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INTEGRATED PRODUCTION OF WARM SEASON GRASSES AND AGROFORESTRY FOR LOW COST BIOMASS PRODUCTION

by R. Samson[1], P. Girouard[2], j. Omielan[3] and J. Henning[4]

[1]Executive Director and [3] Research Scientist, Resource Efficient Agricultural Production (REAP) Canada, Box 125, Ste. Anne de Bellevue, Quebec, Canada H9X 3V9

[2] Graduate Student and [4]Associate Professor of Agricultural Economics, Macdonald Campus of McGill University, Ste. Anne de Bellevue, Quebec, Canada H9X 3V9

Abstract

Increased research on C_3 and C_4 perennial biomass crops is generating a significant amount of information on the potential of these feedstocks to produce large quantities of low cost biomass. In many parts of North America it appears that both C_3 and C_4 species are limited by water availability particularly on marginal soils. In much of North America, rainfall is exceeded by evaporation. High transpiration rates by fast growing trees and rainfall interception by the canopy appear to indicate that this can further exacerbate the problem of water availability. C_4 perennial grasses appear to have distinct advantages over C_3 species planted in monoculture systems particularly on marginal soils. C_4 grasses historically predominated over much of the land that is now available for biomass production because of their adaptation to low humidity environments and periods of low soil moisture. The planting of short rotation forestry (SRF) species in an energy agroforestry system is proposed as an alternative production strategy which could potentially alleviate many of the problems associated with SRF monocultures. Energy agroforestry would be complementary to both production of conventional farm crops and C_4 perennial biomass crops because of beneficial micro climatic effects.

Introduction

Studies involving fast growing plantations of trees have been ongoing since the early 1970's in North America by the United States Department of Energy and Natural Resources Canada. More recently herbaceous feedstocks have received increased attention for their biomass production potential. However, few attempts have been made to understand climatic influences on the choice of biomass feedstocks or the potential to integrate production of woody and herbaceous biomass crops. This paper will discuss the major constraints to monoculture production of short rotation forestry (SRF) and warm season grasses and outline the potential advantages of an integrated production of the two feedstocks. It is believed that a better understanding of the native vegetation of North America and how climatic conditions influenced its development will help biomass scientists understand the choice of biomass feedstocks and strategies to modify the climatic conditions to favour biomass production.

Developing Efficient Biomass Production Systems

Crop production strategies need to be developed which are as efficient as possible in capturing sunlight (solar energy) and storing it in plants (solar battery). Desirable characteristics for energy feedstocks include:

1. Efficient conversion of sunlight into plant material;
2. Efficient water use as moisture is one of the primary factors limiting biomass production in most of North America
3. Sunlight interception for as much of the growing season as possible;
4. Minimal external inputs in the production and harvest cycle (ie. seed, fertilizer, machine operations and crop drying).

We know that to achieve these objectives several issues must be considered:

1. There are two main photosynthetic pathways for converting solar energy into plant material: the C_3 and C_4 pathways. The C_4 pathway is approximately 40% more efficient than the C_3 pathway in accumulating carbon (Beadle and Long, 1985).
2. C_4 species use approximately 1/2 the water of most C_3 species (Long et al., 1987).
3. In Northern climates, sunlight interception is more efficient with perennial plants because annual plants spend much of the spring establishing a canopy.
4. Perennial crops do not have annual establishment costs (seed, tillage etc.). As well they are N efficient because N is cycled internally to the root system in the fall (Clark, 1977). Nutrient leaching and surface nutrient loss through soil erosion is minimal with perennial crop production compared to annual crop production. C_4 grasses have a higher N use efficiency than C_3 grasses (Brown, 1985).

Based on these criteria, the fastest, most resource efficient crops to grow would be perennial C_4 grasses. Since 1986 the US Department of Energy (DOE) has extensively evaluated herbaceous and woody biomass crops for biomass production. It is not surprising then that the lowest cost feedstock production that has been achieved in North America has been with switchgrass ***(Panicum virgatum),*** a C_4 prairie grass. Several studies have estimated production costs below US$30.00/tonne (Sladden et al., 1991; Parrish et al., 1990).

Recent reports by European biomass scientists have further highlighted the significant yield and physiological advantages that C_4 grasses hold over C_3 species (i.e. cool season grasses or fast growing trees) for biomass production (Jones et al. 1987; Long et al. 1990; Stander, 1989; Rutherford and Heath, 1992). As a result of a number of these reports and promising early biomass yields from C_4 species, much of the current research in Europe is now evaluating the perennial C4 grass ***Miscanthus*** and the annual C_4 species sweet sorghum.

Effect of Climatic Conditions on the Centers of Plant Distribution in North America

American ecologists early in the 19th century demonstrated that water relations had a powerful influence on the distribution of plants. Most authors have credited much of the development of the concept to Transeau (in Stuckey, 1981) who in 1905 wrote:

*" **I**nvestigation shows that forests, grasslands and deserts are arranged about certain centers, which owe their positions on the continent mainly to climatic causes. That such centers cannot be correlated with the distribution of heat or rainfall alone is evidenced by examination of the monthly, seasonal and annual distribution of these elements.*

The fact that so large a part of early adaptations shown by plants are more or less directly connected with transpiration, led the writer to construct a map (see figure 2.) combining the figures for rainfall and evaporation. The amount of evaporation depends upon the temperature of the evaporating surface, the relative humidity of the air and the velocity of the wind. Therefore if we combine the figures for rainfall and evaporation we have a number which will represent at least four climatic factors, that must powerfully influence the water relations and distributions of plants.

The Great Plains are marked by an amount of rainfall equal to 20-60 percent of the evaporation. Where the ratio rises to between 60 and 80 percent, the prairie region, where dense forests are confined to the river bottoms, is indicated. The region where "open forests", "oak openings" and "groves" occur on the uplands and dense forests on the low grounds, is indicated by the 80-100% ratios.

The two maps (Figure 1 and Figure 2) that originated from Transeau's work provide a general indication of how vegetation in North America evolved as a result of climatic conditions. Biomass scientists need to understand the native vegetation and climatic conditions of an area to more effectively understand constraints to biomass production. Few biomass scientists may realize that a prairie peninsula (figure 2) once extended from the North Central region of the United States into the northeastern States of Ohio and Michigan and that low soil moisture periods combined with low humidity were among the primary reasons that this ecosystem evolved. The information provided by Transeau's search for an explanation for the prairie peninsula in North America may prove invaluable for scientists looking to understand ecological constraints to maximizing biomass production. For example, many North American (SRF) researchers working in unirrigated monocultures frequently find that low biomass yields are obtained in the areas where the rainfall to evaporation ratio is lower than 100%. Even in areas where the natural landscape has a rainfall to evaporation ratio from 100150%, the yield potential of SRF systems may be water limited because rapid accumulation of biomass increases water loss through transpiration.

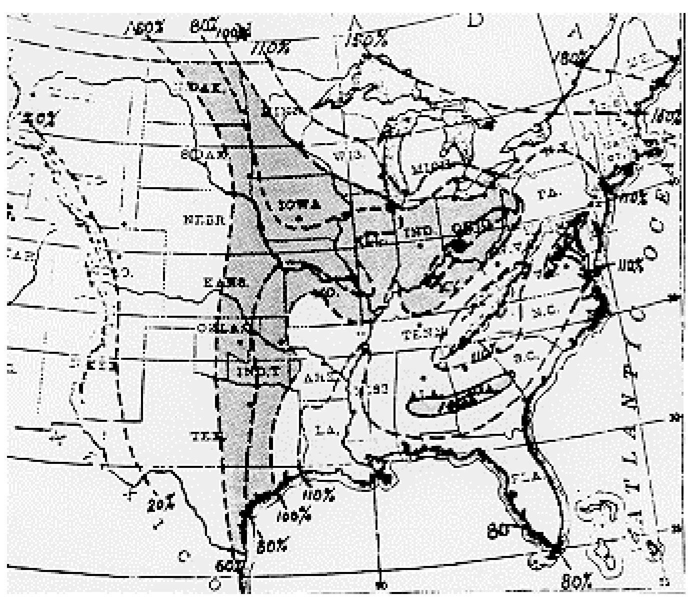

Figure 1. Map of eastern United States showing the ratio of rainfall to evaporation in percentages in different regions; prairie region is the 60 percent to100 percent ratio.

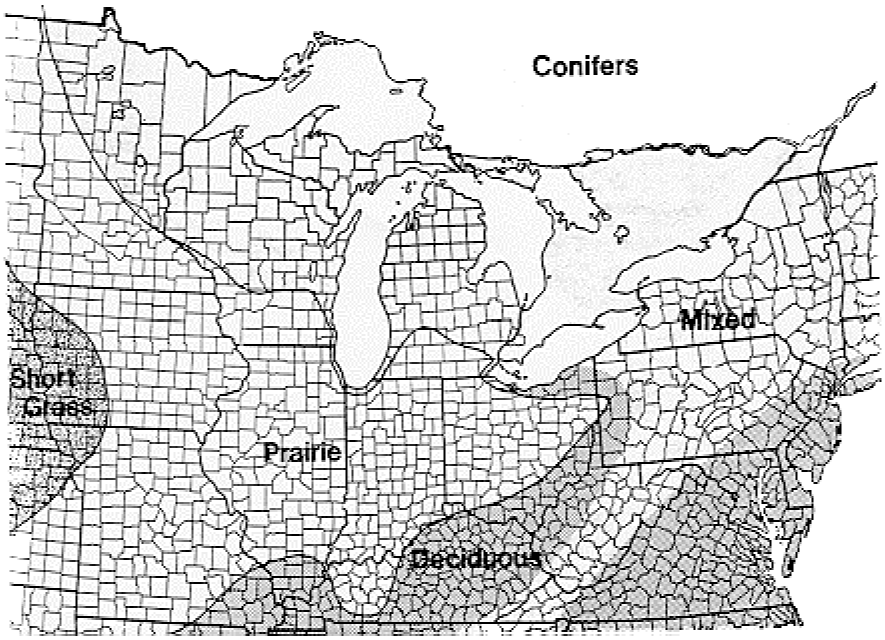

Figure 2. Map of north central United States showing peninsula-like projection of prairie vegetation between the shortgrass region and the forested areas at the time of the "Xerothermic period" as viewed by Transeau (Stuckey, 1981)

Preliminary Assessment of Barriers to SRF Productivity

The low water use efficiency of SRF systems may be the primary reason that yields have not increased when researchers have left small plots and gone to field scale conditions. A summary of large plot and field scale studies (unirrigated sites with borders) from a recent International Energy Agency (IEA) publication indicates current yields being obtained (Table 1).

Table 1. Summary of recent production data from the IEA Report: How to Grow Short Rotation Forests (Ledin and Alriksson, 1992)

Europe	**Species**	**Yield (ODT/ha/yr)**
Austria	Willows	10.5
Sweden	Willows	11
England	Willows & poplars	6-11
Denmark	Willows	8.1

USA		
Pennsylvania	Poplars	10.4
Wisconsin	Poplars	7.5
Washington	Poplars	15.1

- ODT = Oven Dry Tonne

Data from other recent reports with relatively large plots or field scale plantings

France	Poplars	7.9 ODT/ha	Auclair and Bouvarel, 1992
Ontario, Canada	Poplars	2-3 ODT/ha	Hendry, 1990

The Washington study was the only study to have average yields above 11 ODT/ha. This was performed in a high rainfall area of the Pacific Northwest of the United States. If this study is observed as an anomaly for North America (because of the area's unique climatic conditions relative to the rest of North America), it appears that most field scale yields are in the range of 7-11 ODT/ha. This would agree with Hansen (1988), in his review of SRIC (Short Rotation Intensive Culture) yields, who states 7-11 t/ha as a reasonable estimate of potential SRIC field yields.

The problem of low water use efficiency by the trees in field scale plantations has been identified by several researchers (Dickmann et al., 1992; Grip et al., 1989; Persson and Jansson, 1989; Halldin and Lindroth, 1989). In some areas in Sweden where plantings have been made on bogs, willows have lowered the water table (Persson, 1989). A water balance study in Sweden which simulated a production of 12 t/ha indicated an evaporation of 526 mm, of which 375 mm was transpiration, 56 mm interception and 95 mm soil evaporation. This rate of evaporation was 22% higher than the Penman open water evaporation rate of 430 mm (Grip et al., 1989). Several other Swedish studies have also indicated evaporation rates of SRF systems being 10-50% higher than the potential evaporation by the Penman formula (Persson and Jansson, 1988; Halldin and Lindroth, 1989). It should not be surprising that water availability is proving to be a primary factor limiting yield for high biomass producing systems. Forage scientists have demonstrated that biomass production is water limited for C_3 and C_4 grasses on marginal sites in northeastern North America (Stout et al., 1988;

Stout, 1992), and that forage productivity Of C_3 grasses is a good predictor of SRF yields on a site (Wells and Fribourg, 1992). While average rainfall in northeastern North America may be similar to that of Sweden, the intensity of rainfall (frequent storms resulting in higher runoff) and the more continental climate of North America (lower relative humidity), suggest that the moisture use problem would be exacerbated in North America for SRF, particularly on marginal soils (due to low water holding capacity), The low water use efficiency of monoculture plantations of willows or poplars (C_3 species) indicates that the real yield potential for SRF in most of North America is only about 1/2 of that required for economic production, 23 t/ha (Kenney et al., 1991). Yields of 7-11 ODT/ha would put biomass costs in the range of US$ 65-85/ tonne (Turhollow, 1992). Thus, an alternative to monoculture SRF systems needs to be developed if plantation forestry is to have a viable energy future in North America, since plantations using irrigation systems are not an option (economically or ecologically) for energy production. The agronomic and economic problems with the monoculture SRF include:

1. low productivity because of low water use efficiency and low solar energy conversion compared to C_4 grasses,
2. greater reliance on N, P and K fertilizer inputs than warm season grasses if a relatively short rotation period is used (ie. 4 years or less),
3. significant disease and pest problems associated with fast growing trees and clonal material
4. planting, weeding, fertilizing and harvesting may require new equipment or custom operators to perform farm operations,
5. lack of adaptability to marginal soils with low water holding capacity,
6. expensive and difficult harvesting process,
7. cost of reconverting the land back to agricultural production is high,
8. high initial capital investment,
9. not a farmer friendly crop because of long harvest interval compared to conventional crops.

C_4 Grasses as Biomass Crops

Most land suitable for biomass production from plantations in North America has a rainfall to evaporation ratios of 50-110% (Figure 1). The prairie region, found in the 60-100% rainfall/evaporation area, occupies a major portion of this land base. The native prairie grasses that were dominant in this area were the C_4 perennial grasses. Among the most common were big bluestem *(Andropogon gerardii* little bluestem *(Schizachyrium scoparium),* Indiangrass *(Sorghastrum nutans),* switchgrass *(Panicum virgatum)* and prairie cordgrass *(Spartina pectinata)* (Weaver and Fitzpatrick, 1934). These species have all shown potential to produce biomass yields greater than 10 t/ha on unirrigated sites (Stubbendieck and Nielsen, 1989; Gould and Dexter, 1986; USDA, 1991). The most thoroughly researched species has been switchgrass. It has many desirable characteristics for biomass production including:

- **High productivity:** When appropriate cultivars are chosen, productivity is high across much of North America. Yields of 15 to 30 t/ha are being obtained with lowland switchgrass ecotypes in the southern United States (Table 2). In studies near the Canadian border, winter hardy upland ecotypes of switchgrass have produced yields of 9.2 t/ha in northern North Dakota (Jacobson et al., 1986) and 12.5 t/ha in northern New York (Thomas and Lucey, 1987).
- **Moisture efficient:** Switchgrass uses water approximately 2 times more efficiently than traditional cool season grasses (Stout et al., 1988; Parrish et al., 1990; Stout, 1992). Its root system extends up to 3.3 metres and has a greater distribution of root weight at deeper soil depths than other prairie species (Weaver and Darland, 1949).
- **Low N requirements:** Compared to cool season grasses, optimal yields of switchgrass can be obtained with much lower N requirements and response to N may not be observed in the early years of production (Jung et al. 1990). N levels in switchgrass biomass are in the order of 0.5% N at full maturity (Balasko et al. 1984) which is approximately 1/2 that of most cool season grass species.
- **Low P requirements:** On soils with low levels of available P, warm season prairie grasses have higher dry matter yields and have P concentrations approximately 1/2 that of cool season grasses (Morris et al. 1982). An adaptive advantage Of C_4 grass species is their use of mychorrhizal symbiosis for nutrient uptake. This may help explain the abundance Of C_4 plants in prairie soils low in available nutrients (Hetrick et al. 1988).
- **Low K requirements:** Switchgrass has a lower critical K level than cool season grasses and seldom shows response to K fertilizer (Smith and Greenfield, 1979).
- **Stand longevity:** Adapted switchgrass cultivars harvested for hay have excellent persistence, minimal disease and insect problems and good cold tolerance.
- **Acid soil tolerance:** Switchgrass will tolerate extremely low pH soils (<5.0) which do not support the growth of cool season grasses or legumes (Jung et al., 1988).
- **Low harvest costs:** In studies in the northern United States, 1 cut per season maximized biomass yields from switchgrass while most cool season grasses generally require multiple cuts (Wright, 1990).
- **Soil restoring:** Switchgrass is one of the dominant species of the North American prairie that built some of the most productive and rich soils in the western hemisphere.
- **High ethanol yield:** Switchgrass has a higher combined cellulose and hemi-cellulose content than cool season grasses or legumes (Cherney et al. 1988).
- **Farmer friendly:** Compared to other warm season grass species, switchgrass is inexpensive to seed and establishes well. It has good seedling vigor, low seed costs, low seeding rates and herbicide tolerance.

- **Environmentally friendly:** Switchgrass provides nesting cover and seeds act as a food source for birds. The re-establishment of prairie grasses will improve water quality in several ways: annual grain crops responsible for increasing erosion potential will be replaced, ground water nitrate levels (Ramundo et al. 1992) and surface P loading (Sharpley and Smith, 1991) will be reduced. Pesticide impacts on wildlife would be reduced because herbicides would be used probably only in the establishment year unlike the annual use of insecticides and herbicides in field crop production.

Several other prairie species have also shown potential to produce biomass yields as high or higher than the tallgrass prairie species, particularly outside of the main prairie region. Two of the more promising species are prairie sandreed (Calamovilfa longifolia) and Eastern Gamagrass (Tripsacum dactyloides) which have performed well in biomass trials in the Northern US Great Plains (USDA, 1989) and Southern Illinois respectively (Kaiser, 1989). The native range of these plants compared to that of switchgrass give an indication that they may be as well or better adapted to these particular areas than switchgrass. (Figure 3)

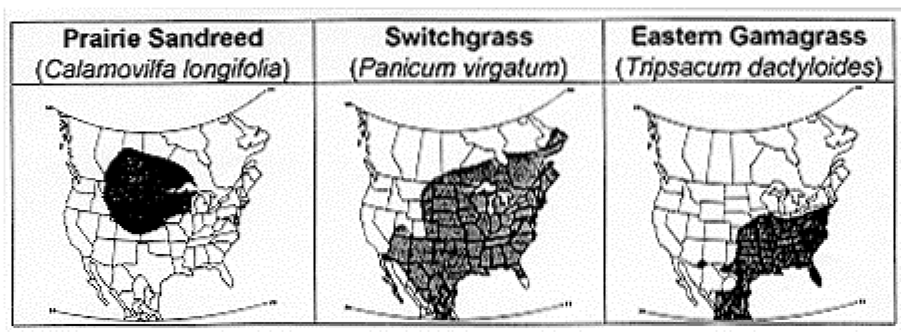

Figure 3. Native Range of Promising Biomass Feedstocks (Maps from Stubbendieck et al., 1992)

Energy Agroforestry as An Alternative

Many of the problems inherent in the SRF system may be reduced or eliminated if an agroforestry approach to energy production is taken. This approach to using trees for energy production has been suggested by others including Newman et al. (1990), Soltner (1991) and Ronneberg (1992). The trees grown in a SRF production system would be used as windbreaks on high value land in order to protect adjacent agricultural crops. The main reasons why an agroforestry approach may be more successful in North America than the monoculture plantation concept are the following:

1) by limiting the plantation to at most a few rows of trees, the availability of sunlight and water would be increased thereby improving tree productivity; (2) compared to conventional windbreaks which are harvested after 25-35 years for timber, SRF windbreaks for energy would make it possible to get a first return after 5 years. The trees would be seen as an asset and not occupiers of valuable crop land; (3) while the reduced competition from the adjacent agricultural crops would benefit the trees, the crops would also benefit from the trees. The benefits of windbreaks have been well documented and include reduced wind speed, increased humidity levels, higher day time temperatures, higher soil moisture, reduced wind and water erosion and increased snow trapping (reviewed by Kort, 1988). (4) in most instances where short rotation windbreaks would be grown in conjunction with field crops, they probably would not need to be fertilized as most farmers tend to overfertilize their crops. The deep root system of the trees would help to recycle nutrients lost in the deepest layers of the soil.

Regarding crop yields, studies have indicated that perennial forage crops (alfalfa and mixed hay) are highly responsive to windbreaks (Kort, 1988). Establishment of windbreaks could potentially have a very beneficial effect on C_4 grass growth, particularly in its northern range, because of their ability to reduce the chilling effect of high winds and increase daytime temperatures. Thus, systems could be developed where fast growing trees would be planted in windbreaks while a C_4 grass such as switchgrass would be grown in between. Those systems would be entirely dedicated to energy production. Because perennial grasses such as switchgrass can be grown effectively on marginal agricultural land, those systems would also help to take out of production either temporarily or permanently land that cannot sustain annual field cropping. In this case, the trees will probably have to be harvested at longer intervals due to a slower growth rate. However, the lower land cost of those marginal soils should compensate for the longer rotation.

Finally, because SRF harvesting technologies are not well developed, trees planted in windbreaks could be **harvested using a chain saw and a tractor pulled** wood chipper. One two row design of this simplified energy agroforestry scheme has been proposed by Soltner (1991) (figure 4). This system would enable at least one row to remain as a windbreak while the other row was harvested or in early coppice regrowth. REAP-Canada is currently assessing this approach to energy agroforestry using combinations of willows, poplars and black locusts in an on-farm research program in Central Canada. The combination of one row of black locust with a row of poplar or willow may enable an opportunity to reduce/ eliminate the competition problems that have sometimes been reported with legume/ non-legume tree mixtures in block plantings (Heilman and Stettler, 1985; Heilman, 1989) and the need for N fertilization.

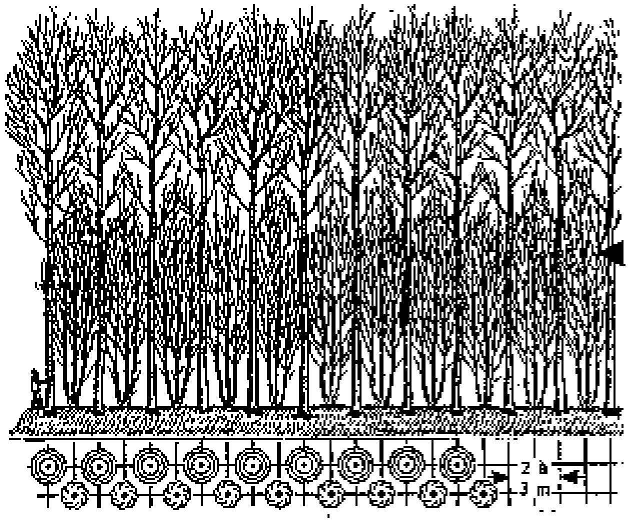

Figure 4. Two row windbreak system with two different species and harvest cycles (Soltner, 1991)

Summary

If biomass production systems are to advance significantly in achieving the goal of low cost and abundant biomass, a greater understanding, of ecological and physiological processes needs to be achieved. Much of the land base in North America that is available for biomass production has significant moisture limitations. C_4 grasses have well developed characteristics for optimizing growth under these conditions compared to C_3 species. The best opportunity to use fast growing trees for biomass production appears to lie with their application in agroforestry systems. Energy production in the form of windbreaks would enable an optimization of growth of fast growing trees while complementing production of traditional farm crops or C_4 perennial biomass energy crops. The production of "green energy" from biomass can only be realized if an ecological approach to biomass production is taken.

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Home Page