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Characteristics of Annual vs Perennial Systems

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Abstract: A fundamental challenge of the 21st Century will be to maintain both agricultural production and the integrity of our natural ecosystems. Monocultures of annual crops, currently providing a majority of humanity's food and fiber needs, provide sharp contrast to the diverse perennial plant communities characterizing, with few exceptions, natural ecosystems. The large-scale conversion of natural ecosystems to annual cropping systems has profound effects from the field to the landscape level. In comparison to perennial plants, annual crops inefficiently utilize water and nutrients resulting in degradation of soil and water quality. North America's Corn Belt provides a vivid example of the impacts of large-scale conversion of native vegetation to annual monocultures. The region, formerly tall-grass prairie under which the world's most fertile soils were formed, was largely converted to annual cropping systems in less than 150 years. The result has been irrecoverable soil loss from the fields, widespread contamination of surface waters in the region, and nutrient contamination of the Gulf of Mexico thousands of kilometers downstream. Conversion of annually cropped land back to perennial cover provides great potential to mitigate these problems. As the global human population grows to an expected 8 to 10 billion people over the next fifty years, it will not be sufficient to merely convert cropland back to native vegetation. Innovative, productive cropping systems employing the efficiencies and conservative strategies of natural ecosystems must be designed to meet the fundamental challenge of this century.

Introduction

A fundamental challenge of the 21st Century will be to meet humanity's basic needs while maintaining the integrity of our natural ecosystems through preservation of global biodiversity. Chief among humanity's basic needs is food, most of which comes from highly managed agricultural systems. Within the past several decades, however, ecologists have become increasingly concerned that negative off-site environmental impacts of agricultural production threaten not only future food productivity but also the integrity of our natural ecosystems (Faeth, 2000; Tilman, 2001). Beyond the more widely cited benefits of natural ecosystems, such as their support of biodiversity, other less widely recognized benefits, such as effective management of soil and water resources and efficient nutrient cycling (Ewell, 1999), have global implications relevant to agricultural production. Even the highest levels of agricultural inputs cannot fully substitute for topsoil on the scale required for adequate food production.

If we look to the planet's many different natural, land-based ecosystems for answers on how to effectively manage soil and water resources in our agricultural systems, the plant communities in nearly all of them have two critical attributes in common: perennialism and diversity. This holds true from tropical rainforests to temperate-zone grasslands. In contrast, more than two-thirds of global cropland are occupied by annual crops grown in monoculture (FAO, 2003). This dramatic vegetative conversion over the last ten millennia has, with few exceptions, cut into the ecological capital built up and conserved by natural systems (Pimm, 2001). Changes from such a conversion, beginning at the micro-scale of the rhizosphere and extending out to the watershed level, can impact seemingly well-buffered systems thousands of kilometers away (Burkhart and James, 1999). These large-scale impacts, ranging from nutrient-contaminated dead zones in coastal waters to global climate change, force us to confront the overwhelming reality of the seamlessness of our global ecosystems; there can be no cordoning-off of our activities.

While in many cases we cannot entirely rewind the tape by converting annually cropped land back to diverse perennial plantings, there is ample evidence that reverting back to vegetative structures more closely resembling that of the previous natural system provides substantial benefits in terms of improved soil and water quality and nutrient cycling (Ewell, 1999; Neher 1999; Pate and Bell, 1999). As the global human population grows to an expected 8 to 10 billion people over the next fifty years, it will not be sufficient to merely convert cropland back to native vegetation. Innovative, productive cropping systems employing the efficiencies and conservative strategies of natural ecosystems must be designed to meet the fundamental challenge of this century.

The Case of North America's Corn Belt

The Corn Belt region of the Upper Mississippi River Basin provides a vivid example of the impacts of large-scale conversion of native vegetation to annual monocultures. Formerly under perennial vegetation - either forest or prairie - this region was aggressively converted to annual grain production over the last century. In Iowa, for example, perennial vegetation accounted for only 13.1 percent of farmland by 1997 (Jackson, 2002). The effects of this conversion are relatively well-documented having been widely studied at the field, region, and watershed levels. With the Mississippi River watershed occupying more than 40 % of the area of the continental United States it also serves as a model for understanding ecological processes on continental scales.

Effects at the field level

At the field level, negative impacts of annual cropping systems include inefficient water and nutrient use and soil loss. Because seeds require a warmer, drier seedbed for germination than is required for soil biological activity to occur, nutrients mineralized from soil organic matter can be leached through the soil profile or lost in surface runoff encouraged by the absence of vegetative cover (Dinnes et al., 2002). Likewise, following harvest, the absence of living plant cover results in poor nutrient and water use in the fall.

Water flow through soil profiles under annual crops may be 5 times greater than through soil profiles supporting perennials (Randall et al., 1997). Losses of 45% of the annual precipitation through subsurface flow have been measured in annual cropping systems (Dinnes et al., 2002). This 5-fold increase in water flow through annual crop systems corresponds to a 35-fold increase in yearly nitrate nitrogen loss from these systems as compared to perennial systems (Randall et al., 1997). In contrast, perennial systems, with extensive living root systems in place year round, capture available nutrients and water any time the soil is warm enough to support biological activity.

Although inefficient water and nutrient use may result in water-logged soils and high fertilizer bills, more troubling for long-term productivity is soil loss. Perhaps the longest-term comparison study in the US on the effects of annual vs. perennial production systems on soil loss, the 100-year study at Sanborn Field, Missouri compared permanent perennial grass cover to two annual cropping systems, one a rotation that included 2 years of perennial grass followed by 4 years of annual crops and one a continuous corn system(Gantzer et al., 1990). After a century, the permanent perennial grass cover maintained 30 % more topsoil than the rotation system even though it included two years of perennials. Cover management (perennial vs. annual) was 35 times more significant than the soil erodibility and 28 times more significant than the slope in explaining the differences. Perennial cover was 54 times more effective in controlling erosion than was the annual crop.

Despite advances in cropping strategies, nutrient use efficiencies of annual crops remain low and heavily dependant on weather conditions (Dinnes et al., 2002). Although reductions in soil loss under annual crops have been achieved in recent years through implementation of no-till and conservation tillage practices, adoption of alternative tillage practices remains difficult in many northern regions due to the need for warm, well-drained seedbeds. Furthermore, much of the reduction in national erosion rates is not attributable to advances in annual cropping practices. Instead, conversion of cropland back to perennial vegetation in the Conservation Reserve Program accounts for more than 60% of the overall reduction in soil loss rates (Brady and Weil, 1999).

Effects at the regional level

Although negative impacts of agricultural production are most often measured at the field level, increasing attention has been given to impacts at the regional level particularly in terms of water quality. Because life cycles of annual crops are not well synchronized with annual climatic and soil conditions they compete poorly with weeds for water and nutrients. Consequently, high levels of fertilizer inputs are required to meet peak-growth crop requirements and herbicide inputs to battle weed growth. The large volumes of water flowing through soil profiles and across field surfaces transport significant amounts of soil and agrochemicals to surface and ground water sources leading to worsening water quality problems in the region.

Under annual cropping, soil transport to Lake Pepin, a natural riverine lake on the Upper Mississippi River, has risen 12-fold over the last 160 years, since European settlement (Kelley and Nater 2000). Annual croplands account for 48% of non-point sourced nitrogen and 37% of non-point sourced phosphorus delivered to surface waters annually (Faeth, 2000). In Des Moines, nitrate levels in the Raccoon River were so high in the spring of 2001 that the city had to switch to the Des Moines River for its drinking water.

In addition to sediment and nutrient loading problems, the National Water Quality Assessment program found at least one pesticide in nearly every water and fish sample collected from streams and in over 50% of sampled wells in agricultural areas (USGS, 2002). Nearly all samples taken from streams and half of those from wells containing a detected pesticide contained two or more pesticides. The most commonly detected herbicide, atrazine, is also the most commonly used herbicide in the region. In 17 out of 40 agricultural streams studied, Canadian aquatic-life criteria for herbicides were exceeded; the United States EPA has no such guidelines for agricultural chemicals (USGS, 2002).

A widely recommended strategy for reversing these trends is the conversion of productive cropland to native perennial vegetation as part of federally funded conservation programs. Without development of productive, ecologically sound production systems such conservation efforts are vulnerable to future failure if commodity prices rise or federal funding of conservation efforts is removed. While increasing the area of restored wetlands and native wildlife habitat is a desirable goal, the long-term health and economic welfare of local communities requires that conservation occurs as a consequence of agricultural production rather than in spite of it.

Effects at the watershed level

These field and regional level problems have been meticulously linked to problems more than 1000 km downstream. Annual nitrogen flux to the Gulf of Mexico from the Mississippi River tripled between 1955 and 1970 and between 1980 and 1996 with nearly two thirds of the flux in the form of nitrate nitrogen (Rabalais et al., 2002). Agricultural contributions account for 66% of the nitrogen additions with areas north of the Ohio River contributing 56% of the overall nitrogen load; Minnesota, Iowa and Illinois alone account for 40 - 50% of the total nitrogen inputs (Goolsby et al. 1999). Overall, nitrate flux to the Gulf of Mexico increased by 300% in the last half of the twentieth century (Rabalais et al., 2002).

The result of this increased flux has been the formation of a midsummer, 20,000 km2 or larger hypoxic zone in the Gulf of Mexico. Nitrogen enrichment fuels algal blooms which deplete oxygen concentrations to levels below those required by many of the Gulf's marine organisms; these low-oxygen zone essentially become dead zones. Coastal ecologists monitoring the phenomenon for decades have tracked the primary cause directly back to landscape conversion of native vegetation to annual cropland within the Mississippi River Basin (Rabalais et al., 2002). As at the regional level, recommended strategies for mitigating the problem typically focus on conservation programs for taking cropland out of production.

The Work of The Land Institute

It is expected that, over the next fifty years, the human population will increase in numbers equal to the total number of people that the planet supported fifty years ago. In order to maintain a population of 8 to 10 billion people we cannot afford to convert large areas of cropland back to native vegetation in order to preserve the integrity of global ecosystems. Nor can we afford to continue losing valuable soil and nutrients under current annual cropping systems. While some changes in diet need to occur for various reasons, it is likely that the majority of human caloric needs will be met by grains which now, produced in annual cropping systems, constitute the majority of our food production (Pimm, 2001).

Rather than work to improve annual production systems by individually addressing the many attendant problems, researchers at The Land Institute (TLI) refer to natural ecosystems for solutions to meeting the challenge of producing adequate grain yields while conserving resources. In particular, the tall-grass prairie ecosystem, composed of plant species analogous to the warm- and cool-season grasses, legumes, and oil crops produced in our annual production systems, serves as the model for TLI's plant breeders and agroecologists whose work is primarily directed to developing high-yielding production systems featuring mixtures of herbaceous, perennial grain crops. These mixtures would essentially be domestic prairies with vegetative structures analogous to that of the prairie but with grain yields similar to annual cropping systems (Jackson and Jackson, 1999). By mimicking the structure of the prairie ecosystem it is hoped that these agricultural systems could support many of the critical functions carried out by the prairie such as efficient water and nutrient management and adequate management of pests, weeds, and pathogens.

Plant breeders at The Land Institute use two approaches to developing the necessary crops for these domestic prairies: 1) perennialize current annual crops and 2) domesticate promising wild perennials (Cox et al., 2002). Wheat, sorghum, and sunflower have proven promising candidates for perennialization efforts while attempts are underway to domesticate Illinois bundleflower, intermediate wheatgrass, and compass plant by improving seed yield and size and addressing seed quality. Efforts at The Land Institute are accompanied by work at Washington State University and several other institutions around the country (Cox et al., 2002; Scheinost et al., 2001). Recent advances in plant breeding tools and methods makes these efforts possible for perhaps the first time in history.

Because perennialization of annuals and domestication of wild perennials requires selection for a wide selection of traits rather than a single gene, success will likely be based more on the continuity of efforts rather than on single instances of ingenuity. Likewise, the agronomic work required to successfully grow mixtures of these crops will require long-term well-organized efforts to address the many questions posed by an entirely new form of agricultural production. For these two reasons, it is expected that 25 to 50 years of work will be required to achieve fully viable domestic prairies (Jackson and Jackson, 1999).

While a 25 to 50 year timeline appears impractical in a world of 3 year research projects, the ecological problems occurring as a consequence of annual cropping systems play out over similar lengths of time. The problems of soil erosion and degraded water quality resulting from annual cropping systems have been with us for millennia. In the future these problems will worsen as efforts to meet the planet's expanding food needs intensify. If, in 50 growing seasons, there are productive agricultural systems in place that both provide adequate yields and support vital ecosystem functions the time required for success will have seemed short.

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