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

By
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2. Application of System Dynamics to SRC System
3. Model Description
4. Model Uses & Applications
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1. Introduction

- **What are short rotation coppices (SRCs)?**
  - Woody, perennial crops: willow, poplar,
  - High-yielding 7-10 T/ha/yr (North America)
  - Harvest: 3-4 year cycle, life cycle > 20 years (~7 coppices)
  - Environmentally friendly: permitting disposal of treated, nutrient-rich, domestic wastewater and biosolids
  - Economically viable: providing a sustainable source of wood fibre for biofuel and biochar production

1. Introduction

- **The Big Picture: SRC as a “SYSTEM”**
  - Complex interactions and feedbacks between the system components
    - Biomass production,
    - WWT, Irrigation,
    - Bioenergy, Land-use,
    - Environmental quality,
    - Production Cost,
    - SRWC policies

(Image source: EUBIA, n.y.)
1. Introduction

• Goals and Challenges:

The interactions and feedbacks within and between components are complex and hard to quantify.

Development of a decision-support model to aid in long-term planning for environmentally and economically sustainable SRC plantations.

Such a model can be used to:

- Simulate crop growth and inputs, their interaction with yield and end-uses.
- Simulate soil water and solute transport.
- Estimate the biomass energy content (biofuel), project economy.
- Identify how alternative decisions affect system behaviour through the use of “what-if” scenarios.
- Provide insights into the SRC plantation and management.
1. Introduction

- Part of our decision-support model:

Content

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2. Application of SD to SRC system

• What is “system dynamics”?  
  “A rigorous method of system description that facilitates feedback analysis – usually via a simulation model – of the effects of alternative system structure and control policies on system behavior”.  
  (Simonovic & Davies, 2007)

• System dynamics tools  
  – Causal loop diagram (CLD),  
  – Stock and flow diagram (SFD) and simulation model (Model)

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Causal Loop Diagram (CLD)  
– Causality: (+), (-), delay  
– Feedback Processes  
– Feedback Loop: reinforcing, balancing  

-- Loop Identifier: Positive (Reinforcing) Loop

\[ A \uparrow \rightarrow B \uparrow \]

\[ A \downarrow \rightarrow B \downarrow \]

Loop Identifier: Negative (Balancing) Loop

\[ A \uparrow \rightarrow B \downarrow \]

\[ A \downarrow \rightarrow B \uparrow \]
2. Application of SD to SRC system

Stock and Flow Diagram (SFD)

“Stocks are accumulations. They characterize the state of the system and generate the information upon which decisions and actions are based”

Examples:
- **Stock**: Bank account balance, number of trees in plot, water in lake
- **Flow**: income, timber harvesting, stream flows

2. Application of SD to SRC system

Basic feedback processes of dynamic behaviour

Combination of basic feedback processes

Note: these behaviors are typically seen in numerical simulation models (based on SFDs), not in CLDs.
2. Application of SD to SRC system

How did we construct the systems model for SRC, ‘WISDOM’, or Willow System Dynamics Model?

Four study components

- Literature Review
- Causal Loop Diagrams
- Stock & Flow Diagrams
- Decision-support Model

Entire system visualization

Sub-system visualization

SFD & Model

DATA

General CLD

7 Sub-system CLDs

Irrigation
Salinity in rootzone
Nutrient leaching
Soil nutrient
Soil water content
Nutrient uptake by SRC
Water uptake by SRC

<SRC planting>
<Salinity in rootzone>

- Decomposition
  - Soil Organic Matter
  - Precipitation
  - Weathering
  - CO2
  - DOC
  - Base cations
  - BC uptake by SRC
  - Mineralisation
  - Water Extraction

- Irrigation
  - Alluvial deposits
  - Base flows
  - Shallow groundwater

- Denitrification
  - Phyto-remediation
  - Heavy metal extraction
  - Selling Fuel/Heat/Energy

- Treatment Plants
  - Waste Water Treatment Costs
  - Nitrification
  - Immobilization
  - Fertilizer

- SRC Growth
  - SRC Foliage
  - Litter

- Photosynthesis
  - Radiation
  - Respiration

- SRC Root Biomass
  - Drainage

- SRC Biomass
  - Irrigation Supply
  - Irrigation Demand

- Entire system visualization

Sub-system visualization

SFD & Model

DATA
3. Model Description

7 interconnected components
3. Model Description

- **Plant growth & yield:** Based on 3-PG

**Challenge:** plant functional type
- 3-PG: developed for evergreen trees
- SRCs: deciduous trees

**Solution:**
- Applied the principle of virtual leaf biomass
  - Frankfurt Biosphere Model (Ludeke et al., 1994)
  - Canadian Terrestrial Ecosystem Model (Arora and Boer, 2005)
- Allows simulation of both deciduous and evergreen trees
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KUP-Ernteplaner (SRC-Harvest-Planner) (Marron et al., 2012)

Ecowillow (Buchholz and Volk, 2010)
4. Model Uses & Applications

· Simulation of Whitecourt SRC system

MODEL INPUTS
- Climate
- Soil properties
- Solute transp.
- Irrigation (optional)
- Harvest & transp.
- Economic inputs
- Energy & carbon mitigation input

MODEL PARAMETERIZATIONS
- Bio-chemo-physical Components
  - PGY
  - Soil water
  - Solute transp.
- Managed/Economic Components
  - Harvest & transp.
  - Energy content
  - Carbon mitigation
  - Economics

MODEL OUTPUTS
- Simulate biomass growth (ODT/ha)
  - Monthly shoots, leaves, & root biomass
  - Mass of woodchips (ODT) produced
  - Simulate soil water balance
  - Calculate irrigation req. (mm/mo.)
  - Simulate solute transport (1-D vertical)
  - Soil EC/TDS/Chloride
  - Soil NO$_3$-N/PO$_4$$^2-$/Avail. P
- Support harvesting and transporting processes; economics
- Estimate energy content and carbon mitigation: biofuels
- Analyze SRC project economy: yearly cash flow, NPV, IRR
4. Model Uses & Applications

Model Input: Set in EXCEL

- Enter inputs
- Change “switch”
- Parameter values

(a) (b) (c)
4. Model Uses & Applications

Model Output

* SD model was tested using data from Whitecourt, Alberta, trial site
4. Model Uses & Applications

• How to deal with uncertainties?
  – Measured data (e.g., shoot biomass, irrigation, soil chemical, soil moisture)
  – Data from literature (i.e., parameter value ranges)

<table>
<thead>
<tr>
<th>No</th>
<th>Parameter</th>
<th>Range</th>
<th>Unit</th>
<th>Note</th>
<th>Source</th>
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<tr>
<td>1</td>
<td>Light use efficiency</td>
<td>1.06 – 2.22</td>
<td>Dmnl</td>
<td>(LUE ~ above-ground biomass)</td>
<td>Green et al. (2001)</td>
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<tr>
<td></td>
<td></td>
<td>1 – 1.38</td>
<td></td>
<td></td>
<td>Cannel et al. (1987)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(cited in Landsberg and Sands 2011)</td>
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<tr>
<td>2</td>
<td>Light extinction coefficient</td>
<td>0.555 – 0.917</td>
<td>Dmnl</td>
<td></td>
<td>Green et al. (2001)</td>
</tr>
<tr>
<td>3</td>
<td>Canopy LAI</td>
<td>2 – 6</td>
<td>Dmnl</td>
<td>1st and 2nd seasons of 2nd coppice rotation</td>
<td>Pellis et al. (2004)</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Afas et al. (2005)</td>
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<td></td>
<td></td>
<td></td>
<td>Laureysens et al., (2005)</td>
</tr>
<tr>
<td>4</td>
<td>Specific leaf area</td>
<td>16 – 21.1</td>
<td>m2/kg</td>
<td>1st GS</td>
<td>Pellis et al. (2004)</td>
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<tr>
<td></td>
<td></td>
<td>16 – 23.5</td>
<td></td>
<td>1st and 2nd GS</td>
<td>Afas et al. (2005)</td>
</tr>
</tbody>
</table>

Use as inputs -> uncertainties

4. Model Uses & Applications

• How to deal with uncertainties?
  -> Using Monte Carlo simulation
4. Model Uses & Applications

‘WISDOM’ as a DST

- Answer “what if?” questions, rather than optimize policies
- Answers offer model users insights into various aspects of SRC plantation and management
- Example of ‘what-if’: Vary leaching fraction = 0.2-0.5 (Gainer, 2012)

![Graphs showing irrigation, drainage, and soil EC over time](image)

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4. Model Uses & Applications

‘WISDOM’ as a DST

- Whitecourt SRC plantation growth and yield: 3 scenarios

<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>
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<tbody>
<tr>
<td>1</td>
<td>Optimistic</td>
<td>max</td>
<td>max</td>
<td>max</td>
<td>Irrigation requirement case:</td>
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<tr>
<td>2</td>
<td>Average</td>
<td>avg</td>
<td>avg</td>
<td>avg</td>
<td>No water, nutrient, and salinity</td>
</tr>
<tr>
<td>3</td>
<td>Pessimistic</td>
<td>min</td>
<td>min</td>
<td>min</td>
<td>f(θr)=1, f(FR)=1, f(S)=1</td>
</tr>
</tbody>
</table>

(Based on 8 years of historical data)
4. Model Uses & Applications

‘WISDOM’ as a DST

- Whitecourt SRC plantation economics

3 yield scenarios (opt, avg, pes) x 3 harvester options (JF, HS, BB) x 3 harvesting speeds (max, avg, min) = 27 economic scenarios

Illustration:

9 scenarios
(Average yield x 3 harvesting options x 3 harvesting speeds)

Cumulative cash flows
Net present values
Internal rate of returns
5. Conclusions

- **Value of feedback-based systems modelling methods**
  - Simulate system behaviour, elucidate cause-and-effect relationships
  - Represent SRC systems in a realistic comprehensive way

- **The application of WISDOM**
  - Good simulation: $R^2 = 0.98$ for biomass production,
    $R^2 = 0.92$ - tree height, and $R^2 = 0.90$ - soil EC
  - Answering “what-if” questions
  - 3 scenarios for yield predictions
  - 27 scenarios for economy forecast
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ABSTRACT
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Thank You!

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