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EVALUATING ENVIRONMENTAL CONSEQUENCES OF PRODUCING HERBACEOUS CROPS FOR BIOENERGY

S. B. McLAUGHLIN* and M. E. WALSH

Biofuels Feedstock Development Program, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6422, U.S.A.

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Abstract—The environmental costs and benefits of producing bioenergy crops can be measured both in terms of the relative effects on soil, water and wildlife habitat quality of replacing alternate cropping systems with the designated bioenergy system, and in terms of the quality and amount of energy that is produced per unit of energy expended. While many forms of herbaceous and woody energy crops will likely contribute to future biofuels systems, The Department of Energy's Bioenegy Feedstock Development Program (BFDP), has chosen to focus its primary herbaceous crops research emphasis on a perennial grass species, switchgrass (*Panicum virgatum*). The choice of switchgrass as a model bioenergy species was based on its high yields, high nutrient use efficiency and wide geographic distribution. Another important consideration was its positive environmental attributes. The latter include its positive effects on soil quality and stability, its cover value for wildlife, and relatively low inputs of energy, water and agrochemicals required per unit of energy produced. A comparison of the energy budgets for corn, which is the primary current source of bioethanol, and switchgrass reveals that the efficiency of energy production for a perennial grass system can exceed that for an energy intensive annual row crop by as much as 15 times. In addition potential reductions in CO_2 emissions, tied to the energetic efficiency of producing transportation fuels and replacing non-renewable petrochemical fuels with ethanol derived from grasses are very promising. Calculated carbon sequestration rates may exceed those of annual crops by as much as 20–30 times, due in part to carbon storage in the soil. These differences have major implications for both the rate and efficiency with which fossil energy sources can be replaced with cleaner burning biofuels. Current research is emphasizing quantification of changes in soil nutrients and soil organic matter to provide improved understanding of the long term changes in soil quality associated with annual removal of high yields of herbaceous energy crops. © 1998 Elsevier Science Ltd. All rights reserved

Keywords—Switchgrass; bioenergy; energy balance; carbon balance.

1. OVERVIEW

The need to reduce national dependency on imported oils, and the opportunity to develop the nations' agricultural potential for producing high yielding energy crops have prompted significant national research on both the agricultural production and energy conversion technologies necessary to realize this potential.[1,2] As with any new technological issue, a variety of potential environmental impacts must be considered in addressing the net benefits or risks of proceeding with development. A wide range of environmental issues related to biofuels development have been identified.[3] These include potential changes in air quality, water availability and quality changes, and residue disposal associated with industrial aspects of biofuels production. In each of these areas there are potential benefits and risks to be considered. An important perspective for considering such risks and associated strategies to reduce them is weighing the environmental tradeoffs between biofuels technologies and the fossil fuel technologies they supplant. A similar approach can also be applied to biofuels feedstock production in asking how dedicating land to feedstock production will alter impacts from current land use. There are three important considerations in making such an assessment:

1. the agronomic attributes of the bioenergy cropping system being considered, including specifically effects on soil and water quality;
2. the net effect of any differences between (1) and the land use system it replaces; and
3. the quality and quantity of energy that is produced from the feedstock per unit of

*Author to whom correspondence should be addressed.

energy expended and per unit of environmental cost of the fossil energy it replaces.

After evaluating yield and agronomic data on 34 herbaceous candidate species, the BFDP at Oak Ridge National Laboratory (ORNL) selected a native perennial species, switchgrass, for further research and development as its primary herbaceous bioenergy candidate. This choice was made based both on the high yields and excellent versatility of switchgrass determined in early field trials, and on its many positive environmental attributes. This article focuses on the nature of those attributes, but, more importantly, on how those attributes relate to the third factor listed above: the net energy return and associated environmental benefits of bioenergy production from perennial grasses, such as switchgrass relative to annual row crops such as corn.

2. AGRONOMIC ATTRIBUTES OF SWITCHGRASS

Switchgrass (*Panicum virgatum*) is a sod-forming, warm season grass, which was an important component of the native, highly productive North American Tallgrass Prairie.[4] Today switchgrass and some of the other native prairie grasses have become increasingly important as forage grasses in the Midwest, because of their capacity to grow during the

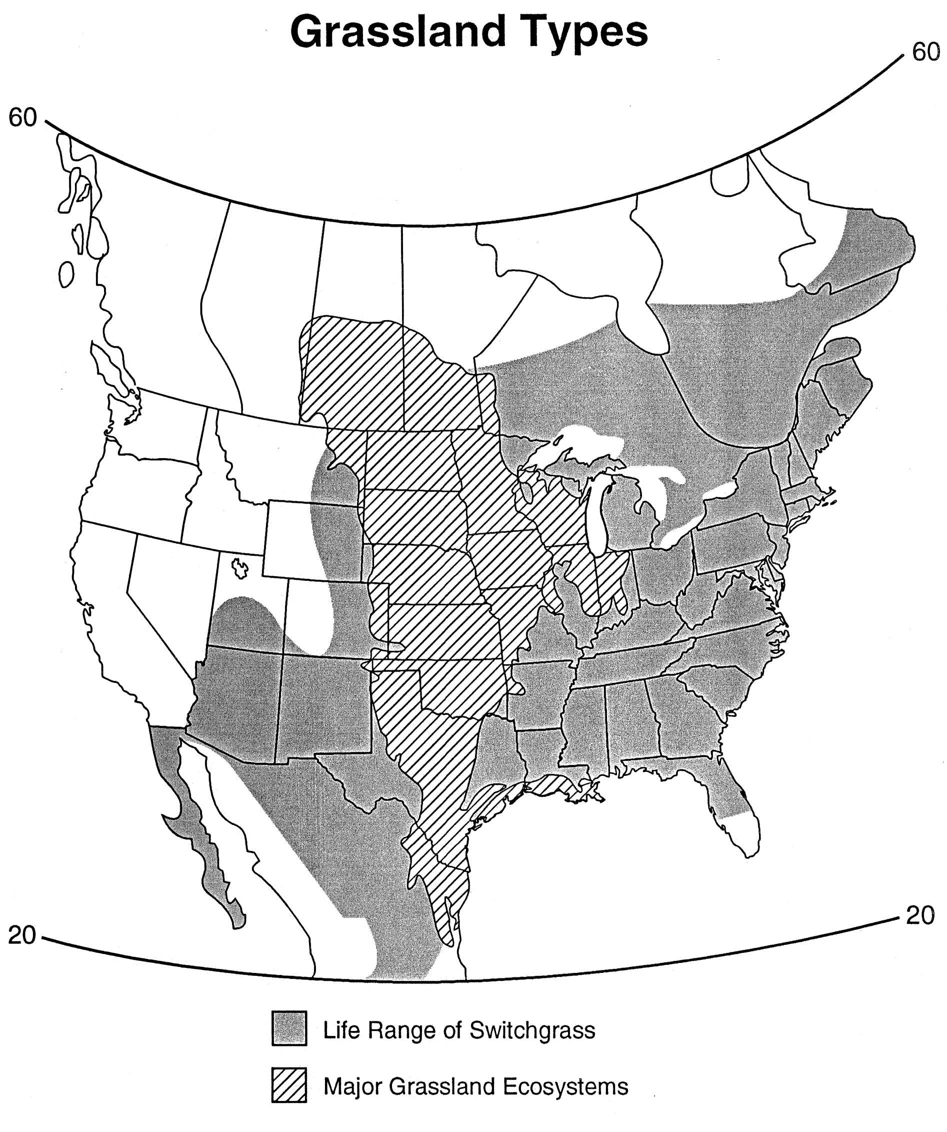

Fig. 1. Switchgrass is adapted to a wide range of environmental conditions, occurs across much of North America, and is an important ecological component of native grassland ecosystems. Map developed from data in Refs[22,37].

hot summer months when water availability limits growth of most other grass and crop species.[5] Switchgrass has a geographical range that covers most of the U.S.A. and portions of Canada and Central America (see Fig. 1) and was found by early settlers in diverse habitats ranging from midwestern prairies to brackish marshes and open woods.[6] Its wide range and associated adaptability, high yields and flexibility to be utilized both as a forage species and as a biofuel were among the main attributes in its selection by ORNL's Bioenergy Feedstock Development Program (BFDP) as a model herbaceous crop.[7] Yields of mature stands have been excellent averaging *ca* $16\ \mathrm{Mg\ ha^{-1}\ yr^{-1}}$ in unirrigated research plots, with a 1 year, single plot, maximum of $37\ \mathrm{Mg\ ha^{-1}}$. Additional considerations for selecting switchgrass were its positive environmental attributes, including low nutrient use, low pesticide requirements and its perennial growth habit.

The perennial growth of warm season grasses is an extremely important aspect of their ecology and economics and essential to their role in soil conservation.[8] Once established, perennial grasses can be produced for many years without the annual replanting cycle that increases soil loss and degradation. The deep, well developed root systems of these grasses can result in standing pools of root biomass being comparable to that produced annually above ground.[9] This 'investment' of energy belowground has many benefits, including efficient acquisition of nutrients and water, a strong energy storage reserve, more stable yields during stress years, and finally, increased soil organic matter (SOM). This latter attribute is one of the keys to perennial grass contributions to soil conservation because it influences soil erosion, water and nutrient conservation, and runoff and losses of agricultural chemicals.

2.1. *Perennial grasses and the CRP*

Soil erosion is a major problem influencing soil and water quality in agricultural areas around the world and in the U.S. is considered a major threat to long term crop production.[10] In the U.S. alone, annual estimates of soil losses were placed at 1–2 billion tons $\mathrm{yr^{-1}}$ in 1977.[11] Approximately 72 million acres of U.S. cropland was estimated to need erosion control in the late 1970s.[12] By 1987, USDA estimated annual cropland erosion at 3 billion tons. Conservation programs have reduced this by *ca* 50%.[13] Annual cropping on erosive soils not only enhances losses of the more productive surface soils and associated nutrients, but also depletes SOM through alterations in soil nutrient cycling. Decades of annual row cropping in the Northern Plains resulted in significant depletion of SOM and soil nutrients on erosive soils.[14] Loss of SOM can alter many important aspects of soil quality. Soil moisture holding capacity, soil density and aeration, and soil nutrient availability and conservation are among the essential properties controlled by SOM.[15] The current rate of loss of SOM through annual row cropping in the United States has been estimated at 2.7 million metric tons per year.[16]

As a means of protecting erodible cropland from continued depletion by agricultural production, Congress established the Conservation Reserve Program (CRP) in 1985. The erosion limiting capacity of perennial grasses has resulted in their being planted on much of the 32 million acres of CRP land, established since 1985 to combat soil loss from the intense cultivation of annual crop production.

3. SOIL CARBON DYNAMICS AND IMPORTANCE

Recent studies by the Soil Conservation Service to examine changes in SOM during 5 years of perennial grass production on CRP lands indicate that perennial grasses added $1.1\ \mathrm{Mg\ ha^{-1}\ yr^{-1}}$ of carbon to the upper 300 cm of mid-western soils.[17] These additions replaced 23% of the soil carbon lost during decades of prior tillage. The large active pools of roots are a major source of this carbon, and both rhizosphere deposition and fine root turnover, which may add up to $3\ \mathrm{Mg\ ha^{-1}\ yr^{-1}}$,[18] and active populations of soil microorganisms and invertebrates, which may total $>4\ \mathrm{Mg\ ha^{-1}\ yr^{-1}}$ are important to soil carbon pools and to the function of soil as a retentive nutrient cycling reservoir.[19]

The addition of significant quantities of organic matter into soils by the prolific rooting systems of perennial grasses has many benefits from a soil conservation standpoint.[8] These include improved soil structure, increased water-holding capacity and infiltration through structural and porosity changes, improved nutrient conservation and availability and decreased soil erosion. The organic material containing soil carbon serves many roles ranging from providing nutrients as decomposition occurs, to enhancing the capacity of the soil to retain, and provide water and nutrients to plants. Ultimately availability of both existing and added water and nutrients to vegetation is enhanced by increasing organic matter in soils.

4. ROLE OF SWITCHGRASS IN SOIL CARBON, EROSION AND SEDIMENTATION CONTROL

Recent studies within the BFDP support the occurrence of improved soil quality under cropping regimes utilizing the high yielding switchgrass varieties being developed as biofuel candidates. Significant augmentation of SOM was noted after only four years of production in Virginia.[20] These increases can be attributed to very high root mass which, in an ongoing study at Auburn University,[21] have totalled almost 8 Mg ha^{-1} in just the top 75 cm of soil. With Alamo switchgrass, over 4 Mg ha^{-1} was found just in the 0–15 cm depth interval. The maximum rooting depth of switchgrass in natural prairie stands ranges from 2.6 to 3.7 m, and annual belowground production of prairie ecosystems is frequently two to four times aboveground production.[22] Grazing apparently stimulates belowground production.

The contrasts in soil erosion between perennial grasses and cultivated row crops, such as corn, which figures prominently in current ethanol production, are striking and have significant economic and ecological implications. Reductions in soil erosion properties under grass cultivation are well documented. Erosion losses associated with corn cultivation in Iowa, for example, were *ca* 70 times greater than for production of grasses on similar land.[12] During heavy rains soil losses from row cropped fields can exceed losses from grasslands by >200 times.[23] Significant differences in runoff accompanied these enhanced soil losses. Fortunately, more modern conservation tillage methods, currently used on *ca* 35% of the corn produced in the U.S., can substantially reduce erosion rates.[24]

Both the quantity of chemicals used to maintain production of grasses and the fate of those chemicals are expected to differ markedly with perennial grass production compared to that experienced historically for row crop production. Annual rates of nitrogen use for switchgrass (70–100 kg ha^{-1}) for example, are typically about half those required for corn production (138–154 kg ha^{-1}). In addition, switchgrass normally requires herbicide use only during the establishment year of what is anticipated to be at least a 10-year growth cycle, whereas corn and other annual crops require annual application. The costs of these additional chemicals must be included both in economic production costs to the farmer, and also in the ecolgical costs of increased rates of infiltration of chemicals into groundwater and runoff into streams.

Graham and Downing[25] have evaluated regional aspects of replacing annual crops in western Tennessee with switchgrass for energy production. Using fertilizer application rates, crop use, land quality and erosion models, they projected improved water quality associated with reduced chemical contributions to groundwater and reduced soil erosion. In addition reduced evapotranspiration was predicted based on the high water use efficiency of switchgrass compared to other grasses and annual crops.[26] Decreased runoff of agricultural chemicals with conversion to switchgrass production was not considered in this simulation, but may add significantly to the environmental benefits noted. On a national scale the U.S.A. loses *ca* \$18 billion in fertilizer nutrients to soil erosion,[27] so one should expect agricultural chemical inputs to aquatic systems also to be large.

In addition to reducing the effects of soil erosion in agricultural fields under cultivation, there is evidence that warm season grasses, such as switchgrass can play an important role in stabilizing soil along streams and wetlands. This attribute can be credited both to growth characteristics, the density of stems and roots, which promote soil stability, and to its tolerance of periodic flooding. Studies to evaluate the capacity of various grass species to withstand flooding indicate that switchgrass has a strong tolerance of flooding and can withstand continuous immersion for 30–60 - days.[28] In Missouri, switchgrass was found to have survived the severe 1993 midwestern flood with minimum damage to the grass stands and very effective control of levee deterioration from flood wash (Missouri, Department of Conservation, 1994). In addition, the capacity of forage grasses to increase soil stability and reduce overland flow of runoff waters from agricultural fields has contributed to their value as a conservation cover to retard sedimentation of wetlands adjoining erosive agricultural fields.[29]

5. NET ENERGY RETURN AND CARBON REPLACEMENT VALUE OF SWITCHGRASS

An important measure of the environmental benefits of energy crops is the extent to which they can offset the environmental costs of extracting and burning fossil fuels. The net benefits of replacing fossil fuels with biofuels will depend not only on the energy contained in the biomass, but also on the energy required to grow the crop and convert it to a usable energy form. In Table 1 comparitive energy budgets are provided for producing ethanol by the current corn-based conversion system that currently supplies 96% of the nation's ethanol and a system based on conversion of switchgrass to ethanol.

Table 1. Comparative energy flow in producing ethanol from switchgrass and corn

Process	Corn[a] (GJ ha^{-1} yr^{-1})	Switchgrass[a] (GJ ha^{-1} yr^{-1})
Crop production	18.9	17.8 (12.8)
Biomass energy[b]	149.5	220.2
Energy ratio $R1$[c]	7.9	12.3 (17.2)
Ethanol production[d]	47.9	10.2
Energy in ethanol[e]	67.1	104.4
Total energy ratio $R2$[f]	1.21	4.43
Net energy gain	21%	343%

[a]Budget data for production and processing corn are from Shapouri *et al.*[31] Production data are adjusted for 0.73 GJ ha^{-1} machinery production costs. Switchgrass data include costs of on-farm storage and secondary handling or direct transfer to buyer (in parentheses).

[b]Yields assumed were 13.5 Mg ha^{-1} for switchgrass and 301 Bu ha^{-1} for corn. Corn biomass energy includes 18.9 GJ ha^{-1} of energy in corn fiber and no credit for stover.

[c]Biomass energy/production energy.

[d]Includes processing and distribution energy. Switchgrass data are derived from analyses of the saccharification and fermentation processes for ethanol production at the National Renewable Laboratory (Tyson *et al.*[32]).

[e]Ethanol yields are 2963 l ha^{-1} for corn and 4487 l ha^{-1} for switchgrass with ethanol energy of 23.3 kJ l^{-1} used to calculate production energy.These are based on conversion rates of 386 l Mg^{-1} (2.6 gal Bu^{-1}) for corn and 333 l Mg^{-1} (80 gal ton^{-1}) for switchgrass.

[f]Total output energy/total input energy (processing, production and distribution energy). Output energy includes allowance of 14.2 GJ ha^{-1} credits for coproducts for corn and 19.8 GJ ha^{-1} for combustion of lignin from switchgrass.

5.1. *Biomass production energy*

Data in Table 1 include both energy required to produce the crops as well as requirements to convert corn or switchgrass to ethanol by two different technologies. Crop budgets are based on summation of energy embodied in the manufacture and transport of machinery, chemicals, fertilizers and lime; seeds; machinery repairs; direct energy use (fuels, electricity, natural gas); transport of fuels; and transport of the crop to processing plants. The data for corn are from recent U.S.DA analyses[30] and assume the most efficient technology for both fertilizer manufacture, conversion of corn grain to ethanol, and coproduct revovery. The energy budget for switchgrass was similarly derived and included credit for energy recovery from combustion of the lignin byproduct.[31]

The energy return ratios (R = output:input) derived here for both switchgrass and corn are dependent on assumptions about harvesting and handling. For switchgrass a yield of 13.5 Mg ha^{-1} yr^{-1} and that the crop would be harvested as big round bales (*ca* 450 kg each), and stored and handled a second time before processing was assumed. This adds *ca* 40% to the production energy reducing R from 17 to 12.4. For corn, it is estimated that *ca* 2.2–3.4 Mg ha^{-1} of stover could be harvested for energy. However, this material has not been routinely included, nor ethanol derivable from it, in the budgets (nor did Shapouri *et al.*[30]) because it is not considered likely to be utilized. Additionally corn fiber represents a source of energy at harvest, but not ethanol energy at present.

The net result is an energy output:input ratio (R) of *ca* 12–17 for switchgrass compared to an R value of 6 for corn grain. The R for corn can be increased to near 8 when corn stover and fiber are also utilized as energy products. Thus switchgrass biomass energy conversion streams represent a 50–100% increase in energy gain over conventional corn energy production.

5.2. *Converting biomass to ethanol energy*

Fermentation of grain starch to ethanol is a time-proven technology[32] currently providing substantial economic benefits to the farm community.[33] For converting lignocellulosic tissues to ethanol, more complex digestion and fermentation processes are required. The saccharification and fermentation (SSF) process through which plants and plant-derived residues are first enzymatically broken down into constituent sugars, which can be bioconverted to ethanol by fermentation,[2] is one such process. The process energy required to produce equivalent amounts of ethanol is *ca* 4.5 times higher for corn than switchgrass (Table 1). For production of ethanol from corn by enzymatic hydrolysis, estimates of an energy output:input ratio (R) for current industrial systems generally range from *ca* 1.1 to 1.2.[2,30,32] The most recent USDA estimate,[30] when adjusted for machinery energy inputs includes a net energy ratio of 1.00 for production of ethanol and a value of 1.22 when the energy content of coproducts is included. For ethanol production from switchgrass, the same energy accounting procedure led to an energy return ratio (R) of 4.34. The net energy gain of producing ethanol from switchgrass (334%) then exceeded that of corn grain-to-ethanol (21%) by a factor of *ca* 15.

The gains in net energy returns from perennial grass production are derived from reduced energy investments at all steps of the crop production/conversion pathway leading to ethanol formation. This includes reduced energy required for agricultural production, increased energy in the biomass produced, and reduced energy to process the biomass into ethanol. The net effect of these differences is that, 55% more ethanol energy can be produced per hectare growing switchgrass than with an annual crop like corn.

5.3. *Net savings in carbon emissions*

Calculations of net carbon gain for switchgrass vs corn produce similar large differences in the capacity of the ethanol produced to offset the CO_2 emissions of the gasoline that it replaces (Table 2). The net carbon dioxide budget is based on the amount of fossil fuel consumed in producing fuels, fertilizer, pesticides, and machinery to produce the crop. Carbon: energy equivalents of 13.78, 19.94 and 21.12 kg C GJ^{-1} for natural gas, petroleum liquids and coal, respectively, in proportion to their use in these processes were used.[34] The total amount of fossil fuel that can be replaced was based on a carbon:energy equivalents value for ethanol of 18.5 kg C GJ^{-1}. The combination of lower energy requirements to both produce and convert switchgrass to ethanol, result in *ca* 20 times higher CO_2 emissions savings per unit of land area with switchgrass compared to corn as seen in Table 2.

Table 2. Comparative carbon flow in producing ethanol from switchgrass and corn

	Corn (kg C acre^{-1})	Switchgrass (kg C acre^{-1})
A. Production costs[a]	1492	598
B. Fuel replacement[b]	1578	2480
C. Net combustion savings[c]	86	1882
D. Soil carbon storage[d]	—	1100
E. Total carbon reduction[e]	86	2982

[a]Includes agricultural production, chemical processing and distribution energy costs.
[b]Replacement of gasoline at 19.94 kg C GJ^{-1} with ethanol. Coproduct credits were allowed for both corn (247 kg C ha^{-1}) and switchgrass (437 kg C ha^{-1}) based on energy equivalence of those coproducts.
[c]B – A.
[d]Assumes 1100 kg C ha^{-1} yr^{-1} gain in soil organic carbon on land depleted by row cropping.
[e]C + D.

Where switchgrass production replaces annual row cropping, these gains may be increased even further due to significant increases in soil carbon storage belowground. In Table 2 an annual belowground carbon storage rate of 1.1 Mg C ha^{-1} yr^{-1} based on perennial grass carbon accretion rates observed by Gebhart *et al.*[17] was estimated. These gains were based on analyses after 5 years of maintenance of native grasses in the CRP. Inclusion of the belowground carbon storage estimate in Table 2 increases total carbon replacement in the switchgrass to ethanol cycle by 58% and brings its advantage over the conventional corn-to-ethanol cycle to *ca* 30 times (2982 vs 86 kg C ha^{-1} yr^{-1}).

Thus, in terms of both energy replacement, as well from the perspective of carbon emissions reductions, the switchgrass-to-ethanol cycle has significant advantages that should make it an environmentally valuable supplement to corn in future ethanol markets.

6. INFORMATION NEEDS

The environmental issues discussed in this paper have been largely the positive soil conservation attributes associated with production of switchgrass and other forage grasses. The CRP experience has provided valuable information in this area. Energy and carbon budgets have been derived from field trial data, for production economics, and from bench-scale studies of conversion of switchgrass to ethanol. It should be noted at this stage, that there are no large, fully operational facilities using switchgrass as a primary fuel. However commerical scale pre-operational testing is being conducted or planned for the near future in Iowa, Wisconsin, Tennessee and Alabama. These activities will provide excellent opportunitiese for documentation of the effects of more extensive cultivation of switchgrass on soil quality, water quality and wildlife utilization of switchgrass plantings.

Current short-term studies indicate that soil carbon can be significantly improved with perennial grass production. Tests to date with diverse soil types in both Virginia and Texas support these findings, however, the extent and regional significance of such changes has yet to be determined and will await an expanded network of test sites to determine longer term levels of soil improvement for various soil types and previous land use characteristics.

There are some additional environmental information needs that will be important to address if switchgrass is to significantly expand as an energy crop. Principle areas of need are the development and licensing of appropriate pesticides for crop management and developing harvesting strategies which consider both yield and wildlife use of bioenergy stands. Tests of herbicides, and possibly insecticides, to aid in weed and insect control during the critical establishment year is currently a part of the DOE BFDP field trial program. Another aspect of that program is development of appropriate cutting strategies to maximize yield potential. Both two and one-cut harvest systems are being evaluated, including leaving the stand until after the first frost. Single-cut systems, pose minimum danger to nesting birds, while the timing of the first cut of two-cut systems may impact some birds in some areas. Studies on the effects of bioenergy crops on wildlife suggest that, with appropriate management, they can provide substantially improved habitat for many forms of wildlife compared to conventional crops.[35]

7. CONCLUSIONS

There are many obvious environmental benefits of increased utilization of switchgrass as a renewable energy crop. A brief summary is provided here of three of the most significant and most obvious of these. They include, improved soil conservation, improved energy gain and improved reductions in emissions of carbon dioxide. Certainly, all of the environmental issues associated with the processes of producing and converting energy crops to fuel and electricity have not yet been quantified in final detail. Process engineering is proceeding to minimize other environmental risks associated with biofuel conversion and combustion processes, and it is reasonable to anticipate that environmental risks will be far lower than for current technologies based on fossil fuels. In the meanwhile, the soil conservation benefits, gains in energy return and reductions in CO_2 emissions reduction discussed above have important ecological and economic dimensions that are known to be positive. These environmental benefits should provide an important impetus for moving forward with larger scale commercialization. The gains in net energy return are particularly important as a measure not only of the rate at which energy self reliance can be increased, but also in terms of reductions in a wide range of environmental costs associated with the aquisition and combustion of fossil fuels.

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