Systems Agriculture: Towards a Sustainable Agricultural and Environmental Policy

Bruce W. Ferguson
Edenspace Systems Corporation
Dulles, VA

Edenspace Systems Corporation seeks to transform industries with innovative plant-based services and products that protect health, increase property values and improve environmental quality. Within the general area of environmental phytotechnologies, the company has specialized in the use of plants to extract minerals from soil and water, with more than three dozen successful contracts completed or ongoing. Current company research seeks to develop multi-trait plants for biosensing, phytoremediation and renewable energy.

The company's 6-year experience as a commercial pioneer in environmental phytotechnology has provided it with an unusual perspective on the intersection of agriculture, biotechnology and the environment. Four of Edenspace's current projects illustrate some of the opportunities and challenges presented by this confluence:

- using ferns to remove arsenic from soils in a Washington, DC, suburb;
- engineering plant biosensors—"phytosensors"—to detect and monitor environmental parameters such as heavy metals;
- engineering plants to produce higher yields of ethanol per acre; and
- forming a new agricultural cooperative to provide additional income to producers who work on environmental projects.

After summarizing these projects, I will list some conclusions and recommendations as to where agriculture, biotech and environment may intersect in the future.

Environmental Phytotechnology Projects

Arsenic Phytoremediation

In 2005, Edenspace expanded a project with the US Army Corps of Engineers to remove arsenic from soils of residential properties in Washington, DC. The project uses Edenspace's edenfern™ phytoremediation plants to extract and concentrate soil arsenic in fern fronds, which may then be harvested for safe disposal.

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In 2004, approximately 2,800 edenfern™ plants were installed in fourteen test plots at three different sites in the Northwest Washington suburb of Spring Valley. The ferns showed excellent growth and arsenic uptake, removing an average of approximately 9 mg/kg of soil arsenic across all sites from starting concentrations that ranged from 16 to 127 mg/kg. Remediation activities were completed with no apparent harm to specimen trees or shrubs, and with little interference to homeowner activities on the properties. Importantly, many of the edenfern™ plants overwintered and showed new growth in spring 2005, a key to reducing costs of arsenic phytoremediation in northern latitudes. Based on these results, in 2005 the project scope was increased significantly, with 10,000 ferns planted on thirty-four plots at twelve residential sites.

The techniques under evaluation in this ongoing project include the planting, cultivation, treatment and harvesting of special ferns that accumulate large quantities of arsenic in their fronds. The edenfern™ has demonstrated that bioconcentration coefficients (ratios of arsenic in the plants to arsenic in the soil or water) greater than 100 promise much lower costs for removing and disposing of this dangerous element. For example, at some sites phytoremediation of arsenic may cost as little as 10% of the cost of excavating and removing contaminated soil. The technique also may be useful at sites where excavation is difficult, such as near valuable landscaping plants or above buried pipes or cables.

The arsenic-extracting capabilities of the edenfern™ were discovered by Dr. Lena Ma of the University of Florida. Edenspace has signed an exclusive license agreement with the university, which has received two patents based on the discovery, to enable cost-effective commercial cleanup of arsenic from soil and water.

Arsenic causes cancer, mutations and birth defects and also has been associated with the development of diabetes. The element was once widely used in insecticides in farming, gardening and ranching, and is used as a component of preservatives in lumber and furniture. In some parts of the world, arsenic occurs naturally in groundwater. In some states, decades after arsenic was introduced into the environment, soil concentrations can be hundreds of times higher than the residential standard. Because of its toxicity to humans, farm animals and household pets, the stability of its compounds in soil and groundwater, its once widespread use, and the lack of cost-effective remediation techniques, arsenic today constitutes a significant environmental health hazard.

The ability of plants such as the edenfern™ to serve as solar-powered pumps and filters for removing environmental contaminants offers numerous potential advantages over other remediation techniques. These advantages include preservation of topsoil, potential recycling of contaminants, joint products or use, and, importantly, lower cost. A cost comparison of different evaluation techniques is provided in Table 1.

TABLE 1. COSTS OF ALTERNATIVE ENVIRONMENTAL REMEDIATION TECHNIQUES (GLASS, 1999).

Technique	Cost per cubic yard ($)
Soil Washing	50–150
Soil Flushing	75–210
Acid Leaching/Extraction	150–400
Solidification/Stabilization	75–205
Vitrification	40–600
Thermal Desorption/Treatment	150–500
Excavation/Landfilling	100–500
Phytoremediation	25–100

Phytosensors

State-of-the-art collection of soil, water, plants and air is typically based on a sampling grid. For example, to measure concentrations of contaminants in soil or water, a trained professional, such as an environmental technician or home inspector, collects samples on a 30-foot grid for laboratory analysis using atomic absorption spectrometry, ICP mass spectrometry, *etc*. Including collection, this method is expensive, providing data at a cost of $20 to more than $200 per sample. One problem with a grid-based technique is the low spatial resolution of the data—the large "pixel" size. No information is provided for areas between the grid-sampling points, so that the reported concentrations may not fairly represent the level or extent of contamination at the site as a whole (Demougeot-Renard *et al.*, 2004). Thus, a high lead concentration in a house's drip zone does not necessarily indicate high concentrations in a play area or pathway, nor does a low lead concentration in a composite sample indicate that a property has low soil levels of lead in all zones of concern. In addition, different sampling events may result in markedly different assessments due to soil and sampling variability. This problem presents additional expense to customers, who usually are required by regulators to remediate the soil some distance outside the perimeter defined by the "high" sample points, in order to account for uncertainty about contaminant distribution. In addition, areas of contamination may escape detection and treatment, presenting a future liability and health risk.

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Development of wide-area sampling techniques that provide higher spatial resolution at lower cost and over time is desirable. Of particular interest would be the development of indicator plants to provide rapid, low-cost, *in-situ* monitoring of environmental and plant conditions. Phytosensors could be easily replicated, solar-powered, and unobtrusive. Phytosensors may be thought of as signal transducers and amplifiers that detect and report on an environmental condition such as the presence of a contaminant or a plant condition such as "hidden hunger." Phytosensors address the "grid problem" by inexpensively providing information with high spatial resolution. Because each plant represents a sample point, information provided can be near-continuous. Such phytosensors could also be used in joint applications such as environmental cleanup, agriculture, and landscaping.

Three elements are essential to successful development of phytosensors:

- an element in the plant, such as a promoter gene, that is sensitive to the target parameter;
- a plant reporter pathway that can provide measurable evidence—such as a color change in leaves or stems—of changes in the target parameter; and
- a plant species that is suitable for the intended use.

Current Edenspace phytosensor projects include using a metal-responsive promoter gene, *BjMTP,* identified by Professor David Salt at Purdue University, linked to different reporters such as green fluorescent protein (GFP) and the anthocyanin gene *B* in Indian mustard, maize and turf grass. The transformed plants may be used to detect the presence of heavy metals such as lead, cadmium and mercury in soil, groundwater and/or landfill leachate. Edenspace is also working with Professor C. Neal Stewart, Jr., at the University of Tennessee to insert an arsenic-responsive promoter from *Shewanella* into the edenfern™. Successful insertion of this construct will create an indicator that is visible under UV light in response to arsenic uptake, potentially showing when arsenic is present in the plants and soil as well as when cleanup has been completed.

Energy Crops

In 2004, ethanol production in the United States attained a record 3.35 billion gallons, up 19% from 2003 (Hillgren, 2005). While it is still a small part of the total US fuel market, representing approximately 2% of the gasoline sold in 2004, the recent rapid increase in oil prices has increased the cost-competitiveness of ethanol and indicates that it can continue to capture market share, particularly if production costs can be decreased. Production of energy, and of ethanol in particular, from plant biomass is especially attractive because of plants' renewable conversion of solar energy and recycling of atmospheric carbon dioxide. In October 2002, the Biomass Technical Advisory Committee established by the Biomass R&D Act of 2000 issued national goals for biobased transportation fuels, calling for a substantial increase in the use of such fuels from 0.147 quads in 2001, or only 0.5% of US transportation fuel consumption, to 20% in 2030 (BRDTAC, 2002a). To achieve these ambitious goals, the Advisory Committee subsequently recommended a comprehensive research plan, the elements of which include increased biomass yields, lower biomass costs, new enzymes and catalysts, multi-trait crops, and environmentally sound biomass production (BRDTAC, 2002b). The overall objective of this plan is to reduce the price of biofuels. In 2004, the Advisory Committee updated its recommended research plan, recommending specifically that the US Departments of Energy and Agriculture (DOE and USDA) significantly increase funding for R&D programs on cellulosic ethanol (BRDTAC, 2004). In 2005, the US Congress appeared likely to implement this recommendation.

A promising biofuel co-production opportunity exists based on a convergence of goals between biomass production for energy and biomass production for phytoremediation. High biomass yields sought for bioenergy, for example, are also desirable in phytoremediation of metals, metalloids and radionuclides, because the rate of contaminant removal is a function of biomass as well as of bioconcentration. In addition, new ways of disposing of contaminated biomass are sought that minimize landfill burdens. Current treatment methods can remove 60% to 90% of recovered metals from plant biomass (Edenspace, unpublished data), which for some contaminants is insufficient to allow disposal of the treated biomass as non-hazardous waste. Metals are typically sequestered inside cell walls, which are difficult to break down cost-effectively using current techniques. The ability to degrade cell walls with low-cost cellulases could significantly improve the current state of the art in contaminant recovery from phytoremediation crops, allowing treatment of contaminated biomass to reduce the costs and liabilities associated with landfill disposal, facilitate recycling of recovered metals, and produce clean, renewable bioenergy feedstocks.

With DOE funding, Edenspace and its research partners, Drs. Mariam Sticklen and Bruce Dale at Michigan State University, have engineered tobacco (*Nicotiana tabacum*) and maize for (i) constitutive production of an hydrolytic enzyme, endoglucanase, to aid post-harvest hydrolysis of plant biomass to simple sugars that are useful as biofuel feedstocks, (ii) greater biomass, and (iii) delayed flowering, which reduces the likelihood of transfer of the transgenes to non-engineered plants. Cellulase levels of about 1% of the plant dry weight (less than 10 mg of enzyme protein per g) are sufficient to convert essentially all of the cellulose and hemicellulose in ammonia-treated plant matter to fermentable sugars in less than 24 h (Dale *et al.*, 1999). Preliminary results indicate that transgenic corn can produce endoglucanase at levels higher than 9% of total soluble protein, close to this benchmark.

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Using such "endoplant" cellulases and biomass augmentation, a primary technical objective of this project is to demonstrate ethanol yields greater than those achievable based on hydrolysis of starch alone, currently at 2.5 to 2.8 gallons of ethanol per bushel of corn grain, or roughly 450 to 600 gallons of ethanol per crop acre. Efficient hydrolysis of the 6 to 8 tons dry weight of corn stover grown per acre, and of the distillers grain that remains after corn grain is processed with amylase, could more than double current ethanol yields. A second major objective is to reduce biomass pretreatment steps that are now necessary to remove lignin and hemicellulose. Performance against these objectives will be measured in a pilot demonstration scheduled for 2006, when transgenic plants will be processed, and the yields and costs of ethanol production assessed, at the National Renewable Energy Laboratory's Bioethanol Pilot Plant facility in Golden, Colorado. A parallel project between Edenspace and the US Department of Agriculture for switchgrass began in mid-2005.

By sharing biomass production and post-harvest treatment costs with phytoremediation, another plant-based technology that has similar goals, costs of producing hydrolyzed feedstocks for biofuels could be dramatically reduced—an essential, if not in itself sufficient, step toward increasing the cost-competitiveness of renewable fuels. In addition, production of biofuel feedstocks, cellulase and cellulase-rich plants, and phytoremediation crops can provide farmers with new sources of income at a time when traditional crops are increasingly subject to severe market price and trade pressures. A joint 2003 USDA/DOE analysis of the economic impacts of bioenergy crop production showed the potential to increase farm income by up to $6 billion.

Plantavit Cooperative

In the United States, an estimated 294,000 hazardous waste sites await cleanup, with total costs aggregating $209 billion (USEPA, 2004). These numbers exclude potential cleanup costs on agricultural and many residential properties, as well as the costs of pollution prevention over wide areas. Given the costs of current environmental technologies and current funding levels, the environmental challenges posed by such sites will persist for decades.

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Capitalizing on the low costs and other advantages of environmental phytotechnologies, many companies, individuals and government agencies are now using plants to restore and protect the environment. Plantavit, a new national agricultural cooperative established in 2004 by Edenspace and farmers in California's San Joaquin Valley, seeks to identify, train and hire its producer members to apply such environmental phytotechnologies in the United States and other countries. Large-scale application of such technologies, both on and off the farm, is expected to achieve significant environmental benefits while at the same time providing a new source of income to farmers. The cooperative's goals are to:

- provide additional sources of nonfarm income to agricultural producers, based on application of producer skills, equipment and other agricultural resources to environmental projects;
- provide professional training to members in agriculturally based environmental techniques and related fields, such as plant sciences and soil sciences;
- increase public recognition of member achievements in environmental activities;
- reduce environmental health risks on farm property; and
- increase farm property values.

Environmental phytotechnologies offer a promising way to address wide-area problems. Grasses, trees and other plants can be used to construct riparian barrier strips to retain runoff. Trees can be planted to sequester atmospheric carbon and remove other contaminants from the air, soil and water. With the use of appropriate techniques, crop plants such as mustard, corn and tobacco can remove arsenic, lead, cadmium, selenium and other contaminants from soil and groundwater. Some of these techniques are already used on farms and ranches by agricultural producers with support from the Conservation Reserve Program, Environmental Quality Incentives Program, the Wetland Reserve Program and the Wildlife Habitat Incentives Program, and other government programs. These techniques are not currently used on the farm, nor is current funding provided for producers to use any of these techniques outside the farm or ranch.

The reliance of environmental phytotechnologies on agricultural techniques provides scale efficiencies similar to those in agriculture: the larger the area, the lower the cost per acre. Because most current phytoremediation sites are less than three acres in size—small for a modern farm—the full cost savings enabled by large-scale phytoremediation have not yet been achieved. For appropriate sites, substantial cost savings may be attained by farmers experienced in modern agricultural techniques, who are also trained in phytoremediation techniques. In particular, the environmental problems that often must be addressed in land development in urban and metro areas may be particularly amenable to environmental phytotechnology techniques employed by adaptive farmers. Edenspace is currently funded by USDA to study the potential environmental markets for agricultural producers under this approach.

Observations and Recommendations

These and similar projects have afforded Edenspace a broad range of experiences, including site characterization and environmental remediation, plant genetic engineering and APHIS field permitting, market research, marketing and sales. Environmental science and regulation, agricultural policy and practice, and plant biochemistry and genetics have all played prominent roles in Edenspace's work. From this experience, we offer the following observations and recommendations.

Change Agricultural Policy from Insulation to Innovation

Current agricultural policy poses high risks for farmers. The 2002 Farm Bill provides nearly $20 billion in farm support annually, primarily intended to slow or stop the erosion of the farm base experienced over the last several decades. However, rapid growth in the federal budget deficit, recent decisions by the World Trade Organization against high tariffs and other farm support, and the ethical issues involved in restricting food imports from developing countries, indicate that, over the long term, agricultural subsidies are not sustainable. The financial supports that allow farmers to ride out temporary rough spots are themselves temporary. When, and not if, these supports disappear, farmers may be left without a means to compete with lower cost food imports, leading to accelerated industry consolidation and the accelerated demise of small farms. One good way to address this problem, successfully achieved in many high-tech US industries, is to encourage rapid innovation and product development, allowing farmers to compete by offering higher-margin, value-added products rather than commodity products, with life cycles of an increasing number of agricultural products measured in months rather than years or decades.

Promote Systems Agriculture

In most of its projects, Edenspace regards its plants as just one element in the overall solution it provides to a client. In remediating a small arms firing range, for example, Edenspace must sift out and recycle the bullet fragments, as well as phytoextract ionic lead, if site goals are to be met. This integrated perspective on designing plants into customer solutions is an essential element of future agriculture, and provides an important pathway for engineering new high-margin plants to be grown by agricultural producers. I call this approach "systems agriculture"—the engineering of plant traits and agricultural protocols on an integrated basis with other production technologies so as to minimize total costs of end-user products and services. Examples are the integration of new plant traits with new farm techniques and new ethanol production steps in order to minimize the cost of ethanol at the fuel pump, and developing new plant traits that facilitate storage of hypoallergenic vaccines in the syringe. The approach requires that new agricultural products and techniques be developed by considering multiple areas of upstream and downstream production expertise together, on an integrated basis, that are now considered separately. New collaborations will be needed between agriculture and other industries, such as the energy and healthcare industries, that today are found infrequently, if at all. Systems agriculture is likely to lead to the creation of surprisingly good products—such as fuels that are better than ethanol, better than gasoline—that are undiscovered today because of a lack of creativity deriving from the failure to take an integrated design engineering approach.

Create More Receptive Public Opinion

Systems agriculture is dependent on use of biotechnology to create transgenic plants. Traditional breeding methods are simply too imprecise and too slow to achieve the rapid development of products needed to support a competitive US agricultural sector. While the regulation of transgenic plants today imposes increasingly high hurdles for the introduction of new crops, the antecedent cause of the problem isn't regulation but the public perception that too often sees the risks of transgenic plants as outweighing the benefits. Public opinion, in turn, has been shaped by a complicated combination of factors, includ-

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ing economic competition among countries, substitution competition among industries, product competition among companies, and a host of scientific and nonscientific beliefs. While this will be a complex area to address, a key element is to develop public demand for new transgenic plant products that directly promote human health, provide low-cost energy, or improve property values, rather than simply—though importantly—reduce producer costs with no significant benefit perceived by consumers.

Increase Government R&D Funding

Transgenic plant development is underfunded by the private sector, largely because of the divisiveness of the transgenic crop wars of the last 10 years. To address this market imbalance, the USDA plant biotechnology budget should be at least quadrupled in size. Half of the increase should be apportioned to other government agencies—EPA, NIH, HUD, DOT, *etc.*—that should be instructed to fund crop-plant research related to their missions. USDA should encourage customers to tell farmers what types of plant they'd like farmers to grow. The only "NIH" in government should be the National Institutes of Health.

The United States has one of the strongest agricultural industries in the world, with tremendous natural advantages including fertile soils, a temperate climate, good precipitation, and skilled producers. These advantages are offset in part by another US blessing: a high quality of life that translates to high labor and materials costs relative to many other parts of the world. If we are to continue to realize the benefits of our strong position, we need to pursue systems agriculture and the plethora of new high-margin markets and products that it promises.

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Bruce Ferguson has served as chairman, president and chief executive officer of Edenspace Systems Corporation since co-founding it in 1998. Edenspace is a leading phytotechnology company specializing in environmental uses of plants. Projects include a contract with the US Army Corps of Engineers to remove arsenic from soil, and development of corn and switchgrass varieties for higher ethanol yields.

From 1997 to 1998, Mr. Ferguson was a visiting fellow at George Washington University's Center for International Science and Technology Policy. From 1982 to 1997, he was an executive officer and director at Orbital Sciences Corporation (NYSE:ORB), a space technology company he co-founded in 1982. Prior to his work at Orbital, he was an attorney in the corporate and securities department of the Chicago law firm of Kirkland & Ellis.

In 1981, he received an MBA from Harvard Business School and a JD from Harvard Law School, where he was an editor of the *Harvard Law Review*. He received an AB *magna cum laude* in government from Harvard College and an EdM from the Harvard Graduate School of Education in 1976. He is a member of the Pegasus launch vehicle team that received the 1991 National Medal of Technology, and is a 1999 recipient of the Harvard Business School Alumni Achievement Award.