Proceedings of the 2nd Biomass Conference of the Americas, 1995, pp. 1618-1627.

ECOLOGY OF AGRICULTURAL MONOCULTURES: SOME CONSEQUENCES FOR BIODIVERSITY IN BIOMASS ENERGY FARMS

Wayne Hoffman, Ph.D., Research Scientist, National Audubon Society, Tavernier Fl 33070, U.S.A.; Jan Beyea, Ph. D., Senior Scientist, National Audubon Society, New York, NY 10003; and James H. Cook, Research Scientist, National Audubon Society, Islip, NY 11751

Abstract

Most developmental work on biomass crops has involved extensive monocultures of genetically uniform crops. We review the relevant ecology of agricultural monocultures, and some consequences of monocultural methods for the biomass industry. Monocultures can have very high primary productivity; indeed biomass crops are selected for high productivity. The seasonal tempo of productivity is often more punctuated in monocultures than in multispecies systems, leaving temporal productivity gaps. In turn, folivorous insect diversity and abundance tends to track the foliage productivity. The productivity gaps may produce bottlenecks in herbivore abundance and diversity. Herbivore population dynamics tend to be less stable in monocultures, driving fluctuations in predator abundance and diversity. These bottlenecks and fluctuations can increase the frequency and severity of pest problems, for herbivorous insects usually respond to productivity increases faster than their predators. The spatial scaling of structural complexity is also critical to habitat value, particularly for vertebrates. At micro scales structural complexity is a function of plant structure. At meso scales, agricultural monocultures tend to be very uniform, compared to multispecies systems, and provide poorer habitat for species needing meso-scale diversity.

We suggest three strategies to enhance or restore biodiversity while developing biomass crops. First, tailor the scale of plantings to the needs of wildlife in the system. Second, manage the deployment of the biomass plantings to be complementary to other landscape features. For example, concentrate biomass plantings on the most favorable sites in the landscape, and develop complementary habitat inclusions on poorer microsites. Third, develop crops and crop combinations to benefit wildlife as well as to provide high yields. Select and deploy crops and clones to bridge productivity gaps, for instance including strains that have earlier spring growth, or grow later into the fall, or that bloom and fruit when food is most needed. Develop polycultures of plants selected for complementarity in productivity, with meso-scale diversity provided by inclusions of complementary habitats in the less suitable microsites. These strategies should not only improve habitat value, but should also provide some protection from pest outbreaks.

Introduction

The National Audubon Society is dedicated to the conservation of natural biodiversity. We recognize that our existing system of refuges, parks, and public forests is critical for conserving biodiversity, but ultimately will be inadequate to support healthy populations of all the species we value. We therefore work to improve habitat quality, and hence maintain biodiversity, in economically productive landscapes. The intent is to find strategies that make habitat quality more compatible with profitable economic activity.

We expect the nascent biomass energy industry to have major effects on land use patterns in North America, and so are working to direct it in environmentally sound directions. Our projections of the eventual size of this industry are larger than most analysts', mainly because we think the need to reduce net CO_2 emissions will eventually drive the industry to provide a substantial percentage of our energy budget.

We have been conducting field studies in "model" plantations of hybrid poplars, hybrid cottonwoods, and switchgrass, to better understand the potential of these crops as habitat for migratory birds. The plantations we surveyed were not planted as biomass crops but we consider them useful models of biomass crop plantations. We have surveyed bird populations in hybrid poplar stands in eastern Ontario, planted by Domtar Corporation and the Ontario Ministry of Natural Resources, to provide fiber for Domtar's Cornwall paper mill. We have conducted similar studies in hybrid cottonwood plantations in western Oregon and Washington planted by James River Corp., again to provide pulp for a paper mill. We have also surveyed bird populations in switchgrass stands planted on public land in Iowa to prevent erosion and to provide habitat for gamebirds. Hybrid poplars and cottonwoods, and switchgrass are considered the leading candidates for biomass crops in much of temperate North America.

Modern agriculture has concentrated on developing highly productive monocultures, and most research toward developing biomass crops has focused on monocultures as well. For purposes of this paper we define monocultures as plantings involving the growing of single species at any one time: a rotational system would be a temporal series of monocultures. We use the terms multispecies systems and polycultures for mixtures of different species of plants growing side by side in the same field.

Modern agriculture's focus on monocultures constitutes an implicit decision that the benefits of specialization, mass production, and product uniformity are worth the energy, labor, and financial-risk costs of monoculture, and the environmental costs as well. In this paper, we review some salient aspects of the ecology of agricultural monocultures and their consequences for habitat quality of croplands, and provide some recommendations for managing biomass plantations to improve habitat quality.

We propose that for energy crops, explicit management to reduce the environmental costs (through habitat improvement tactics) is appropriate, and will be cost-effective, if not actually beneficial financially. We recognize three primary opportunities to direct the industry toward higher-quality habitat; by tailoring the scale of plantings, by managing the spatial deployment of biomass crops in the landscape, and by developing mixtures of biomass crop varieties and species.

Overview of the Ecology of Monocultures

Most developmental work on biomass crops has assumed they should be grown as extensive monocultures of genetically uniform crops. We review the relevant ecology of agricultural monocultures, and some consequences for the biomass industry.

Primary Productivity.

Plants selected to be biomass energy crops must have very high primary productivity, at least compared to other crops adapted to the local environment. Monocultures can have very high primary productivity; indeed for many crop plants, maximum productivity has been achieved in monoculture. However, research on crop polycultures is relatively rare, particularly at industrial scales. With relatively complete harvests, monocultures have greater fluctuations in standing crop than are seen in most natural systems, although some fire-maintained systems have similar fluctuations in standing crop.

Plants' growth rates are also sensitive to temperature and moisture availability, and different species respond very differently to these factors. Monocultures perform best when temperature and moisture are optimal, and tend to be more sensitive to suboptimal conditions than multispecies systems. The C4 grasses, including switchgrass, grow best in hot weather, and are relatively insensitive to diel variation in moisture availability. Cool weather during their summer growing season will slow primary production of switchgrass, but may stimulate growth of other prairie plants. The cottonwood hybrid clones used in the Columbia River plantations are selected to grow best under conditions of high temperature and high water availability.

Tempo of Primary Productivity.

Biomass crops, like most plants, tend to have a seasonal tempo of productivity, with periods of rapid biomass accumulation and periods with lower (or zero) growth rates. The seasonal tempo of productivity is often more punctuated in monocultures than in multispecies systems, leaving temporal productivity gaps. In multispecies systems, different species are likely to differ in detail in the seasonality of their productivity, so that overall productivity is more sustained and extends over a longer season. This punctuation will be more extreme in clonal plantings (e.g. hybrid poplars) and F1 hybrid stocks because the genetic uniformity of the stock removes the variability in timing of productivity normal in genetically diverse plant populations. Two examples using prominent candidates for biomass crops in the United States are illustrative. The examples are temperate plants, but the same principles apply to tropical systems with wet/dry seasonality.

Hybrid poplars (*Populus*) in Ontario appear to cease growing new leaves by late August, and begin turning color well before many of the native trees in adjacent woodlands. Similarly, in western Oregon and Washington, some of the clones of hybrid cottonwoods cease growth in the fall well before nearby wild cottonwoods (*Populus trichocarpa*, one of the parents of the hybrids).

Switchgrass (*Panicum virgatum*) is a native North American prairie grass. As a C4, or warm-season grass, it has a restricted growing season. Switchgrass plantings Iowa exhibit little if any growth before June, and if not harvested, growth is quite slow after

seed maturation in August. In nature, switchgrass was a dominant member of the tall-grass prairie community, and apparently had a similar seasonality of growth. The prairie community as a whole, however, displays much more sustained productivity. Earlier, in April and May, a variety of spring-blooming forbs (e.g. members of families Orchidaceae, Violaceae, Fabaceae, Scrophulariaceae) and in some places cool-season (C3) grasses begin (and may complete) annual growth before the warm-season grasses begin growing in earnest. In fall, when switchgrass has seeded, and is growing slowly if at all, prairie communities may see continued productivity by forbs, particularly members of the Asteraceae - sunflowers, goldenrods, and asters.

The seasonal tempo of primary productivity is highly relevant to wildlife populations. Foliivorous insect diversity and abundance tends to track the foliage productivity. The productivity gaps in monocultures may produce bottlenecks in herbivorous insect abundance and diversity, and consequently predator abundance and diversity as well. These bottlenecks can increase the frequency of pest problems, for herbivorous insects usually respond to productivity increases faster than their predators.

Herbivore Population Dynamics.

This discussion will concentrate on insects and mammals, as they are the most significant non-domesticated herbivores in most North American agricultural and forest systems. The dynamics of plants' interactions with their herbivorous insects are sensitive to several factors, most noticeably the generation times of the plants and insects, the fecundity of the insects, their dispersal strategies and capabilities, the abundance of the plants, the patterns of susceptibility of the plant tissue to attack, and the presence and population dynamics of insect parasitoids and other parasites (Andrewartha and Birch 1954).

Most phytophagous insects feed on only a few of the plant species available in their environments. Plants exhibit a diversity of secondary chemistry, in part to control herbivory, and the insects that feed on particular plants will be species that have evolved tolerance of those plants' secondary substances (Eisner 1970). Monocultures tend to have fewer herbivore species than multispecies systems, but the ones that are present have greater potential to become economically significant pests. In multispecies systems, a major insect outbreak will affect only one or a few species, and other species may even display compensatory growth.

The physical and chemical defense mechanisms of plants tend to be more effective in protecting mature foliage than immature, rapidly growing leaves (apparently the chemical defense mechanisms are somewhat toxic to rapidly growing plant tissue, and the physical defenses involve structural changes that are not feasible in rapidly growing tissues). As a result foliage-eating insects tend to be most abundant and diverse when plants are growing new leaves, and the tempo of insect production tends to track primary production.

In turn, insectivorous birds and animals will find the habitat most attractive when insect availability is greatest (or at least when it is greater than in alternate habitats). Both the Ontario poplar plantations and Columbia River cottonwood plantations received extensive use by insectivorous birds in summer, when the trees were growing rapidly (Hoffman, ms1). In late August and September, however, the plantations received much less use than nearby native forest areas, where some of the vegetation still appeared to be growing (Hoffman, ms2). By late September the Columbia River plantations were receiving more use than in mid-September, but primarily by birds that feed on arthropod resting stages (over-wintering eggs, pupae, and hibernating larvae and adults).

Among mammals, deer (Cervidae, including elk and moose) and rodents are the taxa most likely to be significant pests of biomass crops in temperate North America. Deer (*Odocoileus* spp.), elk (*Cervus canadensis*), beavers (*Castor canadensis*), and voles (*Microtus* spp.) already are significant pests in some *Populus* plantations. Deer are significant pests primarily in the first 1-2 years of growth; James River Corp. personnel consider browsing consequential only when it destroys the uppermost tip of the young tree. Strategies to exclude deer until the trees are 2 meters or so tall may be necessary in some areas. Elk are much larger, and capable of damaging larger trees. Beavers cut down poplars of all sizes, and voles sometimes girdle the trees. Vole populations tend to be highly cyclical, so damage will be episodic. Encouragement of vole predators (raptors, canids) may reduce the damage. In some areas, biomass crop species that are less palatable to these mammals may need to be selected.

Scaling of structural complexity.

Vegetation structure at various scales is known to be important to wildlife in choosing habitat. Structurally complex plant communities tend to support more species of wildlife than simple ones because they provide more opportunities for specialization. Vegetation structure can be measured at scales ranging from centimeters (e.g. vertical density profiles) to meters (e.g. plant dispersion, tree canopy architecture, edge structural changes) to hectares (edaphic effects, land-use patterns in agricultural landscapes) to tens or hundreds of square kilometers (historic distribution of major vegetation communities). In general the complexity at each scale results from the same factors applying at the smaller scales, plus new larger-scale ones. At centimeter scales, complexity is primarily a function of the architecture of individual plants: grasses provide less diversity of shape and structure than most broad-leaved plants, and plants with branching stems provide more diversity than ones with simple stems. At meter scales, architecture of individual plants is still highly relevant, but much structural complexity (most in herbaceous communities) results from the diversity of structure of different plants. At hectare scales, variability in the physical environment (soil chemistry and conditions, moisture, exposure, slope and aspect), or in disturbance history (e.g. fire, windfall, or human manipulation) add complexity. At scales of tens to hundreds of square kilometers, complexity is added by climatic differences and phytogeograpic history.

Wildlife distribution and abundance has been correlated with vegetation structure at all of these scales. Thus Wiens (1969) found grassland birds non-randomly distributed with respect to vertical vegetation profiles, plant types (grass-blade, leaf and stem characteristics), and the landscape mosaic (some species clearly avoided woodlot edges). Forest birds may be attracted to particular features of tree architecture (e.g. MacArthur 195_, Martinsen and Witham 1994), and to stand characteristics, and may require substantial areas of relatively uniform stand structure (e.g. Dawson et al. 1986).

At centimeter to meter scales, the structural complexity of agricultural monocultures is a function of plant architecture and spacing. Thus, a field of corn is structurally

somewhat more complex than a wheat field because corn plants have more pronounced differentiation of stem, leaves, and flowering structures, and because the row spacing is greater. Most trees are inherently more complex structurally than most herbaceous crops. Immature tree plantations generally have higher complexity at meter scales because they have woody, herbaceous (weed), and open ground components in close association. As the plantations mature and the canopies close, the structural complexity at the smaller scales increases (more differentiation of parts in each tree) but at slightly larger scales, complexity decreases as the canopy closes and the herbaceous component is shaded out.

Agricultural monocultures differ from polycultures in patterns of structural complexity most significantly at scales of meters to hectares to square kilometers (meso-scales). In natural systems, species composition and details of plant size and architecture often change gradually over these scales as plants respond to the small-scale variation in topography, soil conditions, and water availability, so complexity continues to increase with increasing scale. Agricultural plantings have almost none of this meso-scale complexity, until the edge of a field is reached, then have much more distinct boundaries than natural systems typically have.

The consequences of these differences for wildlife use are manifold. The structural variation at the meters to kilometers scales in natural systems facilitates species packing, as different portions of a tract are subtly more suitable to different organisms. Species requiring more than one structural habitat type in close apposition (e.g. forests with clearings) are also favored by meso-scale structural complexity. In agricultural monocultures, relatively few wildlife species find attractive habitat, but those that do, tend to build high population densities and often become pests. Natural systems with meso-scale structural complexity also support more complicated trophic webs (taller trophic pyramids) than systems that are simple at meso-scales.

As noted above, some of the meso-scale complexity in natural systems results from plant species assorting according to variation in physical habitat parameters such as micro-topography, soil moisture, and soil structure and nutrient levels. Commonly, monocultural agricultural practices attempt to reduce this underlying variation, by leveling, irrigation, and fertilization, thus reducing the capacity of the site to support larger numbers of species.

Temporal Cycles of Structural Complexity.

As an un-vegetated site succeeds to forest, structural complexity increases secularly at most scales. In seasonal forests, an annual cycle in complexity is superimposed. The most obvious manifestation of this seasonal cycle is the growth, maturation, and death of leaves on deciduous trees (a deciduous forest without leaves provides less habitat structure than the same forest with leaves), but flowering and fruiting also contribute to this annual cycle. As the forest approaches climax conditions, the annual cycle in complexity overshadows the secular increase in complexity. Grasslands have a similar pattern, but climax (at least in terms of complexity) is approached more quickly, so the seasonal cycle normally dominates.

In agricultural monocultures of herbaceous plants, the seasonal cycle not only dominates, but usually is more profound than in natural systems, because harvest causes a more abrupt drop in complexity and standing crop than in most natural systems. Harvests at the end of the growing season lead to extended (winter) periods of low standing crop and complexity. Monocultures of woody plants also tend to have a more profound fluctuation in seasonal complexity because the plants are more synchronous. Thus, a plantation of hybrid clones will drop its leaves in a much shorter period than an adjacent deciduous forest, where the timing of leaf drop is variable both within and among species.

Again, these differences are important to wildlife. An herbaceous monoculture that is harvested close to the ground in fall will have less capacity to support wildlife through the winter than a natural herbaceous system, which will at least have the dead plant stems and leaves. A woody monoculture will have much more abrupt transitions from leafy to leafless conditions, and is likely to be leafless for a larger part of the year than a mixed-species deciduous forest, thus providing less habitat for species needing foliage.

Opportunities to Enhance or Restore Biodiversity

Our studies in hybrid poplar and cottonwood plantations and in switchgrass plantings show that these potential biomass crops provide habitat for substantial populations of songbirds and other wildlife. They certainly support larger breeding populations of songbirds than the cultivated or pastureland habitats they replaced. However, we see opportunities to further increase their value as habitat will little if any reduction in yield. At the same time the tactics we propose may provide some insurance against catastrophic crop failures.

The first of these opportunities is to tailor the scale of plantings to the needs of wildlife in the system. Thus, relatively large contiguous areas of woody plantation might provide much better habitat for forest birds than the same acreage would deployed as small blocks scattered through an agricultural landscape. Large fields of switchgrass might also provide better habitat for grassland specialist birds than smaller fields. In general, species that need relatively large expanses of structurally similar habitat are at a disadvantage in agricultural mosaics, compared to edge-inhabiting species. Similarly, the spatial arrangement of blocks to be harvested in different years can affect the suitability of the plantation as habitat for species needing large areas of heavy cover. Much research is needed to determine the optimal scale of plantings for the wildlife populations of interest.

The second opportunity involves management of spatial relationships of the biomass plantings to other landscape features, to enhance the habitat value of the landscape overall. A simple tactic is to use complementary habitat inclusions to enhance habitat value within biomass plantations (thus increasing meso-scale structural complexity). Small patches of other forest types in a woody plantation can provide critical habitat amenities allowing additional species to use the plantations. For example, the Ontario poplar plantations of course lacked woodpecker holes to provide nest sites for cavity-nesting birds such as chickadees, Great-crested Flycatchers, and Bluebirds. However, fence-rows with mature trees were left within many of the plantations, and these mature

trees provided nesting sites that allowed the cavity-nesting species to occupy the plantations. James River Corporation, with assistance from the US Fish and Wildlife Service is planting patches of shrubs and trees that should provide winter cover and food for birds and other wildlife in selected spots throughout their plantation system.

We recommend that in large-scale plantations, areas of suboptimal moisture or soil conditions be reserved for complementary habitat inclusions (limiting reductions in meso-scale complexity). Rather than spending money and effort draining the wet patches in a plantation area, they can be set aside as habitat inclusions. Similarly, rocky areas, steep slopes, and other over-dry micro-sites might best be left to natural vegetation. The experience from southern pine plantations is that the sites that take the most preparation and maintenance are generally less productive of pines anyway.

On a larger scale, the deployment of biomass plantings in the landscape can affect the habitat value of the overall landscape. Thus, a woody plantation placed on the boundary of a natural forest might serve as an effective buffer, increasing the value of the forest as habitat for forest-interior species. Woody plantations might also be useful as corridors connecting blocks of forest. Woody and perennial biomass plantings likely will be beneficial when planted as buffers adjacent to streams and wetlands, for their ability to filter agricultural runoff, trap nutrients, and provide shade.

The third opportunity involves the choice of biomass crops to improve habitat. Within the framework of agricultural monocultures, one tactic would be to interplant different varieties or clones of the same crop species or hybrids. By inter-planting we mean the mixing of the different stocks within the fields rather than segregation into monoclonal blocks. To enhance habitat, these could be chosen to differ in timing of spring bud break or growth initiation, in timing of flowering and fruiting, and in timing of leaf fall at the end of the growing season, thus reducing productivity gaps. They also could be chosen for differences in plant architecture, thus increasing small- and meso-scale structural complexity.

In the various poplar and cottonwood plantations, clones have been found to differ greatly in susceptibility to a variety of fungal diseases and insect pests, including some unknown in the areas until after plantation establishment. Employing a greater diversity of clones, and inter-planting them, is likely to reduce the chances of catastrophic crop loss to these pests. In inter-planted plantations, compensatory growth may further reduce the yield loss to pest outbreaks.

The same logic extends to inter-planting different species of crop plants. We see an opportunity to greatly improve the habitat value of plantations by developing polycultures - mixtures of energy crops that can be grown together. These mixtures should enhance habitat in the same ways as the clone mixtures described above, but the effect should be much greater. They also should provide greater protection against catastrophic pest damage. We think a spring-growing legume could enhance the habitat value of switchgrass plantings by providing early cover and food. At the same time it would fix nitrogen, and if its growing season were short enough, it should not compete with the switchgrass for light or water. For woody crops, mixtures containing nitrogen-fixing leguminous species seem promising. In the southeastern United States, black locust is a candidate crop that we would like to see inter-planted with other species, such as sycamore. We also think more effort should be expended on developing mixtures of warm-season grasses, rather than concentrating on "clean" stands of selected switchgrass varieties. Cover crops under woody biomass plantations would also improve habitat conditions, although the woody crops tested so far seem to suffer from competition with understory plants.

Conclusions

Biomass energy crops have the potential to become dominant components of agricultural landscapes in North America and elsewhere. They also have the potential to provide better habitat for a variety of wildlife than many existing agricultural crops. Intensive agricultural monocultures are very different ecologically from natural systems. These differences need major energy investments to maintain, tend to reduce the agricultural systems' value as wildlife habitat, and make the crops more susceptible to pests.

The strategies we propose for biomass crops are directed to reducing the ecological differences between them and natural systems. First we propose adjusting the scale of biomass crop plantings (field sizes) to improve habitat conditions for target species, such as grassland specialist and forest interior birds. Second, we propose deploying the crops in the landscape in ways that are complementary to the habitat qualities of the other landscape elements. These include the retention or placement of complementary habitat inclusions in biomass plantations (e.g. patches of mature trees within a short-rotation woody plantation), and deploying biomass croplands as buffers for forests and streams, and to serve as corridors connecting patches of forest or other habitat. Finally, we propose breaking away from monocultures, and developing mixtures of crop varieties and clones, and even multispecies polycultures of biomass crops.

We believe that these strategies will not only improve habitat, but also reduce the risks of devastating pest outbreaks. The economics of the energy marketplace seem to mandate that biomass crops will be low-profit-margin crops in the near future, at least in comparison to food crops. Therefore, successful energy farming will need to achieve high yields while minimizing costly investments. Energy crops will need to be low-maintenance crops, and strategies such as polycultures that lessen the severity of pest outbreaks are likely more affordable than chemical pest controls.

Literature Cited

Andrewartha, H.G. and L.C. Birch. 1954. The distribution and abundance of animals. Chicago, Univ. Chicago Press.

Dawson, W.R., J.D. Ligon, J.R. Murphy, J.P. Myers, D. Simberloff, and J. Verner. 1986. Report of the advisory panel on the Spotted Owl. Audubon Conservation Report No. 7.

Hoffman, W. ms1. The Habitat Value of Short-Rotation *Populus* Plantations to Forest Birds.

Hoffman, W. ms2. Bird populations of hybrid *Populus* plantations during fall migration.

MacArthur, R.H. 1958. Population ecology of some warblers of northeastern coniferous forests. Ecology 39:599-619.

Martinsen, G.D. and T.G. Witham. 1994. More birds nest in hybrid cottonwood trees. Wilson Bulletin 106: 474-481.

Sondheimer, E. and J. Simeone, eds. 1970. Chemical Ecology. New York, Academic Press.

Wiens, J.A. 1969. An approach to the study of ecological relationships among grassland birds. Ornithological Monographs No. 8. American Ornithologists' Union.