Life cycle analysis of willow biomass production in agroforestry

Project Team: John Kort and Bill Schroeder

Background:
The use of biomass to produce bioenergy for biofuels, electricity or heating is being investigated worldwide as a way to reduce greenhouse gas (GHG) emissions, with at least one scientific journal, Biomass & Bioenergy, dedicated to the topic (www.elsevier.com). However, the production of biomass requires energy inputs that also release GHG’s, with the net emissions and energy efficiency depending on the form of biomass, its productivity and the management practices used to produce it (Bourne, 2007). Life Cycle Analysis (LCA) is a total accounting exercise in which the analyst attempts to account for all energy inputs and GHG emissions to determine the net energy and GHG balances. Although the GHG implications of willow biomass production in monoculture was considered by Heller et al. (2003), this study was done to evaluate the use of willows in agroforestry configurations as a renewable source of biomass.

Project Objective:
To compare the carbon and energy costs of agroforestry willows to that of other land use and energy options.

Methods:
The Saskatchewan Research Council was contracted by AAFC to conduct an LCA on agroforestry willows according to designs, practices and assumptions provided by the AAFC Agroforestry Division. The analyses used the software GHGenius (v. 3.11), developed for Natural Resources Canada – Canadian Forestry Service by (S&T)² Consultants. Although the model was focused on the production of biofuels, the upstream parts of the model (i.e. the production and harvesting of biomass) could be compared, regardless of the biomass end use. For this study, the model was used to calculate 1) the energy required for the upstream activities (biomass production and harvesting), 2) the energy required for the entire process, assuming ethanol to be the end-product and 3) the GHG emissions for the upstream activities.

The agroforestry configurations considered were 1) alley-cropped willow with perennial grasses growing in the alleys between double rows of willow that were coppiced every four years 2) planted riparian willow buffers that were coppiced every four years and 3) native willows surrounding natural prairie wetlands that were coppiced every four years. These agroforestry systems were compared to four monoculture options on the same land area: perennial crops (hay); coppiced willows (SRIC); annual corn; annual wheat. The management practices that were included in the analysis were the preparation of the sites and site establishment for the first two agroforestry scenarios and the on-going management and harvest practices for all three scenarios. Productivity estimates were provided for the analysis for the yields of native and planted willows and, in the case of the alley-cropping scenario, for the yields of the perennial grasses with an estimate of tree-crop interactions.

The final results of the LCA were based on the assumption that the biomass was used for ethanol rather than for heat or electricity and so the report also presented the energy balances in the conversion of these biomass sources (starch and cellulose) to ethanol.
Results:
Life Cycle Analysis results through GHGenius, as through any model, are calculated results rather than actual results and therefore reflect the assumptions that were made for the calculations. The GHGenius results are instructive because the software requires the user to enter a thorough list of relevant inputs.

The model calculated fossil fuel energy consumption in the production and harvesting of biomass as well as for the entire process, assuming conversion of biomass to ethanol (Table 1). Annual crops (corn and wheat) required greater energy inputs because of the requirements for fuel use in annual field operations and nitrogen fertilizer requirements. Cellulose from hay was less energy-intensive than SRIC or alley-cropped willow because, even though the woody biomass was harvested only every fourth year, the energy required for harvest was considered to be less for the annually harvested hay crop. The planted riparian scenario and the native willow rings were calculated to have lower energy input costs because no fertilizer application was assumed for those scenarios.

When the energy ratio was calculated for the entire cycle, including ethanol production, the annual crops were still more energy-consuming, in terms of fossil fuels (Table 1). An important assumption in considering the difference between starch-based ethanol production, (corn and wheat) and cellulose-based ethanol production (hay and wood), is that the fermentation technology is significantly different because the cellulose, under current technologies, is more difficult to break into fermentable sugars. Therefore the assumptions made in GHGenius were that the biomass weight required to produce one litre of ethanol was 2.53 kg for corn, 2.70 kg for wheat, 3.27 kg for hay and 3.15 kg for wood. This affected the biomass transportation costs, in terms of both energy requirements and net GHG emissions.

Table 1. GHGenius modeling results of energy consumption in upstream processes for feedstock production.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Energy consumed per unit energy delivered for biomass production ($J_{con}/J_{del}$)</th>
<th>Energy consumed per unit energy delivered for biomass production and processing to ethanol ($J_{con}/J_{del}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>0.20</td>
<td>0.68</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.23</td>
<td>0.75</td>
</tr>
<tr>
<td>Hay</td>
<td>0.12</td>
<td>0.55</td>
</tr>
<tr>
<td>SRIC</td>
<td>0.16</td>
<td>0.50</td>
</tr>
<tr>
<td>Alley-crop</td>
<td>0.15</td>
<td>0.52</td>
</tr>
<tr>
<td>Riparian</td>
<td>0.10</td>
<td>0.48</td>
</tr>
<tr>
<td>Willow Ring</td>
<td>0.09</td>
<td>0.44</td>
</tr>
</tbody>
</table>

The GHG balance for those same agroforestry or monocropping scenarios was modeled to estimate the net CO₂ equivalent emitted by the practice, again limited to the upstream processes of biomass production (Figure 1). The greatest net emissions were calculated by
the model for the two annual cropping options, consisting mainly of the emissions related to field operations, including harvesting, and the nitrogen fertilizer applied. The fertilizer requirements and field operations were less for the hay, SRIC and alley-cropping options but the harvest emissions were greater for the latter two. For the SRIC, alley-cropping and riparian scenarios, it was assumed that the land had changed from annual cropping to a permanent culture, which resulted in it becoming a carbon sink. For the willow ring, there was no change in land use assumed, but the net emissions were very low. As the low-lying areas on which the riparian and willow ring options occurred were assumed to be nutrient-rich and have adequate water for growth, they were considered to be naturally productive areas without the need for GHG-emitting inputs.

![Graph showing GHG emissions per tonne (g CO₂e/t) of feedstock produced.](image)

**Figure 1.** GHGenius results comparing upstream GHG emissions per tonne (g CO₂e/t) of feedstock produced.

In general, the LCA was a valuable exercise in showing the implications of producing woody cellulose-based biomass compared to annual starch-based biomass crops or perennial hay crops, which also produce mainly cellulose. Analysis of the agroforestry options showed that alley-cropping with willows and hay, as expected, gave results intermediate between those of monocropped willow (SRIC) and hay scenarios, both in terms of energy requirements and GHG emissions. Energy requirements and net GHG emissions were somewhat less for riparian willow plantings since natural productivity was considered to be high while having no fertilizer requirements, at least under these assumptions. Harvesting of native willows surrounding prairie wetlands was considered to require the lowest energy inputs because there was no planting, maintenance or fertilization required and GHG emissions were also low.
Key Findings:

- Estimated energy inputs for biomass production, including planting, fertilization, management and harvest was lowest for riparian buffers and willow rings, mainly because they were assumed to require less management and no fertilization, while productivity was high because of adequate moisture and nutrients.

- Estimated energy inputs for biomass production from SRIC, alley-cropping and hay was lower than for annual crops because of lower fertilizer requirements and lower fuel use in field operations.

- Annual cropping was also estimated to emit more net GHG’s because of the higher fuel and fertilizer requirements.

- Converting land from annual crop to permanent culture like SRIC, alley-cropping or riparian buffers also reduced net GHG emissions.

- The net GHG emissions from willow rings were low because they were non-intensive, requiring no nutrient inputs and fuel was burned only during harvest once every four years.

References:


