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Short-Rotation Forestry and the Water Problem

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Abstract

Significant research effort has been put into the development of short-rotation forestry (SRF) systems for growing energy crops, yet yields in field-scale trials have generally been well **below those predicted** from small plot trials. The major problem with yield in SRF systems appears to be water-related. Most field-scale yields in high-density plantings on productive land have been in the 7-11 oven-dried tonne (ODT)/ha range. This range is below the production level required for SRF to become competitive as a dedicated energy crop in the foreseeable future. The 7-11 ODT/ha range is similar to farm-scale yields being experienced with other C_3 perennial agricultural crops grown for forage, such as grasses or alfalfa. Midsummer water deficits have been identified as a major yield-limiting factor for C_3 perennial crops in northeastern North America. Monocultures of fast-growing willows or poplars share this problem. The only realistic solutions to the problem appear to be: (1) irrigate the trees with waste water from municipalities or rural food-processing industries to increase yield; (2) grow the trees in windbreaks where higher growth rates than monoculture systems can be achieved and where the trees can increase farm revenues by increasing yields of adjacent cash crops; and (3) use SRF plantings for higher value markets, such as pulp, with the residues used as energy.

Résumé

Le développement de la foresterie de courtes révolutions à des fins énergétiques a été l'objet d'efforts de recherche intenses, Même si les rendements au champ ont été en général bien en deçà des rendements que permettaient de prévoir les essais sur de petites parcelles. Le principal problème que pose le rendement de ces systèmes semble être lié à l'eau. La plupart des rendements au champ enregistrés jusqu'à maintenant en plantation dense sur terre productive sont de l'ordre de 7 à 11 tonnes anhydres par hectare, et ce niveau de production est inférieur à celui qui est requis pour que le système devienne compétitif comme culture exclusivement énergétique dans un proche avenir. Or, la plage de 7 à 11 tonnes anhydres par hectare est comparable aux rendements obtenus à l'échelle d'exploitations agricoles. Pour certaines cultures fourragères, comme les graminées et la luzerne, qui sont également des cultures vivaces de type C_3, et les déficits hydriques du milieu de l'été ont été reconnus comme le principal facteur limitant le rendement de ces cultures dans le nord-est de l'Amérique du Nord. Les monocultures de saule ou de peuplier à croissance rapide sont aussi exposées à ce problème. Il semble que les seules solutions réalistes soient: (1) l'irrigation des arbres au moyen des eaux usées de municipalités ou d'industries rurales de transformation des aliments, en vue d'augmenter le rendement; (2) la plantation des arbres en brise-vent, qui donne un rendement plus élevé que la monoculture et génère des revenus agricoles supplémentaires en augmentant le rendement des cultures commerciales ainsi protégées; (3) le recours à la foresterie de courtes révolutions pour les marchés de grande valeur, comme celui de la pâte, avec utilisation des résidus pour la production d'énergie.

Introduction

Biomass crops grown under a short-rotation forestry (SRF) system are potentially important not only as new crops for agriculture but on a larger scale as a new source of renewable raw material. But just as the world economy growth potential is finite due to the resource limitations of the planet so is that of biomass crops at the farm level. Plants need access to resources such as solar radiation, water, and nutrients to fully exploit their growth potential on a site. This paper will examine current levels of productivity that are being experienced with SRF crops and relate it to other perennial crops. The analysis of the limits on growth of biomass crops is addressed to create a better understanding of how important a role water plays in limiting biomass yields of SRF systems. Finally, several strategies to overcome the problem of water limitations on SRF systems are outlined so that the potential of these crops can be optimized.

Yields of Short-Rotation Forestry Systems

Biomass scientists have extensively discussed the relatively low yields obtained in field-scale trials versus the high yields from small plot trials. The following data have been derived from field-scale trials or relatively large-plot research trials where no irrigation has been used and borders exist on the research plots (Table 1). Yields in Table 1 do not usually represent average results; they are generally from productive clones on productive sites. Most of the yields from these field trials are in the 7-11 oven-dried tonne (ODT)/ha range except for the study done in Washington State (a high rainfall region). The range is similar to what was assessed by Hansen (1988), who states that 7-11 ODT/ha is a reasonable estimate of potential SRF field yields.

Table 1. Summary of recent SRF production data on poplar or willow.

Location	Source	Species	Yield (ODT/ha)
Europe			
Austria	Ledin and Alriksson 1992	Willows	10.5
Denmark	Ledin and Alriksson 1992	Willows	8.1
England	Ledin and Alriksson 1992	Willows & poplars	6-11
France	Auclair and Bouvarel 1992	Poplars	7.9
Sweden	Ledin and Alriksson 1992	Willows	11.0
North America			
Ontario	Hendry 1990	Poplars	2-3
Pennsylvania	Ledin and Alriksson 1992	Poplars	10.4
Wisconsin	Wright et al. 1993	Poplars	8.3
Minnesota	Wright et al. 1993	Poplars	6.9
Washington	Wright et al. 1993	Poplars	18.8

The question that remains is how much increase can we expect in these yields? Will we see the same major gains that agriculture has achieved with field crops? For example in Illinois, corn yields tripled and soybean yields doubled from 1935 to 1975 (Boyer 1982). When crop scientists plant both old and new varieties using the cultural practices of today, they estimate that the gain in productivity has been approximately equal in terms of genetic improvement and cultural management. Can we expect similar large yield gains from SRF energy production systems where whole plants are being harvested rather than just the grain? The answer may be that it will be much more difficult. There are several reasons for this. In grain-producing systems much of the gain in productivity has come from shifting the harvest index, that is, the percentage of the total plant biomass that is expressed as grain. When compared to varieties of the past, total biomass yield in modem small grain-producing systems has not changed appreciably with the advent of new high-yielding cultivars.

The progress in increasing yields of perennial forages has been much less successful than in grain-producing systems. This may be partly related to a lower level of breeding and cultural management effort, but it may also be that it is much more difficult to increase whole plant yield than just grain yield. Of all the perennial forages in central Canada, alfalfa is among the most productive species. As well, because it is a high-value crop, alfalfa has received perhaps three-quarters of the total breeding effort in perennial forages in North America. Yet the progress in increasing alfalfa yield through breeding has been anything but spectacular. In the 1950s the leading variety was Vernal. However, when Vernal is included in the provincial yield trials in Quebec for example, it is only 9% lower-yielding than the most productive cultivar (CPVQ 1995).

Why has so little yield progress been made with this "biomass" crop and will the same slow progress be made for SRF crops? After all, alfalfa is a C_3 perennial biomass crop and biomass scientists have found that C_3 perennial forage crops are a good predictor of SRF yields on sites (Wells and Fribourg 1992). Progress in perennial forage yields may be slow because breed- and cultural management have to optimize forage quality in addition to quantity. Although this may be partly true, a better explanation may be that resource constraints are limiting biomass yields of alfalfa and that it is very difficult to make progress when biological factors are limiting production.

What Are the Limits to Growth?

The fundamental process of biomass accumulation is based on photosynthesis:

$$6\,CO_2 + 6\,H_2O \xrightarrow[\text{sunlight}]{} C_6H_{12}O_6 + O_2$$

This process also requires adequate nutrients for cell functioning and an adequate temperature in which to take place.

The following analysis will examine the effect of sunlight and water on potential biomass yields in central Canada. The analysis will be made on SRF willow and switchgrass, the 2 crops that are currently under study by REAP-Canada in its research program. The 2 species have different metabolic pathways, since willow is a C_3 species and switchgrass a C_4 species.

Sunlight: Estimating Maximum Photosynthetic Efficiency of Biomass Plantations as Affected by Solar Radiation

The following analysis made by Hall et al. (1993) is an estimate of the upper threshold for converting incident solar energy into biomass production for C_3 and C_4 species.

For C_4 plants: 100% x 0.50 x 0.80 x 0.28 x 0.60 = 6.7%

- 0.50 = The 50% of light that is photosynthetically active radiation (PAR), wavelengths between 400 and 700 nm.

- 0.80 = The about 80% of PAR captured by photosynthetically active compounds; the rest is reflected, transmitted, and absorbed by non-photosynthesizing leaves.

- 0.28 = The theoretical maximum energy efficiency of converting the effectively absorbed PAR to glucose, 28%.

- 0.60 = The about 60% energy stored in photosynthesis remaining after 40% is consumed during dark respiration to sustain plant metabolic processes.

The 6.7% applies to C_4 plants (plants where the first stable products of photosynthesis are 4-carbon compounds).

For C_3 plants 2 additional losses occur: C_3 plants lose about 30% of the already fixed CO_2 during photorespiration, and C_3 plants become light-saturated at lower light intensities than C_4 plants, so that C_3 plants are unable to utilize perhaps 30% of the light absorbed by photosynthetically active compounds.

For C_3 plants: 6.7% x 0.70 x 0.70 = 3.3%

These figures can be now used to calculate the potential dry matter yield for each biomass crop. However, the following information is also required:

- **Length of growing season:** The growing season for SRF willow is assumed to be from 1 May to 15 October (168 days) and for switchgrass from 15 May to 30 September (137 days).

- **Average daily solar radiation:** The average gigajoules per hectare for the growing season in Montreal (1967-1976) are as follows: May, 201 GJ/ha; June, 216 GJ/ha; July, 217 GJ/ha; August, 186 GJ/ha; September, 137 GJ/ha; October, 80 GJ/ha. Average daily solar radiation for the respective growth periods is 190 GJ/(ha ·day) for switchgrass and 182 GJ/(ha · day) for SRF willow.

- **Energy content of the feedstocks:** Switchgrass and willow have different energy contents, approximately 17.5 GJ/ODT and 19.5 GJ /ODT, respectively.

- **Partitioning of the biomass above and below ground:** The annual biomass partitioning of SRF willow has been estimated by Swedish scientists: stems 61%, leaves 26%, and roots 13% (Ledin and Alriksson 1992). However, in high yield conditions it is likely that the partitioning above ground to below ground will improve. For switchgrass biomass production, no equivalent analysis has been performed but it would probably be more favorable as leaves are harvested. The harvestable yield will be assumed to be 65% for each species.

Using this information the maximum light restricting yield for these species would be as follows:

Switchgrass (C_4):

$$\frac{6.7\% \times 137 \text{ days} \times 190 \text{ GJ/(ha} \bullet \text{day)} \times 65\ \%}{17.5 \text{ GJ/ODT}} = 64.8 \text{ ODT/ha}$$

Willow (C_3):

$$\frac{3.3\% \times 168 \text{ days} \times 182 \text{ GJ/(ha} \bullet \text{day)} \times 65\ \%}{19.5 \text{ GJ/ODT}} = 33.6 \text{ ODT/ha}$$

Water: Estimating Maximum Potential Accumulation of Biomass Based on Water Use

Water use is a relatively complicated factor to discuss because it is influenced by many factors. A review of some existing studies in temperate regions will provide some insight into the impact of water use on biomass accumulation in these areas.

There has been a significant amount of research in Sweden in recent years that indicates that the annual water consumption by fast-growing willow trees creates water deficits. Several models have been developed from field studies which indicate that the annual evaporation exceeds the Penman open water evaporation by between 5% and 40% (Grip et al. 1989; Persson, and Jansson 1989). In a simulation study, Grip et al. (1989) estimated 526 mm of water was used for a normal willow stand with a production of 12 t/(ha · yr). Of this 526 mm water, 375 mm was transpired, 56 mm was intercepted, and 95 mm evaporated from the soil. This rate of evaporation was 22% higher than the Penman open water evaporation rate of 430 mm. The 12 t/ha crop would represent a water use of approximately 44 mm/t if 526 mm water was used.

Persson and Jansson (1989) estimated a reasonable range for the actual evaporation to be between 370 and 420 mm during the third year of a willow stand that had been coppiced after the planting year. No yield was provided in this study but if we assume a typical annual increment in Sweden of 10 t/ha, then approximately 40 mm of water was required per tonne.

Several studies in temperate regions in North America have been performed in grassland systems that measured water use and productivity of C_3 and C_4 species (Table 2). A review of water-use efficiency in 38 species indicated that water use by C_4 species is only 48% that of C_3 species per grain of dry matter produced (Black 1971). The study, conducted in the relatively dry climate of Colorado, found C_4 monocots used from 267 to 349 g water per gram of dry matter, while C_3 monocots used 518 to 977 g of water per gram of dry matter.

Table 2. Water use by C_3 and C_4 Crops.

Species	**Total water use (mm)**	**Water use/Tonne biomass (mm/t)**	**Yield (t/ha)**	**Study and region**
SRF willow	526	44.0	12.0	Grip et al. 1989
Tall fescue (C_3)	132	35.3	3.7	Stout et al. 1986
Switchgrass (C_4)	147	21.1	7.0	
Tall fescue (C_3)	336[a]	59.0	5.7	Stout et al. 1988
Switchgrass (C_4)	257[a]	33.8	7.6	
Orchardgrass (C_3)	639[a]	106.5	6.0	Stout 1992
Switchgrass (C_4)	367	35.4	10.0	

[a] Data were not indicated but were calculated from means across research sites and years.

From the above information, an estimate of water use by the C_3 and C_4 species under non-irrigated systems in the temperate climate of the study area can be made. Willows in Sweden are apparently using about 400-500 mm of water or about 40 mm/t. If C_4 grasses such as switchgrass are using about one-half the water of the C_3 species, they would be using about 20 mm/t. The studies comparing switchgrass and a C_3 species (Stout et al. 1986, 1988; Stout 1992) generally report higher estimates than these ones because they were performed on marginal soils in the relatively dry climate of West Virginia.

If we assume that approximately 400 min of water is available for growth (i.e., 40% of the annual 1000 mm rainfall in the study region), then the upper yield limits for willow and switchgrass would be approximately 10 and 20 t/ha respectively in central Canada. This would be on the more productive soils. It is well below the maximum light-restricting yields identified earlier for switchgrass and willows, 64.8 and 33.6 ODT/ha, respectively.

In 1994, a study was performed by REAP-Canada to assess water use on one of the 3 large plantation sites where both switchgrass and willows were growing in monoculture stands (plot size of at least 25 m x 80 m). The study was undertaken at the Ignatius Farm near Guelph, Ontario. This site was chosen because of the uniformity of the SRF willow and switchgrass stands and of the soil across the site. The site was sampled 8 times to a 50-cm depth throughout the growing season to assess differences in soil moisture. Soil moisture levels declined rapidly at this site following the first sampling date in early May and remained low to the last sampling date in late September (Fig 1).

The switchgrass appeared to be more successful in accessing and using the low available soil moisture than the willow. Yields of willow were only 2.5 ODT/ha on the site, while switchgrass yielded 8.0 ODT/ha. The switchgrass and willow both depleted soil moisture at the surface horizon (0-25 cm) approximately equally, but the switchgrass was more successful in using water from the 25-50-cm soil depth (data not shown). Of the 3 sites established by REAP-Canada for its field-scale plantations, this site is by far the most water-constrained.

Strategies to Circumvent the Water-Use Problem in SRF Energy Production

Irrigation

The response to irrigation can be dramatic in the region. A study performed by the State University of New York (SUNY) in Syracuse found that irrigation almost tripled yields of willow over a 3-year period (Table 3). An average annual growth increment of 27.5 ODT/ha was obtained with irrigation and 8.9 ODT/ha without it. Clearly there is limited opportunity to develop irrigated field-scale SRF plantations for energy production. It is too expensive in most instances, and if the size of the industry increased, it would cause major public concern about the use of water for that purpose. However, SRF plantations would provide an excellent opportunity to biofilter waste water from food-processing industries and sewage waste from municipalities.

The work by SUNY makes it clear that willows can be extremely productive in the Great Lakes region if adequate water and soil nutrients are present. The use of the willow as a biofilter is an excellent strategy to optimize this growth potential.

Table 3. Oven-dry biomass production of 3-year-old coppiced SVI willow planted at 1 x 3 ft spacing at Tully, N.Y. (Abrahamson et al. 1994).

	Biomass production (tons/acre)	Biomass production (t/ha)	Average annual increment (t/ha)
Irrigated	36.8	82.6	27.5
Non-irrigated	11.9	26.7	8.9

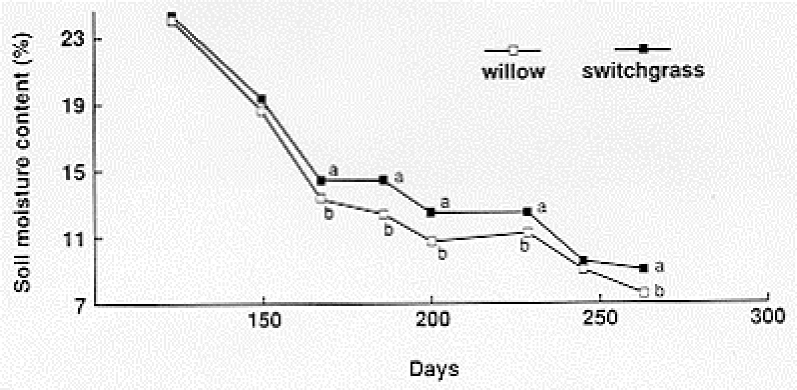

Figure 1. Soil moisture content (0-50 cm) at the Ignatius Farm site in 1994. Note: Different letters at each sampling date indicates a significant difference at p = 0.05.

Table 4. Average growth of promising 2-row windbreak plantings after 3 years (1992-1994).

	Spacing	Clone	3rd-year height (m)	Yield (ODT/ha)
Wilhelm Farm	2.5 x 2.0 m	Austree willow	4.82	-
Vandorp Farm	1.5 x 2.0 m	Austree willow	3.60	-
Smith Farm	1.54 x 2.0 m	Austree willow	5.73	25.3
Morgan Arboretum	0.77 x 0.72 m	Salix viminalis	4.92	47.1

Agroforestry Systems

The second strategy to help overcome the water problem is to plant trees as windbreaks instead of monoculture plantations. This strategy has several potential benefits as it relates to improving moisture access to the trees. One is that the trees can access some water from soil adjacent to the windbreak planting. Perhaps as importantly, windbreaks provide the opportunity to access higher quality soils with higher water-holding capacity than marginal soils.

In 1992, as part of the research program evaluating the technology of SRF, we established windbreaks on 4 sites. Of the 4 windbreak experiments, all the systems apparently experienced relatively good growth, ranging from 3.6 to 5.7 m high after 3 years. Destructive harvests at the end of 3 years indicated biomass yields of 25 and 47 ODT/ha from the windbreaks at the Smith Farm (Thamesville, Ontario) and Morgan

Arboretum (Sainte-Anne-de-Bellevue, Quebec) sites. Assuming first year yields are only about 10% of the 3-year total, annual yields of approximately 11 and 21 ODT/(ha·yr) were obtained at the Smith Farm and Morgan Arboretum sites, respectively, after the first-year establishment. All of the sites in Table 4 would be number-1 or number-2 class farmland. In monoculture plantations it is unlikely that these types of quality sites could be accessed, as farmers would reserve their best land for cash crop production.

The growth on these sites was relatively good considering that at the outset of the experiments the technology of growing SRF plantations in windbreaks was not well developed and clone availability limited. Average windbreak heights of 4.5 - 5.0 m after 3 years could probably be expected on most class-1 and class-2 soil types in the study region. With the advent of more productive clones and planting of longer cuttings (50 cm or greater) to improve first-year growth, these results may be improved significantly.

The land taken up by the windbreaks is greater than the spacing indicates in Table 4. However, crop yield increases of approximately 5%-10% are generally experienced over a distance of 10-15 times the height of the windbreak (including the land taken up by the windbreak).

At the Morgan Arboretum site, willow plantings were made of 1, 2, 4, and 6 rows to assess yield differences between plots and between rows in individual plots. Through the course of the experiment it became increasingly evident that single- and double-row windbreaks and outside rows of the 4- and 6-row strips were accumulating more biomass than interior rows of the 4- and 6-row strips. There were larger stem diameters and more numerous stems on the material free from trees on at least one edge. Both greater access to water and sunlight are suspected as the major factors responsible for the observed increase in growth. The inner rows of the 6-row planting had only maintained a canopy in the top 1 m of the trees by the end of the 1993 and 1994 growing seasons, while the single- and double-row plantings had maintained a canopy through the entire height of the windbreak, particularly on the south face. Tree growth measurements indicated that height had varied little between treatments (data not shown).

Biomass yields in the single- and double-row systems averaged approximately 75 and 47 ODT/ha in yield over the 3-year period (Table 5). Outside rows of the 4- and 6-row plantings also had high yields in the range of 37-42 ODT/ha. Interior rows were inferior for both center rows of the 4- and 6-row plantings. They had yields in the range of 23-25 ODT/ha over the 3 years. These yields are somewhat representative of what might be achieved in a monoculture planting at this site (at least from a sunlight standpoint). From a water-availability standpoint, it may not be representative as the water table of the field may have been lowered had the whole field been in willows. If it is assumed that in the establishment year, growth represented about 10% of the 3-year total, then biomass accumulation in the latter 2 years was approximately 34 ODT/(ha - yr) in the 1-row system, 21 ODT/ha in the 2-row system, and 10- 11 ODT/ha for the center rows (monoculture planting). After the establishment phase, the 1- and 2-row windbreaks are apparently growing 2-3 times faster than a SRF monoculture system at this site. These relatively high yields may be partly explained by the high soil organic matter level (7.5%) at this site.

Higher Value Markets

The third strategy is to accept that yields for SRF are going to be in the 7-11 ODT/ha range under rainfed conditions for the foreseeable future and to find higher value markets for the material. By-product residues such as bark could then be used for energy. There is increasing concern about the ability of softwood plantations, in combination with the harvesting of. natural forests, to sustain the fiber supply for Canada's pulp and paper industry. Wood prices and demand continue to rise, The economics of using wide-spaced poplar for pulp production may be becoming more attractive. As well, REAP-Canada has currently been supplying Robin Berlyn of Paprican with high-density-planted willow. Paprican and the Forest Engineering Research Institute of Canada (FERIC) have been working on a process, known as the Paprifer process, to debark material previously chipped. The process removes inorganics (stones, tramp metal, etc.) as well as the level of organic contaminants. In doing so, it relies on the fact that bark, foliage, and decay, for the most part, are weaker than chips, and are therefore more susceptible to being broken down into smaller-sized fragments (Berlyn 1995). These are then separated from the larger ones (the wood chips) by flushing them through suitable-sized holes in a screen plate.

Table 5. Three-year biomass yields (ODT/ha) of individual rows and plots in the Morgan Arboretum Agroforestry Experiment.

Orientation from north-south	1 Row	2 Rows	4 Rows	6 Rows
1	74.9	44.1	41.6	37.7
2		50.0	25.4	24.2
3			24.2	23.7
4			37.6	23.2
5				23.6
6				41.9
Plot yield/area planted	74.9	47.1	32.2	29.1

Summary

Short-rotation forestry has the potential to become a commercial farming system in Canada but probably not as vast monoculture plantations for energy production. More likely it will continue to develop as a fiber source with residues used as energy. Finding ways to increase yields through irrigation of waste water or through agroforestry systems will hasten the development of the technology as yields are currently restricted by water requirements.

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