CONVERTING WASTE TO RESOURCES: A DECISION-SUPPORT MODEL FOR WASTEWATER-IRRIGATED SHORT ROTATION CROPS

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ABSTRACT

Short-rotation coppice (SRC) plantations of willow or poplar are intended to be both environmentally friendly, permitting disposal of treated, nutrient-rich, domestic wastewater and biosolids, and economically viable, providing a sustainable source of wood fibre for biofuel and biochar production. These SRC systems are complex and involve interactions between numerous factors, including climate, wastewater and biosolids characteristics, soil chemistry and physical characteristics, woody crop establishment and growth, bioenergy, environmental regulations, and economics. A framework is therefore required to identify and understand interactions and feedbacks between these various system components in order for decision makers to plan appropriately, maximize biomass end-uses, and optimize their investments. This paper describes the development of the “WISDOM” model, a new, comprehensive, decision-support model for short-rotation coppice (SRC) systems. WISDOM can be used to aid stakeholders and decision-makers in long-term planning for environmentally- and economically-sustainable SRC plantations. The model is composed of seven, linked components: 1) soil water, 2) solute transport, 3) energy content, and 4) carbon mitigation, while three were adapted from existing models of 5) plant growth and yield, 6) SRC harvest and transport, and 7) SRC economic assessment. The model successfully simulated based on eight years of Whitecourt, Alberta, historical data. The model can be used to identify how alternative management decisions affect system behaviour through the development of “what-if” scenarios, with three climate scenarios run for Whitecourt SRC to predict biomass yields and irrigation requirements, and nine combined yield-harvest economic scenarios produced for a complete SRC life cycle of more than twenty years. These scenarios provide insights into the plantation and management of the Whitecourt site into the future and provide an example of how the model could be applied to other sites.

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INTRODUCTION

Short rotation coppice (SRC) plantations consist of densely-planted, perennial woody crops, which are typically high-yielding varieties of willow or poplar (Isebrands and Richardson, 2013). Over the past eight years, researchers at the Canadian Wood Fibre Centre (CWFC) of the Canadian Forest Service (CFS) have conducted studies into the viability and environmental implications of the establishment in Alberta of SRCs irrigated with treated municipal effluents and fertilized with biosolids. Such SRC plantations are intended to be both environmentally friendly, permitting disposal of treated, nutrient-rich, domestic wastewater and biosolids, and economically viable, providing a sustainable source of wood fibre for biofuel and biochar production.

SRC plantations and their management have been studied in depth (Dimitriou et al., 2011; Langeveld et al., 2012; Marron et al., 2012; Weih, 2009). These studies have focused on:

- Crop production, including site selection, preparation and management, tree conditioning and planting, SRC growth and yield, nutrients and fertilization, vegetation management, and harvesting, transporting, drying, and storing biomass,
- SRC cultivation and its environmental impacts, including carbon mitigation and capture, soil quality, nutrient leaching, ground and surface water quality, biodiversity and landscape,
- SRC biomass energy content, including biomass moisture content, combustion system efficiency, higher and lower heating values, and SRC system energy balance, and
- Economic analysis, based on SRC expenditures and revenues.

As a result, there are numerous models available that represent individual aspects of SRC plantations; however, none of them – to the best of our knowledge – have been developed as decision-support tools for use in planning viable, sustainable SRC systems. Indeed, it is not just the dynamics of individual SRC components that make SRC plantations difficult to plan and manage, but also the interactions between them (Wallman et al., 2005; Weih, 2009). An interdisciplinary approach is therefore required to create a decision-support tool that can aid stakeholders and decision-makers in addressing a variety of components for SRC plantation planning and management. Such a tool could help to improve understanding of the interactions and feedbacks between different components of SRC systems (i.e., soil water, solute transport, energy content, carbon mitigation, plant growth and yield, SRC harvest and transport, and SRC economics) that affect their behaviour and ultimate viability, and provide insight into many aspects of SRC plantations and their management. The tool is the subject of this paper, which describes a feedback-based systems modelling tool for SRC plantation and management named “WISDOM”, or the Willow System Dynamics Model.

As a decision-support tool, the WISDOM model should aid stakeholders and decision-makers in addressing a series of “what-if” statements. For instance, what happens to a SRC system, especially plant yield, soil and drainage water quality, if wastewater irrigation input increases or decreases; what happens in terms of economic and energy output if SRC harvest occurs on a 4-year rather than 3-year rotation cycle; what is the effect of lower harvester efficiency than expected, or to changes in the harvesting method?, and so on. Rather than helping to optimize plant yield by calculating optimum irrigation or nutrients, answering to these “what-if” questions will provide model users with insight into the plantation and management of SRC systems. The result may be
improved plans for the establishment of future SRCs in Alberta in particular, or more broadly in Canada and globally, and the optimization of investments and end-uses of the obtained SRC biomass.

The approach used in WISDOM – system dynamics – and the model structure and simulation procedures are introduced in section 2. The validation and use of WISDOM for a case study are investigated in section 3. Section 4 analyzes the effects of different climate and irrigation scenarios to SRC yield and economic performance. Section 5 provides conclusions about WISDOM’s present capabilities and applications.

WISDOM DESCRIPTION

This section describes WISDOM in details from the methodology – system dynamics, to its structure with seven interconnected components, and the three steps in model set-up and use.

Model Approach

WISDOM was developed using system dynamics (Forrester, 1961; Sterman, 2000), a well-established simulation modelling methodology that has been employed widely in the past 50 years to represent and model complex systems in many different practical and scientific fields. Sample applications include economics, engineering, education, management, ecology, public health, and sociology (Forrester, 2007; Sterman, 2000).

System dynamics is “a rigorous method of system description, which facilitates feedback analysis via a simulation model of the effects of alternative system structure and control policies on system behaviour” (Simonovic, 2009). Using “causal-descriptive” mathematical models, system dynamics can be used to reproduce and then forecast real-world behaviours, and to assess the impact of alternative policies on the systems under investigation (Barlas, 1996). In addition, as complex systems can give rise to problems that resist solution, system dynamics aims to aid identification and clarification of the feedbacks and interactions among interconnected subsystems that govern the larger system’s dynamic behaviour, and to determine their root causes (Mirchi et al., 2012). System dynamics models can incorporate both empirical and mechanistic approaches and produce comprehensive simulation models quickly and easily (Prodanovic and Simonovic, 2009); further, the mathematics, despite nonlinearities, delays, and potential simultaneous equations, are represented relatively simply through first-order ordinary differential equations (Davies and Simonovic, 2011).

System dynamics methods rely on two main tools: causal loop diagrams (CLD), and stock and flow diagram-based simulation models. CLDs are used primarily to represent the nature of complex systems, in terms of key variables, important cause and effect relationships, and feedback linkages, and can also be used to communicate alternative understandings, or “mental maps”, of a system. Stock and Flow Diagrams (SFD) and simulation models are quantitative tools, and they are often used for decision support (Sterman, 2000), or for answering “what if?” questions rather than for optimizing policies (Davies and Simonovic, 2011).
Model Structure

WISDOM contains seven interconnected components, four of which are newly developed, including 1) soil water, 2) solute transport, 3) energy content, and 4) carbon mitigation, while three were adapted from existing models of 5) plant growth and yield, 6) SRC harvest and transport, and 7) SRC economic assessment. The interconnections between these components are shown in Figure 1.

Figure 1. The model components and model boundary

The soil water component applies the soil water-balance method (Hillel, 2004) to estimate the irrigation requirement, which is the deficiency between precipitation input and crop demand and leaching requirement outputs for both the root-zone and deeper layers. The solute transport component uses the mass conservation principle for both conservative solutes (soil electrical conductivity, total dissolved solids, and chloride) and non-conservative solutes (soil nitrate-nitrogen, phosphate-phosphorus, and available phosphorus). The energy content component estimates the lower heating values (or net calorific values) of harvested biomass production by adjusting the higher heating values (or gross calorific values) with woodchip moisture content based on Kenney et al. (1991)’s or Marron et al. (2012)’s method. The carbon mitigation component calculates the fossil-fuel-carbon offset and the yearly carbon sequestration amount.
The plant growth and yield (PGY) component – the core of the WISDOM model – was developed based on 3-PG (Landsberg and Sands, 2011) – a well-known, process-based, forest growth model, which has been proved successful in simulating SRC biomass production in the US and Canada (Nair et al., 2012). The harvest-transport component of WISDOM was developed based mainly on the “KUP-Erneplaner”, a German harvest-support tool (CREFF, 2012) with two major improvements: use of the detailed cost calculations presented in the “Ecowillow” model (Buchholz and Volk, 2010), and inclusion of a new harvest method, the biobaler harvester. The economic assessment component was built primarily based on “Ecowillow”, a well-known budgeting program developed by Buchholz and Volk (2010), with two improvements. Firstly, it used the concept of SRC process chain expenditures presented in Marron et al. (2012), and secondly, it replaced the static harvest-transport cost calculation in Ecowillow with a more detailed version in the WISDOM harvest-transport component.

Model Set-up and Use

Simulation of an SRC system using WISDOM, as illustrated in Figure 2, involves three steps, (1) selection of the simulation timespan and model inputs, (2) adjustment of model parameters, and (3) model simulation and analysis.

For step one, WISDOM requires input values for each component – biophysical, harvest, economic, and so on – of the SRC system. The climate-driven growth engine requires climate data: solar radiation, air temperature, precipitation, humidity, and wind speed values. The soil-water component uses the soil-moisture retention curve, permanent wilting point, field capacity, and saturation point. The solute transport component requires information on the treated wastewater used for irrigation, such as electrical conductivity, chloride, nitrate-nitrogen, and phosphate-phosphorus values. Further, to assist stakeholders and decision-makers in planning harvest and transport operations and estimating energy contents and the project economy, WISDOM requires information on the site, available machinery, harvesting costs and other management operations,
and the biomass sale price, that together contribute to the expenditures and revenues for a complete SRC project life-cycle. A monthly input interval is used in WISDOM to capture the primary feedbacks within and between model components and to avoid excessive data input requirements for future scenarios associated with the long timeframe of SRC systems.

The second step in simulating an SRC system in WISDOM is to parameterize the model, as shown in Figure 2. A parameterization consists of the common settings that replicate the behaviours of specific crops. For example, one parameterization corresponds to willow SX64, and another to willow SX61. In contrast, inputs are used to set up scenarios; therefore, the focus of simulation is typically to determine the model behaviour with alternative sets of inputs rather than parameterizations, which do not change from one scenario to the next. Parameterization is compulsory for the bio-chemo-physical components, including plant growth and yield, soil water, and solute transport components in order to obtain the best model behaviour.

The third step is model simulation and analysis. WISDOM provides biomass production as shoots, leaves, and root biomass, and the amount of oven-dry woodchips produced as output. It also simulates the soil-water balance and irrigation requirements based on selected leaching fractions, or if the irrigation amount is “user-specified”, it is treated as a model input. As mentioned above, the model can also be applied to determine solute transport rates for different conservative (EC/TDS/chloride) and non-conservative solutes (NO$_3$-N, PO$_4$$_3$-, and available P) in soil. Furthermore, WISDOM can be used to simulate biomass harvest and transport processes, and to analyze project economics. The net calorific value of biofuels produced, as well as the mitigated carbon emissions and the amount of carbon captured are also estimated.

Depending upon the simulation time step and the total simulation length, each simulation takes from seconds to minutes to complete. The modelling software – Vensim DSS, produced by Ventana Systems, Inc. (VensimSoftware, 2014) – provides a variety of tools to support users and decision makers. These include the “Optimize” tool, which aids in model calibration, Monte-Carlo simulation, which quantifies the sensitivity of model variables to prescribed ranges of change in selected model parameters, and dynamic simulations that allow users to adjust model values to compare effects of changes in model parameters quickly.

**CASE STUDY: WHITECOURT, ALBERTA, CANADA**

**Site Introduction**

The Canadian Wood Fibre Centre of the Canadian Forest Service (CWFC-CFS) established an SRC research site in 2006 in Whitecourt, Alberta. Whitecourt has a humid continental climate, with a mean daily temperature of 2.6 °C and extremes ranging from -41 °C in January to 33.5 °C in August. Average annual precipitation is 577 mm, with rainfall and snow water equivalent of 440.3 mm and 134.2 mm, respectively. Since 2006, seven clonal varieties have been planted on 0.7 ha at Whitecourt: five willow clones including Charlie, SX64 (S. myabeanna), SX61 (S. sachalinesis), SV01 (S. dasyclados) and Psuedo (S. alba); and two poplar clones including Brooks 1 and Green Giant. Data collected by the CWFC-CFS, show that willow SX64 has the highest and most stable yields (based on their low standard errors) among the seven clones – see
Figure 3 and note the error whiskers, which illustrate the standard error values. WISDOM is therefore parameterized using data from the SX64 clone.

![Graph showing yields of different clones over time](image)

**Figure 3. Comparison of the yields of different clones planted at the Whitecourt trial site from 2006 to 2013 (Data source: CWFC – CFS)**

**Simulation of Whitecourt SRC System Dynamics**

The period of 2006 – 2013 was simulated which included two harvests in 2008 and 2011. The climate data shown in Figure 4 were used as representative inputs. Different key model variables based on historical Whitecourt SRC data were simulated and analyzed, including stem biomass production (see Figure 5a), since it directly affects project economics and energy production plans, and irrigation application (see Figure 5b) soil quality and solute transport values (see Figure 5c) based on irrigation with treated wastewater effluent. Data on electrical conductivity (EC), chloride, nitrate-nitrogen (NO$_3$-N), and phosphate-phosphorus (PO$_4$-P) concentration of the wastewater used for SRC irrigation are presented in Table 1.

![Graph showing climatic characteristics](image)

**Figure 4. Climatic Characteristics. Left-hand axis: monthly precipitation (P; mm) and humidity (H; %); right-hand axis: monthly maximum, minimum, and mean temperatures (T$_{\text{max}}$, T$_{\text{min}}$, T$_{\text{mean}}$; °C), solar radiation (R$_{\text{n}}$; MJ/m$^2$/d), and wind speed (U; km/hr)**
Table 1. Electrical conductivity (EC), chloride, nitrate-nitrogen (NO$_3$-N), and phosphate-phosphorus (PO$_4$-P) concentration in waste water irrigation (source: CWFC – CFS, 2013)

<table>
<thead>
<tr>
<th>Solute type \ Year</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater EC (dS/m)</td>
<td>0.77</td>
<td>0.76</td>
<td>0.81</td>
<td>0.81*</td>
<td>0.82</td>
<td>0.89</td>
<td>0.81*</td>
<td>0.81*</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>81.9*</td>
<td>81.9*</td>
<td>81.9*</td>
<td>81.9*</td>
<td>85.9</td>
<td>77.9</td>
<td>81.9*</td>
<td>81.9*</td>
</tr>
<tr>
<td>NO$_3$-N (mg/L)</td>
<td>19.24</td>
<td>17.07</td>
<td>20.48</td>
<td>29.8*</td>
<td>20.5</td>
<td>71.9</td>
<td>29.8*</td>
<td>29.8*</td>
</tr>
<tr>
<td>PO$_4$-P (mg/L)</td>
<td>1.58</td>
<td>0.83</td>
<td>2.04</td>
<td>1.3*</td>
<td>0.88</td>
<td>1.10</td>
<td>1.3*</td>
<td>1.3*</td>
</tr>
</tbody>
</table>

* indicates that observed data is not available and an average value is used as a substitute.

Comparison of predicted and observed values for eight years of simulation showed a good match between biomass production ($R^2_{irr}=0.98$) and tree height ($R^2_{irr}=0.92$). The model also predicted summer-season irrigation requirements at a monthly scale acceptably well ($R^2_{irr}=0.72$). At a seasonal scale, differences between predicted and observed irrigation were 46%, 14%, and <1% in 2007, 2008, and 2010 respectively. These differences may have a variety of sources, including irrigation equipment malfunctions, approaches to calculate irrigation amounts, and values of the leaching fraction required to move accumulated salts in the root zone into deeper layers. Comparison between predicted and observed soil EC values is shown in Figure 5c for conservative solutes, which match with $R^2_{irr}=0.9$. In addition to comparison between observed and simulated values, an alternative validation approach compares the simulated soil EC with values from the analytical solution of Rose et al. (1979).

Figure 5. Comparison between predicted and observed values of a) stem biomass (SB; ODT/ha) and stem height (SH; m) and b) irrigation (mm); c) soil EC (dS/m) from WISDOM, observations,
and the approximations of Rose et al. (1979)’s analytical solution (time step = 1 month and 0.25 month).

SCENARIO ANALYSIS WITH WISDOM

WISDOM can be used to explore a variety of “what if” questions related to SRC planning and management. For example, what happens to the soil water-balance and solute transport processes or biomass production with increasing or decreasing leaching fractions or irrigation applications? What is the effect on project economics if the biomass yield is lower than expected? What is the harvesting cost or the effect on the overall project economy if the bio-baler is used rather than the JF-192 or Claas-HS2? The following scenarios investigate effects of different irrigation application scenarios on solute transport and concentrations, changing climate conditions on biomass production, and alternative harvesting approaches on project economics.

Irrigation Application Scenarios

Based on her investigation at Whitecourt of deep drainage fluxes and water quality from SRCs irrigated with treated municipal wastewater, Gainer (2012) suggested that the ideal leaching fraction (LF) is between 0.2 and 0.5. However, the best choice of LF and the effects of values of 0.2 or 0.5 are uncertain. As the leaching fraction is closely connected to irrigation requirements, an increase (decrease) in its value will increase (decrease) both the quality and quantity of irrigation water, and the solute transport and concentration in the soil.

To investigate effects of changing leaching fractions, four scenarios were simulated with LF = 0.2, 0.3, 0.4, and 0.5, with the resulting changes in irrigation requirements, root-zone drainage, and soil EC plotted in Figure 6. The simulations revealed differences in drainage and irrigation requirements of up to 250 mm, as in 2008 and 2013, for instance. They also showed higher leaching fractions or irrigation requirements (Figure 6a) produced higher root zone drainage (Figure 6b) and lower soil EC (Figure 6c) values. Further, under the highest leaching fraction (LF=0.5), the maximum soil EC was reduced from 3 dS/m (LF=0.2) to 1.5 dS/m (LF=0.5). Of course, farmers and decision-makers will determine the appropriate leaching fraction based on acceptable salinity levels and irrigation costs; WISDOM also produces the latter in its economic component.
Climate Scenarios

Because plant growth and yield depends on monthly, climatic conditions, the simulation of a complete life cycle – 21 years – requires either climate data for the full period or assumptions about possible future conditions. Three scenarios described here – optimistic, average, and pessimistic, designed to generate maximum, average, and minimum yields – used data based on eight years (2006-2013) of historical records to predict biomass production into the future. For example, as shown in Table 2, the optimistic scenario used the maximum net monthly solar radiation values and the lowest temperature stresses (or temperature variations) recorded for Whitecourt from 2006-2013. Note that different climatic values can be combined easily to see their impacts on SRC plantations. Further, with Monte Carlo simulations of tens to hundreds of climate scenarios, it would be possible to see the effects of a wide range of future conditions on biomass production.

Full irrigation supply was assumed for the three scenarios, resulting in no water and salinity stresses (see Table 2). Although nutrient stress would differ for each case as the irrigation quantity and nutrient content varies between the scenarios (see Table 3), any nutrient deficiency was assumed to be correctable by fertilization; therefore, nutrient stress was neglected. The key drivers of yield in this case were then the total incoming solar radiation and air temperature, as presented in Table 2. The other climatic factors, including precipitation, humidity, and wind speed, only influenced irrigation requirements through evapotranspiration, but did not affect biomass yield because the water deficiency between ET, drainage, and precipitation was offset by the irrigation applications.

Table 2. Scenarios of potential yields under imposed climatic conditions

<table>
<thead>
<tr>
<th>No</th>
<th>Scenario</th>
<th>Yield case</th>
<th>Net rad. Rn (MJ/m²/d)</th>
<th>Air Temperature (°C)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T_max</td>
<td>T_min</td>
</tr>
<tr>
<td>1</td>
<td>Optimistic</td>
<td>max</td>
<td>max</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>2</td>
<td>Average</td>
<td>avg</td>
<td>avg</td>
<td>avg</td>
<td>avg</td>
</tr>
<tr>
<td>3</td>
<td>Pessimistic</td>
<td>min</td>
<td>min</td>
<td>max</td>
<td>min</td>
</tr>
</tbody>
</table>

Figure 6. Effect of variation of leaching fraction to a) irrigation requirement (mm), b) root-zone drainage (mm), and c) soil electrical conductivity (dS/m)
Table 3. Scenarios for irrigation correspond to the scenarios for yield

<table>
<thead>
<tr>
<th>No</th>
<th>Scenario</th>
<th>Irrigation case</th>
<th>Precipitation (mm)</th>
<th>Humidity (%)</th>
<th>Wind speed (km/hr)</th>
<th>Corresponding Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Optimistic</td>
<td>min</td>
<td>max</td>
<td>f(ΔT)</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>2</td>
<td>Average</td>
<td>avg</td>
<td>avg</td>
<td>f(T_{max} - T_{min})</td>
<td>avg</td>
<td>avg</td>
</tr>
<tr>
<td>3</td>
<td>Pessimistic</td>
<td>max</td>
<td>min</td>
<td></td>
<td>max</td>
<td>min</td>
</tr>
</tbody>
</table>

In terms of results, the scenarios produced only slight differences (a range of approximately 22-25 ODT/ha) in the 2014 yields, which is to be expected, since the climate inputs only diverged from the start of 2014 onward. For future harvests, using the 8-year average and optimistic data resulted in an increase in biomass production, with a maximum of approximately 25.5 and 30 ODT/ha/3-year-rotation, or of 8.5 and 10 ODT/ha/year respectively, as shown in Table 4 and Figure 7. Compared with the observed data from the first and second rotation, the anticipated yield in the average case increased by 88% and 36%, while the increases in the optimistic case were 120% and 60%, respectively. In the pessimistic scenario, future yields decreased to 19.5 ODT/ha/3-year-rotation or 6.5 ODT/ha/year. Overall, the scenarios produced yield ranges of 6.5-10 ODT/ha/year, which are reasonable values compared with the range of 5-11 ODT/ha/year from the North American field-scale studies conducted by many researchers (Kenney et al., 1991; Heller et al., 2003; Volk et al., 2011).

Table 4. Predicted biomass production at different harvesting points of the three yield scenarios

<table>
<thead>
<tr>
<th>Biomass (ODT/ha)</th>
<th>Rotation / Harvest Year</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
<th>7th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>2008</td>
<td>13.14</td>
<td>18.65</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Predicted</td>
<td>Optimistic</td>
<td>13.56</td>
<td>18.73</td>
<td>25.44</td>
<td>28.97</td>
<td>29.69</td>
<td>30.13</td>
<td>30.20</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>13.56</td>
<td>18.73</td>
<td>23.94</td>
<td>24.56</td>
<td>25.23</td>
<td>25.72</td>
<td>25.87</td>
</tr>
<tr>
<td></td>
<td>Pessimistic</td>
<td>13.56</td>
<td>18.73</td>
<td>21.91</td>
<td>18.36</td>
<td>19.16</td>
<td>19.60</td>
<td>19.96</td>
</tr>
</tbody>
</table>

Figure 7. Prediction of biomass production for the complete 7-rotation cycles: optimistic (opt), average (avg), and pessimistic (pes) based on validated (val) results and observed (obs) values from 2006-2013
Plantation Economics

This section investigates the effects on project economics of alternative harvesting methods, and of different harvesting speeds – the most important element of the harvesting operation (Phillips, 2013) – with the aim of demonstrating the value of WISDOM in assessing parameter and operational sensitivities to changes in climatic conditions and management decisions. For illustration purposes, only the average yield results from section above are used here, in combination with three harvester options (JF-192, HS-2, and bio-baler) and three harvesting speeds (maximum, average, and minimum speeds); these harvesting speeds were obtained from Phillips (2013) and manufacturers’ manuals. Note that published harvesting speeds may be higher than actual harvester speeds. For example, the Claas HS-2 was operated at an average harvesting speed of 5.3 km/hour (Phillips, 2013) in a recent experiment, while the lowest speed stated by the manufacturers’ manuals is 6.4 km/hour. Furthermore, published bale weights for the bio-baler (500-600 kg/bale; AndersonGroup, 2013) overestimate the values from field tests in Alberta of 250-350 kg/bale (Phillips, 2013).

Simulation results for the nine economic scenarios (Figure 8) show that the Claas HS-2 harvester operated at its maximum speed brought the highest profits of approximately $4700 per hectare. The bio-baler at maximum speed (forty 300 kg bales/hour) produced similar profits to the Claas HS-2 harvester operated at its medium speed: approximately $3700 per hectare. Finally, the JF-192 harvester only broke even at the end of the lifecycle, even operated at its maximum speed, probably because of longer harvesting-times. Note that it took at least four rotations (12 years) in all situations to produce a profit, shown in Figure 8 as a positive cumulative cash flow. WISDOM can produce similar graphs for net present value (NPV) and internal rate of return (IRR); results are not shown because of space constraints.

Figure 8. Prediction of the overall project economy under the case of average yield using different harvesters (JF = JF-192, HS = claas HS-2, and BB = bio-baler) combining with different operating speeds (max = maximum, avg = average, and min = minimum). Note: the legend is denoted by yield_harvester_speed, for example, Avg_HS_max is read as the economic performance under the case of average yield using class HS-2 harvester operating at maximum speed.
CONCLUSION

This research shows the value of feedback-based systems modelling for SRC planning and management, representing SRC systems in a realistic, comprehensive way that accurately simulates their behaviour and clarifies important cause-and-effect relationships. It also describes the development of WISDOM, a new, linked, seven-component, decision-support model for SRC systems that represents connections between climate, soil, water resources, crop production, crop harvest, biomass transport, energy production, and project economics. WISDOM can simulate a variety of aspects of SRC systems. For example, based on eight years of data from Whitecourt, Alberta, WISDOM produced close matches between simulated and observed irrigated production values for biomass production ($R^2 = 0.98$), tree height ($R^2 = 0.92$), and soil electrical conductivity ($R^2 = 0.90$), and acceptable values for unirrigated production.

WISDOM can be used to aid stakeholders and decision-makers in long-term planning for environmentally- and economically-sustainable SRC plantations in Alberta in particular, and more broadly. The model was used to identify how alternative decisions affect system behaviour through the use of “what-if” scenarios, with three climate scenarios run for Whitecourt SRC yield predictions and nine yield-harvest-based economic scenarios forecasted over a complete SRC life-cycle of more than twenty years. These scenarios provide insights into the plantation and management of the Whitecourt site into the future.

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