The Green Fuse:
Using Plants to Provide Ecosystem Services

A literature review

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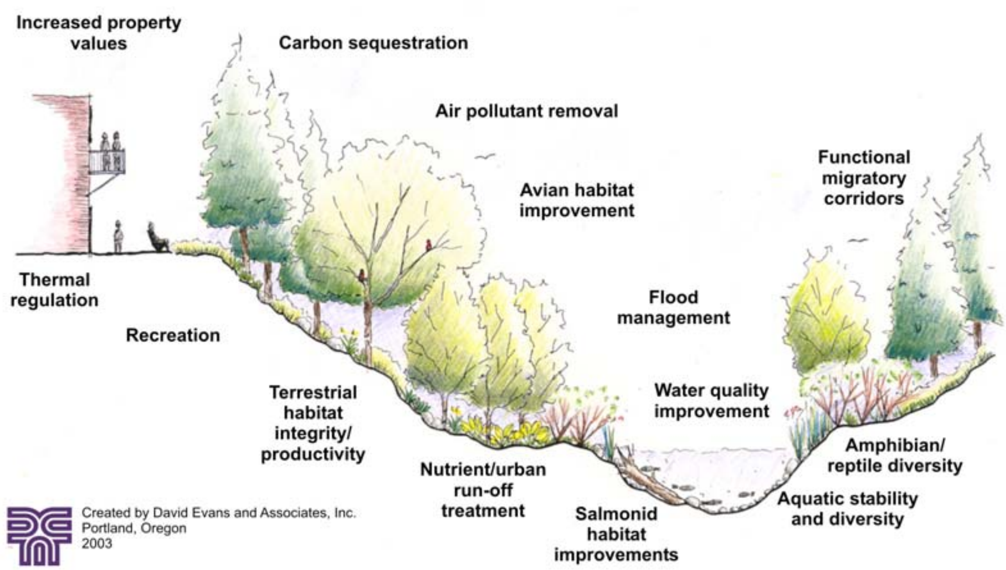
Rene Kane

Contents

Introduction

Plants are uniquely designed to provide a variety of ecosystem services. At their most primary level, plants absorb, filter and release water and oxygen back into the atmosphere. Through their roots, plants take up water and nutrients from the soil, simultaneously absorbing many naturally occurring as well as anthropogenic substances. Through transpiration, plants cool their immediate environment and provide shade for surfaces below. Plants reduce wind speed in urbanized areas, and create microclimates that mitigate extremes in temperature and noise. Plants provide essential habitat for many species of insects and birds, many of which are recognized as important to a healthy ecosystem. From the most diminutive algae to the tallest urban canopy, plants are both “lungs” and ‘liver” for our environment. As an example the figure below illustrates the range of ecosystem services provided along a riparian corridor.



Ecosystem Services provided along a riparian corridor.
(Source: David Evan and Associates, Inc. Used with permission.)

Increasingly, we are relying on plants to provide these valuable ecosystem services across all scales of human activity. In cities, the urban “heat island” is being moderated through deliberate additions to the urban forest, construction of green roofs, and improved care and preservation of existing parks and natural open spaces. New suburbs and towns are being designed to preserve existing green space, relying on constructed wetlands to filter stormwater runoff from streets and rooftops, and reducing the ecological impact of development. On industrial lands, plants are being used to cleanse water that has accumulated heavy metals, and to capture other soil born pollutants. Plants are being utilized to offset carbon emissions from industrial and urban processes. In rural areas, constructed treatment ponds are filtering excess nutrients from livestock waste and planted buffers are filtering runoff from adjacent agricultural fields and nurseries. Plants are being used to restore valuable habitat for threatened or endangered species. Researchers in numerous fields have explored the potential for utilizing, modifying and enhancing plants to be more perfect providers of these increasingly essential services.

How this review was conducted

This literature review is the result of numerous searches via academic, and both governmental and non-governmental avenues including ISI Web of Science, the National Agricultural Library of the Agricultural Research Service (USDA), website of the Environmental Protection Agency, The U.S. Department of Energy, Agricola, J-stor, ArticleFirst, Academic Elite, National Academies of Sciences website, Avery Index to Architectural Periodicals, and others.

How this review is organized

Some uses of plants to provide ecosystem services rely on the *functional* characteristics of plants such as photosynthesis and metabolism, while others rely on the *structural* characteristics of plants as in erosion prevention or sound mitigation. However, the concept of using plants to provide ecosystem services cuts across many disciplines and is conducted at many scales, from a broad landscape or regional approach to a focus on individual plants and their gene structure – a nested hierarchy of scales and applications.

In order to present this information so that it valuable to a wide audience, the review is organized according to a “nested-scale” framework. Each section of the review starts with the landscape scale (as large as watersheds) which includes sites such as a building or agricultural enterprise. The review then proceeds to research that examines the role of individual plants and leads eventually to the scale of genetic function. Not all scales of research are present in each section. The review begins with **Phytoremediation**, perhaps the broadest area of plant-based research, and concludes with **Plants in the Built Environment** which discusses current research into utilizing plants to mitigate the effects of excess stormwater, wind and noise in the designed landscape.

Some areas of this research are well established, others are nascent. This review is designed to be a “working document” that can grow as new research findings are revealed and as new challenges to science and application emerge.

PHYTOREMEDIATION RESEARCH

Phytoremediation is the "use of plants to remove, contain, or transform pollutants" (Bollag and Bollag 1995, p. 5). Phytoremediation includes the categories of phyto-extraction (where plants remove contaminants from soils -- nickel), phytovolatilization (where plants convert soil elements to a volatile state – selenium and mercury) and phytostabilization (plants convert heavy metals to less toxic forms while not removing them -- chromium and lead) (Wainright 1999, 56). Phytoremediation is utilized to treat soils that are contaminated with pollutants such as explosives, metals, various pesticides, PCBs, and fuel hydrocarbons, as well as oil-contaminated soils (ibid.). Phytoremediation is also used to filter out waterborne pollutants such as phosphorous, nitrogen, and pesticides.

Research in phytoremediation techniques and principles has been wide-ranging across disciplines, applied to numerous target contaminants, and conducted at many scales from genetic enhancement to whole landscapes. This literature review aims to describe the range of research across those scales. It is by no means exhaustive, but describes the breadth and depth of research on phytoremediation. For the purposes of organization, the review begins at the largest, landscape scale and proceeds to the smallest scale, that of gene research in phytoremediation.

Phytoremediation: Landscape and Site-Scale Research

At this largest scale, phytoremediation is used to contain or control water and soil borne anthropogenic pollutants. Industrial manufacturing, storage of chemicals, disposal of fuel, agricultural production and processing, transportation networks and facilities, and residential and urban development are all human-generated activities that have been identified as having adverse and cumulative impacts on water quality. While much of the landscape-scale phytoremediation research is focused on non-point source (NPS) pollution, several anthropogenic pollutants have clearly identified inputs and measurable impacts on water and soils. The methods used to mitigate both NPS and point source impacts range from reducing the quantity of pollutant input (e.g., reducing stormwater runoff from roadways; developing alternatives), adjusting the timing of input (e.g., applying agricultural chemicals when the adverse impact is less), and creating physical barriers that prevent a pollutant from entering the waterway. Buffer strips, treatment wetlands, and constructed wetlands effectively prevent both chemical pollutants and sediment from affecting adjacent waterways.

Industrial Sites/Brownfields

Industrial sites (brownfields) pose unique challenges to remediation efforts. Phytoremediation is used extensively to ameliorate the effects of industrial activities and processes, and storage of industrial materials and waste by-products. The increasing need for re-developing impacted sites in urban (and rural) areas has resulted in innovative approaches to using and repairing industrially damaged properties. In Baltimore, Maryland reclaimed brownfields are being used for both luxury residential development and affordable housing. Similarly Portland's south waterfront re-development is reclaiming previous industrial lands. In San Francisco, Crissy Field, part of the Golden Gate National Recreation Area, occupies a former U.S. Army military installation. Since 1997, the National Parks Service has conducted extensive remediation of the Crissy Field landscape, planting over 100,000 native plants (http://www.nps.gov/partnerships/rest_crissy_field.htm).

Westphal and Isebrands outlined both the ecological and social issues present in a proposal for using brownfield phytoremediation in Chicago's Calumet region. Using cottonwood (*Populus deltoides*) and black willow (*Salix nigra*), the authors constructed tank experiments using contaminated soil and water from the target site. In discussing the social aspect of phytoremediation of brownfields, the authors write, "brownfields in distressed neighborhoods are seen by many people on a daily basis…. Residents and workers seeing phytoremediation plantings could potentially experience reduced stress, greater coping ability, increased productivity, and other effects of views of green space" (Westphal and Isebrands 2002) (http://www.brownfields2002.org/proceedings2001/BB-11-02.pdf).

Stormwater/Wastewater treatment
Urban watersheds are impacted by a variety of land uses including agricultural industrial, commercial and residential land uses. The National Water Quality Assessment Program of the USGS focuses on impacts to water quality in urban areas including the widespread presence of contaminants in urban streams, high levels of pesticide residues in urban stream sediment, detected solvents in urban waterways, and harmful impacts on urban aquatic wildlife (http://water.usgs.gov/nawqa/informing/urbanization.html). In the urbanized landscape, the quantity and quality of stormwater runoff is being addressed through various means. New urban development (see below) as well as retrofitted development is being designed to reduce the quantity of stormwater runoff from impervious surfaces such as roofs, sidewalks, and roads. Utilizing existing wetlands in urban areas or constructing new wetlands can reduce the amount of stormwater entering streams and rivers. Constructed wetlands are used to filter out many anthropogenic substances that are carried by stormwater such as street and parking lot runoff that carries the residue of spilled fuel, and runoff from residential yards, golf-courses, parks and commercial landscapes that have been treated with pesticides.

Urban watershed organizations provide information and promote waterwise construction, landscaping and stewardship for both industry professionals as well as homeowners (Connecticut River watershed; Center for Watershed Protection).

The Rocky Mt. Institute publication "Re-evaluating Stormwater: The Nine Mile Run Model for Restorative Development" outlines restoration strategies for urban watersheds. “The techniques are many, but the approach is consistent: "softening" the urban landscape to allow water to soak into the soil where it nourishes plants, recharges aquifers, and supports the base flow of streams during dry periods. Soil and vegetation can also filter, transform, bind up, or otherwise neutralize much of the pollutants found in urban stormwater runoff” (http://www.rmi.org/sitepages/pid277.php).

New Urban/suburban development

Prairie Crossing is just one of many recent residential developments that integrate stormwater treatment throughout the landscape. Utilizing a treatment train, stormwater at Prairie Crossing is gathered from rooftops and streets, conveyed into rain gardens or swales where some of it infiltrates, overflow is then directed to wetlands that filter the water and allow sediments to settle out, and finally the water is deposited into a constructed lake. Other projects recenlt completed or under construction include Coffee Creek in Northern Indiana, and Villebois near Wilsonville.

In a another comprehensive approach Schertenleib, et al, explored the feasibility of closing the “nutrient loop” by integrating environmental sanitation (disposal of human waste) and urban agriculture (Schertenleib 2004, p. 223) as a means to alleviate three significant urban challenges of poverty, food security, and waste management.

Nurseries

The Agricultural Research Service of the USDA is sponsoring specific research into the effects and mitigation of nursery runoff. Albano and Wilson at the University of Florida are assessing the potential use of bioremediation filtration systems to treat nursery runoff (ARS Project Number 6618-13000-002-04). Briggs and Whitwell studied the movement of pesticides generated with container nursery production and found that combination of 6 ft wide water way and cattails (*Typha latifolia*) was effective in reducing runoff of Isoxaben and Thiophane-methyl (herbicide and fungicide respectively) (Briggs and Whitwell 2002).

Stearman explored the effectiveness of several BMPs on reducing pesticide and nutrient runoff from container nurseries in Tennessee. Using constructed wetlands they compared the effects of 2- to 8-day retention times. They found that increased retention time of runoff water significantly increased removal of the herbicide Simazine. Nitrogen removal was 90 percent and 85 percent of phosphorous was removed regardless of the retention time (Stearman 2000).

Agricultural Production Sites

Like many other anthropogenic activities, agricultural production impacts soil and water quality within production areas as well as the adjacent landscape. Water runoff from agricultural fields often contains high sediment and nutrient loads as well as potentially harmful pesticides and metals. Both sediment and agricultural pollutants can adversely affect the quality of water available and place enormous stress on ecosystem health (ARS Project Number 6408-13000-015-002003 Annual Report). Increasingly agricultural producers are being required to reduce the negative impact of agricultural processes on the surrounding landscape. The Agricultural Research Service of the USDA, the Environmental Protection Agency and the Department of Environmental Quality as well as other governmental and NGO agencies support research into the most effective methods for mitigating the effects of potentially harmful agricultural runoff.

Many such efforts are focusing on agricultural watersheds in an effort to improve water quality across a broader area. Knight, et al are developing guidelines for Total Maximum Daily Loads (TMDLs) of sediments in streams, design criteria for controlling stream erosion and restoring stream habitats, and procedures for low-cost, rapid re-vegetation of degraded stream corridors.

Best Management Practices (BMPs) to decrease effects of stormwater runoff containing potential agricultural pollutants were investigated by Cooper et al. Their findings indicate that 99% of the targeted insecticide (esfenvalerate – Asana XL) was retained in the vegetated drainage ditch and they designed a mathematical model that would determine the optimum length for an effective drainage ditch. Similarly Rankins, et al found that the presence of a perennial grass filter strip reduced the volume of total runoff from cotton fields by as much as 55%. They investigated the efficacy of several specific grasses (big bluestem, eastern gamagrass, switchgrass, tall fescue) in reducing herbicide runoff and found that runoff was reduced by at least 59% (Rankins et al 2001, 647). Runes et al found that atrazine was reduced by wetland microcosms via sorption and degradation with less than 12% of the original application amount remaining in the water column after 56 days (Runes et al 2001).

In the Midwest (US) Kovacic et al studied the effectiveness of constructed wetlands in removing non-point nitrogen and phosphorous from agricultural fields that had extensive tile drainage systems. Constructed wetlands removed 37% of the N inputs and when coupled with a 15.3 m buffer strip an additional 9% of N was removed. However, they found that only 2% of the total P was removed over a three-year period. Similarly, Kamppa et al compared phosphorous removal from buffer zones, constructed wetlands, and ponds in Finland. They found that wider buffer zones retained a higher percentage of P, but that the upper part of the buffer retained more P than the lower due to sedimentation as a retention process. Comparing ponds and constructed wetlands (CW) they found that ponds reduced TP loads by 17% while CW reduced TP by 41%, and determined that the difference was due to shallower depths and dense vegetation in the CW (Kamppa et al 2000) .

Soil quality is essential to agricultural productivity and phytoremediation of saline-sodic soils is especially important in arid climates where production is dependent on irrigation and where re-use of irrigation water usually results in a build-up of soil salts. Qadir and Oster (2004) outlined two strategies for improving crop production under irrigated agriculture. The first involves phytoremediation using "agriculturally significant" plant species (Qadir and Oster 2004, 1); the second strategy involves dedicating saline soils to production of salt-tolerant species. The authors outlined several additional strategies for optimizing the use of good-quality irrigation water when plants might be most susceptible to salinity and poorer quality water when plants were less liable to be affected. This coupled with the authors' recommendations on developing markets for salt-tolerant agricultural crops constituted a uniquely broad-based approach to the challenge of soil salinity.

Livestock Facilities

Livestock production facilities can concentrate sources of potential agricultural pollutants and challenge producers to economically and responsibly filter, dispose and manage the effects of effluent and manure.

Wood et al, quantified the ability of constructed wetlands to remove odors from swine facility wastewater. Utilizing gas chromatography they found that planted wetlands were effective in removing 80% and 83% of the dimethyl-sulfide and p-cresol respectively from the effluent and the unplanted wetlands removed 52% and 64 % of the two substances respectively -- not a significant difference between the two treatments. However, a human sensory panel evaluated the efficacy of the two treatments compared to untreated swine facility wastewater. The untreated water was rated as 4 (identifiable odor – offensive, but tolerable) while the rating for both the planted and unplanted treatment wetlands was significantly lower at 1 (Wood et al 2000). In another study, Prantner et al found that a combined soil infiltration system and constructed wetland resulted in significant removal of both N and P (Prantner et al 2001).

Algae have been utilized to scrub nutrients from manure as an alternative to land application which can adversely impact water quality as well as release N into the atmosphere through the volatilization of ammonia. Kebede-Westhead et al conducted experiments on flushed dairy manure wastewater and tested the levels of algal biomass produced, N and P removal rates and the effects of pH.

They found that while maintaining a high pH allows greater nutrient removal, a neutral pH yields great algal biomass and more balanced N:P ratio. They recommended utilizing this method with other processes such as anaerobic digestion.

Phytoremediation: Plant-scale Research

Researchers have investigated the suitability of specific plant species for phytoremediation of substances such as heavy metals, nitrogen and phosphorous, pesticides and petroleum based substances such as gasoline and diesel fuel. Plants that have been identified as particularly well-suited to phytoremediation often have structural aspects such as well-developed root systems that make them more effective accumulators of toxins; rapid growth rates; resistance to a particular toxin; or the ability to metabolize certain toxins without suffering adverse affects.

Pesticides

Karthikeyan et al conducted a review of literature and summarized the responses of nontarget tree, shrub and tree species to various pesticides (Karthikeyan 2004). The potential for such research to inform the effective design and construction of riparian buffers is significant. Some pesticides are degraded in the rhizosphere; others are accumulated and bound or transformed through the plant's metabolism. Certain species are resistant to the pesticides tested, but reasons for that tolerance remain unknown. Other species absorb but do not metabolize the pesticides tested while others accumulate toxic amounts due to their unique structures (Karthikeyan 2004, 96-97).

Nutrients

Wetland plants have been found to be particularly suited for uptake of excess nutrients in waterways, much of which is the result of agricultural and urban non-point sources. Kao, et al investigated the relative N and P retention rates of five different wetland species (including the invasive non-native reed canary grass, *Phalaris arundinacea*). They found that the five species differed markedly in their ability to store N and P in above ground and in below ground biomass and in the percentage of N and P retained after decomposition and concluded that plant structure can be a significant determinant in the suitability of wetland species for N and P accumulation.

Metals

Several metals that result from industrial or agricultural processes pose significant potential harm to humans and wildlife. Reclamation of metal contaminated brownfield sites is increasingly important to protecting urban populations from the effects of long-term storage or exposure to toxic levels of metals.

High levels of Cadmium (Cd) in agricultural soils are often the result of fossil fuel burning, metal refining processes, and the application of phosphate fertilizers and sewage sludge to agricultural soils. Cadmium is highly mobile in soils and its bioavailability to plants is high due to its solubility.

Thlaspi caerulescens has been identified as a hyperaccumulator of cadmium, and Schwartz et al used two different populations, *Thlaspi caerulescens* and *Thlaspi caerulescens* Viviez (from zinc/cadmium smelters in Belgium and France respectively) to compare the root growth and rate of Cd accumulation under different fertilization regimes, and varying availability of Cd. Their findings indicate that root growth increased near localized concentrations of Cd and probably contributed to the enhanced uptake of Cd by *T. caerulescens*. Nitrogen fertilization and a low pH favorably impacted cadmium accumulation. They also noted that the higher uptake of Cd by the *T. caerulescens* Viviez was probably due to the existence of specific and efficient transport channels in the root cell membranes. They concluded that *T. caerulescens* would be appropriate where pollution was heterogeneous and that *T. caerulescens* Viviez would be appropriate in soils where the concentration of Cd was low (e.g., residential garden soils) provided that sufficient numbers of pants were used and soil N was sufficiently available.

Willow (*Salix spp.*) has been investigated as an efficient accumulator of metals including cadmium. Klan-Westin et al investigated a clone of *Salix viminalis* in ten short-rotation willow coppice stands. In Sweden, about 15000ha of willow coppice are used to generate woody biomass for use as fuel in municipal heating plants (Klan-Westin et al 2003, 128). The woody material is harvested every 4-6 years during plant dormancy and a stand is productive for 20-25 years. The researchers found that *S. viminalis* accumulated higher concentrations of Cd in its leaves than in its stems but that the cumulative amount in the stems was magnified by the gains in stem biomass vs. leaf biomass. The researchers found that stands with higher biomass production had lower stem and leaf concentrations of Cd than stands with low biomass production. Soil pH also affected biomass accumulation inversely with high biomass stands found on non-acid soils and low biomass stands on more acid soils. The authors observed that the influence of soil pH on biomass in *S. viminalis* could be due to various factors including the negative effect of low pH on root function (hence lower biomass production), higher Cd concentrations in low acid soils, and a decrease of Cd availability to plants at higher pH. It is common practice to fertilize willow coppice stands with sludge, further adding to soil Cd. However, Klan-Westin found that because of the large output of Cd through stem harvest, the amount of Cd in the stands would not increase over time (Klan-Westin et al 2003).

Lunackova et al studied four willow species and two poplar species for their tolerance to and ability to accumulate cadmium. They noted that relative Cd tolerance for the chosen species was indicated by stomata location, density and function; that the most sensitive species also accumulated the most Cd (*S. purpurea*) and that *S. alba* had both better root growth and higher accumulation than the other plant species (Lunackova et al 2003).

Chromium (Cr) is also a serious environmental pollutant, appearing in soil, groundwater and sediments. Mei, et al assessed the ability of ten economically important plant species to tolerate and accumulate Cr (*Avena setiva* – oats, *Brassica juncea* - Indian mustard, *Brassica napus* L. – canola, *Trifolium brachycalcinum* – clover, *Glycine max* – soybean, *Helianthus annuus* – sunflower, *Hordeum vulgare* – barley, *Lemna minor* – duckweed, *Nicotiana tabacum* – tobacco, *Pinus taeda* – loblolly pine). They utilized two different Cr treatments Cr(III) and Cr(VI), which is more toxic and carcinogenic. In a controlled laboratory experiment, they found that loblolly pine, soybean and sunflower were more tolerant of both Cr regimes. Further study indicated that soybean was more tolerant than either the pine or sunflower and maintained a higher growth rate with both forms of Cr. . However, the researchers also observed that several aspects of sunflower would make it a better bioaccumulator of Cr at low concentrations due to its larger size (Mei et al 2002).

Weis et al found a pattern to the accumulation of metals (Copper, zinc and lead) in two tidal marsh plants, *Spartina alternifolia* and *Phragmites australis* and that leaves of the two plants continued to accumulate metals throughout their lifespan. That accumulation varied widely, however, from leaf to leaf on the same plant. Their findings impact further research into the capabilities for these plants to accumulate metals as well as the impact on wildlife that may forage on these two species (Weis et al 2003).

Petroleum and related contaminants

Diesel fuel, gasoline and oil are common contaminants in both urban and rural environments. Tesar, et al studied the effects of various concentrations of diesel fuel on the rhizosphere bacterial communities of several clones of black poplar in order to identify plant/microbe combinations that would be suitable for remediation of diesel fuel. They isolated several strains of bioremediating bacteria that were associated with given plants and further identified a promising plant-microbe combination for remediation of diesel contaminated soils (Tesar 2002).

Phytoremediation: Gene-scale Research

Arabidopsis thaliana is a relatively efficient accumulator of arsenic, a soil contaminant. However, arsenic is not readily transported to the leaves of most plants and so cannot be easily harvested. Doucleff and Terry (2002, 1094) overexpressed two genes in *Arabidopsis* that resulted in greater movement of arsenate from root to leaf as well as increased accumulation of a catalyzed form of arsenate that is less toxic to the plant.

Arabidopsis is also considered a hyperaccumulator of mercury. Lasat described a process where *Arabidopsis* and tobacco plants were bioengineered to express bacterial genes that converted mercury to a less toxic, volatile element that is then released into the atmosphere. Brewer et al generated hybrids between another hyperaccumulator *T. caerulescens*, and canola (*Brassica napus*) that resulted in a high biomass hybrid that had superior zinc tolerance (Lasat 2001).

Phytoremediation research at the scale of sites and whole landscapes coupled with related research regarding the effectiveness if specific plants can inform agricultural practices, land use decisions, regulatory frameworks and policy directions. Multi-scale information that is widely available can improve our ability to mitigate the effects of damaging anthropogenic processes.

CARBON SEQUESTRATION

Carbon sequestration is part of the natural carbon cycle. Carbon is sequestered in plants through the process of photosynthesis, sequestered in soils by conversion into inorganic carbon compounds (such as calcium and magnesium carbonates), and in oceans as dissolved CO_2.

The U.S. Department of Energy measures the global carbon cycle in billions of metric tons or *gigatons*. The two major anthropogenic sources of carbon are the burning of fossil fuels for electricity and cement production (6.0 gigatons annually), and changing land use (1.4 gigatons annually). Globally, vegetation accounts for a net annual sequestration of 1,960 gigatons of carbon (USDOE NETL 2000).

Research studies have addressed carbon sequestration at various scales. At the federal level, the USDOE (Net Energy Technology Laboratory and Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems), USDA, as well as NGOs such as The Climate Trust and Utilitree have investigated the feasibility of long-term carbon sequestration in vegetation and soils, the effects of various management practices on carbon sequestration in agricultural and forest landscapes, and the economic feasibility and potential of carbon offsets.

Carbon Sequestration Research at the Landscape Scale
Researchers at the University of Washington and Oregon State University attempted to determine the upper bounds of carbon storage potential in northwest forests by examining several old-growth forests in western Washington and Oregon. They estimated both above- and below-ground tree C including stem wood, stem bark, live and dead branches, foliage, live and dead coarse roots, and fine roots and estimated the understory, detritus and soil carbon for all stands. By establishing these upper bounds, the researchers hope to provide guidance for resource managers on selecting appropriate sequestration strategies (Smithwick et al. 2002).

In Oregon, the Forest Resource Trust operates as a carbon dioxide offset project by providing financial assistance to private landowners who implement forestation projects on "underproducing" lands that are "occupied by pasture, agricultural crops, light to heavy brush, or scattered to dense noncommercial tree cover" (Cathcart 2000, 33). In 1995, 22 such projects were implemented covering 974 acres. Since then, the Klamath Cogeneration Project has also invested in the Forest Resource Trust to produce offsets for 1.16 million metric tons of carbon emissions (2.8 percent of the total) from its plant in Klamath Falls (Cathcart 2000). The Forest Resource Trust has developed a process of carbon accounting that considers the amount of short-term stored carbon that fluctuates with the growth and harvest cycles as well the long-term stored carbon in the offset projects.

Although the soil carbon pool is about three times that sequestered in terrestrial vegetation, effective carbon sequestration efforts must consider the interrelationship between soil carbon and that stored in terrestrial vegetation. "…[S]oil carbon ultimately derives from vegetation and therefore must be managed indirectly through aboveground management of vegetation and nutrients. Hence the response of whole ecosystems must be considered in terrestrial carbon sequestration strategies" (Unkefer 2001, 127). Research into this interrelationship has focused on increasing vegetative biomass by including multiple plant species (Pfannstiel 1999), as well improving soil nutrient quality (Knight and Unkefer 1988), and developing management practices that increase soil carbon. Other research has been aimed at developing tools for effective modeling of carbon and nitrogen in managed landscapes (Qian et al 2003).

West et al studied the effects of cropping practices, yield and land use change on fluctuations in soil organic carbon in agricultural ecosystems (West et al. 2003). They compared several management practices (conventional till and no-till), and four different nitrogen application rates in plots of corn (*Zea mays*) and a winter cover crop of rye (*Secale cereale* L.). With the assumption that decreases in crop yield would be an unacceptable result of changes in management strategies, they determined that "If yields decrease, emissions associated with the additional lands necessary to replace lost yields can offset the savings in emissions associated with decreased rates of fertilizer application or the increase in SOC [soil organic carbon] that may have occurred from a change in agricultural practice" (West et al 2003, 82).

Agroforestry systems are most often found in tropical areas and combine agriculture and forestry to yield multiple crops. Although agroforestry exists in Canada and the US it is still an emerging agricultural practice. Montagnini and Nair (2004) studied the potential for carbon sequestration in agroforestry systems and results of their study may impact the wider acceptability of multi-crop strategies for carbon sequestration. Montagnini and Nair noted that agroforestry systems in tropical areas were less effective at C-sequestration than the mature tropical forest they generally replaced; agroforestry systems accumulate considerably more C than the monoculture of annual crops; and that agroforestry with perennial crop-tree combinations were better C sinks than intensively managed agroforestry systems. Their research on the C-sequestration potential of agroforestry systems was complicated by the lack of information on 1) the extent of current or potential acreage in agroforestry; and 2) carbon storage and dynamics in agroforestry systems. This last measure is further complicated by the wide variety of cropping practices and crops grown in agroforestry systems.

Urban forest systems also sequester carbon. American Forests estimates that in the Portland metropolitan area, trees store 12,516 tons of carbon annually and remove over 2 million pounds of airborne pollutants every year. With respect to the value of removing that air pollution American Forests estimates the cost savings to be about $4.8 million (American Forests 2001). More recently, ECO Northwest and David Evans and Associates conducted an ecosystem services valuation for the Lents Flood Abatement Project in Portland and found that the project would save over $1200 annually by removing one ton of CO emissions (City of Portland Watershed Management Program 2004).

Carbon Sequestration Research at the Plant Scale
Research into the potential for carbon sequestration at the plant scale includes examination of the capabilities of individual plants as well as combinations of plants. This research contributes valuable information to C-sequestration at the landscape scale by determining the best plants for C-sequestration projects, the value of multiple-species plantings and the interrealtionahsip between Carbon sequestration and other plant/soil processes.

Kaye et al studied carbon sequestration in a *Eucalyptus saligna* tree plantation. They found that plantations that were interplanted with *Albizzia falcataria* (a nitrogen-fixing legume) had twice the levels of C storage as a monocrop plantation (Kaye et al 2000).

Houpis et al found that Ponderosa pine seedlings responded to increased concentration of atmospheric carbon dioxide by exhibiting increased rates of photosynthesis (Houpis 1999). However, Temperton et al studied the growth and nitrogen-fixing response of alder to elevated CO_2 and found that *Alnus glutinosa* showed increased N-fixing and photosynthesis regardless of supplemental nitrogen concluding that elevated CO_2 would benefit alder grown on poor soils more than alder grown on fertile soils (Temperton et al 2003).

Looking at mature oak trees (*Quercus ilex*) Marek at al measured the effects of elevated CO_2 concentrations on photosynthesis in oak leaves. They found that regardless of sun exposure and consistently over time, the rate of photosynthesis was higher for trees exposed to higher CO_2 concentrations. Because there was no apparent photosynthesis acclimation over time, the authors speculate that *Q. ilex* as well as other tree species may pose greater potential for carbon sequestration than was previously estimated (Marek et al 2001).

Like research in phytoremediation, research into carbon sequestration at both the landscape scale and the plant scale are mutually informative, serving to advance knowledge of the applicability of specific plants, crop management strategies, and the value of landscape ecosystems to reducing the impacts of carbon emissions on the environment.

Plants in the Built Environment

Plants provide one of the most striking counterpoints to urban development. In gardens, front yards, backyards, along streams, and increasingly on top of buildings, plants supply much needed "nature" in the city. This section reviews research on green roofs, green walls, and the use of plants to mitigate the effects of noise and wind. As in previous sections, the nested scale approach to presenting information is used here.

Green Roof Research: City/Region Scale

In 2000, Germany had 10 million square meters of green roofs (Kwik 2000); in mid-1990s Chicago launched a $1.25 million USEPA study to test the efficiency of green roofs for cooling the city (Kwik 2000); Portland's most recent green roof project is over 16,000 square feet (Hauth, personal communication 2004). Green roofs cool buildings, capture and filter stormwater, provide wildlife habitat, reduce the urban heat island effect, provide a valuable aesthetic and recreational experience, and sometimes food, for urban residents. New buildings are being designed to include green roofs and historic buildings are being retrofitted to accommodate the increased weight of plants, substrate, and water (Ferrante 2001). Green roofs also save money over the long term since the cushion of plants and soil eliminates the conditions that usually contribute to the rapid degradation of a conventional black membrane roof: UV radiation, extreme fluctuations in surface temperature, and foot traffic (Solomon 2003).

There is an extensive array of technologies, approaches and design solutions in green roofs. Some of this information has been developed by private or commercial firms and is proprietary. However, several governmental agencies and academic institutions in the U.S. are conducting research that is yielding important information about plants, substrates, and the performance of green roofs at several scales.

Ferrante and Mihalakakou (2001) applied a computer model (TRANSYS) to Cantoni, a city near Milan, Italy to estimate the effects of a comprehensive approach to integrating “green and passive” techniques with restoration of historic industrial buildings. They modeled the cumulative effects of numerous approaches - green roofs, atriums, and passive solar and natural cooling techniques - on the building to be re-developed. Their thermal performance calculations indicated that combining an indoor atrium and an insulated greenroof, for example would result in more energy efficient control of indoor air temperature (Ferrante and Mihalakakou 2001).

Likewise, Theodosiou utilized a similar model for building energy simulation to focus on green roofs used for passive cooling. By converting the planted roof to a physical model with 12 nodes and corresponding coefficients, he was able to model the interactions between the numerous components of the green roof. For instance, he accounted for the effect of taller vegetation shading (and cooling) the substrate below, the effect of different substrate depths and the conductance coefficient of roof insulation (Theodosiou 2003).

Green Roof Research: Site Scale

Chicago and Portland, Oregon are at the forefront of cities adopting green roof technology in the U.S. In Chicago, a 33,000 square foot green roof tops Chicago’s retrofitted City Hall. In Portland, “ecoroofs” top garages, Multnomah County’s administrative building, affordable housing and college housing.

Hamilton West, a cooperative effort between BES and the Housing Authority of Portland is a ten-story mixed use building constructed in 1999 and its ecoroof has been monitored for water quality, stormwater retention and peak intensity attenuation. In addition BES tested two different substrates 1) 15% digested fiber/25%encapsulated Styroforam/15% perlite/15%peat moss/15% compost and 2) 20% digested fiber/10% compost/22% coarse perlite/ and 28% sandy loam. BES staff collected information on the vegetative characteristics of the roof, wildlife, and substrate conditions over time and human activities. Water quality samples were sent to the BES lab for testing of dissolved substances, phosphorous, pH, and organisms such as *E. coli*. Among other findings (see Hutchinson et al, nd) BES found that stormwater retention approached 69% and increased between 2002 and 2003 owing to differences in rainfall patterns between the two years and to vegetation maturity. BES compared the ability of the ecoroof to manage stormwater from four different typical rainfall events: high volume, short-duration winter and summer storms, low intensity high volume winter storms, and low intensity low volume winter storms. They found that "even when the substrate is saturated, the ecoroof system attenuates the intense run-on peaks of even the largest storms" (Hutchinson et al, nd.). Additionally, BES found that because the ecoroof reduced the volume of roof runoff, it could significantly affect loading levels for target substances.

In Toronto Macmillan (2004) found similar results from an experimental roof at York University. There, a web-based monitoring system archives data on all climate and hydrometric measures (www.sustainabletechnologies.ca). McMillan has found that total runoff has been reduced by 55% and peak flow was reduced by 85% for smaller storm events but was less for larger events. The green roof exceeded increased concentrations for most metals, bacteria, and several nutrients. McMillan also found that compared to the control roof, the green roof has larger pollutant loadings (for total phosphorous, phosphate, and most metals), but less suspended solids and less loading of N complexes (McMillan 2004).

Moran et al studied plant growth and runoff from two extensive greenroofs in North Carolina. They measured the effects of two different substrate depths (2 and 4-inch) as well as quantity and quality of roof runoff. Similar to the Portland BES study, Moran et al found that both roofs retained about 60% of the total recorded rainfall and reduced the average peak flow by 85%. High concentrations of total nitrogen (TN) and total phosphorous (TP) were found in runoff from both roofs and the authors attributed this to high amounts of organic matter (compost) in the substrate composition. Ina laboratory column study of the substrate medium, they found that TN decreased over time and speculated that the same conditions would occur on the green roof.

Researchers in Vancouver, Canada found that their monitored green roof on top of the Vancouver Public Library was more effective at capturing runoff in smaller storm events vs. larger events as they expected. They modeled the effects of runoff on a traditional (torch on membrane) roof, pre-development conditions, and the green roof with 14" of growing medium and determined that the green roof could potentially reduce runoff by 70% and attenuate summer peak flow by as much as 80%, summer peak flow by 30% (Johnston et al 2004).

Beattie and Burghage (2004) developed recommendations for considering soil substrates for green roofs. They considered the weight, water-holding capacity, pore-space, pH, nutrient capacity, considerations regarding cation exchange capacity, and depth of the medium on green roof functioning and suitability in various climates. As mentioned in previous studies, the presence of nutrients or heavy metals may pose additional challenges in identifying a suitable medium for a green roof. The authors conclude with the recommendation that suitable substrates for green roofs should be specified for the climate and intended green roof plants and construction (Beattie and Burghage 2004).

The thermal properties of the green roof substrate influences plant growth as well as affecting the insulating qualities of a roof. Researchers in Greece studied four different substrates for temperature fluctuation and growth of *Lantana camara*. Using sandy loam soil (S) as a control, Tsiotsiopoulou et al tested substrates consisting of 1) sandy loam soil amended with urea-formaldehyde resin foam (S:F); 2) sandy loam soil amended with peat and perlite (S:P:Per); and 3) peat amended with urea-formaldehyde resin foam (P:F). Their results indicate that substrates with higher bulk density such as the sandy loam soil had greater temperature fluctuation than those with lower bulk density such as the peat and resin foam formulation. Plant growth rate also affected substrate temperature. For example, in the S:F substrate, plants grew rapidly at first, leading to faster rates of water loss from the substrate and a corresponding increase in substrate temperature (Tsiotsiopoulou et al 2003).

Plants in green roof systems need to withstand exposure to extreme cold as well as extreme heat. Boivin et al studied the effect of substrate depth on the degree of cold injury to plants growing on a green roof in Quebec. Six herbaceous perennials (*Ajuga reptans, Arenaria verna 'Aurea', Armeria maritima, Draba aizoides, Gypsophila repens, Sedum x hybridum*) were planted into three substrate depths 2, 4 and 6 inches. Their results indicated that the effect of substrate depth was more pronounced in *Sedum* than in *A. reptans, A maritima,* and *D. aizoides* and that the 2-inch substrate over all was most effected by low temperatures with a significant fluctuation in soil temperature. Boivin et al recommended a 4-inch substrate depth for the particular green roof technology being used (Sopranature) (Boivin et al 2004).

Green Roof Research: Plant Scale

Plants on green roofs must withstand extremes in water availability, shallow soils, heat and wind. In Michigan, Duhrman et al tested three species of sedum, a native herbaceous perennial and a native grass for their adaptability to various water regimes. They measured drought tolerance of the five species and found that the two native species (*Coreopsis lanceolata* and *Schizachyrium scoparium*) were unable to withstand fewer than two days between watering. The Sedum species (*S. kamtschaticum, S. acre,* and *S. reflexum*) were able to withstand up to 88 days between watering, but with reduction in the rate of photosynthesis. In a related study, Duhrman et al compared the growth of 25 Crassulaceaen species in three different substrate depths. Using digital photographs of the plant cover and image analysis software, they determined that substrate depth was positively correlated to plant growth as a result of “greater moisture retention and root protection from temperature fluctuations” (Duhrman 2004, 9). They also found that information on the growth characteristics of plant species is essential for design of a heterogeneous planting palette in order to predict competition and plant succession (Duhrman 2004).

In Milwaukee, the Metropolitan Sewerage District experimented with using native plants and the commercially available Green-Grid roof system. The district selected a combination of native grasses and forbs that could withstand summer conditions typical in the Midwest and planted the roof using plugs and seeds. Complete results from this project will be available in the third year, however initial success rates for plant establishment were generally good with some plants thriving and setting seed in the fall, and others unable to withstand the extreme conditions of the roof. Some damage from gulls was recorded and the district is experimenting with methods to discourage nesting in the rooftop cells (McCarthy 2004).

Chiaffredo and Danayer (2004) explored plant dynamics in a green roof system a nd suggested that mosses could be an accepted, even preferred, option to the more common green roof planted with what they term “horticultural vegetal species (introduced species, ornamental plants or cultivars)” (2004, 5). They developed a process to inoculate soils with mosses and small amounts of native seed in order to initiate a more natural plant succession, what they term “renaturalization” (2004, 5) and propose further research into the application of their method to green roofs.

Still other research has examined the use of supplemental mycorhizza and soil microorganisms to enhance the quality of green roof substrates that are, by necessity, low in organic matter. Meyer tested the effects of two commercially available formulations on the growth of plants in a mixture that included herbaceous perennial species as well as sedums and related species. He found that the best results were obtained with the application of a combination of both soil microorganisms and mycorrhizal fungi, and that surface application (rather than substrate application) yielded better results (Meyer 2004).

Green roofs are being adopted throughout the US and have become an established architectural component of many European cities. Green roofs not only add a valuable aesthetic component to roof tops but have been proven to effectively modify the urban environment. In some cases, food crops are grown on green roofs, adding yet another dimension to their use. Coffman and Martin analyzed the sustainability of an agricultural green roof in Chicago by evaluating the total energy and resource flow of the roof. This included the energy inputs required to build and maintain the green roof (materials, labor and construction) and outputs of produce, together termed “emergy”. They then compared green roof indices to various indices of energy inputs/outputs and affects on the local ecosystem for traditional agricultural systems, constructed landscapes, and a city to develop a measure of sustainability for the green roof. While the green roof scored in the middle of the sustainability measure, the study did not take into account the stormwater and urban heat amelioration effects of the green roof and recommended additional research to reach a more accurate evaluation (Coffman and Martin 2004).

Green Walls

In contrast to green roofs, there is comparatively little definitive research on the benefits of green walls. A few brief mentions in the popular press and several resources (in German) indicate that green walls could contribute significantly to improvements in urban environmentally quality. A more extensive discussion of green walls appears in *Planting Green Roofs and Living Walls* (Dunnett and Kingsbury 2004). Peck (1999) discusses several potential environmental impacts of green facades including reduction in temperature of the exposed exterior, reduction in the heat island effect, and reducing wind chill, while Dunnett and Kingsbury cite a study by Kohler (1993) of *Parthenocissus tricuspidata*. Dead leaves and wood of *P. tricuspidata* were shown to have concentrations of lead and cadmium, although the mechanism through which bioaccumulation occurred was not indicated. Biodiversity benefits of green walls include habitat for invertebrates that subsequently attract birds, and shelter and nesting sites.

Additional research in Germany has been focused on the suitability of various climbing species for green walls including their potential for damaging the façade, suitable soils, maintenance and supports. Several manufacturers (both US and in Europe) have developed cable systems for green wall application and for some innovative projects the plant support is designed as an integral part of the building façade.

Mitigating Noise and Wind

Plants are frequently used to reduce the impacts of noise and wind in rural environments as well as in urban environments. Shelterbelts are a common component of the agricultural landscape, particularly in regions where prevailing or seasonal winds can result in extremes in temperature affecting both crops and rural inhabitants. In urban areas plants are used to create microclimates at the site scale, reducing fluctuations in temperature and modifying wind patterns. At a larger scale, masses of trees and vegetation are used to reduce the effects of noise where residential neighborhoods intersect with roads, and highways or other noise-producing activities.

In the U.S. as well as in Europe, noise barriers are planted to mitigate traffic noise along highways. Kotzen (2004) termed these “Environmental Noise

Barriers” and outlined the basic considerations for designing effective barriers including aesthetic considerations for both the highway user and the adjacent residents, and transparency to reduce visual impact. Kotzen recommended a combination of earth mounding and dense mixed species planting was most effective in reducing the impact of highway noise. He further determined that a planted “bio-barrier”, a green wall, also took up less space (approximately 18%) than an earth mound of equal height (Kotzen 2004).

In an urban park (National Garden of Athens), Papafotiou found that both vegetation composition of the gardens and topography determined noise levels. More open landscapes - lawn, planting beds and paths - provided less noise protection than taller vegetation and the portion of the garden below street level was less impacted by noise as well (Papafotiou 2004).

Plants for noise barriers, particularly those that are constructed modular systems need to withstand extremes in temperature, availability of water, wind, and soil conditions while maintaining an acceptable appearance. Eppel-Holz (2004) studied four wall systems, four different substrates, two “core” materials, and 41 species of perennials and shrubs that were known to perform well under water/temperature/soil stress. Results show that the concrete system was preferable to other materials (combinations of wood, jute, steel), and the “core” materials (local soil and crushed rock) showed no significant difference. The substrates were topsoil and topsoil lava combinations and two commercial soilless mediums. Plant performance varied over the duration of the study (1998-2001) with the perennials performing better over all than shrubs. Substrate performance was comparable across all four substrates. Results show that concrete systems with connection to a “core” are better for plant performance and supplemental watering during extreme drought was recommended (Eppel-Holz 2004).

Conclusion

This review offers a window into the broad reaches of plant-based research. As we uncover new ways that plants can assist us protecting healthy natural resources and improving those that have been adversely impacted by human activities, the body of research and practice that is represented will continue to grow.

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