercial sector responsible for implementing, maintaining and monitoring these technologies
- exploit new economic opportunities such as the production of bioenergy and bio-fortified crops; long-term remediation activities also provide economic gain
- secure more funding for phytotechnology research for the coming years and exert pressure on federal and private sources to ensure that the primary and applied research activities will continue to be developed, building on the work of previous years.

Large remediation operations usually come in association with significant commercial or urban development projects. Developers and regulators are to be encouraged, along with the design and planning professions, in certain situations to consider phytotechnologies as a viable alternative in site remediation, regeneration and reuse. Commercial soil remediation occurs in relation to: the growth of urban areas or significant infrastructure, where low levels of contamination must be reached; change of soil use; or toxic spills, where urgent solutions are needed to maintain socio-political acceptance. In these cases, conventional remediation options are often the best, due to their rapidity, despite their high initial cost and often detrimental ecological and property impacts. The desire for rapidity makes it difficult for phytotechnologies to compete. Therefore, phytotechnologies are often relegated to projects with low economic value and the following profile: (a) a long-term period is possible; (b) current use of the soil does not imply risks to humans or the environment. These kinds of projects are usually restricted to marginal areas without short-term economic value, such as former mining areas, landfills, DOD lands or post-industrial sites.

For the landscape architect the main lesson here is to understand clearly what the use of these installations can achieve and what it cannot, and to realize that all phytotechnology projects have to be pollutant specific and plant specific. Science-based efforts will avoid repetition of the 'overselling' period where planted installations failed to carry out the specific task of remediation. Projects must also be monitored appropriately to show impacts and results accurately. In addition, the landscape architect has to become familiar with the current research and literature on the subject. In fact, each project site can be considered a unique condition with regard to soils, groundwater and location (climate and context), yet employ standard approaches to design and vegetation that are based on site typologies and an understanding of the history of the site. In this respect they appear to be similar to conventional landscape project sites, yet the true conditions underlying the site – pollutants and their type, location, intensity and state – make these contemporary landscapes both unique and important to confront and address.

Following this introduction to phytotechnology and the contemporary environment, let us now move on to review in Chapter 2 the fundamentals of how plants carry out the remediation of soils and groundwater, and the precise nature of their interaction with organic and inorganic contaminants.