A Systems Model for Short-Rotation Coppices:

A Case Study of the Whitecourt, Alberta, Trial Site

by

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Abstract

Short-rotation coppice (SRC) plantations, including 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. However, because 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 method is required to identify and understand interactions and feedbacks between the various system components in order for decision makers to plan appropriately, maximize biomass end-uses, and optimize investments.

This research shows the value of feedback-based systems modelling methods, which simulate system behaviour and elucidate cause-and-effect relationships, and represent SRC systems in a realistic, comprehensive way. The thesis describes the development of the "WISDOM" model, a new, interconnected, seven-sector, decision-support model for short-rotation coppice (SRC) systems that represents feedbacks between climate, soil, water resources, crop production, crop harvest, biomass transport, energy production, and project economics. In terms of model performance, WISDOM provided good simulation results. Most of the key SRC system components were simulated successfully based on eight years of Whitecourt historical data – for instance, the match between simulated and observed values was R^2 = 0.98 for biomass production, R^2= 0.92 for tree height, and R^2 = 0.90 for soil electrical conductivity.

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 in Canada and internationally. 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 twenty seven yield-harvest-combined 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 future years.

The thesis concludes with recommendations on improving WISDOM components to improve its accuracy or make the model more broadly applicable, and for incorporating new components to represent socio-economic feedbacks at larger scales.

Preface

This thesis is an original work by Huy T. Nguyen. No part of this thesis has been previously published.

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List of Abbreviations

CFS	Canadian Forest Service
CLD	Causal Loop Diagram
CWFC	Canadian Wood Fibre Centre
DST	Decision Support Tool
EC	Electrical Conductivity
ET	Evapotranspiration
FC	Field Capacity
GCV	Gross Calorific Value
GHG	Greenhouse Gases
GPP	Gross Primary Productivity
HHV	Higher Heating Value
HTDS	Harvest, Transport, Drying, and Storage
IPC	International Poplar Commission
IRR	Internal Rate Of Return
LF	Leaching Fraction
LHV	Lower Heating Value
MC	Moisture Content
MRC	Moisture Retention Curve
MWW	Municipal Waste Water
NCV	Net Calorific Value
NPP	Net Primary Productivity
NPV	Net Present Value
NUE	Nutrient Use Efficiency
ODT	Oven Dry Tonne
PAR	Photo-synthetically Active Radiation
PBM	Process-Based Model
PFT	Plant Functional Type
PGY	Plant Growth and Yield
PPMR	Preparation, Planting, Management, and Re-cultivation
PWP	Permanent Wilting Point
SAT	Saturation Point
SD	System Dynamics
SFD	Stock and Flow Diagram
SLA	Specific Leaf Area
SRC	Short-Rotation Coppice
SWE	Snow Water Equivalent
TDS	Total Dissolve Solid
WUE	Water Use Efficiency

1 INTRODUCTION

This research describes the "WISDOM" model, or the Willow System Dynamics Model, a new seven-component integrated assessment model for short-rotation coppice (SRC) systems that represents feedbacks between climate, soil, water resources, crop production, crop harvest, biomass transport, energy production, and project economics. WISDOM is then applied to an SRC plantation and management case study at Whitecourt, Alberta. The result is an improved understanding of the interactions and feedbacks between different SRC system components, which may help to produce better solutions for many aspects of SRC plantation management – such as irrigation requirements, soil-salinity control, harvest mechanics, biomass transport, project economics, and so on – and the availability of WISDOM for SRC decision-making.

Simulations using the WISDOM model explore the manner in which feedbacks between its constituent parts affect SRC plantation management and provide insights into these aspects of its complete life cycle over twenty years. Because the model includes environmental and economic elements, the model allows an evaluation of the impact of wastewater-irrigated SRC cultivation on soil, drainage water quality, economics and their effects on one another, as well as an exploration of the influences of different climatic conditions, and harvest and transport scenarios on the SRC system.

1.1 Research problem

Over the past eight years, researchers at the Canadian Wood Fibre Centre (CWFC) of the Canadian Forest Service (CFS) have conducted studies into the efficiency and environmental implications of the establishment in Alberta of short-rotation coppices (SRCs) irrigated with treated effluents and fertilized with biosolids. These SRC plantations are intended to be environmentally friendly, permitting disposal of treated, nutrient-rich, domestic wastewater and biosolids, and providing a sustainable source of wood fibre for biofuel and biochar production.

SRC systems are complex and involve interactions between climate, wastewater and biosolids characteristics, soil chemistry and physical characteristics, woody crop establishment, growth and crop fibre characteristics, and fibre suitability for biofuel production, environmental regulations, and economics. In practice, such complexity means that crop establishment, performance, environmental impact, response to environmental factors, and end use is variable. A method is therefore required to identify and understand interactions, linkages and feedbacks between the various system components in order for decision makers to plan appropriately, and optimize end uses and investments.

1.2 Research questions

Numerous aspects of SRC plantations and their management have been studied in depth (Caslin et al., 2011; Dimitriou et al., 2011; Langeveld et al., 2012; Marron et al., 2012; Weih, 2009); however, the complexity of the interactions and feedbacks between and within various components of an SRC system (Dworak et al., 2008; Wallman et al., 2005; Weih, 2009) requires an interdisciplinary approach to create a decision-support tool that can aid stakeholders and decision-makers in addressing many problems in SRC plantation managements. A decision-support tool could help to improve understanding of interactions and feedbacks between different components of SRC systems and provide insight into many aspects of SRC plantations and their management. To deal with this problem, this research adopts a methodology, called system dynamics, that focuses on feedbacks not only within individual elements of SRC crop production, such as SRC growth and yield, but also on their interconnections. The resulting seven-sector model of wastewater-irrigated SRC systems – called “WISDOM”– reproduces the key characteristics of climate-driven, physiological process-based biomass growth and yield, soil water dynamics, solute transport, product harvest and transport, energy content and carbon mitigation, and SRC project economics.

The WISDOM model was designed to address the following important questions:

1. Can a systems modelling methodology improve planning for – and understanding of the behavior of – SRC systems?
2. Does an interdisciplinary approach, with the inclusion of intersectoral feedbacks, produce a greater insight into the function and management of SRC systems than is available from disciplinary work?
3. Can newly developed components and existing, validated “sectoral” models for several SRC components be incorporated into a single, comprehensive, decision-support tool using the selected methodology in question 1?
4. Can the completed systems model be used to increase understanding of the unpredictable effects of feedbacks between natural and socio-economic components of SRC systems, and to aid stakeholders and decision-makers in long-term planning for environmentally- and economically-sustainable SRC plantations?

The first question deals with system concepts and modelling methodologies, and their applicability to the management of short-rotation coppice systems. A variety of different methods are available to study system problems, such as operations research, optimization, simulation, and systems modelling approaches like system dynamics. However, the concerns are whether SRC can be considered as a system and more importantly, whether these methods are applicable to SRC and can be used to construct a useful simulation model – a decision-support tool.

The second question essentially involves the construction of a system map for SRCs, which guides stakeholders and decision-makers to identify the key variables and components, as well as the feedbacks between them, in a SRC system. This system map, once built, should assist stakeholders and decision-makers to trace causes-and-effects of changes in variables throughout the system – in other words, to recognize how a change is transferred from one variable to others in the system.

The third question is practical. As WISDOM contains many different components that simulate variable values and system feedbacks between bio-chemical-physical and socio-economic components of SRC systems, in addition to newly developed components, WISDOM should be developed based on existing, validated sub-models for several SRC system components with or without adaptation or improvement to obtain a reliable, useful, and practical tool. This approach not only saves time and effort, but also combines strengths of these models.

The fourth question is related to model application. 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.

1.3 Thesis scope and outline

Chapter 2 provides a background on short-rotation coppices (SRC), the systems approach, and why SRC is a system. Components of SRC systems including 1) crop production, 2) cultivation and environmental impact, 3) energy content, 4) economics are described in detail. This background information forms the basis of the SRC system map in chapter 3 by identifying key variables and components, as well as the linkages and feedbacks between them. Further, chapter 2 provides a literature review of models for components of SRC systems – which aid the construction of the system model introduced in chapter 3 – and background information on several environmental standards and regulations that apply to the cultivation and management of the SRC trial site at Whitecourt, Alberta.

Chapter 3 contains three parts. The first part describes "system dynamics", the methodology used to develop the system model, and its main tools: causal loop diagrams (CLDs), stock and flow diagrams (SFDs) and simulation modelling. It also explains the selection of this approach as a framework for SRC system simulation. The second part presents SRC system maps, or SRC causal loop diagrams, which were constructed based on the identification of key variables, sectors, and feedbacks from chapter 2. A general CLD and seven sectoral CLDs are presented. The third part describes seven components of the SRC simulation model, their interconnections, and their capabilities, namely the simulation of 1) plant growth and yield, 2) soil water, 3) solute transport, 4) harvest and transport, 5) energy content, 6) carbon mitigation, and 7) economic assessment. These components, or sub-models, are constructed based on the CLDs mentioned above and the SRC component models described in chapter 2.

Chapter 4 presents the application of WISDOM to the Whitecourt, Alberta, trial site in two parts. The first part introduces the site, in terms of location, climatic conditions, and topography, as well as the seven different SRC clones grown there. The second part illustrates model simulation results for the willow SX64 clone, which has the highest- and most stable yield, with a focus on 1) simulation time and model inputs, 2) model parameters, and 3) model performance and validation.

Chapter 5 demonstrates how WISDOM can be used to improve understanding in the establishment and management of SRC systems, as well as to plan appropriately for sustainable development of SRC in the future, in three parts. The first part illustrates the use of the WISDOM model to improve understanding of how alternative decisions affect model behaviour, through the use of “what-if” scenarios. The selection of different leaching fractions is portrayed here as an example of a “what-if” scenario. The second and third parts provide insights into the plantation and management of the Whitecourt site into future years. Three climate scenarios were run for their yield predictions and twenty seven yield-harvest-combined scenarios were carried out to illustrate economic forecasts over a complete SRC life cycle of more than twenty years.

Chapter 6 concludes the thesis. It describes the success of the research in addressing and answering the four questions posed above. It also provides a summary of the major findings of this research and a set of recommendations for future research of SRC system simulations.

Five appendices are included in the thesis. Appendix A illustrates the seven sectoral CLDs mentioned in chapter 3. Appendix B provides more detailed information on the WISDOM plant growth and yield components presented in chapter 3. Appendix C describes the relationship between the Windfall and Twinlake wind speed stations used in chapter 4. Appendix D is a model users’ guide that provides basic instructions for working with WISDOM. Finally, Appendix E describes the content of the CD-ROM included in this thesis.

2 SHORT-ROTATION COPPICES

In recent years, short-rotation coppices (SRC) have drawn the attention of researchers and scientists all over the world for their many potential benefits: a green source of energy, a role in phytoremediation, the mitigation and capture of carbon emissions, and potential profitability. Research on different aspects of SRC establishment and management over a complete life-cycle has been carried out in many countries from North America to Asia, and especially in Europe, which has more than three decades of experience with SRCs.

This chapter provides a review of different aspects of SRC plantations, starting from a general background on short-rotation coppices, to the viewing of SRCs as systems. Details are presented on the components of a SRC system, including 1) SRC crop production, 2) cultivation and environmental impacts, 3) biomass energy content, and 4) SRC project economic analysis. These sections provide knowledge about SRC plantations, and the application to them of systems approaches. Further, they help to identify key variables, sectors/components, and the interactions, or feedbacks, between them, which form the basis of the construction of SRC system maps. These maps, called “causal loop diagrams” and their related simulation models, are the main tools of the system dynamics approach, which is introduced in chapter 3.

2.1 Background

Short-rotation coppices (SRCs) are woody, perennial crops and consist of densely planted, high-yielding varieties of either willow or poplar. SRC cultivation is an emerging method for biomass production and is considered a sustainable source for raw woody biomass feedstock in North America (Heller et al., 2003; Keoleian & Volk, 2005; Yemshanov & McKenney, 2008), across Asia (Ball et al., 2005; Isebrands &

Richardson, 2013), and in Europe, where SRCs have been grown for over thirty years (Langeveld et al., 2012; Marron et al., 2012). SRCs yield a variety of benefits, including the provision of green, renewable bioenergy, disposal of treated wastewater effluent and biosolids, phytoremediation, carbon sequestration, biodiversity increases, and economic profitability.

A report from the International Poplar Commission (IPC) (FAO, 2008) reveals that until 2007, for natural SRC stands (see Figure 1), Canada has the highest number of natural poplar stands with 28.3x10^6 ha, while Russia has the highest natural willow stands with 2.85x10^6 ha. The report also indicates that, for planted SRC stands (see Figure 2), China has the highest planted poplar and willow areas with 4.9x10^6 ha and 43.2x10^3 ha respectively.

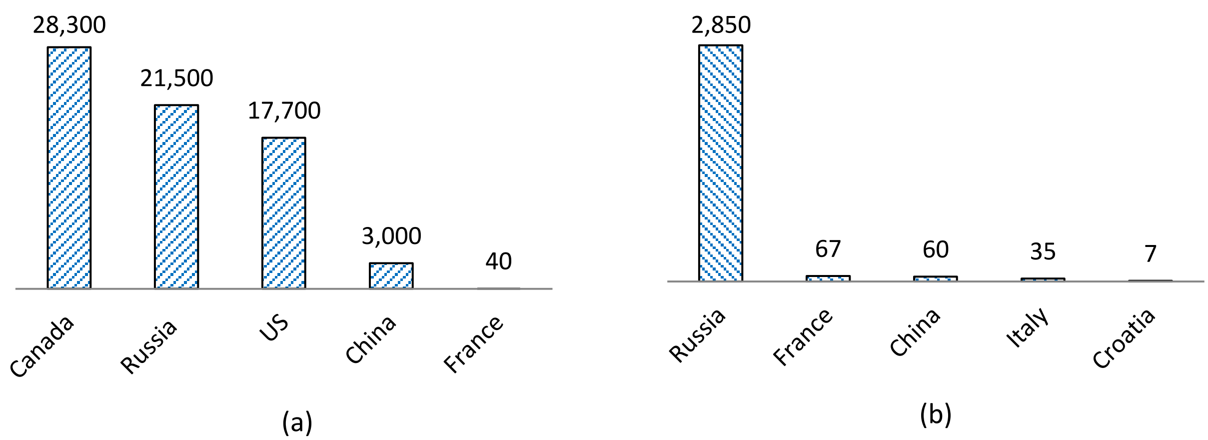


Figure 1. Areas of natural (a) poplar and (b) willow stands, by country (x1000 ha, source: FAO, 2008)

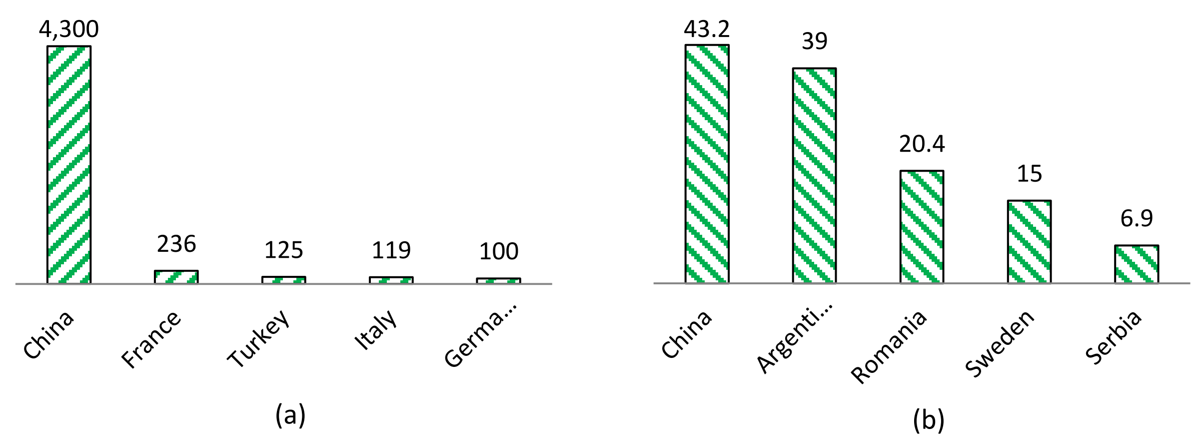


Figure 2. Area of planted (a) poplar and (b) willow stands, by country (x1000 ha, source: FAO, 2008)

SRC plantations may be grown on two- to five-year cycles; however, they are normally harvested (coppiced) every three years in North America, or four years in Europe. After each harvest (coppice), the rootstock or "stool" remains in the ground and new shoots emerge the following spring. The coppice can occur repeatedly for up to 7 rotations before replanting is required, giving an expected crop life cycle of 21 or 22 years with harvesting occurring every four or three years respectively (Allen et al., 2013; Marron et al., 2012), or it is even viable for up to 30 years before re-planting becomes necessary, although this depends on the vitality of the trees and the soil characteristics (Fraleigh, 2011).

SRC products can be used for a variety of purposes, from forest products to fuel wood or bioenergy (see Figure 3), and for various environmental applications. As forest products, SRCs can be utilized directly for the pulp and paper industry, for the wood industry (plywood, poplar-based composite board, reconstituted wood panels, packaging), for furniture manufacturing, and for handicrafts and wicker work (Ball et al., 2005). SRC biomass is commonly used by heat plants to generate energy. Depending upon the harvesting methods (Blank, 2012; Marron et al., 2012), SRC biomass can take the form of woodchips, billets, whole stems, or bales. In addition, heating plant material in the absence of oxygen (Dieterich, 2013) produces "biochar", a type of charcoal, which can be used as a soil amendment. Furthermore, solid biomass can be also converted to a number of liquid fuels or biofuels: (1) bioethanol, a petrol additive or substitute, (2) biodiesel, a fuel that acts like a mineral diesel, and (3) bio-oil, which is used as a liquid fuel in engines and turbines for power generation and combined heat and power installations, or used in boilers for heating and in a variety of chemical applications as a substitute for synthetic fossil fuel-derived products (Woodfuel, 2014).

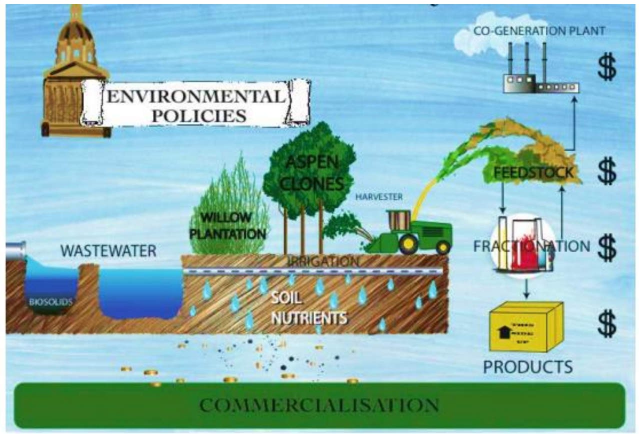


Figure 3. SRC – production system (Image source: Rutley, 2012)

SRCs can be also used for various environmental purposes: as shelter-belts, for sand dune stabilization, as riparian buffers, for riverbank stabilization, and to reduce sedimentation (Ball et al., 2003; Isebrands & Richardson, 2013). More importantly, SRCs can be used to improve environmental quality, such as in wastewater treatment and reuse, carbon sequestration and phytoremediation. SRCs can be planted with or without irrigation and both options affect many different aspects of their surrounding environment. They can help to mitigate and capture CO2, or to improve soil quality. Furthermore, when combined with pre-treated municipal wastewater (MWW) irrigation and fertilized with sewage sludge, SRCs offer producers various advantages, including the low cost of nutrients and irrigation water, bioenergy production, and phytoremediation of wastes. However, the economic analysis of SRC plantations by "balancing maximum environmental benefits and maximum attained biomass production from SRCs is a big challenge that all stakeholders involved in SRC cultivation must consider" (Dimitriou et al., 2011, p. 22).

As interest in green energy has increased, two critical elements have made SRC biomass production very attractive (Fraleigh, 2011): 1) there is a large amount of underutilized agricultural land that has limited capacity to support food crop production (such as corn, soybeans, wheat) and the landowners face continuing pressure to increase income, and 2) the presence of existing biomass markets and facilities.

However, it is challenging to grow SRCs in North America because for several reasons. Unlike Europe and Asia, growing SRCs in Canada in particular and in North America in general is subject to more environmental constraints. A shorter and cooler growing season – that is, less solar radiation – and colder, wetter soils constrain overall plantation productivity (Fraleigh, 2011).

2.2 Short-Rotation Coppice as a "System"

To investigate a view of SRCs as systems, it is first necessary to understand what a system is. According to Simonovic (2009), a system is "a collection of various structural and non-structural elements that are connected and organized in such a way as to achieve some specific objective through the control and distribution of material resources, energy and information." Our human body is a lively example of a system with many interconnected components and processes, such as nervous, sensory, skeletal, circulation, digestion, and respiratory systems, and so on. Another good example is the climate system which involves the individual behaviours of the atmosphere, oceans, ice sheets, land surface, and their interactions.

Similarly, the basis of considering SRCs as systems is presented in Figure 4. Willow or poplar species are irrigated by pre-treated municipal waste water during their growth; then, when the trees are ready to be coppiced, they are harvested and transported to a biomass market for trade or to a heat and power plant for energy generation. The SRC system thus involves many interconnected components, including biomass production, wastewater, irrigation, bioenergy, land-use, environmental quality, production economics, and SRC policies. In fact, SRC can be considered a system even at the level of individual stands of trees (Messier & Puettmann, 2011), and as a type of short-rotation forestry (Willebrand et al., 1993) – see Figure 5 with different components and processes, such as plant growth, plant uptake, transpiration, evaporation, infiltration, and so on.

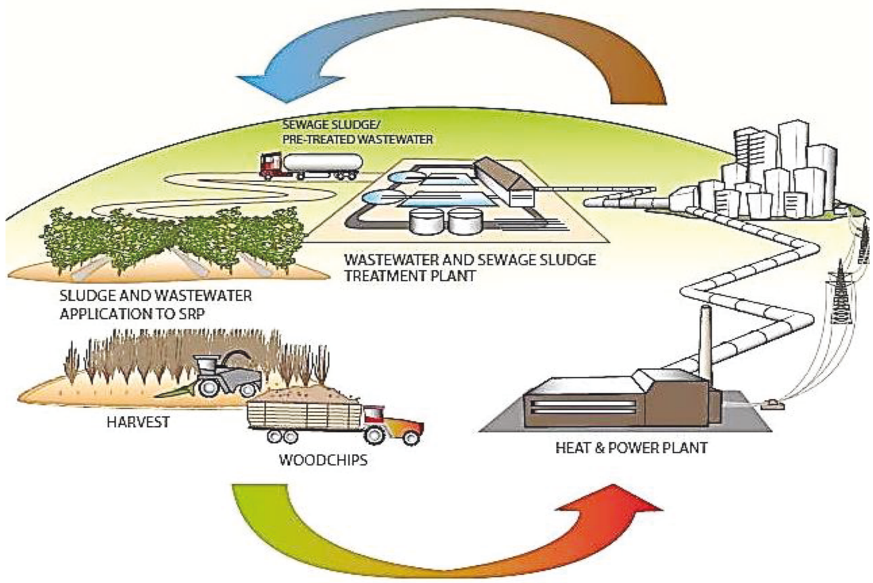


Figure 4. SRC as a "system" (EUBIA, n.y.)

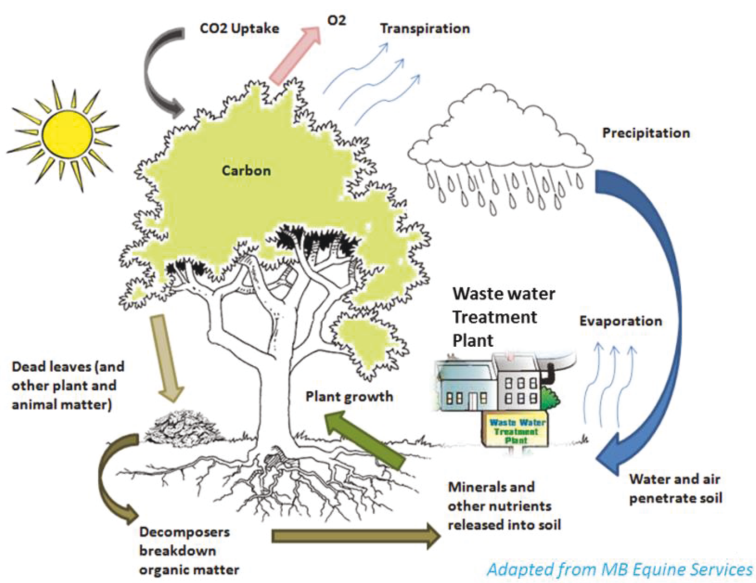


Figure 5. SRC growth and yield as a "sub-system" of SRC system (MBEquineservices, 2013)

A review of the literature on these different aspects of SRC system, including crop production, SRC cultivation and environmental impacts, energy content, and economic analysis as well as validated models for each SRC component – which supports the model development work in chapter 3 – will be introduced in the following sections (sections 2.3-2.8).

2.3 Crop Production

There are many steps involved in planting and managing these energy crops; however, they can be grouped into several main categories for crop production (Caslin et al., 2011; Fraleigh, 2011), including (1) site selection, preparation and management, (2) tree conditioning and planting, (3) SRC growth and yield, (4) nutrients and fertilization, (5) vegetation management, and (6) harvesting, transporting, drying, and biomass storage. The literature reviews below on categories (2), (3), (4), and (6) are useful for the model development work introduced in chapter 3, while those of group (1) and (5) provide extra information which will be useful in the establishment and management of SRCs.

2.3.1 Site Selection and Management

The most important consideration in establishing a new SRC is site selection, which depends upon the purpose of growing SRCs, whether economic or environmental. Weih (2009) stated that SRC plantations are established and managed for purely economic reasons, which guide the location, design and management of plantations. If plantations were established mainly for other reasons, such as phytoremediation to achieve the environmental objectives of “a non-toxic environment” or “zero eutrophication”, it may be that other factors would govern the location, design and management:

> For example, location and design of plantations along rivers (e.g., to reduce nitrate leakage from nearby agricultural fields) will be guided by the topography and landscape, implying that factors such as distance to end-user or optimum harvest conditions might become less important. Nevertheless, the phytoremediation capacity of plantations is commonly strongly linked to biomass production capacity and all factors favoring high biomass yield will also favor phytoremediation capacity. Consequently, phytoremediation capacity of plantations will generally be favored by the same factors as in pure (commercial) biomass plantations, with the exception that the variety choice for maximized biomass production might differ from the variety choice for phytoremediation purposes. (Weih, 2009, p. 8)

There are many different criteria in the site selection in order to provide the ideal conditions for SRC growth: 1) production sites should generally be below 100m above sea level, and slopes should be lower than 13% to assist harvesting machinery (Caslin et al., 2011), 2) soil pH should be between 5.5-7.5, 3) areas should have an annual rainfall greater than 450 mm (20 inches) for willow plantations and 400 mm (16 inches) for poplar plantations (Fraleigh, 2011; Krygier, 2012), and 4) a variety of soil parameters should be satisfied, including the suitability of the soil for irrigation, based on the soil order (e.g. chernozremic, solonetzic), soil texture, soil salinity (EC) and sodicity (SAR), soil drainage that is imperfectly- to moderately-well drained, as presented in Table 5.4 and 5.10 of Isebrands and Richardson (2013, pp. 210, 239), and surficial stratigraphy (Fraleigh, 2011; Krygier, 2012). In addition, to achieve the most favourable conditions for SRC growth and to facilitate mechanical harvesting and machinery access, the crop is planted in double rows, with double rows spaced at 1.6m and an in-row spacing of 0.6m (Blank, 2012)

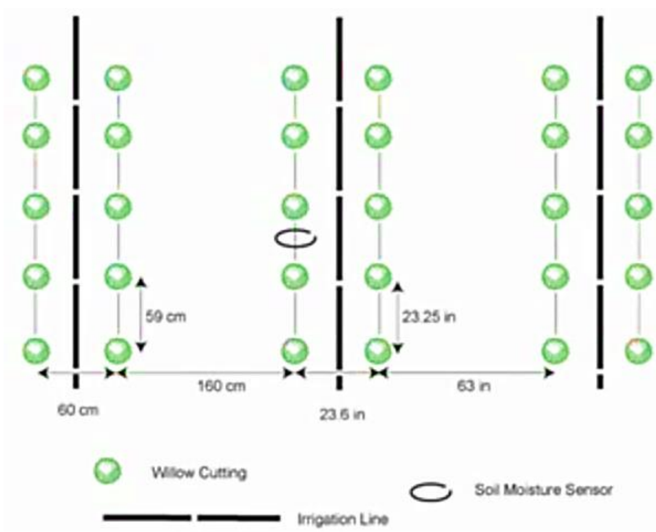


Figure 6. SRC plantation scheme (Blank, 2012)

Unlike the ideal elevations for SRC production sites – in other words, below 100m above sea level – Alberta has a much higher elevation that ranges from 147 to 3,747 metres above sea level (Topography, 2014), as shown in Figure 7. The six new SRC trial sites have studied since their establishment in 2006 at Whitecourt, Beaverlodge, Clairmont, Ohaton and the city of Edmonton (see Figure 8). Note that soil information for Alberta can be found on the web site for Agriculture and Rural Development, Government of Alberta (AARD, 2014a), or Soil Survey Reports for Alberta, Agriculture and Agri-Food Canada (AAFC, 2013).

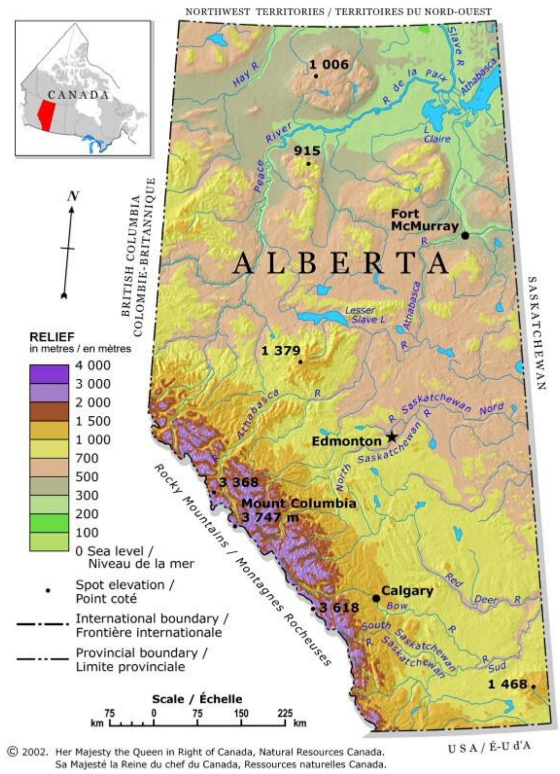


Figure 7. The topography map of Alberta province (Yellowmaps, 2010)

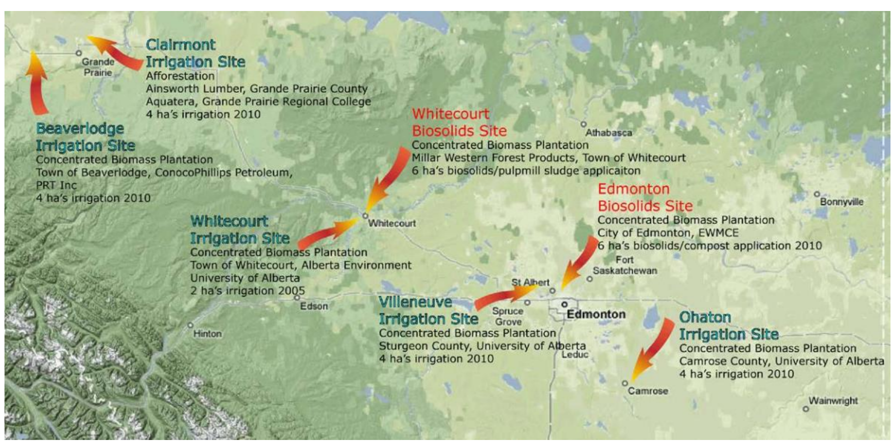


Figure 8. SRC plantation places around Alberta (Krygier, 2012)

After a number of rotation and harvesting cycles, the site must be restored to either grass or arable production. To avoid soil damage through mechanical removal of root systems, after the last harvest, SRC stools are often allowed to re-sprout until they are 30 -50 cm tall (mid-May), then they are extracted and incorporated into the soil surface layer. This leaves the majority of the root system in place without damaging the soil structure (Caslin et al., 2011, p. 33).

2.3.2 Coppice species

There are many different clones of willow and poplar species planted widely in North America and around the world. In Canada, some common poplar and willow clones are found in different trial sites as shown in Table 1.

Table 1. Different types of clones of poplar and willow species
(Source: Fraleigh, 2011; Labrecque & Teodorescu, 2005; Larocque et al., 2013)

Poplar (Populas)		Willow (Salix)	
Common	**Latin**	**Common**	**Latin**
2293-19	Unknown	Pseudo	S. alba
DN-34	P. deltoids x nigra	Hotel	S. perpurea
DN-74	P. deltoids x nigra	India	S. dasyclados
DN-136	P. deltoids x nigra	Charlie	Unknown
DN-54	P. deltoids x nigra	SV-01	S. dasyclados
NM-05	P. nigra x maximiwiczii	SX-61	S. sachalinesis
NM-06	P. nigra x maximiwiczii	SX-64	S. myabeanna
NM-01	P. nigra x maximiwiczii	SX-67	S. myabeanna
Brooks	-	Acute	-
Green Giant	-	Viminalis	S. Viminalis
		Alpha	-

Among them, the clones SX-64 and SX-67 (Salix myabeanna) are readily available for planting in Northern Ontario at a commercial scale (Fraleigh, 2011, p. 11), while in Quebec the clones SX64 and SX61 are among the best for biomass productivity (Labrecque & Teodorescu, 2005). Other clones, like poplar NM-06 (Populus nigra x Populus maximiwiczii), have been planted in Ontario for more than 15 years and have proven to be among the most productive; however, they have not been selected for long-term plantations because of their susceptibility to a disease called Septoria. The clone SV-01 (Salix dasyclados) is the standard for bioenergy plantations in Europe and is characterized by very fast growth and excellent coppice ability, sprouting multiple stems per stool (Fraleigh, 2011).

2.3.3 SRC Growth and Yield

Like conventional crops, SRC growth and yield is strongly dependent on site/soil, weather conditions and water and nutrient consumption. The optimization of SRC growth and its yield was illustrated in Marron et al. (2012) through the interactions among three cycles: the water cycle (irrigation activities), the nitrogen cycle (fertilization) and the carbon cycle (production). These factors are also manipulated through plantation management, plant materials (e.g. genera, species and genotypes, mixed or not) and site conditions.

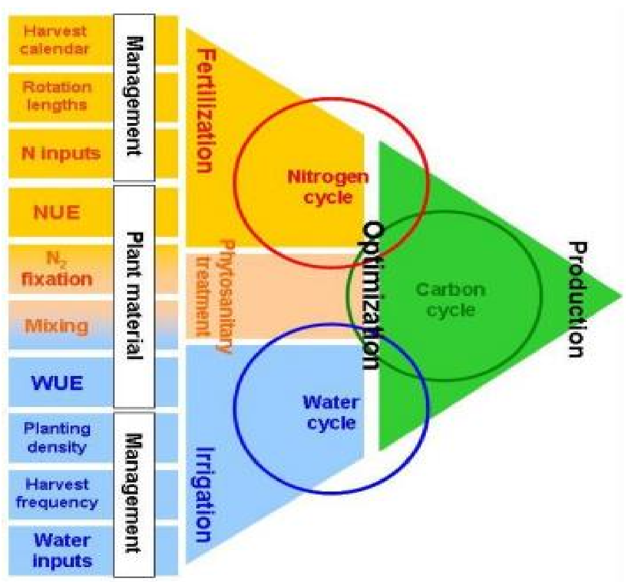


Figure 9. Summary of the different ways to maximize biomass production (Marron et al., 2012, p. 17)

According to Marron et al. (2012), water is often the main yield-limiting factor. In their report, the values of energy crops' water-use efficiency (WUE) were shown generally to vary between 0.3 and 15 g biomass per kg water used, while the data on nutrient (N, P and K) use efficiency (NUE) often varies by a factor of about 20. Another factor with a significant impact on SRC yield is root-zone salinity, which can be minimized by using a leaching fraction (or "leaching requirement") to remove the salt to below the root zone (Hillel, 2004). Gainer (2012) recently investigated drainage water quality below the SRC root zone at Whitecourt, Alberta, and suggested that the leaching fraction should range between 0.2 and 0.5

to prevent soil salinization, protect groundwater users, and utilize the large supply of treated municipal waste water available in Alberta.

The principle on which crop yield is based is the conversion of light energy through photosynthesis into the chemically-bound energy in the woody biomass of the crop. To maximize the biomass growth and thus the economic yield, the crop canopy must be maximized as early as possible in the rotation and maintained for as long as possible throughout the growing season. This ensures efficient interception of solar energy, thereby maximizing yield potential (Caslin et al., 2011, p. 28).

A wide range of SRC yield data has been published. Values are normally quoted in tonnes of dry matter (T_{dm}) (that is, the mass after all moisture has been removed) per hectare per year to standardize figures, while fresh weights (which include variable moisture content) may vary. Fiala and Bacenetti (2012) carried out field tests on 69.2 ha of biennial SRC in Italy and reported that the yield ranged from 16.7 to 33.71 T_{dm}/ha, the chip moisture content between 50.4 and 64.8% and bulk density between 118.8 and 169.2 kg_{dm}/m^3. Data on North American field-scale studies conducted by Samson and Chen (1995) and others (Kenney et al., 1991; Heller et al., 2003; Volk et al., 2006, 2011) showed that SRC biomass production ranges from 5 to 11 ODT/ha/year. Caslin et al. (2011, pp. 7, 28, 46) described SRC yields in the range of 7-12 T_{dm}/ha/year or 21-36 T_{dm}/ha for a three-year harvest cycle in Northern Ireland. However, the yields from the first cropping cycle (3-year harvest) can be expected to be lower than subsequent cycles. The yield from the first harvest cycle would be expected to achieve 23 T_{dm}/ha, the equivalent of 51 tonnes of fresh material at 55% moisture. The yield from subsequent harvests on a 3-year cycle should be 30 T_{dm}/ha, equivalent to a fresh harvest weight of 67 tonnes at 55% moisture content. Studies by Heller et al. (2003b) and Volk et al. (2011) showed agreement with Caslin et al.’s (2011) results by pointing out that yields in later harvests will increase by 30% to 40%. Finally, in general, the total biological SRC yield has been found to consist of 60% for the above-ground biomass, 10% for the leaves, and 30% for the stool/root system (Caslin et al., 2011, p.28).

2.3.4 Nutrients and Fertilization

As mentioned above, the nutrient cycle is one of the most crucial factors in maximizing the yield. Caslin et al. (2011, pp. 18, 42) reported that typical willow stem N content is 3-4 kg per dry tonne of wood where no fertilizer has been applied. However, where nutrients are not limited, it has been measured in the range 6-25 kg N per dry tonne of wood. Under these circumstances, annually exported N in harvested stems would be 60-250 kg, assuming a productivity of 10 dry tonnes per year and hectare. Published nutrient off-take figures for the harvested crop vary, but are in the following ranges: 150-400 kg N, 180-250 kg K, and 24-48 kg P per hectare per three year rotation based on an 8-10 T_{dm}/ha/yr crop. Dimitriou et al. (2012a) showed that nitrogen fertilization recommendations for willow SRC have been established and vary between 70 and 120 kg N/ha/year. Simpson et al. (2009, p. 10) suggested application of nitrogen at a rate of 100 to 200 kg/ha during each rotation, although they indicated that annual doses of as little as 60 kg N/ha/yr have been found to be sufficient to maintain biomass production over time. Leaching of nitrogen compounds from established willow systems is negligible when this practice is employed, even when the recommended amount of applied nitrogen is exceeded.

In order to increase soil nutrient levels and reduce the fertilization budget, biosolids (municipal wastewater sludge) can be applied, with the amount of biosolid injected into a willow plantation, for example, most often limited by phosphorus. Caslin et al. (2011, p. 43) stated that nitrogen removal from the soil is almost entirely dependent on biological processes, making the risk of leaching very small; however, phosphorus removal from the soil is regulated primarily by chemical and physical processes, and thus the biosolid P content poses a considerable problem. As a result, biosolids should only be applied to soils with a P index of 2 or less (which corresponds to about 16-25 mg/L P), and must be discontinued if the P-index approaches 3 (or about 26-45mg/L).

2.3.5 Weed Control through Herbicides

Herbicides are used at various stages during the establishment and growth of SRCs (Caslin et al., 2011, pp. 10, 16). For site preparation, a pre-ploughing herbicide application is required when weeds are still actively growing, with glyphosate (e.g. roundup at 4.0 – 5.0 l/ha) typically used. A minimum of ten days after herbicide application is required before the site can be ploughed. More generally, weed control can be divided into four distinct phases: (1) pre-ploughing, (2) post-planting application of a pre-emergent residual herbicide to keep the crop clean during the establishment phase, (3) application when weeds become a problem during establishment, and (4) application following the establishment or after cutback, to keep the crop weed-free until it achieves canopy closure.

2.3.6 Harvesting, Transporting, Drying, and Biomass Storage

Biomass material is generally harvested during the winter, and particularly January-February, when the buds are fully dormant (Caslin et al., 2011, p. 14). There are many different harvesting methods, but they can be classified based on harvest products (Kofman, 2012) or on the scale of harvesters (Blank, 2012).

In the first classification, there are four harvesting methods or four specific harvest products possible (Koftman, 2012; Savoie et al., 2013): (1) whole-stem harvesting, (2) chip harvesting, the so-called cut-and-chip method, (3) billet harvesting, the so-called cut-and-billet method, and (4) bale harvesting, the so-called cut-and-bale method. Whole-stems, billets will generally have to be chipped, while bales have to be ground at a later stage to be utilized as a fuel, while material from the cut-and-chip method is ready for use.

In the second classification, there are two harvester scales (Blank, 2012): (1) large, including the use of modified agricultural equipment often known as “self-propelled machines”, such as forage harvesters (the commonly-used Claas HS-2, shown in Figure 10a) and a modified round baler (the widely-used Anderson W55 bio-baler, shown in Figure 10b); and (2) small, using a modified corn/sugarcane harvester often known as “tractor-mounted equipment” (the well-known JF-192, shown in Figure 10c). Both the forage and corn/sugarcane harvesters require willow to be planted in rows but a few, such as the bio-baler can harvest either rows or non-row plantations (Phillips, n.y.). In comparison, the ownership cost and weight of the tractor-mounted equipment is lower, and this equipment also has lower weight than self-propelled machines, with the disadvantage that its productivity is also lower. The harvesting machine capacity ranges from 10-60 tons per hour (Kitchen, 2012). Once harvested, chips and bales should be dried to 20% water content before use to maximize efficiency.

As stated above, there are many types of harvester on the market. However, in Canada in particular and North America in general, the three harvesters often used – as mentioned above – are the JF-192, the Claas-HS2, and the bio-baler. At the Whitecourt trial site, all three harvesters have been used to compare their efficiency with their information described in Table 2. This information is required for the model inputs in Chapter 4 – the case study of the Whitecourt site.

The transportation of biomass is divided into two parts (Marron et al., 2012): (1) from the field to the storage place, often called on-site transport, and (2) from the storage place to end-users, often called highway transport. Storage is not mandatory, and depends upon many factors such as the biomass moisture content, consumers/end-users, product markets, distance from the harvesting site to end-users, climate conditions, and so on, which can affect the biomass quality.

(a)

(b)

(c)

Figure 10. Three SRC harvesters: (a) Claas HS-2, (b) bio-baler, and (c) JF-192 (Willowpedia, n.y.)

Table 2. Descriptions of the three harvesters JF-192, Claas HS-2, and bio-baler (Phillips, n.y.)

No	Description	JF-192	Claas HS-2	Bio-baler
1	Original (distributor)	Ny Vraa Bioenergy (www.nyvraa.dk)	Claas – Jaguar (www.claasofamerica.com/product/forage-harvesters)	Anderson group (grpanderson.com/en/biomass/biobaler-wb55)
2	Product produced	Chip	Chip (7.5-22mm)	Bale
3	Row harvested	Single row	Double row	Row independent
4	Harvesting speed	Distributor: 2-5 km/hr; Prince George operation: 3-4.8 km/hr	Distributor: 6.4-9.7 km/hr; Real operation: 5.3 km/hr on average	Distributor: 15-40 bales/hr; Real operation: 20 bales/hr
5	Harvesting productivity	PEI study: 0.5-0.66 ha/hr and 3.5-12.9 green tones/hr	-	Distributor: 500-600 kg/bale; CWFC data: 245-350 kg/bale
6	Required support	100-150 HP tractor prime mover and collection bin	450-550 HP tractor prime mover and collection bin	200-250 HP prime-mover with PTO drive
7	Cost (approx.)	\$30,000-\$40,000 for harvester; \$150,000 for tractor prime mover	\$160,000 for HS-2 head; \$350,000 for forage harvester	\$100,000 for baler; \$200,000-\$250,000 for tractor prime-mover

One of the most important factors that significantly influence the storage of SRC biomass is water content. After cutting, the moisture contents of willow and poplar are about 52.4% and 58.5% respectively (Marron et al., 2012, p.73); however, long-term storage normally requires moisture levels below 20% to maintain material quality and to be ready for combustion. Transportation and storage processes can contribute to the reduction of biomass moisture content but it takes time to reach adequate moisture content under specified methods for biomass quality protection. To decrease the moisture content of fresh biomass efficiently, several methods of woodchip drying are available, including technical drying (e.g. cold air or warm air), natural drying, or a combination system. The selection of different methods will affect the material quality and drying expenses.

2.4 SRC Cultivation and Environmental Impact

SRC plantations in combination with irrigation by treated wastewater effluents offer various economic and environmental benefits, but also pose several risks to the environment. Hanegraaf et al. (1998) (cited in Simpson et al., 2009) proposed several criteria for assessment of energy crop sustainability, including (1) the carbon balance, (2) soil erosion, (3) fertility threats, (4) emission of minerals and agrochemicals to soil and water, (5) ground water use and protection, (6) contribution to biodiversity and landscape quality, and (7) the energy balance. Reviews of the literature on the two first points – the carbon balance and soil erosion – are relevant to the WISDOM model, as described in chapter 3, while information on the remaining points is useful in the establishment and management of SRC systems. All of these points are discussed below in this section, except for the last point, SRC energy content, which is presented in section 2.5.

2.4.1 Carbon Mitigation and Capture

The mitigation of carbon dioxide emissions comes from displacing fossil fuel sources for heat generation, the carbon-dioxide-neutral status of biomass from energy, and the carbon balance (i.e. the ratio of energy used in cultivation compared to that produced).

In relation to the displacement of fossil fuel, the following simple calculation illustrates the significance of biomass production. According to (Caslin et al., 2011, pp. 4, 52),

> One hectare of willow (25% moisture) produces approximately 13 tonnes of willow every year with an energy content of 13.2 Gigajoules (GJ) per tonne. Therefore, one hectare produces 172 GJ of energy per year. Assuming that 1,000 litres of home heating oil has an energy content of 38 GJ, then one hectare of willow has the same energy content as 4,500 litres of home heating oil and an average medium-sized house will burn around 3000 litres of oil per year, which releases 8.02 tonnes of CO2.

In its growth as a short-rotation coppice crop, willow has a great carbon sequestration potential. This carbon sequestration capability depends on a number of factors, including carbon inputs to the system, decomposition of the major carbon pools, the initial carbon content of the soil, crop management, and the depth of soil influenced by the willow. Caslin et al. (2011, p. 52) stated that carbon can be stored in three ways after harvesting: 1) in the unharvested above-ground biomass (stumps); 2) in the below-ground biomass (coarse and fine roots); and 3) in the input of the carbon into the soil organic matter. SRC willows can sequester around 0.12 t of carbon/ha/yr. Dimitriou et al. (2011, p. 11) explained that values for total carbon sequestration by SRCs are significantly higher than for annual crops in arable soils, but still below the carbon sequestration possible in mature forests.

SRC willow wood is a carbon-neutral fuel, since the carbon that is released during its combustion was originally absorbed by the crop as it grew. Caslin et al. (2011, p. 52) explains that for every gigajoule (GJ, or 10^9 J) of energy produced from wood chips, about 7 kg CO_2 is released, compared to 79 kg CO_2 released when the same amount of energy is produced from oil – this difference corresponds to a 90% reduction in emissions. Similarly, Simpson et al. (2009, p. 5) showed a ratio of approximately 1:17 between CO_2e (the carbon dioxide equivalent, which is the net emission of gases associated with the greenhouse effect) emitted during cultivation and CO_2e saved by substitution of biomass for fossil fuel.

Regarding the carbon balance, research has provided a wide range of results. For example, Weih (2009) reported that SRC biomass yields 20 times more energy than the energy input and 3 times more than the energy balance of annual energy crops such as wheat and canola, while Caslin et al. (2011, p. 6) stated that, at a minimum, a SRC willow crop will yield 14 times more energy than is needed to produce and deliver it.

2.4.2 Soil Quality

Cultivation of SRCs improves some aspects of soil quality. According to Langeveld et al. (2012), SRCs affect seven distinct dimensions of soil quality: (1) carbon (C) sequestration ability, (2) soil bulk density,

(3) phosphorus (P) availability, (4) nitrogen (N) availability, (5) soil erosion rate, (6) pH and mobility of trace elements (excluding cadmium), and (7) cadmium concentration in the soil. A scenario that substituted 20% of the arable land crops in the EU for cultivation of SRCs – which corresponds to about 32.8 million ha of a total of 164 million ha according to data from Fischer et al. (2010) – leads to enhanced C sequestration and decreased soil N availability, which decreases N loss and decomposition rates and increases the stability of the organic matter in the soil. Bulk density is slightly increased compared to tilled arable land, which may have some impact on SRC root and above-ground biomass development. SRCs decrease the availability of soil P, which will eventually affect the P supply for crops, and also reduce soil erosion. The impact on heavy metals is unclear: on the one hand, a decrease in soil pH is expected to increase metal mobility, while on the other hand, an increase in mobility will lead to increased metal uptake by SRC plant, thus improving the soil remediation function. Cadmium concentrations in particular can be reduced significantly in the long run due to enhanced uptake and removal by SRC crops.

Dimitriou et al. (2012b) compared a number of soil quality parameters in 10-20 year-old commercial SRC fields and the adjacent fields with annual crops. The results showed that organic C concentrations in the topsoil and sub-soil of SRC fields were, on average, significantly higher (9% in topsoil, 27% in sub-soil) than in the reference annual crop fields. Cadmium (Cd) concentrations in the topsoil of SRC fields were 12% lower than in the topsoil of respective reference fields. Further, even Cd concentrations in the topsoil of SRC fields treated with municipal wastewater sludge and/or wood ash were lower than in the top soil of reference fields. In the corresponding comparison of sub-soils, no such difference was found. For chromium (Cr), copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn), there were no significant differences in concentrations between SRC fields and the reference fields in either topsoil or subsoil. Differences in pH were also negligible. Finally, microbial biomass affects the decomposition of material and nutrient cycling in soil. Due to the lack of tillage in SRC cultivation, the microbial biomass in the soil was found to be higher in the upper 5 cm of soil but decreased in sub-soils compared to the agricultural soil (Dimitriou et al., 2011, p. 13).

Simpson et al. (2009, p. 14) described the capability of SRCs to remove cadmium from soil. They found a content of approximately 20 g cadmium per 10 to 12 ton in dry harvested biomass, proving that SRC can be used as a relatively cheap soil remediation tool. Also of note is that the cadmium content of willow tissues (0.5-4 mg/kg) is much higher than that of straw (0.1 mg kg^{-1}) or winter wheat (0.5 mg/kg), because of the high rate of willow biomass production. In general, Dimitriou et al. (2011) emphasized that although SRCs are more appropriate for remediation of rather shallow contamination, since most of their active roots are concentrated near the soil surface, a large scale SRC cultivation offers great potential for removing metals such as Cd, Zn, Cu, Ni and Se from moderately contaminated soil.

2.4.3 Nutrient Leaching

Dimitriou et al. (2012a) studied the nitrogen and phosphorus leaching from a number of commercial "old" SRC willow (i.e. at least 10 years old) stands compared to adjacent arable fields grown with "ordinary" crops (i.e. grass with no fertilization or cereal with commonly recommended fertilization) in 16 locations in Sweden during three vegetation seasons. They found that NO_3-N leaching from willow SRC fields was significantly lower than from reference fields with cereals. The opposite was observed for PO_4-P, where concentrations in the groundwater underlying SRCs were high compared to the reference fields. Sewage sludge applications were not responsible for the elevated PO_4-P leaching under SRC compared to reference crops. Caslin et al. (2011, p. 42) also stated that the risk of N leaching from an SRC site where biosolids or effluents have been added is extremely low in most soils, including sandy, well-drained soils. Application rates with equivalent-N content of up to 180 kg/ha would pose virtually no risk of N leaching. Additionally, Dimitriou et al. (2011, p. 9) suggested that wastewater application at least 150 kg N/ha/yr should not pose any threat in terms of NO_3-N leaching. Specifically, concentrations of N in the drainage water below 5 mg/l were recorded in an experimental willow SRC field in northern Ireland where approximately 200 kg N/ha/yr was applied; even when a higher amount was applied (300 kg N/ha/yr), N concentrations in the drainage water at different depths were found to lie between 5 and 10 mg/L (Dimitriou et al., 2011, p. 9)

2.4.4 Ground and Surface Water Quality

Since SRC soil management practices are quite different from those of conventional agricultural crops (e.g. weed control only during the establishment phase, tillage only before the establishment phase, and lower inorganic fertilization than other crops), SRCs are generally considered to improve the quality of water that seeps to groundwater, and they absorb and reduce significantly the N and P leaching to groundwater, which is considered responsible for the eutrophication of water bodies (Dimitriou et al., 2011). Furthermore, SRC can aid in efforts at phytoremediation – once the SRC plantations are well-established – as wastewater applications are well-treated by the soil-plant system. For example, Dimitriou and Aronsson (2011) showed that application of even high doses of approximately 370 kg N/ha/yr and approximately 30 kg P/ha/yr in wastewater is unlikely to contaminate groundwater.

Langeveld et al. (2012) evaluated the influences of SRC cultivation on water quality in four categories: (1) nitrate-nitrogen concentrations in groundwater, (2) phosphate-phosphorus concentrations in groundwater, (3) surface runoff, and (4) impact on groundwater recharge. Their results indicated that the introduction of 20% SRC cultivation leads to a large reduction of nitrate-nitrogen concentrations in the groundwater, while the phosphate-phosphorus concentrations in contrast increased slightly, leading to a minor deterioration of water quality. Surface runoff and soil erosion decreased because of whole-year land cover and the permanent root system of SRCs, thus improving surface water quality and limiting flooding risk for water bodies. Finally, as water percolation is expected to decline with the growth of SRCs, groundwater recharge maybe limited, leading to a slight lowering of the groundwater table.

2.4.5 Impact on Hydrological Process

In addition to its influence on water quality, SRC cultivation also affects water quantity through hydrological processes. In terms of evapotranspiration (ET), Guidi et al. (2008) studied the ET and crop coefficient of poplar and willow plantation in Pisa, Italy, using two-year-observed data of ten-day evapotranspiration. Their results showed that the maximum crop coefficients, K_c values, for the first year growth ranged from 1.25-2.84 in willow and 1.06-1.90 in poplar, whereas for the second year, they ranged from 1.97-5.30 in willow and 1.71-4.28 in poplar. Caslin et al. (2011, p. 40) stated that depending on site location, the ET in a SRC willow plantation in Northern Ireland can be approximately 5 million L/ha during the growing season.

Stephen et al. (2001) conducted modelling exercises to explore effects of energy crops on hydrology in the UK using a simple conceptual model with the effects of water used by energy crop represented through two key components: surface runoff and deep percolation below the root zone. Their results demonstrated that, in comparison to arable crops, the hydrologically effective rainfall – defined as the part of the total incident precipitation that reaches stream channels as runoff – in SRC fields is reduced by 10-15% due to the increase in canopy interception. However, at the catchment level the effect on hydrology would be minimal, at roughly 0.5% of the mean annual amount. Hall (2003, cited in Dimitriou et al., 2011, p.8) add that in areas where precipitation is below 550 mm, relatively high-yielding SRC plantations (above 12 T_{dm}/ha/yr) should be avoided as a precaution, because the consequences of reduced hydrologically effective rainfall can be much more serious in such areas.

2.4.6 Biodiversity and Landscape

Langeveld et al. (2012) investigated the potential impacts on biodiversity of SRC plantation expansions in the EU if 32.8 million of arable land is used to cultivated SRC as the demand for bioenergy are increasing rapidly in the EU. Their comparisons are based on six dimensions related to plant species (phytodiversity) and seven dimensions related to breeding bird species (zoodiversity):

- Phyto-diversity:
    - Total number of plant species,
    - Number of woodland species,
    - Number of ruderal species,
    - Number of arable species,
    - Number of grassland species,
    - Number of endangered species, and,
- Zoodiversity:
    - total number of species,
    - Forest species,
    - Scrub species,
    - Open land species,
    - Ecotone species,
    - Tall-herb/reed species, and
    - Endangered species.

Generally, their results demonstrated that replacing 20% of the crops by SRCs will have a positive impact on biodiversity since all elements are significantly improved. Weih (2009) investigated the effects of SRC on biodiversity and claimed that flora and fauna diversity was frequently found to be higher in willow and hybrid poplar stands compared to agricultural croplands.

In relation to the impact of SRC on the landscape, Caslin et al. (2011, p. 9) argued that poorly-planned SRC plantations have the potential to affect the rural landscape adversely. As mature SRCs can be up to 8m tall by the end of a three-year-growing cycle, they create a three-dimensional mass in the landscape which arable crops do not. However, well-designed and carefully-sited plantations could bring small but important landscape upgrades. For example, Weih (2009) argue that the establishment of SRCs provide an exciting new feature of the landscape, which can help to enhance the aesthetic value of landscape by adding variation (e.g., autumn colors) and structure in an otherwise homogeneous agricultural landscape.

2.5 SRC Energy Content

As mentioned above, in addition to their role in phytoremediation, SRC plantations are intended to provide biomass products or woodchips as a source of bioenergy. Depending upon their moisture content, the woodchips might be dried before burning for heat energy. During the burning process, the efficiency of the combustion system plays a significant role in the net calorific value achieved.

As SRC energy content is a component of the WISDOM model discussed in Chapter 3, this section provides knowledge relevant to the calculation of SRC energy content – that is, moisture content, combustion system efficiency, higher and lower heating values, gross and net calorific values, and an explanation of what they are and how they are used to estimate the energy content. This section provides additional information on the energy balance of SRC systems, one of reasons that makes SRC plantations attractive as sources of green energy.

2.5.1 Moisture Content

Biomass moisture content has a close relationship with the wood chip net calorific value, and plays a significant role in the combustion of wood chips, as described in the following sections. Moisture content is also helpful in switching between fresh mass (used to calculate harvest and transport of biomass production, for example) and oven dry mass (evaluating biomass productivity of a field, for instance). It is expressed as a percentage, measured either on a wet or dry basis which is calculated, according to CarbonTrust (2008, p. 20) as,

$$MC_{wet} = \left(\frac{Fresh\,mass - Oven\,dry\,mass}{Fresh\,\text{mass}} \right) \times 100\,(\%) \tag{1}$$

$$MC_{dry} = \left(\frac{Fresh\, mass - Oven\, dry\, mass}{Oven\, dry\, mass} \right) \times 100\,(\%) \qquad (2)$$

where MC_{wet} and MC_{dry} are the moisture contents that correspond to the wet and dry basis calculation (%); the fresh- and oven-dry mass is defined as the mass of the biomass, once it has had either none or all of its moisture driven out, respectively.

The formulas show that higher moisture content produces a lower calorific value, as each unit mass of fuel contains less oven-dry biomass, which is that part of the fuel that undergoes combustion to release heat. For instance, the energy content of completely dry wood was approximately 19 MJ/kg; however, in wood at 30% moisture, the energy content was reduced to approximately 14 MJ/kg of usable energy because of the need to use a portion of the energy to remove additional water before combustion occurs (Caslin et al., 2011, p. 31). Wood suppliers and the majority of the biomass industry typically use the wet-basis MC_w definition because it gives a better indication of the water content in timber.

2.5.2 Appliance Efficiency of Combustion System

In addition to the moisture content, the efficiency of the combustion system is the second major element that contributes to energy losses in a heating system. The design of every heating system differs, for example direct-burn combustion or two-chamber combustion (Maker, 2004); however, a typical wood chip system should contain the following main parts (Girouard et al., 1997): a fuel reserve, a fuel-metering bin, a fuel-feed system, a combustion chamber, a heat exchanger, and a heat distribution system, as shown in Figure 11.

Depending upon the combustion system type and design, the appliance efficiency values currently range from about 70-85% (McKenney et al., 2012; Girouard et al., 1997; Maker, 2004; Prasad, 1995).

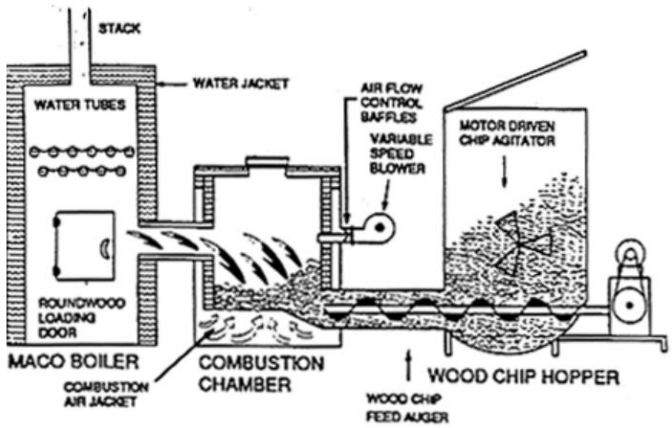


Figure 11. A typical wood chip combustion system (Girouard et al., 1997)

2.5.3 Higher and Lower Heating Value (Gross and Net Calorific Value)

In order to evaluate the energy content of SRC biomass, a value is first calculated based on an oven-dry basis (GJ ODT^{-1}), which is the so-called higher heating value (HHV) or the gross calorific value (GCV), and then adjusted by the average moisture content of biomass to produce the lower heating value (LHV) or the net calorific value (NCV). As CarbonTrust (2008, p.20) explains,

> Gross calorific value (GCV) is the quantity of heat liberated by the complete combustion of a unit of fuel when the water vapor produced is condensed, and the heat of vaporization is recovered. Net calorific value (NCV) is the quantity of heat given off by the complete combustion of a unit of fuel when the water vapor produced remains as a vapor and the heat of vaporization is not recovered. This can be calculated by subtracting the heat of vaporization of the water produced from the GCV (CarbonTrust, 2008, p. 20).

There are two methods to determine the lower heating value (LHV) for wood fibre of different moisture content. The first method is described by McKenney et al. (2011), who use Kenney et al. (1991)'s lower heating value (LHV) – see equation (3) – to adjust the higher heating value (HHV) of wood, which is 19.5 GJ ODT^{-1} at 0% of MC_w and 9 GJ ODT^{-1} at 50-55% of MC_w, for energy losses due to moisture removal (Caslin et al., 2011, p. 67).

$$LHV = HHV - \left(0.2205 \times h + \left(\frac{2.45 \times MCw}{1 - MCw}\right)\right) \tag{3}$$

Equation (3) provides the lower heating value (LHV; GJ ODT^{-1}), where HHV is the higher heating value (GJ ODT^{-1}), h is the hydrogen content (6%), and MC_w is the moisture content in the wood before combustion.

The second method to calculating the LHV uses the empirical equations shown in Figure 12, as proposed by Marron et al. (2012, p. 75), which are different for poplar and willow species. When plotting both of the two methods on the same graph (see Figure 13), the Kenney et al. (1991) values lie between those of Marron et al. (2012) for moisture content values between 20% to 30% – which is the moisture content often achieved before combustion – and both sets of values are quite similar.

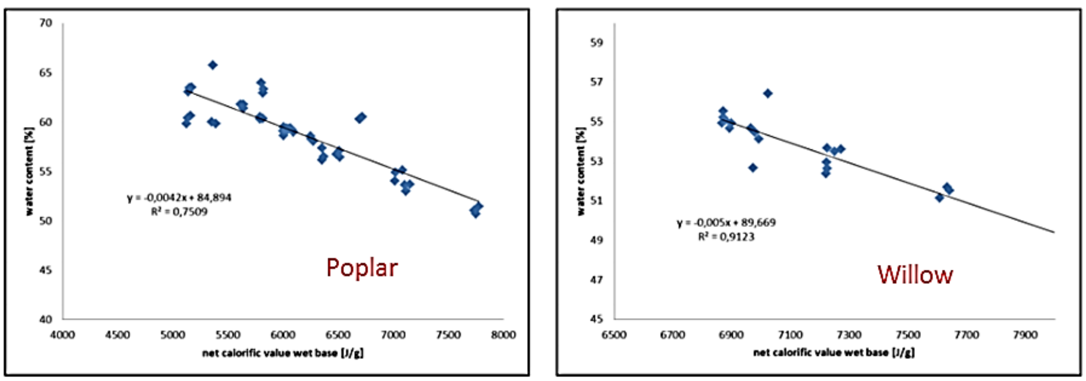


Figure 12. Correlations between the moisture contents MCw (%) and the net calorific values NCV ($J.g^{-1}$) for the poplar and willow species proposed by Marron et al., (2012)

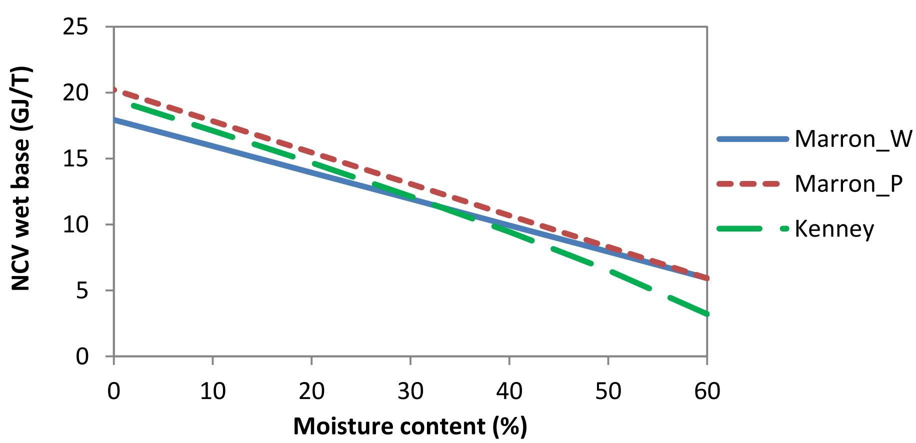


Figure 13. Comparison between Kenney et al.(1991)'s and Marron et al. (2012)'s methods (where Marron_W and Marron_P are for willow and poplar respectively)

2.5.4 Energy balance of SRC system

Matthews (2001) attained an energy ratio of 1:29 (1 unit of energy consumed during the production of 29 units of energy) for calculating the energy balance of short-rotation coppice systems, although energy consumed in fertilizer treatment was not clearly presented in his analysis. By accounting for the fertilizer treatment (i.e. approximately 40% of the total energy input), Heller et al. (2003, cited in Simpson et al.,2009) obtained a higher energy ratio of 1:55 and also showed that transportation of the biomass to a power plant and co-firing with coal with a combustion efficiency of about 20% caused a reduction of the energy ratio to only 1:1. Substitution of municipal wastewater sludge for chemical fertilizer resulted in a 40% increase in the energy ratio. Finally, Dubuisson and Sintzoff (1998, cited in Simpson et al., 2009, p.6) reported on the overall energy efficiency of SRCs:

> Short-rotation willow biomass was estimated to have a 94% energy efficiency (i.e. 6% of the total energy stored per unit fuel was spent on cultivation and transportation when biomass was used to fuel a prototype generator at the plantation site). However, use at a distance of 30 km reduced the energy yield to 86%.

2.6 Economic Analysis: Expenditures and Revenues

In addition to the assessment of SRC engineering and technical issues, such as biomass production (section 2.3), soil and water quality (section 2.4), and energy content (section 2.5), the project economy is always a critical consideration. The analysis of the SRC project economy takes into account all of the potential expenditures and revenues during the full life-cycle of a SRC project. However, a complication in assessing the project economy is that the costs and revenues may occur every year, at the end of each harvesting cycle, or only once from the time of preparation until the end of the project.

As SRC economics is a component of the WISDOM model described in chapter 3, this section reviews the literature on potential expenditures as well as revenues for SRC plantations and how they are affected by changes in the SRC site area, harvesting methods, and transportation systems.

2.6.1 SRC Expenditures

Fiala and Bacenetti (2012) showed prominent elements in calculating SRC economic costs and addressed their optimum values to achieve the best SRC economics. According to their study, biomass yield, annual machine use requirements, and operations scheduling significantly affect the costs. Thus, the best economic results are obtained when harvest and transport (to the storage yard) occurred on an area larger than 400 ha, that included an efficient plantation design, a properly-sized transportation system, and operation without mechanical failures. Under such circumstances, the productivity of the harvest-transportation system can reach 65 T_{wb}/h (tonne wet-basis) for which the economic costs have corresponding minimum values of 15 €/T_{dm}.

Marron et al. (2012) described all potential expenditures in the entire life-cycle of an SRC plantation, from establishment to re-cultivation at the end of the life-cycle as an eight-part SRC value-chain, as shown in Figure 14, which covers all the critical steps for the production of SRC biomass. Note that over the lifetime of the plantation, process modules like harvest, transport, drying, and storage occur several times, depending upon the rotation period, while modules like field preparation, planting and maintenance take place only in the first year of the plantation. In addition to the costs of the individual process modules, Marron et al. (2012) included the yearly costs for rent and fixed- and indirect costs for the farm, such as insurance, energy and water costs, building maintenance, and so on. They also described a share of these module costs on the total yearly costs of SRC production with the standard process chain in Figure 15. In Canada, Kitchen (2012) addresses the expenditures for some of the module costs in Figure 18, including seedbed preparation, weed control, cuttings, planting, and tractor hire and management, for project sizes from 40 to 640 acres and for both willow and poplar. Depending on the project size, prices range from $1,500 to $3,000 per acre (see Figure 16).

As a reference for estimation of SRC process chains, a standard process chain (SPC) is provided by Marron et al. (2012) for poplar, planted on a field size of 2 ha with a 4-year-rotation and an average annual yield of 10 T_{dm}/ha. Presented in Figure 14, this SPC offers four possible modifications – input into the model as scenarios – and then breaks down costs for each scenario into the eight SPC categories:

- Modification of field sizes
- Modification of species (i.e. poplar or willow)
- Modification of harvest techniques
- Modification of transport systems and transport distances

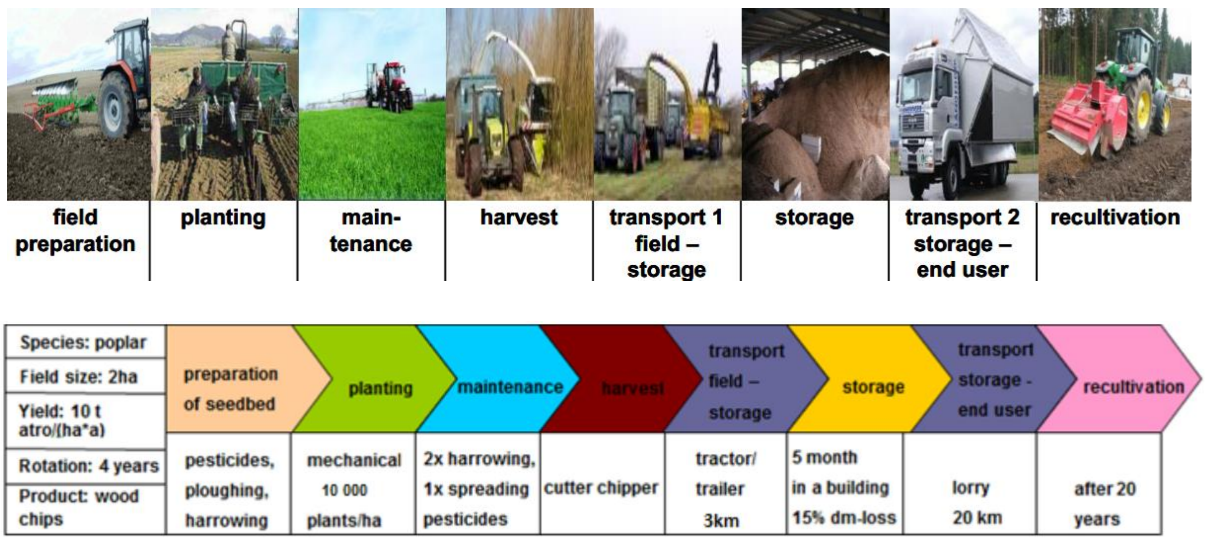


Figure 14. Standard process chain (SPC) of SRC – wood with individual process modules *(Marron et al., 2012, p. 92)*

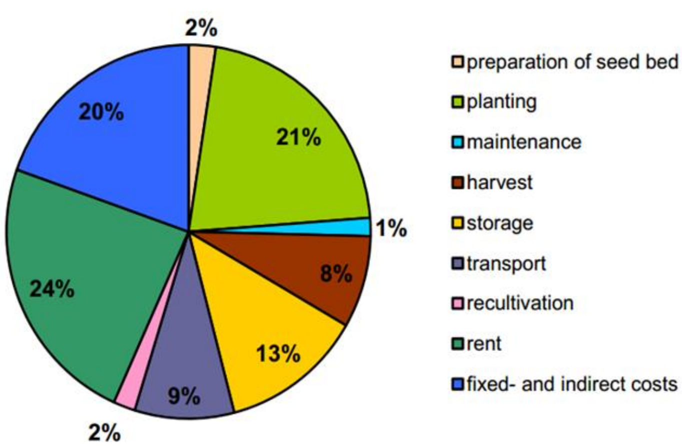


Figure 15. Share of costs for each module on the total yearly costs of SRC production with the SPC (Marron et al., 2012, p. 98)

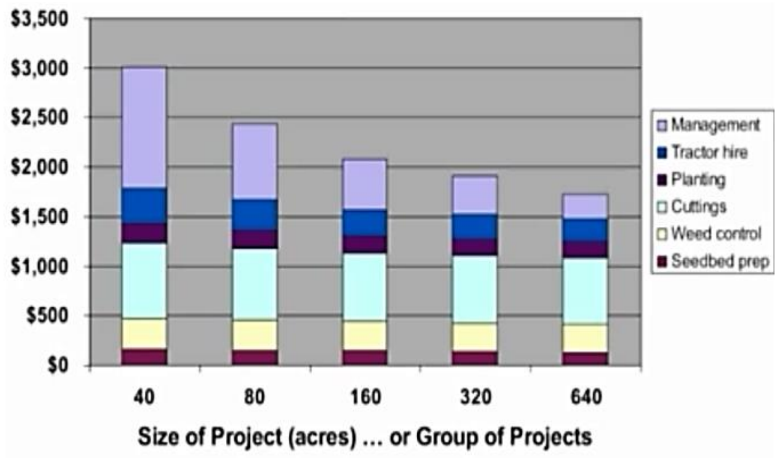


Figure 16. SRC crop establishment costs (Kitchen, 2012)

2.6.2 SRC Revenues

SRC plantations, in addition to their many environmental benefits described in section 2.4, bring revenue for project owners. These revenues come from two main different sources: (1) the sale of SRC biomass production, and (2) the potential sale of carbon credits from carbon mitigation and capture.

The primary revenue of a SRC project comes from the sale of SRC biomass products either as wood chips or as electricity generated from wood chip combustion. However, in analyzing SRC economics, most researchers consider only the first situation, using a farm gate biomass price that can vary significantly by region. For example, Allen et al. (2013) used a biomass price of C$85/oven-dried tonnes (ODT) (+/- $5/ODT) at farm gate, while Bunchholz and Volk's (2010) base-case analysis used US$60.

Other SRC project revenues can come from the benefits from carbon sequestration and offset calculations as stated in section 2.4.1. Usually these two options are considered alternative strategies (Baral & Guha, 2004), mostly due to different timings of CO2 emissions. However, when occurring at the same location, they can be combined under two conditions (Allen et al., 2013): (1) woody biomass is used solely for energy production, and (2) IPCC rules (IPCC, 2003) are used to track carbon emissions in harvested forest products to avoid double-counting. In Allen et al. (2013), a constant unit carbon price, which is \$10/tonne CO_2e, and different discount rates of 2%, 4%, and 8% were applied to the amount of carbon sequestered or emitted.

2.7 Useful Simulation Models and Components

As systems, SRCs involve numerous sub-systems or components – see section 2.2. The construction and simulation of the entire SRC system therefore requires a well-established systems modelling approach. The development of each SRC sub-model/component and of the entire model requires a significant investment in time, money (data purchase), and effort (data collection, component/model validation). To save time and effort, but still to obtain a sophisticated model, it is possible to construct a model based on existing, validated models for each SRC component, or "sector". The biggest challenge is connecting these models into a comprehensive and validated decision-support tool.

There are numerous available models that are used for qualification different aspects of SRC plantation; however, none of them – to the best of our knowledge – has been developed as a decision-support tool for use in planning viable, sustainable SRC systems (i.e. to simulate crop growth and inputs, and their interaction with yield and end uses). Nonetheless, these sectoral models will be very helpful in the development of the WISDOM model. The author, therefore, focuses here on the models that have been developed to quantify a specific sector of an SRC project – for example, SRC biomass production, harvest and transport, or project economics – or are constructed using the system dynamics method and have been used to quantify a relevant SRC issues, such as the soil-water balance and solute transport.

2.7.1 SRC Plant Growth and Yield

Because the SRC project economics depend on the sale of biomass, accurate prediction of biomass production is the most critical factor. Several models have been developed or adapted for use for SRC biomass production.

Evans et al. (2007a) presented a yield-prediction model for poplar and willow systems based on their empirical equations from a ten-year research program (1995-2005). Their model consists of four major components: 1) evapotranspiration (including light interception, photosynthesis, and assimilation), 2) soil water balance, 3) allocation and growth (including functional balance, heights, diameters, dry masses, and carbon storage) and 4) shoot numbers and management (including spacing, and rotation length). The key inputs are daily meteorology, physiological parameters of the species, soil characteristics, nutrient contents and plant initial conditions, while the key outputs include biomass (yield), number of shoots per stool and shoot diameter at 1 m height above ground.

Another model that successfully predicts SRC biomass production is 3-PG, a process-based forest growth model that represents the basic processes underlying the growth of forests in a relatively simple structure. 3-PG has been adapted and used successfully to predict short-rotation coppice biomass production in USA and Canada (Amichev et. al., 2010, 2011, 2012; Headlee et al., 2012; Nair et al., 2012).

2.7.2 Soil Water

Simulation of soil water is important as the soil-water content can significantly affect SRC growth and yield. In addition, solute transport in soil is dominated by the soil-water flux, such as infiltration and drainage. Soil water budgeting also permits estimation of the irrigation requirements. This section presents two soil-water models that applied the system dynamics approach. Both of the models, Luo et al. (2009) and Huang et al. (2011), are used to develop the soil-water sector of the WISDOM model described in chapter 3.

Luo et al. (2009) constructed a soil-water model that simulates time-varying water balance components, and that tests water management strategies using a system dynamics approach. Their model simulates actual evapotranspiration, deep percolation, surface runoff and capillary rise at a daily time-scale. However, although Luo et al.'s (2009) model represents the soil water depth quite well, the model omits differences in soil textures and structures, and considers the total soil depth as a single layer. Huang et al. (2011) were able to account for multilayered soils in a simulation of soil water movement, including transient infiltration and drainage processes using a system dynamics method. Their model combined both physically-based formulations and empirical assumptions to describe one-dimensional saturated-unsaturated water flow in the vadose zone.

2.7.3 Harvesting and Transporting

As stated in section 2.6, there are different component costs in the SRC value process chain. A German harvest planner tool, called "KUP-Ernteplaner" (SRC-Harvest-Planner) developed by FVA Freiburg under the CREFF program of the EU (CREFF, 2012), provides an excel-based tool for optimizing the harvesting and transporting costs and time requirements for individual harvests (Marron et al., 2012, p. 55).

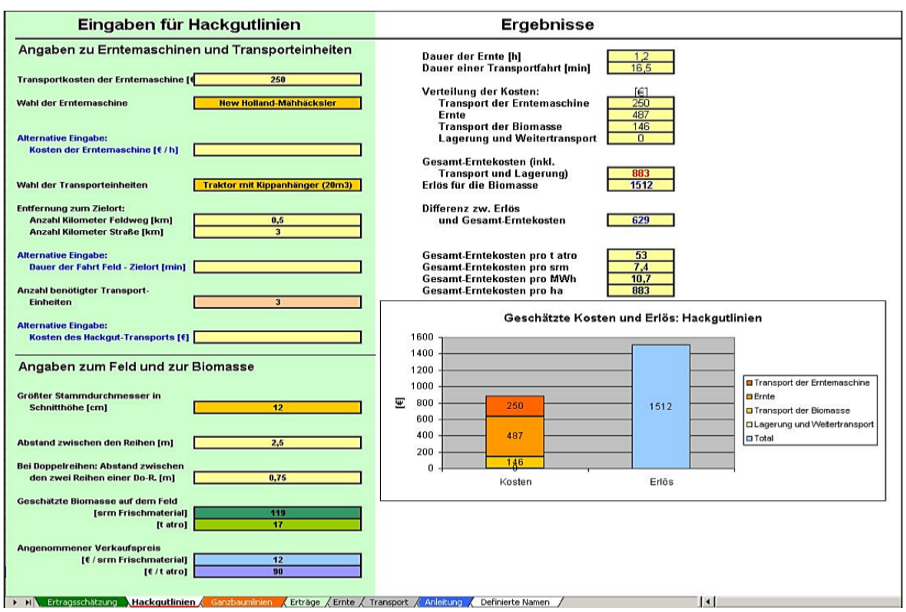


Figure 17. Screenshot of a part of the sheet Hackgutlinien (or "wood chip lines") of the KUP-Ernteplaner (Marron et al., 2012, p. 56)

According to Marron et al. (2012, p. 57) the KUP-Ernteplaner provides a detailed representation of the harvest and transport of SRC, which permits (1) the planning of harvesting operations on a specific field site based on realistic scenarios, (2) the identification of key parameters and their effects on the calculations, and of ways to reduce the expected costs, and (3) the investigation of the suitability of a field site for an SRC plantation. The KUP-Ernteplaner is used in combination with the Ecowillow model, described in the following section, to construct the harvest, transport and economics components of the WISDOM model, as described in chapter 3.

2.7.4 Economic Analysis

As explained above, project economics are critical to the success of SRC plantations, along with engineering and technical problems related to SRC growth and yield, the soil-water balance, and solute transport. Currently, there are only two models available for estimating the SRC project economy: the CREFF economic model, which is from the EU and still in testing (Marron et al., 2012), and the other from the US, called Ecowillow (Buchholz and Volk, 2010).

The CREFF economic model, an excel-based calculation model currently under development, as explained by Marron et al. (2012), permits estimation of different expenditures involved in the SRC value chain. Its aim is to provide an instrument to assess the effect of parameter variations – for example field size, planting technique, harvesting technique, and so on – on expenditures related to establishment, harvest, and transport costs, and so on. Furthermore, as costs were calculated as annual values (€ /ha/year), the tool also provides an easy way for farmers to compare SRC costs with those of common annual crops. However, the tool is still in testing and is not yet available for the economic analysis of SRC production in specific projects.

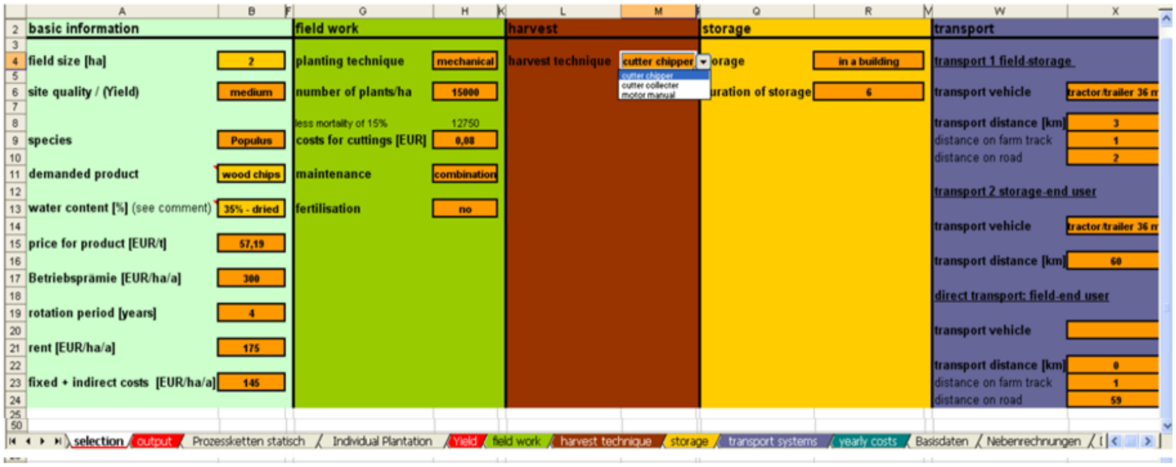


Figure 18. Input sheet of the CREFF economic model (Marron et al., 2012, p. 96)

Another tool that is helpful for analyzing SRC economy is "Ecowillow" (Buchholz & Volk, 2010), which is a budgeting model for farmers, land owners, agricultural extension workers, or project developers that determines how yield, management options, and a variety of cost factors influence the cash flow and internal rate of return of willow biomass crops. The model runs in Microsoft Excel (see Figure 19) and can be downloaded free-of-charge (Buchholz & Volk, 2010). It allows users to vary input variables and to estimate cash flow and profits throughout the entire production chain from site preparation and crop establishment to the delivery of wood chips to an end user.

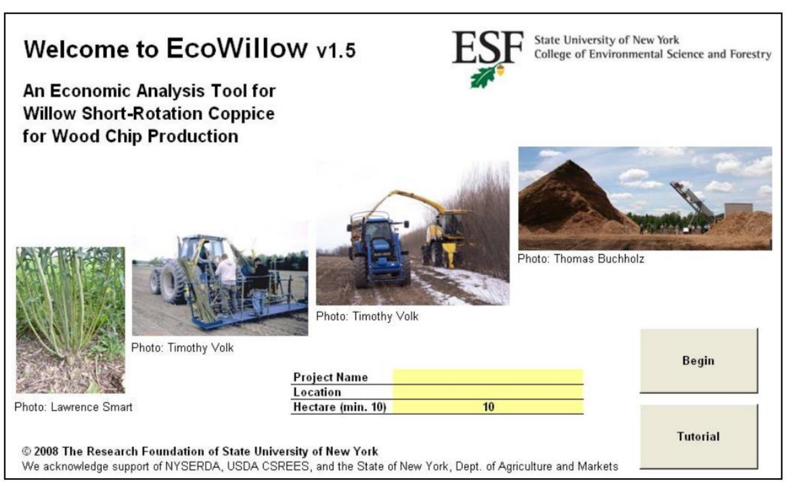


Figure 19. The user interface of the Ecowillow model

2.7.5 Irrigation supply and demand

As mentioned in section 2.1, irrigation of SRCs with treated municipal wastewater effluents offers producers various benefits. However, use of wastewater requires consideration of the balance between SRC evapotranspirative demands and the effluent produced by the municipality. One available tool developed by Hurdle (2012) for Natural Resources Canada solves the proposed problem above. Hurdle's (2012) wastewater treatment decision-support tool was designed as a user-friendly tool for estimating the number of acres of willow SRC required by a municipality to treat their effluents. The user enters a variety of parameter values, such as the number of people in the municipality, soil characteristics, and so on, and the program then estimates the plantation size, cost of planting, cost of capital, and the size of the storage lagoon – see Figure 20. In future, a similar model could be incorporated into WISDOM, as discussed in chapter 6.

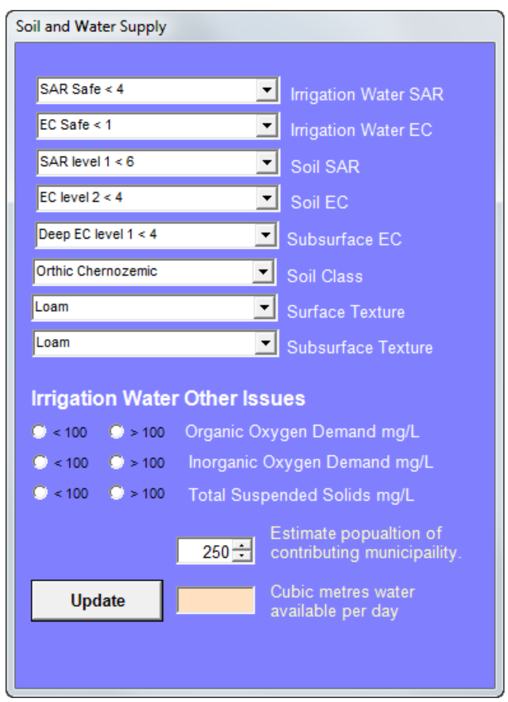


Figure 20. The user interface of the wastewater treatment decision support tool

2.8 Environmental Regulations

SRC irrigation with treated municipal wastewater effluents is subject to many environmental standards and regulations, depending on the region or country. In Alberta, any system connected to advanced waste systems – for example, water reuse for commercial applications, alternate infrastructure models, energy from waste, subsurface irrigation using treated wastewater, and so on – is subject to the "Environmental Protection and Enhancement Act" (EPEA) and Alberta Environment (AENV) laws and regulations (Krygier, 2012; Neurohr, 2012), and should consider the Canadian Council of Ministers of the Environment (CCME) guidelines. Several regulations for the protection of agriculture lands and crops, aquatic life, and public health from potential water pollution that are relevant to the application of municipal waste water and sludge to SRC plantations in Alberta include,

- AENV (1999): surface water quality guidelines for use in Alberta
- AENV (2000): guidelines for municipal wastewater irrigation in Alberta
- AENV (2001 (updated 2009)): guidelines for application of municipal wastewater sludge to agricultural land
- CCME (2012a): Water quality guidelines for the protection of agriculture
- CCME (2012b): Water quality guidelines for the protection of aquatic life

3 MODEL APPROACH and DESCRIPTION

The literature review of chapter 2 helps to identify key variables, components, and their linkages in SRC systems which are the basis of SRC system maps – the causal loop diagrams, stock and flow diagrams, and simulation models that are key components of the system dynamics approach, a widely-used method for representing and modelling complex systems.

This chapter describes the system dynamics methodology and explains its application to SRC systems. It begins with the development of a set of causal loop diagrams (CLDs), which are qualitative tools that identify key variables and components, as well as connections and feedbacks between them, based on the literature review of chapter 2. These causal loop diagrams are then used to develop stock and flow diagrams (SFDs) and a decision-support tool, the WISDOM model, for planning viable, sustainable SRC systems. Descriptions of different components or sub-models of the decision-support tool, their capabilities, and connections between them are also presented. These sub-models include 1) plant growth and yield, 2) soil water balance, 3) solute transport, 4) SRC harvest and transport, 5) energy content, 6) carbon mitigation, and 7) economic assessment.

Finally, the validation and application of the WISDOM model to SRC plantation management at the Whitecourt, Alberta, trial site is provided in Chapters 4 and 5.

3.1 Methodology – System Dynamics

This section describes the application of the ‘‘system dynamics” methodology to the construction of a systems model for Short-Rotation Coppice (SRC) systems. The section begins with the construction of system maps, called “causal loop diagrams” (CLDs), from which stock and flow diagrams (SFD) and the WISDOM model, a decision-support tool, are developed.

3.1.1 System Dynamics and Decision Support

System dynamics (Forrester, 1961, 1969) is 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, such as economics, engineering, education, management, ecology, public health, and sociology (Forrester, 2007a, 2007b; Sterman, 2000). System dynamics is a rigorous method of system description that facilitates feedback analysis of the effects of alternative system structure and control policies on system behavior, usually via a simulation model (Simonovic & Davies, 2007).

In essence, the role of system structure – stock and flow dynamics, material and informational delays, and nonlinear feedbacks – is the focus of system dynamics in representing and replicating system behavior (Winz et al., 2009; Simonovic and Fahmy, 1999). Using "causal-descriptive" mathematical models, system dynamics can be used to reproduce and then forecast real-world behaviors, and importantly, assist with assessment of 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 "facilitate recognition of interactions among disparate but interconnected subsystems" that govern the larger system's dynamics behavior, and to capture and comprehend their root causes (Mirchi et al., 2012, p. 2423).

System dynamics models can incorporate both empirical and mechanistic approaches and produce comprehensive simulation models quickly and easily (Prodanovic & Simonovic, 2009); further, the mathematics, despite nonlinearities, delays, and potential simultaneous equations, is represented relatively simply with first-order ordinary differential equations (Davies & Simonovic, 2011).

System dynamics methods rely on two main tools: causal loop diagrams (CLD), and stock and flow diagrams (SFD) – the latter forms the basis of simulation models. CLDs present cause and effect relationships and feedback linkages, and are intended to improve understanding of system connections and complexity. CLDs represent a sort of "mental map" of a system. SFDs and simulation models are quantitative tools, and they are often used for decision support (Sterman, 2000), or for answering ''what if?'' questions (Davies & Simonovic, 2011).

3.1.2 Causal Loop Diagrams (CLDs)

A causal loop diagram (CLD) shows the connections between the state variables in a system and how a change in one variable affects the others – in other words, how a change is transferred from one variable to others in the system.

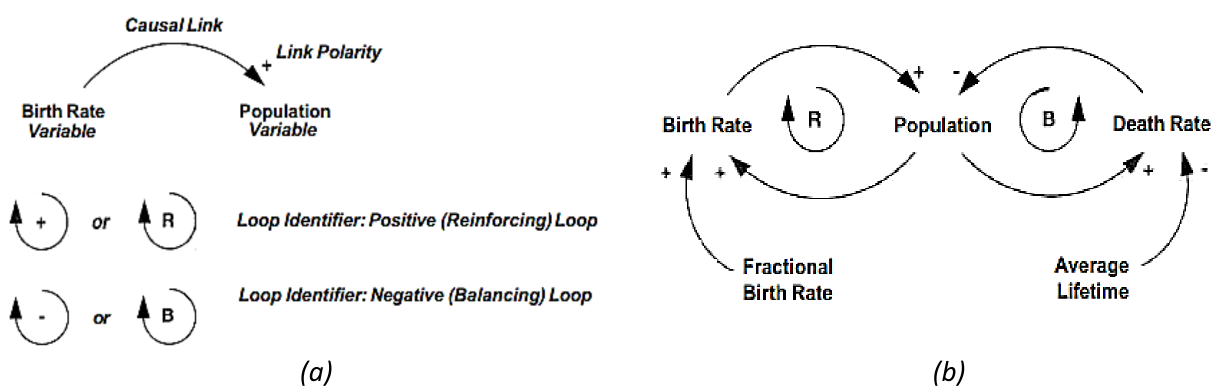


Figure 21. Causal loop diagram notation: a) Key factors in a causal loop diagram, and b) reinforcing and balancing feedback loop examples (Sterman, 2000)

In a CLD, there are only two possible causal connections: positive and negative. An arrow with a plus sign between two variables means that the variable at the starting point of the arrow causes a change in the value of the second variable at the ending point, with an increase/decrease in the first variable causing an increase/decrease in the value of the second variable (i.e., positive causality or reinforcing behavior). If an arrow has a minus sign, the influence is the opposite, with an increase/decrease in the first variable causing a decrease/increase in the second variable – see Figure 21. Furthermore, an arrow sometimes has two short, bisecting lines which denote a delay (Sterman, 2000).

Connections between two variables can be expanded into networks of connections, with some of the causal linkages forming loops, as shown in Figure 21b. Such loops, called “feedbacks”, mean that the variables in the loop affect each other, with a change in one variable of the loop ultimately affecting its own value at some time in the future. As an example, an increase in the population variable in Figure 21b causes an increase in the birth rate, since more people have more babies, and an increased birth rate leads to a higher population. This higher population then further increases the birth rate, thus increasing the population beyond its original value. Such a process leads to exponential growth, and is termed a positive feedback. These feedback loops, positive and negative, are the focus of a causal loop diagram. Note that there are normally combinations between the basic feedback loops (including positive, or reinforcing, and negative, or balancing, feedback) to form other behaviors (that are S-shaped growth, S-shaped growth with overshoot, and overshoot and collapse) (Sterman, 2000); however, such behaviors are typically seen in numerical simulation models rather than in causal loop diagrams.

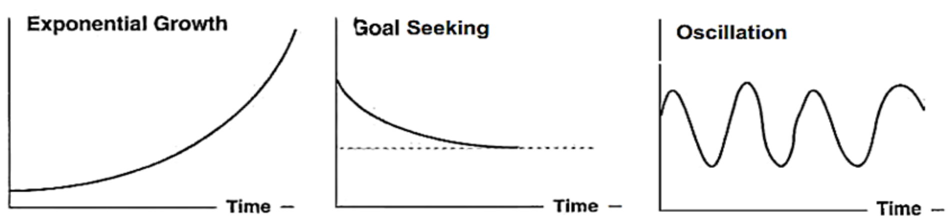


Figure 22. Basic feedback processes of dynamic behaviour

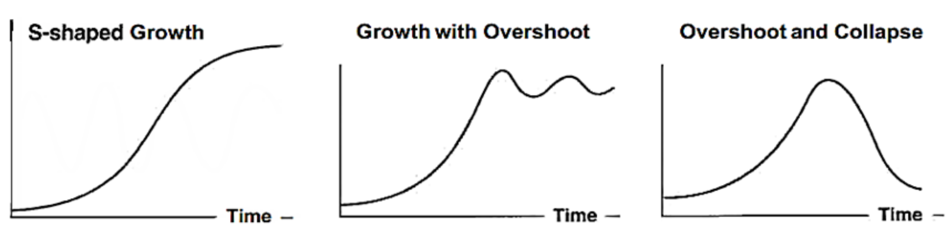


Figure 23. Combination of basic feedback processes (Sterman, 2000)

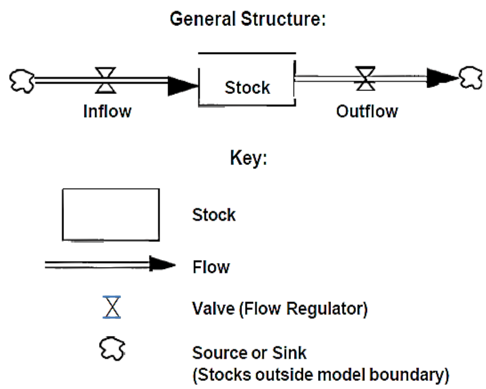
The prime purpose of constructing a CLD for a dynamic system is to identify the existing feedbacks, and how they may work over time to create dynamic behavior.

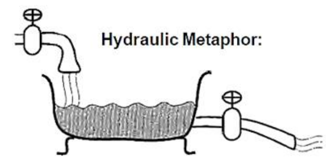
3.1.3 Stock and Flow Diagrams (SFD) and the Simulation Model

A stock and flow diagram shows relationships between stocks, flows, internal dynamics, and characteristics of the external environment, beyond the "boundaries of the problem". It can be used for a wide range of audiences and makes it easier to relate a causal diagram to the dynamics of the system. More specifically, explicit representation of stock and flow dynamics is what separates CLDs and SFDs. In an SFD, "Stocks accumulate their inflows less their outflows. Stocks are the states of the system upon which decisions and actions are based, are the source of inertia and memory in systems, create delays, and generate disequilibrium dynamics by decoupling rates of flow" (Sterman, 2000, p.229). Flows are the only means of change to stock values.

Figure 24a shows the graphical notation used for SFDs. Stocks are represented as "boxes", or rectangles, while inflows are represented by a pipe (arrow) pointing into, and thus adding to, the stock, and outflows are represented by pipes pointing out of, or subtracting from, the stock. These flows are controlled by valves. Clouds represent the sources and sinks for the flows. A source represents the stock from which a flow originating outside the boundary of the model arises, while a sink represents the stock into which flows leaving the model boundary drain. Sources and sinks are assumed to have infinite capacity and can never constrain the flows they support.

The rate of change of a stock is the total inflow less the total outflow over a fixed period of time. Thus a stock and flow map corresponds precisely to a system of integral or differential equations. The mathematical representation of SFD is presented in Figure 24b: stocks accumulate or integrate their flows, and the net flow into a stock determines the rate of change of the stock. In general, flows are functions of the stock and other state variables and parameters (Sterman, 2000).





- Integral equation:

$$Stock(t) = \int_{to}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_o)$$

$$Stock = INTEGRAL(Inflow - Outlow, Stock_{to})$$

- Differential equation

$$d(Stock)/dt = Net\,Change\,in\,Stock = Inflow(t) - Outflow(t)$$

(a) (b)

Figure 24. a) Stock & flow diagramming notation and b) mathematical representations (Sterman, 2000)

Stock and flow diagrams form the basis of a system dynamics simulation model, with mathematical equations that determine connections between system variables, and the effects of a change in one variable on others linked to it, forming a "secondary layer" of the model that is typically hidden from model users. The resulting combination of diagrams and mathematical equations can then be used to simulate the effect of proposed actions on the system as a whole. Simulation – and the resulting "surprises" in model behavior as parameters are changed from one scenario to the next – helps to clarify the problem and makes modellers' assumptions about the way the system works explicit (Stave 2003).

3.1.4 System Dynamics as a Framework for SRC System Simulation

As explained above, system dynamics has been applied successfully in a variety of real-world situations – to problems in engineering, the environment, policy analysis, economics, biology, sociology, and medicine at local to global scales (Forrester, 2007a, 2007b; Sterman, 2000). In particular, its ability to capture and identify effects of feedback loops between system components provides "insights into potential consequences of system disturbances, thereby serving as a suitable platform for sustainable planning and management at the strategic level" of any system (Mirchi et al., 2012, p.2423).

SRCs irrigated with treated effluents and fertilized with biosolids form a complex system that involves interactions between climate, wastewater and biosolids characteristics, soil chemistry and physical characteristics, woody crop establishment, growth and crop fibre characteristics, and fibre suitability for biofuel production, environmental regulations, and economics. In practice, such complexity means that crop establishment, performance, environmental impact, response to environmental factors, and end use is variable. System dynamics offers the ability to identify and understand interactions, linkages and feedbacks between various system components to help decision makers to plan appropriately and optimize end uses and investments (Nguyen et al., 2013).

Although no specific systems model previously existed for SRC systems – to the best of our knowledge – problems relevant to SRC plantations have been modelled successfully in the past through system dynamics. For example, Wallman et al. (2005) proposed a series of CLDs to illustrate linkages and feedbacks amongst soil, water and trees in a forest system in terms of the soil water balance, water and nutrient uptake, photosynthesis, and cation and anion exchanges. Luo et al. (2009) constructed a single layer soil-water model used for simulating time-varying water storage on a daily time step and for testing different water management strategies based on the system dynamics approach. Khan et al. (2009) applied system dynamics to simulation of surface-ground water dynamic interactions in an irrigation area where river water and groundwater are two key sources for irrgation. Huang et al. (2011) simulated one-dimensional saturated-unsaturated water flow based on system dynamics in the multi-layer vadose zone by combining both physically-based formulations and empirical assumptions. Saysel and Barlas (2001) proposed a dynamic model of salinization of irrigated lands as part of a large-scale socio-economic model of irrigation-based regional development. Schoumans and Groenendijk (2000) conducted research on the phosphorus cycle in soil, sediment, and wetlands in detail using a system dynamics model.

3.2 System map for SRC: Causal Loop Diagram

As mentioned in section 3.1, system dynamics produces qualitative models, called "causal loop diagrams", of the causal linkages, or feedbacks, that are responsible for the behaviour of complex systems. These models may help to 1) identify and clarify the relationships between disparate components of a complex system, and 2) direct investments and research efforts.

In order to construct a causal loop diagram (CLD) for an SRC system, a broad-based literature review on many different aspects of SRC systems (i.e. chapter 2) was conducted to identify the key variables and their linkages and feedbacks, as shown in Figure 25. Based on the identification of the key inputs and their feedbacks, a series of CLDs is proposed, including a high-level CLD (see Figure 26) and seven sub-CLDs or sectoral CLDs, which together portray a comprehensive picture of SRC plantations.

Figure 26 shows a high-level CLD as a holistic representation of the entire SRC system. The CLD accounts for the various components of the SRC and the dynamic links amongst them, namely: SRC growth, treated waste water, irrigation, environmental concerns (including soil quality, water quality, GHG emissions and biodiversity), land-use (for both SRC and agriculture), bioenergy, producers/farmers, the local economy, environmental regulations and government policies.

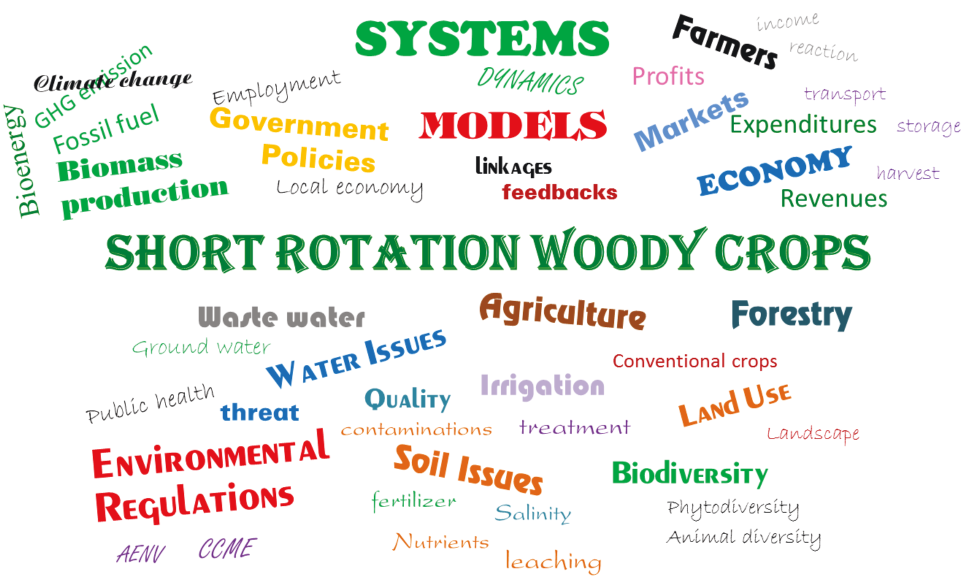


Figure 25. Different aspects of SRC system from literature

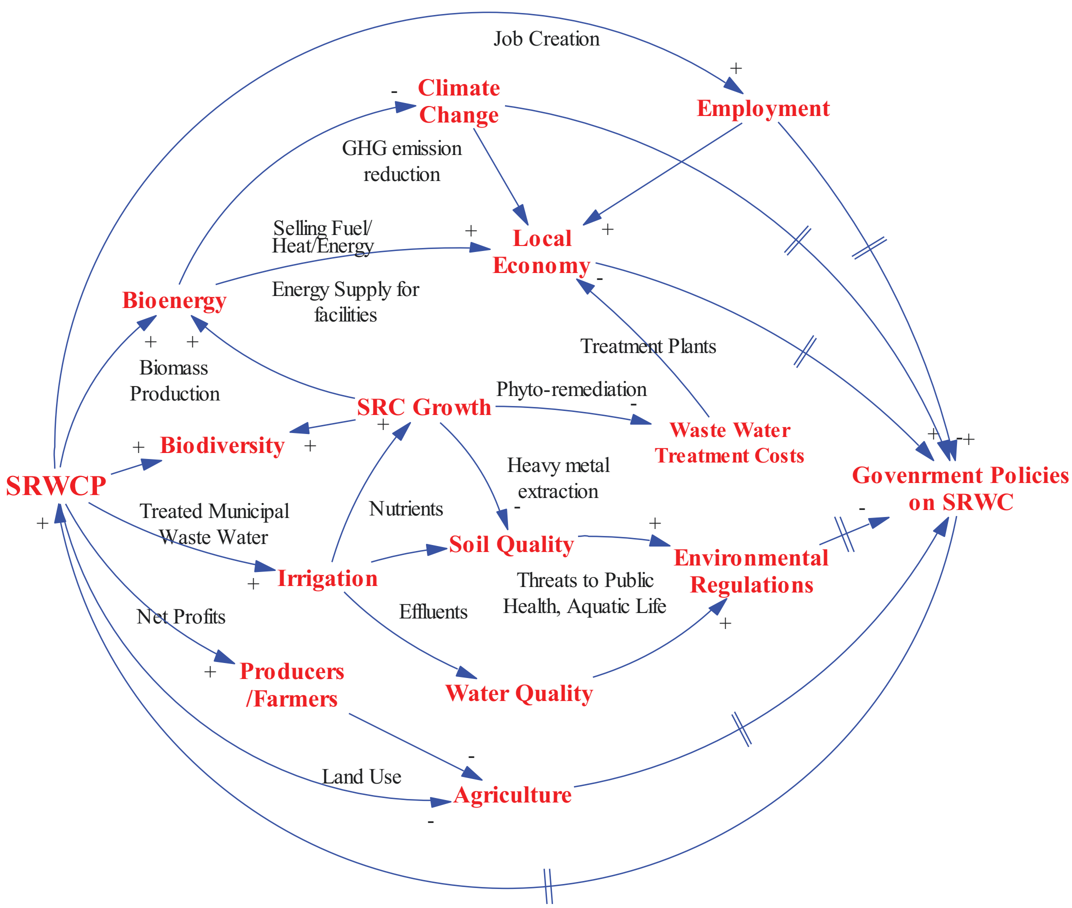


Figure 26. General CLDs for Short-Rotation Coppice Plantation (Nguyen et al., 2013)

Because of the necessary simplifications at this large scale, numerous linkages are omitted; therefore, the general CLD of Figure 29 was broken down into seven sub-systems (or seven sectors) in order to identify and clarify the many dynamic links between variables in each sector, and between variables in a given sector with those of other sectors. The sectoral CLDs include,

1. **Biomass production**: *SRC Growth-Soil-Water*
2. **Irrigation supply**: *SRC Growth-Wastewater Treatment-Irrigation Supply*
3. **Environmental quality**: *SRC Growth-Irrigation Water Quality-Soil Quality-Water Quality*
4. **Bioenergy**: *SRC Growth-Bioenergy-Climate Change*
5. **Land use**: *SRC Growth-Producers-Land Use-Biodiversity*
6. **Production cost**: *SRC Growth-Production Costs and Profits*
7. **SRC policy**: *SRC Growth-Local Economy-Government Policy*

As the thesis focuses more on simulation modelling, with model description and simulation results provided in the following sections, the details of the sectoral CLDs are not discussed here but can be found in appendix A.

3.3 Description of the Simulation Model

3.3.1 Model Components and Capabilities

As demonstrated in the CLD section above, SRCs are complex systems that involve many linkages and feedbacks both among different elements within a single component (plant biomass, soil-water balance, solute transport, and so on), and between different sectors within a whole system. Model construction is therefore a selective process: starting from core components and expanding to other relevant components, building from low-level (less complex) models and refining them into high-level (elaborate) models. The key purpose is to "develop a model to solve a particular problem, not to model the system"

(Sterman, 2000, p.79). Based on this premise, of particular interest in the SRC system is plant growth and yield (PGY) (i.e. biomass production), as well as two other relevant components, soil water (i.e. irrigation) and solute transport and their feedbacks to the PGY. The other four components of interest, which are constructed based on the PGY sub-model, include SRC harvest and transport, economic analysis, energy content and carbon mitigation (see Figure 27).

The heart of the plant growth and yield (PGY) component is the 3-PG growth engine developed as a simplification of a well-known forest model, 3-PG from CSIRO, Australia (see section 3.3.2). The PGY calculations are dominated by climatic factors through the effects of solar radiation and air temperature stress, which are among the model inputs (see Figure 27).

The soil water component is constructed based on the soil-water balance approach (Hillel, 2004; see section 3.3.3). The irrigation component in the model offers two approaches: calculated irrigation requirements based on crop demands and the required leaching fraction, or user-determined irrigation (to match, for example, historical irrigation practices and records). Soil-water storage influences the PGY component through water stress but is also affected, in turn, by PGY through evapotranspiration.

Because SRCs are irrigated with treated municipal wastewater, which contains many chemical and biological constituents, solute transport and its effects on soil, ground and surface water quality are also among the concerns with SRC systems. The solute transport component is built in a generalized fashion so that it can be used to simulate a variety of both conservative solute concentrations – soil electrical conductivity (EC)/total dissolved solids (TDS)/Chloride – and non-conservative solute concentration – soil nitrate-nitrogen (NO_3-N)/phosphate (PO_4^{3-})/available P – in the soil root-zone layer and other soil layers under the root-zone (see section 3.3.4). Solute transport is coupled with the soil-water component, because the solute concentration in irrigation and drainage water will dominate the solute concentration in soil. In addition, it is also necessary to account for the amount of solute uptake by the plants. All of these factors will determine the nutrient content of the soil, which can create nutrient stress in the PGY sector when the nutrient concentrations are lower than required for plant growth (see Figure 27).

The other four remaining sub-models in the WISDOM model, which rely on the amount of biomass production produced from the PGY component, include harvest and transport, economic analysis, energy content and carbon mitigation. Because it amounts to about 30% the total expenditure (see section 2.6), the harvest and transport of SRC draws the attention of stakeholders and decision makers. In the WISDOM model, this component is built based on the well-known German harvest-planner tool – "KUP-Ernteplaner" – developed by FVA Freiburg (see section 2.7.3). The outputs from the harvest and transport component, such as cost of harvest and transport, then become the input for another bigger component, the "economic assessment", which simulates and analyzes the project economy. This economic budget sub-model is adapted and modified based on the "Ecowillow" program described in section 2.7.4. The "energy content" component estimates the lower heating value (LHV) or the net calorific value (NCV) of the amount of biomass production based on the wood moisture content and the efficiency of boilers. This net calorific value generated can then be used as a substitute for the energy produced from fossil fuel sources, with the amount of carbon emissions reduced by this substitution as well as the amount of carbon captured and sequestered during the growth of the SRC estimated by the "carbon mitigation" component.

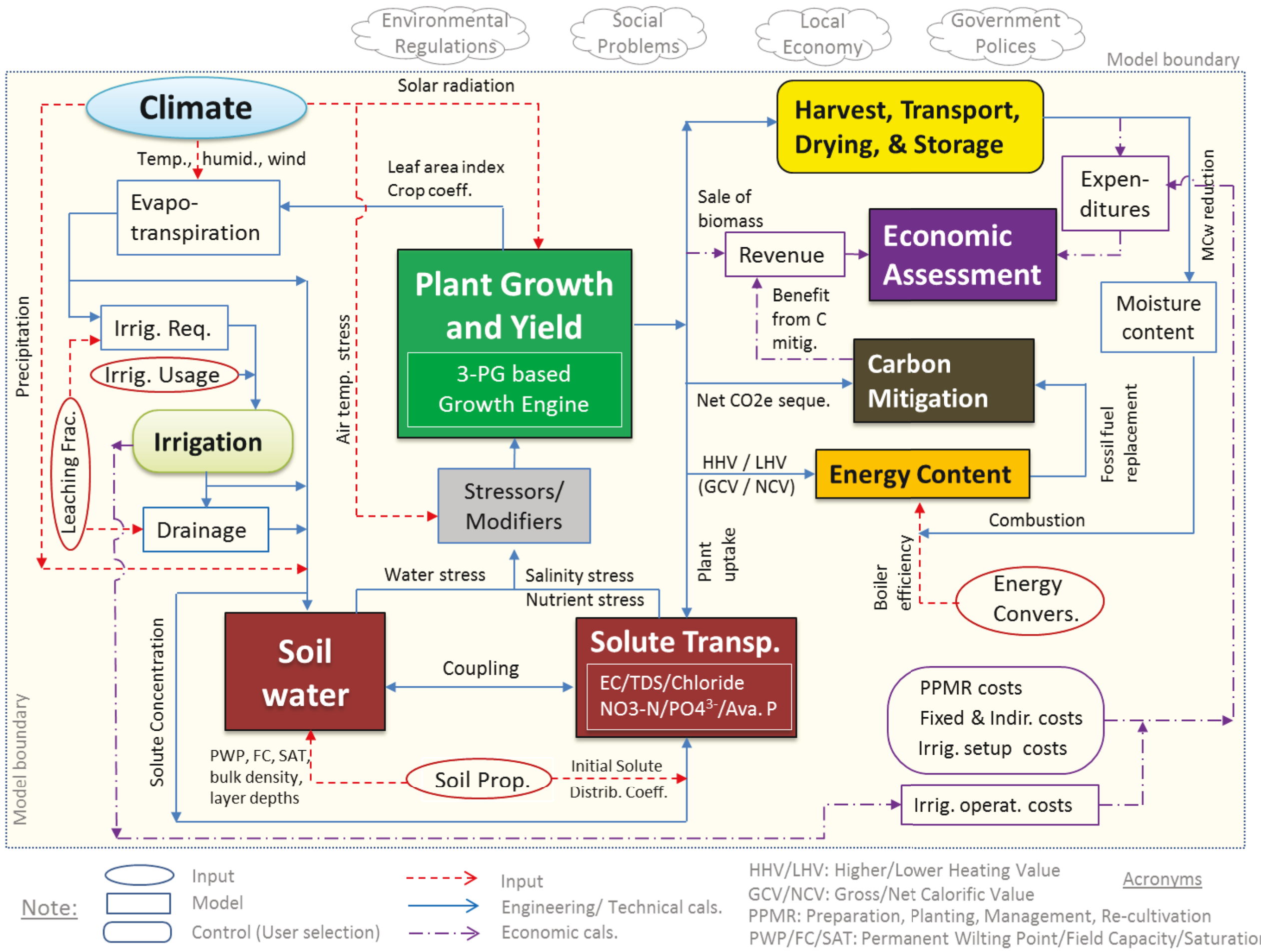


Figure 27. The model components and model boundary

In terms of model capabilities, the WISDOM model can be used to simulate biomass production in terms of shoots, leaves, and root biomass, and the amount of oven-dry woodchips produced. It can also simulate the soil-water balance and the irrigation requirements based on different inputs of the required leaching fractions. If the irrigation amount is known or is user-specified, it is treated as a model input. Additionally, as mentioned above, the model can be applied to determine solute transport for different conservative solutes (EC/TDS/chloride) and non-conservative solutes (NO_3-N, PO_4^{3-}, and available P) in soil. Furthermore, equipped with the “harvest-transport” and “economic assessment” sub-models, the WISDOM model can be used to aid the 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 estimated in the “energy content” and “carbon mitigation” sub-models.

In the long term, depending upon user demands and the level of available data, the entire simulation model could eventually account for all the components currently outside the model boundary but that are described in the general CLD – Figure 26: environmental regulations, social effects, the local economy, and government policies (see Figure 27).

The model is developed using Vensim, a system dynamics software package produced by Ventana Systems (VensimSoftware, 2014). Depending upon the simulation time step, the input interval, and the total simulation length, each simulation may take a couple of seconds to minutes to complete – overall, very quick performance.

Figure 28. Decision supporting tools in the current model (VensimSoftware, 2014)

In addition, the current model provides many powerful tools integrated into the Vensim environment to support users and decision makers – see Figure 28 (VensimManual, 2014). For example, the “SyntheSim” mode allows users to compare effects of different proposed actions on a variety of model variables, by moving “sliders” and “switches”, without the need to set up and run individual simulations, and the integrated “Monte-Carlo” tool helps users to understand and quantify the sensitivity of different variables within the system. Finally, the integrated “Optimize” tool helps users to save time and effort in model calibration by providing the best agreement between observed (input) and model predicted values based on different model variable adjustments (or “payoffs”).

3.3.2 Plant Growth and Yield (PGY)

As stated in section 3.3.1, the PGY model is the core component of the current systems model, while other components are based on the PGY results. It is therefore necessary first to obtain a good model to simulate SRC growth and yield. A variety of such models exists. For example, Nair et al. (2012) recently conducted a literature review of 14 models that have been used for simulating bioenergy crops. Among them, only two models (i.e. SECRETs and 3PG) have been used for simulating woody perennial bioenergy crops.

The SECRETs model (Stand to Ecosystem CaRbon and EvapoTranspiration simulator) is a modular, process-based model developed originally to simulate growth and development of mixed-species forest Sampson and Ceulemans (2000, p. 146). SECRETs has recently been used to simulate biomass production from aspen and poplar (Deckmyn et al.,2004; Lasch et al., 2010). The 3PG (Physiological Processes Predicting Growth) model is a process-based forest growth model that represents the basic processes that underlie the growth of forests in a relatively simple structure, and has been used successfully to predict short-rotation coppice biomass production (Amichev et al., 2010, 2011, 2012; Headlee et al., 2012; Nair et al., 2012).

Landsberg and Sands (2011, ch8) recommend using process-based models (PBM) rather than empirical models, since PBMs are written in terms of the mechanisms that govern tree growth and respond to environmental variables, and therefore permit understanding of the consequences of a range of conditions outside those for which empirical data and experience are available. Once confidence in the performance of the model in observed situations is gained, the model can then be used to extrapolate to other conditions. PBMs thus “contribute to improved knowledge and understanding of how trees grow, taking it for granted that such improved understanding must lead, sooner or later, to an improved ability to predict responses to conditions we have not observed” (Landsberg & Sands, 2011, p.237).

Figure 29 shows a general CLD for the 3-PG model developed based on Landsberg and Sands (2011). While the model has relatively few parameters and is simple to use, it is capable of producing accurate results across a number of tree species, and requires minimal input data (Landsberg & Sands, 2011). Further, 3-PG uses a set of allometric constraints – the soil water content, site fertility rating, tree diameter at breast height, tree age, vapour pressure deficit – to ensure that biomass allocation among key plant components (roots, stems, and leaves) reproduces typical patterns observed in a stand of trees; therefore, although it is a process-based model, it is sometimes referred to as a hybrid model (Landsberg & Sand, 2011). Finally, the model code is freely available (CSIRO, 2011).

3-PG estimates the radiant energy absorbed by a forest canopy and converts it into biomass. The efficiency of radiation conversion is modified by the effects of different stressors or modifiers through the growth modifier variable; such stressors and modifiers include water, soil nutrients, salinity, air temperature, drought, atmospheric vapour pressure deficits and stand age. The carbon captured by the canopy, or the total net primary productivity (NPP), is then allocated to leaves, stems and roots, using dynamic equations that update the system state on a monthly time-step.

There are two major simplifications and one major adaption of the original 3-PG (Landsberg & Sands, 2011) required for the PGY model,

1. Simplification of the basic stand-level sub-model,
2. Simplification of the growth modifiers for site and environmental effects, and,
3. Modification of plant functional types in 3-PG.

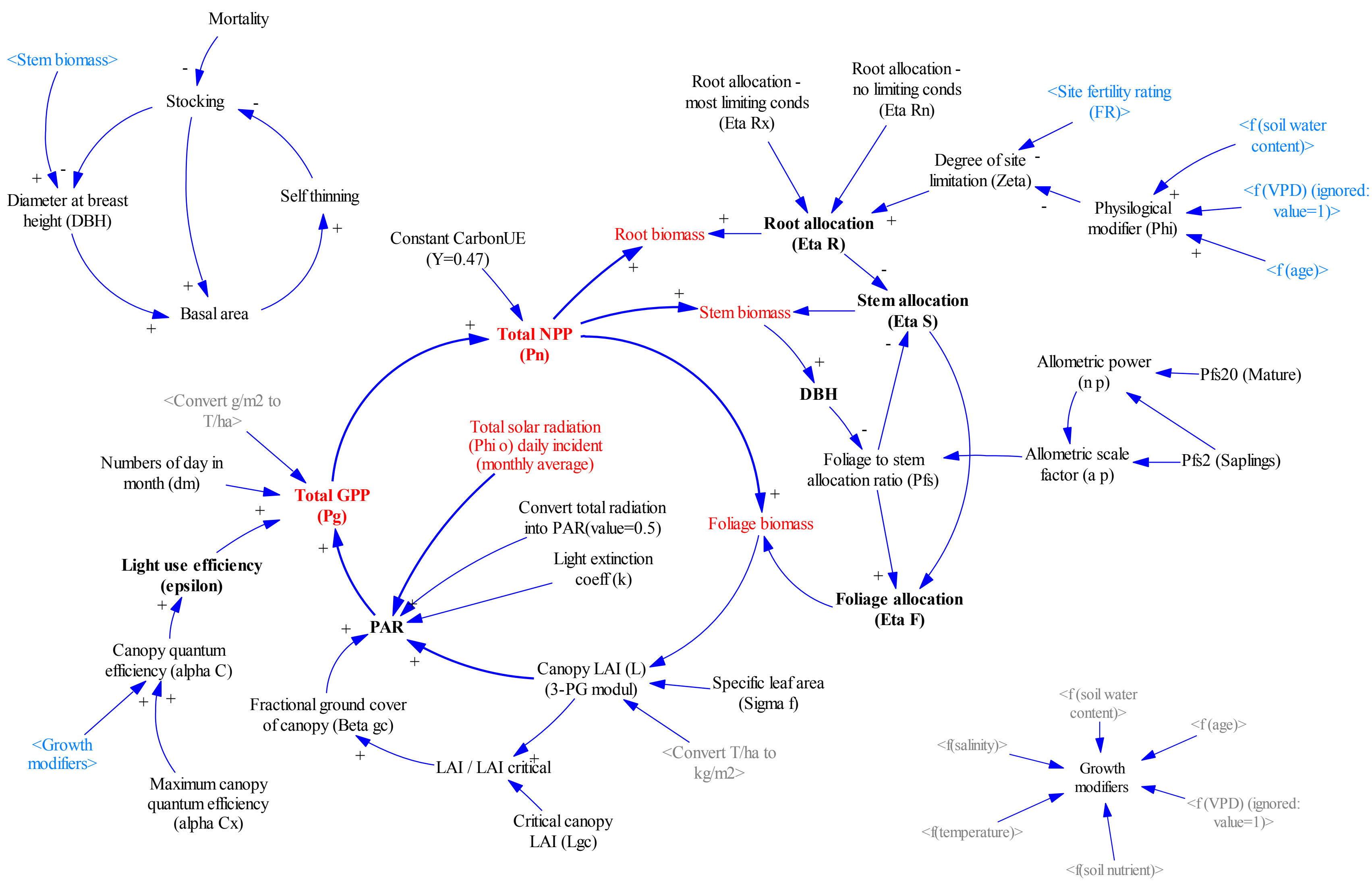


Figure 29. General CLD of the 3-PG model (based on Landsberg and Sands, 2011)

3.3.2.1 *Simplification of the basic stand-level sub-model*

In the original version of 3-PG (Landsberg & Sands, 2011), the stand-level sub-model contains three parts (see Table 3): (1) the allocation of net primary production, $\eta_i.P_n$, (2) the biomass lost and turnover from each biomass pool, $\gamma_i.W_i$, and (3) biomass lost due to stem mortality, $m_i.\gamma_N.W_i$. To reduce the complexity from the original 3-PG in the system dynamics version, the model does not incorporate loss and turnover of biomass, $\gamma_i.W_i$, or stem mortality, $m_i.\gamma_N.W_i$, but only considers the allocation of net primary production $\eta_i.P_n$ (see Table 3). However, this simplification does not decrease the model accuracy. In fact, lumping these components together reduces model complexity, but it still achieves the necessary accuracy despite its prediction of fewer stems than in reality. This is because willow or poplar stems only last three or four years in SRC systems, while 3-PG is developed to simulate forest growth over much longer periods.

Table 3. Simplification of the basic stand-level sub-model

Original 3-PG model	Simplified model	Assumption
$\frac{dW_F}{dt} = \eta_F P_n - \gamma_F W_F - m_F \gamma_N W_F$ $\frac{dW_s}{dt} = \eta_s P_n - \gamma_s W_s - m_s \gamma_N W_s$ $\frac{dW_R}{dt} = \eta_R P_n - \gamma_R W_R - m_R \gamma_N W_R$	$\frac{dW_F}{dt} = \eta_F P_n$ $\frac{dW_s}{dt} = \eta_s P_n$ $\frac{dW_R}{dt} = \eta_R P_n$	No loss and turn over $\gamma_i(\gamma_F, \gamma_S, \gamma_R) = 0$
$\frac{dNs}{dt} = -\gamma_N N_s$	$\frac{dN_s}{dt} = 0 \;\; or \;\; N_s = const.$	No stem mortality $\gamma_N = 0$

Where t is time in months, P_n is net primary production at the stand-level (t/ha/month), W_i (W_F, W_S, W_R) are the biomass pools for foliage/stem/roots (T/ha), η_i (η_F, η_S, η_R) are the biomass allocation ratios for each biomass pool (month^{-1}), γ_i (γ_F, γ_S, γ_R) are loss and turnover rates for each biomass pool (month^{-1}), γ_N is the stem mortality rate (month^{-1}), N_S is the stem number of the stand (tree/ha), and m_i are fractions and default values for the m_i are m_i=0.5. Parameter details can be found in appendix B.

3.3.2.2 *Simplification of the growth modifiers for site and environmental effects*

A series of growth modifiers is used in 3-PG to take into account the effects of site and environmental factors on stand-level gross primary productivity (GPP) (Landsberg & Sands, 2011) . However, the system dynamics model neglects the effect of frost days, atmospheric CO2 concentration, and vapor pressure deficit to reduce model complexity, but focuses on the dynamics of more active stressors, such as soil water, soil nutrient, salinity and air temperature instead.

Table 4. Simplification of the growth modifiers for site and environmental effects

Original	Simplified	Assumption
$\alpha_C = f_T.f_F.f_{FR}.f_S.f_{C\alpha}.\varphi.\alpha_{Cx}$	$\alpha_C = f_T.f_{FR}.f_S.\varphi.\alpha_{Cx}$	$f_F = 1,\ f_{C\alpha} = 1$
$\varphi = f_{age}.\min\{f_D, f_\theta\}$	$\varphi = f_{age}.f_\theta$	$f_D = 1$

Where α_{Cx} is the canopy quantum efficiency when no factors are limiting growth (mol mol^{-1}) and atmospheric CO_2 is 350 ppm, f_T is a function of the monthly-average daily temperature (dmnl), f_F is a function of the number of days d_f of frost per month (dmnl), f_{FR} is a function of the site fertility rating F_R (dmnl), f_S is a function of the salinity of a site as measured by the soil electrical conductivity C_S (dmnl), $f_{C\alpha}$ is a function of the atmospheric CO_2 concentration C_α (dmnl), φ is physiological modifier (dmnl), f_{age} is a function of stand age (dmnl), f_D is a function of daytime average vapour pressure deficit D (dmnl), and f_θ is a function of the relative plant-available soil water content θ_r in the rootzone, which is the ratio of the current plant-available soil water to the maximum plant-available soil water for the soil type (dmnl). Parameter details can be found in appendix B.

3.3.2.3 *Modification of the plant functional type for the WISDOM model*

As described in chapter 8 of Landsberg and Sands (2011) and can be seen from the stand level sub-model, the original 3-PG is used for simulating evergreen trees. The model therefore simulates leaf biomass as accumulating over time, and the specific leaf area (SLA) used in the model tends to be underestimated when using the model to simulate deciduous trees. For example, Amichev et al.

(2010) applied 3-PG model to predict poplar biomass production with a specific leaf area value of 10.8 m^2/kg obtained from Gielen et al.'s (2001) research. However, research on poplar specific leaf areas from Pellis (2004) and Afas et al. (2005), which come from the same country as Gielen et al.'s (2001) study, indicate a range of 13-20 m^2/kg.

To develop the WISDOM model, the plant functional type (PFT) in 3-PG was modified and improved to simulate both evergreen and deciduous trees. For this purpose, the principle of virtual leaf biomass (see curve B and its relationship with curves A and C in Figure 30) used in the Frankfurt Biosphere Model (FBM; Ludeke et al., 1994) and the Canadian Terrestrial Ecosystem Model (CTEM; Arora and Boer, 2005) was applied.

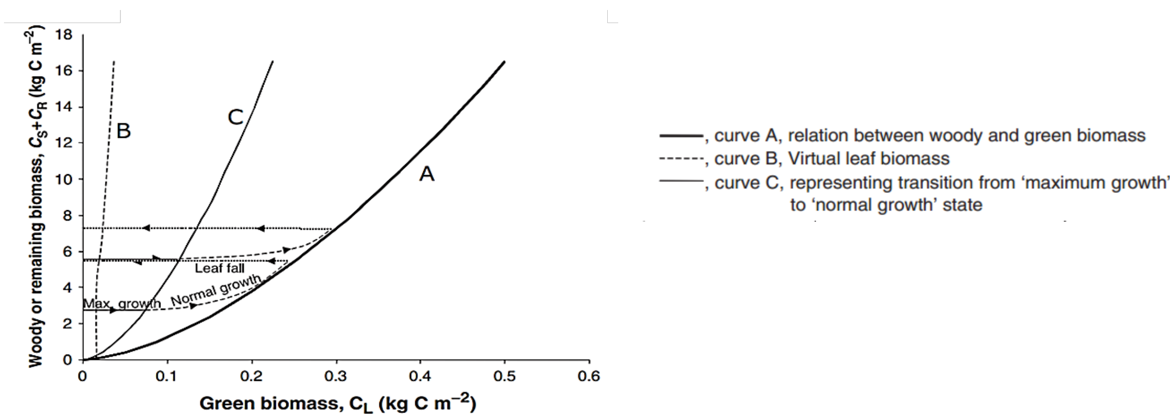


Figure 30. Relationship between remaining biomass and green biomass (Arora and Boer, 2005)

In terms of the CTEM, the approach connects the "remaining biomass", which is the woody biomass (stems and roots), with "green biomass" (the leaves). The remaining biomass accumulates from year to year and permits a greater maximum green biomass – see the circular patterns in Figure 30, shown as dashed lines that connect the y-axis with zero green biomass at the beginning of a year to curve A as green biomass accumulates in a growing season. At the end of the growing season, the green biomass is shed and the curve returns to the y-axis, but at a greater numerical value than at the start of the year. This relationship can be shown mathematically as:

$$(C_S + C_R) = \varepsilon C_L^{\kappa}, \tag{4}$$

where (C_S + C_R) is total woody remaining, or the sum of stem and root biomass in other words, C_L is green biomass which is virtual leaf biomass if tree is dormant, and ε and K are plant functional type dependent constants (Ludeke et al., 1994; Arora and Boer, 2005). Nine plant functional types were investigated and sorted into four groups by Arora and Boer (2005): (1) Needle leaf (evergreen, deciduous), (2) Broadleaf (evergreen, cold/dry deciduous), (3) Crops (C3, C4), and (4) Grasses (C3, C4).

3.3.2.4 SFD and simulation sub-model for plant growth and yield

Simplification and modification of 3-PG yielded the PGY sub-model shown in Figure 31 and Figure 32. The total net primary production (NPP) is obtained by converting total solar radiation into photosynthetically active radiation (PAR) and then into gross primary production (GPP), as shown in Figure 31. This NPP is then allocated to the three biomass pools (stocks) of roots, stems and foliage biomass. The rates of allocation, or the sizes of the inflows in other words, are controlled by the

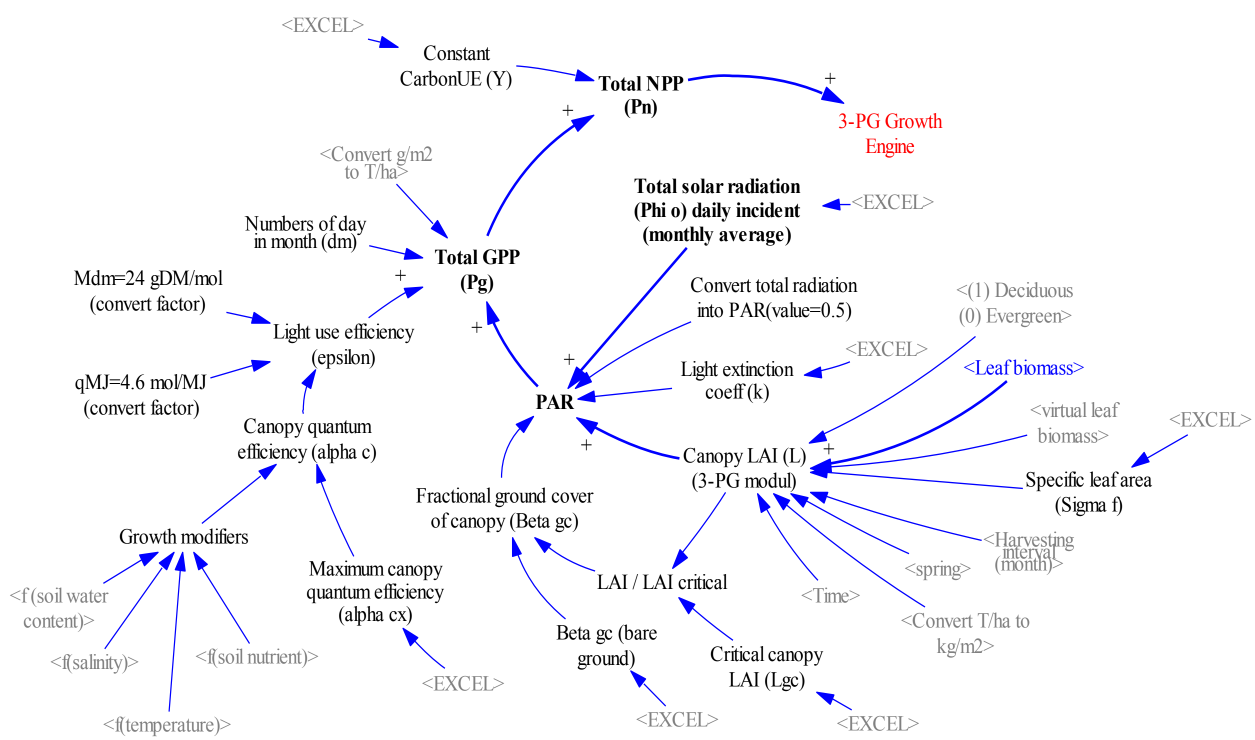


Figure 31. 3-PG represents by stock and flow diagram in the current systems model

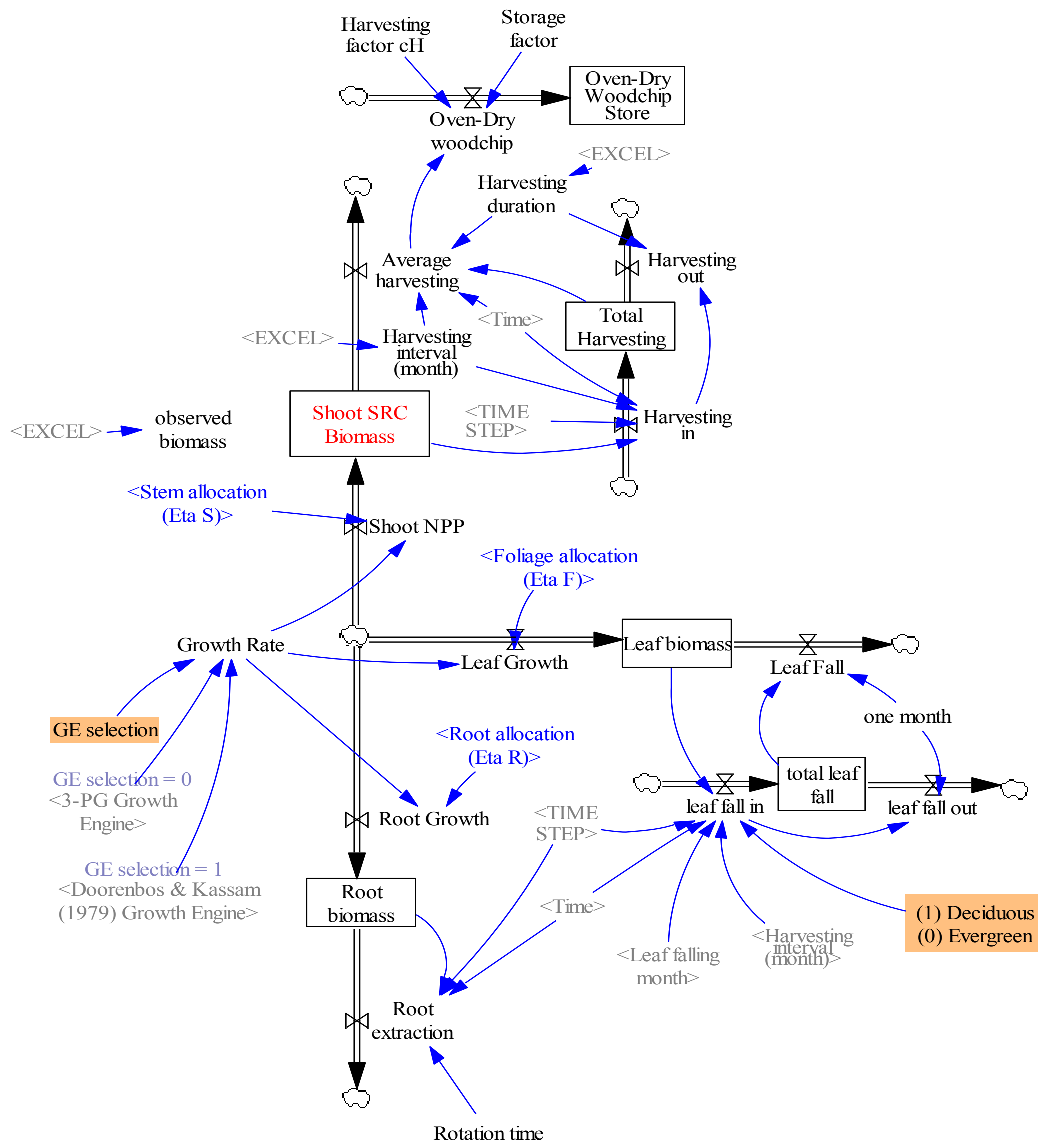


Figure 32. Plant growth and yield SFD in the current systems model

fractions of root, stem and foliage allocations, called “root growth”, “shoot NPP” and “leaf growth”, respectively, in Figure 32. Because the model does not take into account the biomass loss and turnover and stem mortality, as explained in the simplification of the stand-level sub-model above, there are no outflows of biomass lost and turnover, or stem mortality, as can be seen from each biomass pool in Figure 32. Furthermore, a switch – at the bottom right of the figure – was provided to allow selection between deciduous and evergreen tree types.

3.3.3 Soil Water Balance (1-D soil water flow)

As stated in the model component description in section 3.3.1, soil-water and solute transport are two components of interest for the WISDOM model, along with the PGY component. Similar to most other models that deal with soil water-flow problems, especially for irrigated soil, the systems model accounts only for 1D (vertical) soil water flow.

Different approaches to quantifying soil-water flow have been proposed, all of them rooted in the Darcy-Buckingham continuity equation or the Richards partial differential equation (Scott, 2000). However, because of low variation of soil-water storage with a monthly time-step, the soil-water balance method from Hillel (2004) was selected for quantification of the soil-water flow.

3.3.3.1 Root-zone soil water balance

The soil-water balance component for the root zone, shown in Figure 33, is written as (Hillel, 2004),

$$\Delta S = P + I - ET_a - D - R \qquad (5)$$

Where ΔS is the change in soil water storage over a time period (mm), P is precipitation (mm), I is irrigation (mm), ET_a is actual Evapotranspiration (mm), D is drainage (mm), and R is runoff (mm). Here, it is assumed that capillary rise (CR) is zero for the sake of simplicity.

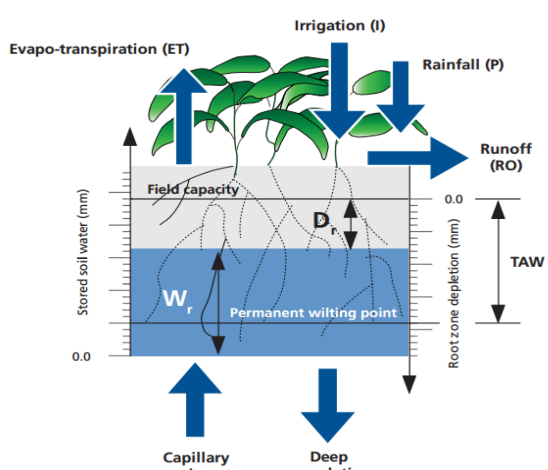


Figure 33. Soil water balance model (image source: Steduto et al., 2012)

All of the terms in equation (5), except precipitation, come directly from observed climate data and are quantified as follows.

a. Irrigation, I

Irrigation is normally controlled to provide optimal growth conditions. It can be set based on actual field conditions (case 1), or calculated by the WISDOM model based on plant water demands (case 2).

In case 1*,* the irrigation application is set, ideally based on actual field conditions, by users. In this situation, it is treated as an input in the system dynamics model.

In case 2, the optimal irrigation application is calculated based on the plant water requirement and the amount of water needed to leach the salt accumulated in the root zone to deeper layers of the soil. The irrigation requirement is calculated as follows:

$$Irrigation\ \mathrm{Req} = \frac{P - ET_a - LF \cdot P}{LF - 1} = \frac{P - Crop\ \mathrm{Req\ -\ LF \cdot P}}{LF - 1} \tag{6}$$

Equation (6) provides the irrigation requirement (mm) where P is precipitation (mm), ET_a is actual evapotranspiration (mm) or the crop requirement (mm), and LF is the leaching fraction, which is treated as model input (dmnl).

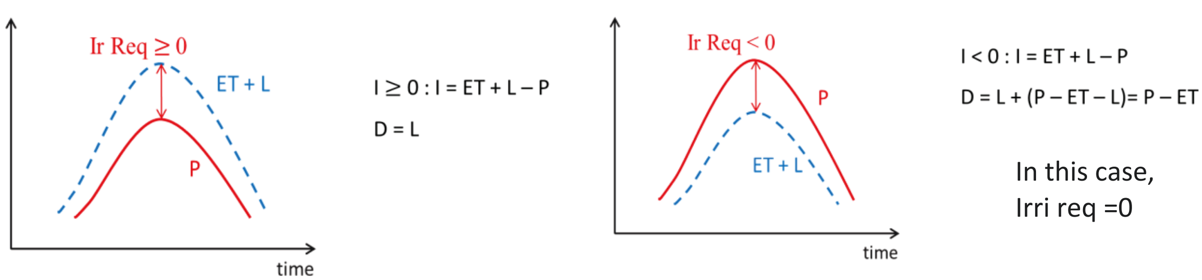


Figure 34. How to calculate the irrigation requirement in different cases

Irrigation requirements can be positive to offset the deficiency between precipitation and the sum of evapotranspiration (crop requirement) and the leaching or drainage, as shown in Figure 34a, or can be zero, as shown in Figure 34b.

b. Actual Evapotranspiration, ET_a

The actual evapotranspiration, ET_a, can be estimated by multiplying the maximum or potential evapotranspiration, ET_x, with a water stress coefficient k_s. The ET_x, in turn, is determined based on the multiplication of a reference evapotranspiration ET_o with a crop coefficient (Allen et al., 1998). Therefore,

$$ET_x = K_c.ET_o \qquad (7)$$

$$ET_a = k_s.ET_x = k_s.k_c.ET_o \qquad (8)$$

in which ET_o , ET_x , ET_a are the reference, maximum and actual evapotranspiration respectively (mm), and k_c and k_s are the crop and water stress coefficients (dmnl).

The value of ET_o can be obtained by applying various evapotranspiration calculation methods, including Penman-Monteith, Priestley-Taylor, Hargreaves or Maulé at al. (2006). While Penman-Monteith is the method recommended by the FAO, Maulé et al. (2006) is convenient since it requires only commonly measured meteorological data – minimum, maximum and average daily air temperatures – but provides a good approximation of the Penman-Monteith results for dry continental weather (Gainer, 2012). Therefore, both of these methods are imbedded in the current systems model. The crop coefficient, k_c, is a function of leaf area index (LAI) or leaf biomass, and it is estimated dynamically from the “plant growth and yield” component in the WISDOM model. The water stress coefficient, k_s, is a function of the soil water content, with a value of 1 (i.e. no water stress) at soil field capacity (FC) and 0 (i.e. extreme water stress) at the permanent wilting point (PWP).

c. Drainage, D

If irrigation is known (case 1), then drainage can be calculated based on Hillel (2004) as equation (9):

$D = P + I - ETa$ (9)

where P is precipitation (mm), I is irrigation (mm), and ET_a is actual evapotranspiration (mm).

If the irrigation amount is calculated by the model (case 2), drainage can be written as a function of the calculated irrigation amount as in equation (10):

$D = (P + I)*LF$ (10)

where P is precipitation (mm), I is irrigation (mm), and LF is leaching fraction treated as input.

d. Runoff, R

Runoff is assumed to occur solely at the beginning of each spring. The snow water equivalent (SWE) volume that infiltrates into soil is calculated based on the percentage of (%) SWE infiltration, which the user provides as model input.

3.3.3.2 The soil water balance in deeper layers

For soil layers below the root-zone layer, it is important to determine the soil-water storage profiles as well as the water fluxes (drainage and deep percolation) between different soil layers (see Figure 35). The infiltration obtained from this component is used to quantify solute concentrations in the coupled solute transport component that is introduced in section 3.3.4. To make specification of the soil layer input parameters flexible (for example, the soil layer depths and properties), subscripts [ ] are introduced for the soil layer depths and soil layer properties, including field capacities, and saturation points. They are also used for both the drainage and capillary rise between these soil layers (see Figure 35).

The soil-water balance method is again applied here to quantify the drainage and the change of soil water content of various soil layers. Furthermore, as both unsaturated and saturated layers are considered, the effect of capillarity is taken into account. By considering both the change of soil water and drainage, capillary rises are estimated in the model as follows:

Drainage $\begin{cases} D_i = S_i - S_{i\max} & if \quad S_i \geq S_{i\max} \\ D_i = 0 & if \quad S_i < S_{i\max} \end{cases}$ (11)

Capillarity $\begin{cases} C_i = 0 & if \quad S_i \geq S_{i\max} \\ C_i = S_{i\max} - S_i & if \quad S_i < S_{i\max} \end{cases}$ (12)

Soil water storage $\begin{cases} S_i = \theta_{v,i} * L_i \\ S_{i\max} = \theta_{v,FC} * L_i \end{cases}$ (13)

where D_i is drainage in layer i (mm), C_i is the capillary rise in layer i (mm), S_i is the water storage in layer i (cm), $\theta_{v,i}$ is the water content in layer i (cm^3/cm^3), $\theta_{v,FC}$ is the water content in layer i at field capacity (cm^3/cm^3), and L_i is the depth of layer i (cm).

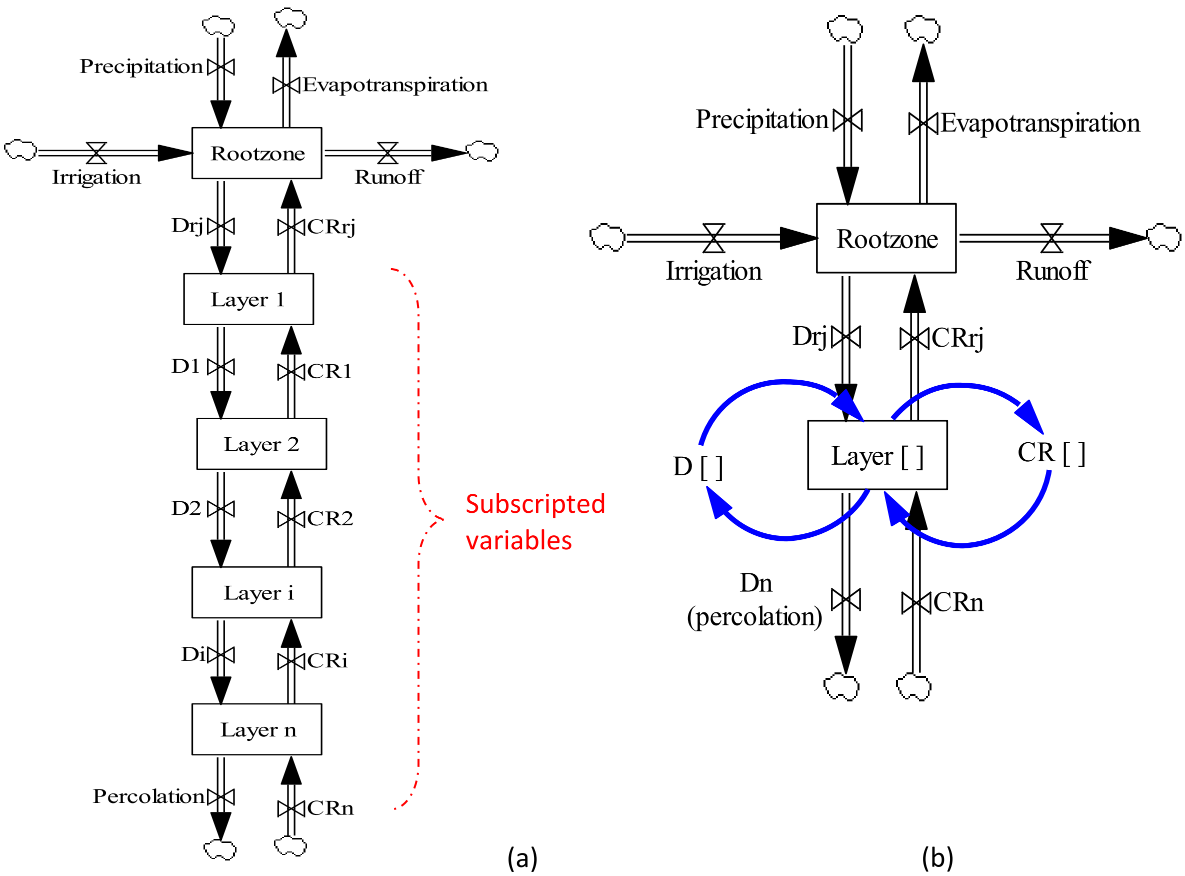


Figure 35. Subscripted [] infiltration rates of different layers below the root zone, with (a) no subscript used, and (b) Subscripted drainage, capillary rise, and soil water storage of deeper layers

Based on observed data from Gainer (2012), the groundwater table is located deep below the bottom of the root-zone layer. It is therefore reasonable to assume that the groundwater table is a sink that is not affected by deep percolation or capillary rise – see Figure 35 and Figure 36. The right-hand-side soil-water flow component shown in Figure 35b represents the basic calculation for the soil-water storage and infiltration of the root-zone and other soil layers, using the soil-water balance approach. A full model for soil-water flow with the interactions and feedbacks among different variables is shown in Figure 36.

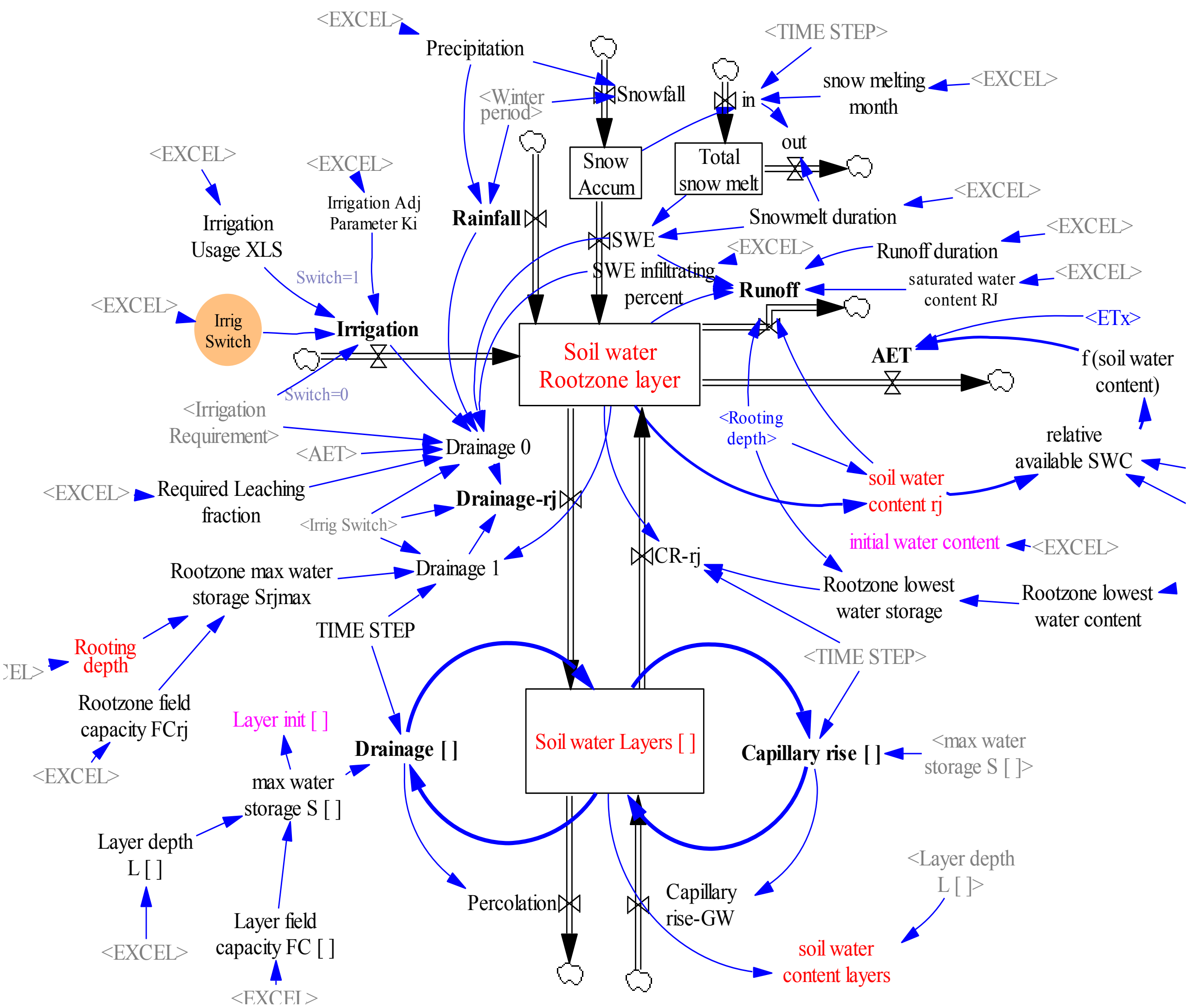


Figure 36. Full model for soil water flow quantification using the soil water balance approach

This soil-water component runs simultaneously with the solute transport component. Therefore, the results of soil-water storage profiles and infiltration rates from this component are coupled to the solute flux in the solute transport component, which is described next.

3.3.4 Solute Transport

Solute transport in the soil is driven by various processes: diffusion, convection/advection and dispersion. Depending upon soil properties and infiltration rates, they can occur simultaneously or one may dominate (Scott, 2000). To reduce the complexity of the systems model but ensure replication of the behavior of primary processes, the model only accounts for the convective process and neglects molecular diffusion and hydrodynamic dispersion. This assumption is reasonable since SRC plantations are irrigated with effluent water and, in irrigated soil, convective processes normally become prominent compared with hydrodynamic dispersion and molecular diffusion (Schoups & Hopmans, 2002; Scott, 2000).

Conservative solute transport (EC/TDS/Chloride) can be estimated from Rose et al. (1979), while the non-conservative solute (NO_3-N/PO_4^{3-}/Available P) can be determined by the Schoups and Hopmans (2002) model if only convection is considered . The WISDOM model solves the solute transport problem for both conservative and non-conservative solutes based on the general approach – the mass conservation principle – as follows.

For any layer, the governing equation is the conservation of solute mass:

$$m_i = m_{i-1} + m_{top} - m_{bottom} - m_{sorbed} + m_{desorbed} - m_{plant\ uptake} \tag{14}$$

Equation (14) provides the solute mass in a layer at time step i, where m_{i-1} is the calculated solute mass in soil at time step i, m_{top} is the solute mass flux in, m_{bottom} is the solute mass flux out, m_{sorbed} is the solute mass sorbed by the soil, $m_{desorbed}$ is the solute mass desorbed by the soil, and $m_{plant\ uptake}$ is the solute mass taken up by the plant. Each of these parameters is quantified as follows.

The solute mass that is the flux in, or m_{top}, is calculated as equation (15):

$$m_{top} = I_i.C_{I,i} + P_i.C_{P,i} + F_i \tag{15}$$

Where I_i is irrigation (mm), $C_{I,I}$ is concentration in irrigation (mg/L), P_i is precipitation (mm), $C_{P,I}$ is concentration in precipitation (mg/L), F_i is fertilizer application for each time step i.

The solute mass that is sorbed by the soil, m_{sorbed}, is calculated as equation (16):

$$m_{sorbed,i} = (m_{i-1} + m_{top}).K_d^* \tag{16}$$

Where K^*_d is the distribution coefficients $K_d^* = K_d.\rho_b.z / S_i$, K_d is distribution coefficient of solute in question (cm^3H_2O/g soil); ρ_b is bulk density of layer j (g/cm^3); z is thickness of layer j (cm); S_i is storage of layer j (cm^3H_2O/cm^2 soil)

The solute mass that is desorbed by the soil, $m_{desorbed}$, is calculated as:

$$m_{desorbed,i} = \frac{m_{sorbed,i-1}}{K_d^*} \tag{17}$$

The solute mass taken up by plants, $m_{plant\ uptake}$, is calculated as:

$$m_{plant.uptake} = a.C_i.ET_{a,i} \tag{18}$$

Where a is the plant uptake parameter, ET_a is actual evapotranspiration, C_i is solute concentration in the soil at time i

$$C_i = \frac{(m_{i-1} + m_{Top,i} - m_{sorbed,i} + m_{desorbed,i} - m_{plant.uptake,i})}{S_i} \tag{19}$$

The solute mass which is the flux out, or m_{bottom}, is calculated as:

$$m_{Bottom} = C_i . D_i \tag{20}$$

Where: D_i is the drainage at time i, obtained from the soil water component, C_i is solute concentration in the soil at time i

The full solute transport sub-model with the interactions and feedbacks among different variables and connection with the soil water component is shown in Figure 37.

Again, two subscript types are introduced in the solute transport component to quantify different types of solutes and soil layers. The first subscript was introduced in the soil water component section and denotes the layer number. The second subscript represents different types of conservative and non-conservative solutes (see Table 5).

Table 5. Different type of subscripts, their values and meanings

No.	Subscript	Value ranges	Meaning
1	[Solute]	0, 1, 2	[Solute0] = EC/TDS/Chloride [Solute1] = $N0_3$-N [Solute2] = $P0_4^{3-}$/Available P
2	[Layer]	1 -> 10	Layer 1 -> Layer 10
3	[Solute, Layer]	Combination	[Solute0, Layer1] = EC/TDS/Chloride, in layer 1 [Solute1, Layer1] = NO3-N, in layer 1 …

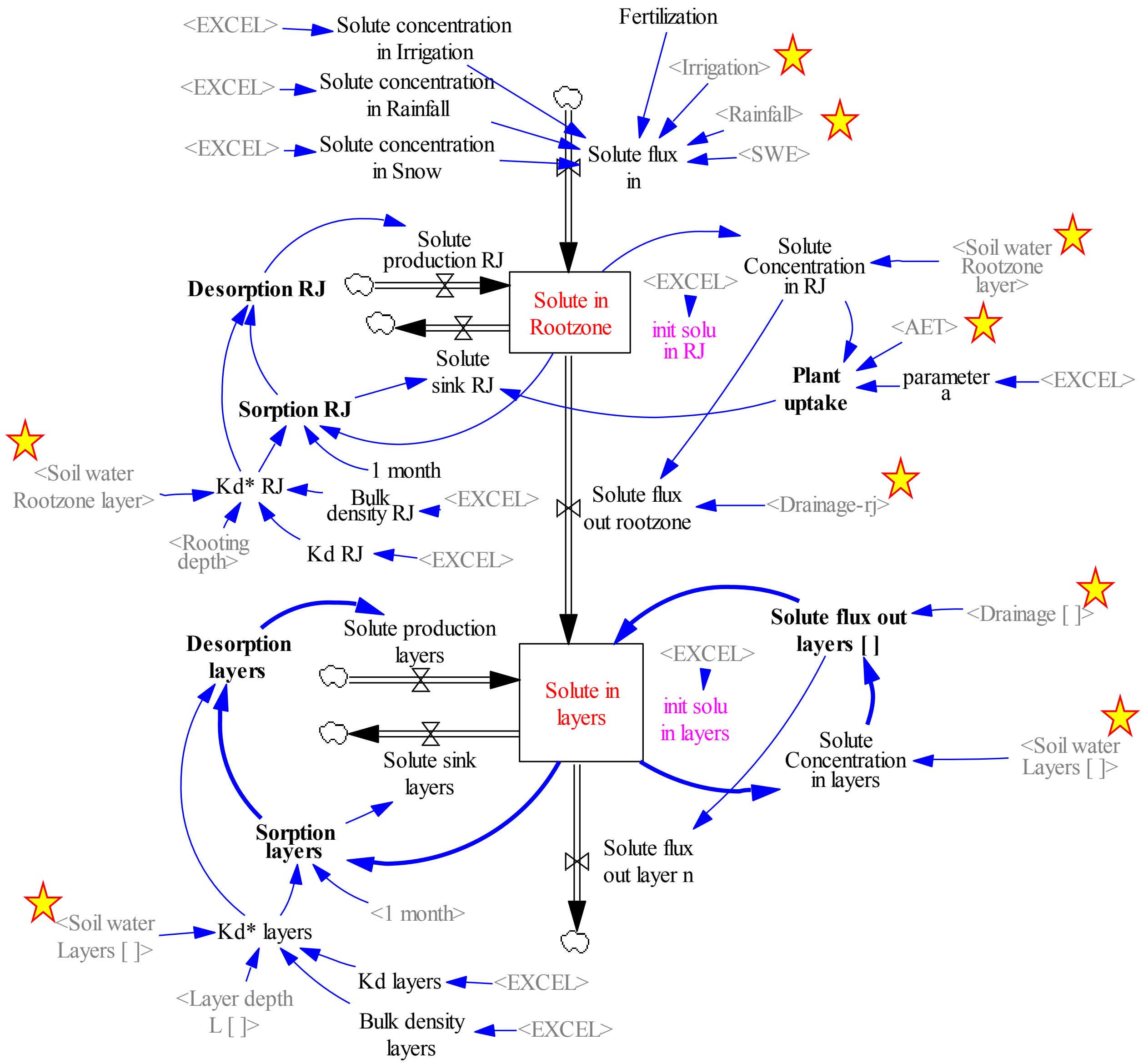


Figure 37. Full model of solute transport quantification using the mass conservation principle for conservative and non-conservative solutes. Note that the ☆ symbol denotes the coupling between soil water and solute transport components

3.3.5 Harvesting, Transporting, Drying and Storage (HTDS)

The harvest, transport, drying, and storage component is developed based on the combination of the "KUP-Ernteplaner" and "Ecowillow" models (see section 2.7). The "harvest and transport" component thus provides the advantages of the two models and reduces the drawbacks from both models. It not only compares the efficiency of different harvesting methods (e.g. woodchips, billets, whole stem) and harvesters (e.g. JF-192, claas HS2, bio-baler) like the KUP-Ernteplaner model, but also provides a detailed cost estimate like the Ecowillow model.

An improvement in this sub-model that makes it both attractive and more accurate than the KUP-Ernteplaner or Ecowillow model is that the model input – the plant yield – links dynamically to the output of the plant growth and yield component (see section 3.3.1 and 3.3.2). In addition, for flexibility, the yield can be entered directly by a model user without connection to the PGY component. The HTDS component can then be run separately from the remainder of the WISDOM model.

The HTDS cost is the sum of five sub-process costs, as illustrated in Figure 38, including: 1) harvesting, 2) on-field transportation, 3) storage, 4) highway transportation, and 5) grinding costs.

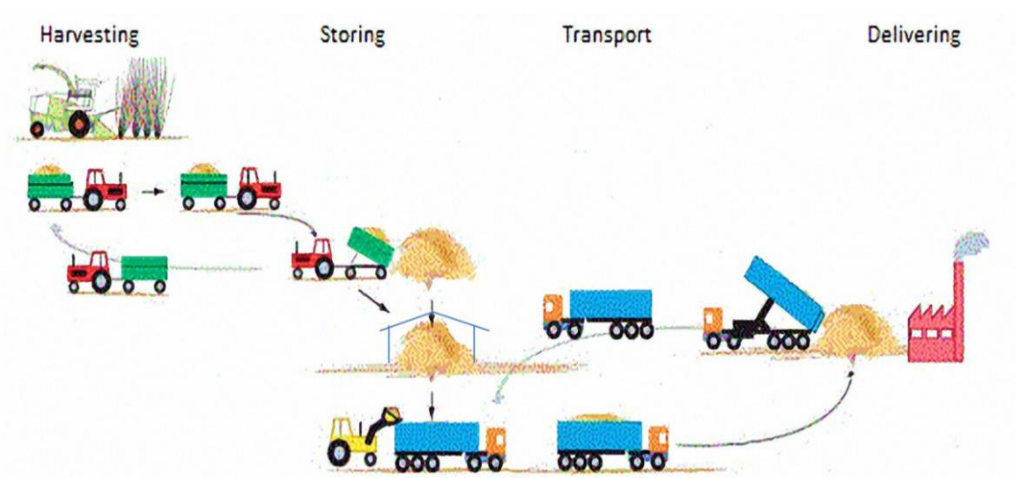


Figure 38. Five sub-processes in the HTDS subsequence process in the WISDOM model (IEE, n.y.)

HTDS is an SRC harvest decision-support tool. The biomass production can be set as “automatic link” (which means biomass production is obtained from the PGY component) or as entered value (which is estimated by the users). Moreover, the model allows users to compare different harvesting and transporting scenarios, such as different harvester types (the JF192, Claas HS2, and the bio-baler), harvester efficiencies in terms of speed, operating time and fuel, and machine operations with pulled dump carts behind the harvester or self-propelled dump carts that run parallel to the harvester. Furthermore, users can also make decisions related to renting or purchasing equipment. Each sub-process can be optionally included in the entire HTDS economic assessment through “yes” or “no” decisions (see Table 6).

Table 6. Harvesting sequence process

	Option	Harvesting			On-field transporting	Field storage			Highway transporting to End-user		Subsequent process (Grinding)	
		Raw Product	Equipment		Equipment	Deci-sion	Equipment		Deci-sion	Equipment	Deci-sion	Equipment
			Harvester	Prime mover			Store	Re-loading				
1	Default	Chip	JF 192	100-150HP	Tractor Dump wagon	Y/N	Storage place	Frontend loader	Y/N	Tractor-Trailer (lorry/truck)	n/a	
2		Chip	Claas HS-2	450-550HP		Y/N			Y/N		n/a	
3		Bale	Bio-baler	200-250HP	Frontend loader	n/a			Y/N		Y/N	Grinder
4	User input	Whole stem										
5		Billet										
6		…										

Table 7. Moisture content before and after combustion

	Option	Raw Product	Harvester	Init. Moisture content (%)	Moisture content lost								Total MC_w lost	MC_w before combustion
					Harvest	Field storage	Transport	Grinding	Enduse storage		Drying			
					%	%	%	%	Decision	%	Decision	%	%	%
1	Default	Chip	JF 192	50	-	input	input	-	Yes/No	input	Yes/No	25	25	25
2		Chip	Claas HS-2		-	input	input	-	Yes/No	input	Yes/No	25	25	25
3		Bail	Bio-baler		-	25	input	input	Yes/No	input	Yes/No	0	25	25
4	Your input	Whole stem												
5		Billet												
6		…												

3.3.6 Energy Content

The WISDOM model uses two methods presented in section 2.5 (Kenney et al. (1991)'s and Marron et al. (2012)'s methods) to estimate the net calorific value (NCV) of biomass production. The NCV per unit mass is determined based on the moisture content remaining in the wood before combustion. This moisture content is obtained by subtracting the total moisture content lost during the harvesting processes – harvest -> field storage -> transport -> grinding -> end-use storage -> drying – from the initial moisture content. Recall that the moisture content after the harvest is about 50% (see section 2.3.6). The calculation is illustrated in Table 7 as an example. The total NCV, assuming 100% efficiency of the boiler, is then achieved by multiplying the NCV per unit mass (GJ/T) with the total mass of biomass production per ha (T/ha), which comes from the "plant growth and yield" component and is adjusted by the moisture content, and the project size (ha). The total NCV is multiplied finally by the boiler efficiency, which is about 70-85% (see section 2.5), to obtain the real NCV. The energy content component of WISDOM model is shown in Figure 39.

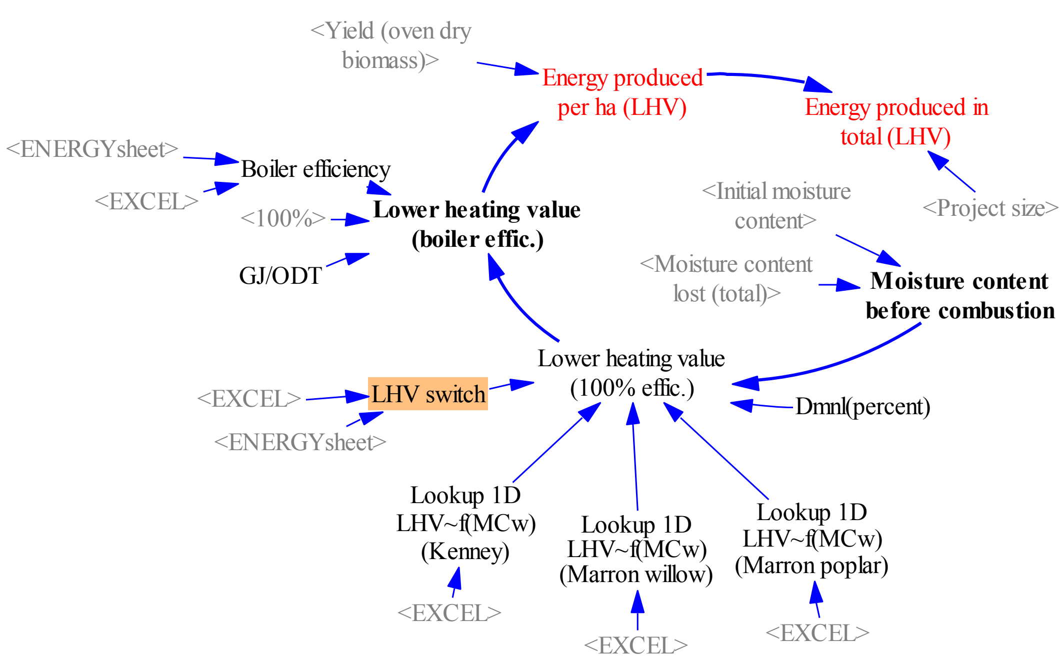


Figure 39. Energy content simulation sub-model

3.3.7 Carbon Mitigation

As mentioned in section 2.4.1, carbon mitigation can be achieved through carbon sequestration or offset calculations. In the WISDOM model, carbon sequestration is calculated by entering the amount of CO_2 sequestered per ha per year as an input. The default value is 0.25 t C/ha/yr as suggested by Volk et al. (2004); other reference values from low to high are 0.12 T C/ha/yr (Caslin et al., 2011, pp.52), 0.22-0.39 T C/ha/yr (Walker et al., 2008), and a variety of values reviewed by Walker et al. (2008), including 0.41 T C/ha/yr (Matthews & Grogan, 2001), 0.6 T C/ha/yr (Smith, 2004), and 0.15-0.22 T C/ha/yr (Bradley & King, 2004). The total carbon sequestered annually is obtained by multiplying the chosen value (T C/ha/yr) by the project area (ha). For the offset calculation, depending upon the type of fuel substitution (see Table 8), the total C offset amount is determined by multiplying the unit value by the total energy produced from the "energy content" component.

Table 8. Fuel types and the amount of emitted carbon (source: Caslin et. al., 2011, pp.68)

No	Fuel type		t CO2/GJ LHV,NCV	kg CO2/kWh LHV,NCV
1	Liquid fuel	Gas/Diesel oil	0.0733	0.264
2		Residual oil	0.0760	0.274
3	Solid fuel	Coal	0.0946	0.341
4	Gas	Natural Gas	0.0571	0.206

Note: 1 t CO2/ GJ = 3.6 kg CO2/kWh

3.3.8 Economic Assessment

The economic sub-model is adapted from the Ecowillow economic budget program (see section 2.7). Applying the concept of SRC process chain component costs proposed by Marron et al. (2012) (see section 2.6), combined with the HTDS sub-model (section 3.3.5), and a representation of the cost of irrigation system operation and setup (see Figure 40), the "economic assessment" component in the WISDOM model provides a complete picture of expenditures of the SRC project. Moreover, as the biomass production is produced from the PGY sub-model rather than estimated by the users and the carbon mitigation is also taken into account, the economic sub-model provides a more comprehensive view of the revenues from the sale of biomass production and of carbon sequestration and offsets (see Figure 41). These characteristics address the limitations of the Ecowillow economic budget program and permit the stakeholders and decision-makers to conduct a more accurate analysis of the project economy.

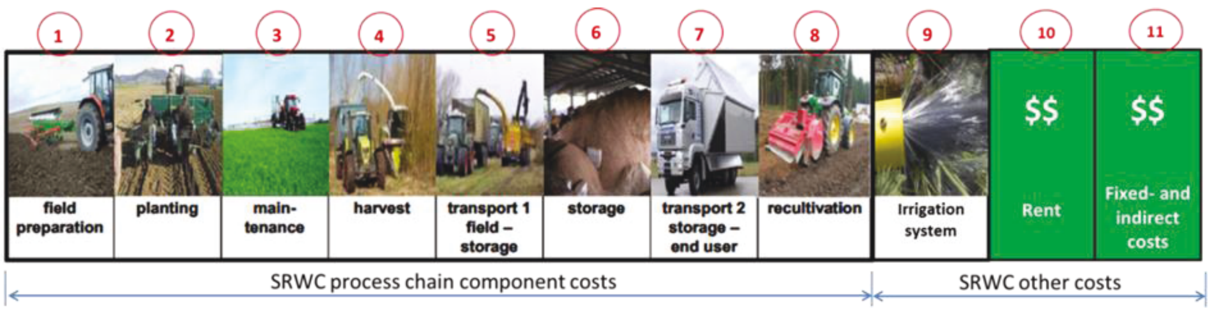


Figure 40. SRC expenditures in the economic sub-model of the WISDOM model (Image source: adapted from Marron et al., 2012, pp.92)

In the WISDOM model, project expenditures are categorized into three main groups (see Figure 40 and Figure 41) depending upon the frequency which they occur during the life cycle, which is typically about twenty years (see section 2.6.1). The first group includes one-time costs such as (1) field preparation, (2) planting, (3) maintenance, (8) re-cultivation and (9a) irrigation system setup – note that (1), (2), (3) and (8) are together abbreviated to "PPMR". The second group includes costs at each harvest, including (4) harvesting, (5) & (7) for transport 1 and 2, and (6) storage; their sum is referred to as the HTDS cost and is obtained from the HTDS sub-model. The last group is the annual costs, such as (10) rent, (11) fixed- and indirect costs and (9b) irrigation system operation.

As stated in section 2.6, SRC project costs that are estimated based on the standard process chain need to be adjusted according to (1) field sizes, (2) tree species, (3) harvest techniques and (4) transport systems and distances (Marron et al., 2012, p.100). In the economic sub-model of the WISDOM model, all of these modifications are considered both implicitly and explicitly. The modification of field size is explicit and shown in Table 9 below based on data from Marron et al. (2012). Note that because of data limitations, if the study field size is outside this range (1 to 5 ha), the WISDOM model uses the closest field size for the calculations. The other three modifications are implicit and are embedded in different components of the WISDOM model. The tree species type is embedded in the PGY sub-model, and the modifications of harvest techniques, and transports and distances, are embedded in the HTDS sub-model.

Table 9. Modification of field sizes (Data source: Marron et al., 2012, p.100)

Field sizes	Recultivation		Harvest		Maintenance		Planting		Prep. of seedbed	
(ha)	€/ha/yr	K_{recul}	€/ha/yr	K_{harv}	€/ha/yr	K_{maint}	€/ha/yr	K_{plant}	€/ha/yr	K_{seed}
1	21	1.24	86	1.25	16	1.14	189	1.02	25	1.19
2	17	1.00	69	1.00	14	1.00	185	1.00	21	1.00
5	15	0.88	60	0.87	12	0.86	183	0.99	18	0.86

The SRC economic sub-model provides users and decision-makers with many options in estimating the project economy of different scenarios. First, by varying the PGY component, different scenarios of potential SRC yield from unfavorable to favorable climate conditions can be achieved. The link between PGY and economic sub-models can be also broken and substituted with a direct yield input for locations where climate data are not available but where biomass yields can be estimated. Second, as the HTDS sub-model is part of the economic sub-model, different harvest scenarios can be taken into account and combined with those of potential yields in analyzing SRC economics. This is presented in chapter 4 to demonstrate the advantage of the WISDOM model.

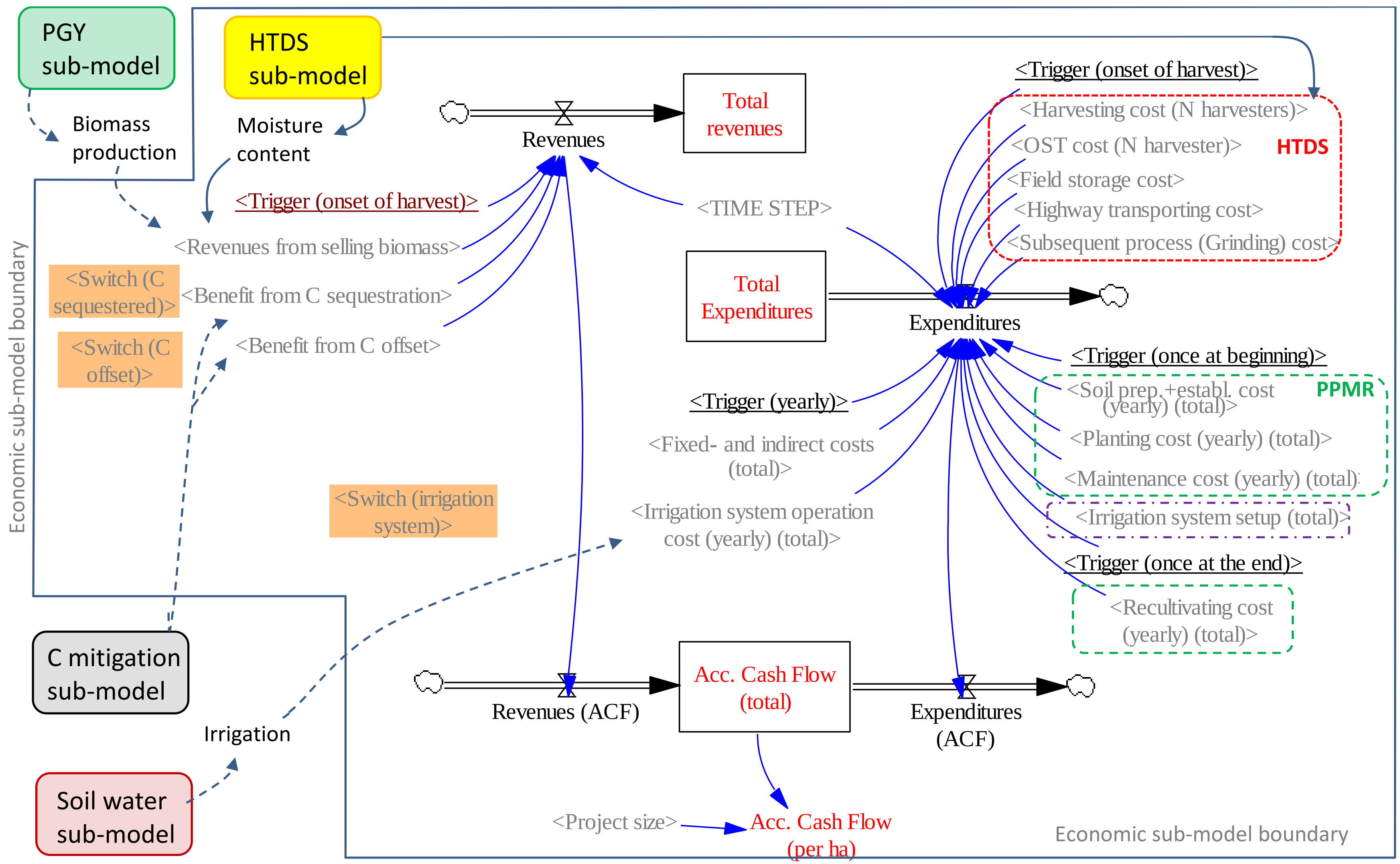


Figure 41. SFD and DST of the "economic assessment" component of the WISDOM model

4 CASE STUDY: WHITECOURT, ALBERTA, TRIAL SITE

This chapter validates and assesses the performance of the WISDOM model, described in section 3.3, in quantifying important components of a Canadian Forest Service (CFS) SRC plantation at Whitecourt, Alberta. The chapter contains two parts. The first part introduces the Whitecourt site and provides information on its location, climate conditions, and topography, and describes seven different SRC clones assessed for growth there. The second part illustrates simulation results for willow SX64 – the clone with the highest and most stable yield – through the description of 1) simulation time and model inputs, 2) model parameters, and 3) model performance and validation. Results show that the model may be helpful in supporting decision-makers to plan appropriately for the establishment of future SRCs in Alberta in particular, or more broadly in Canada, and thereby to optimize their investments and the end uses of the obtained SRC biomass.

4.1 Whitecourt Site Introduction

The research site – at latitude 54^{o} 09’ 08’’ and longitude 115^{o} 39’ 04’’ – is located in the north-east section of the town of Whitecourt, which is about 180 km northwest of Edmonton, Alberta (see Figure 42) (Gainer 2012, p.28).

Whitecourt has a humid continental climate, with warm summers and long, cold winters (Longley 1968). Data from Gainer (2012, p.28) indicate that the mean daily temperature at Whitecourt is 2.6 ^{o}C with extremes ranging from -41^{o}C in January to 33.5 ^{o}C in August. Average annual precipitation is 577 mm, and rainfall and snow water equivalent (SWE) are 440.3 mm and 134.2 mm respectively. The majority of rainfall occurs between May and September, with the highest amount occurring in July. Snowfall is chiefly between November and March with the highest average amount falling in January.

Annual average wind speed is 7.4 km h^{-1} and most frequently in the westerly direction (Gainer, 2012, p.28).The average number of frost-free days is about 65 (Wynnyk et al 1969).

The soil in the research site area was described in Gainer (2012, p.29) as follows,

> The study site area is classified as a Gleyed Dark Gray Chernozem of the High Prairie series (Wynnyk et al 1969). The soils are imperfectly drained and developed on recent alluvial material deposited by the nearby Athabasca River (Table 2.2; Wynnyk et al 1969). The measured solumn depth at the site varies with slope position from about 50 cm on slope shoulders to 1 m on slope toes (see Figure 46). Below the solumn is a thin layer of sand and a thick gravel layer (estimated at about 7 m thick). The measured groundwater table at the site ranges from 1.5 to 3.8 m below the ground surface, depending on study site position and time of year. Piezometers on the site indicate that groundwater direction is generally south in the spring and typically east in the summer and fall (Gainer, 2012, p.29).

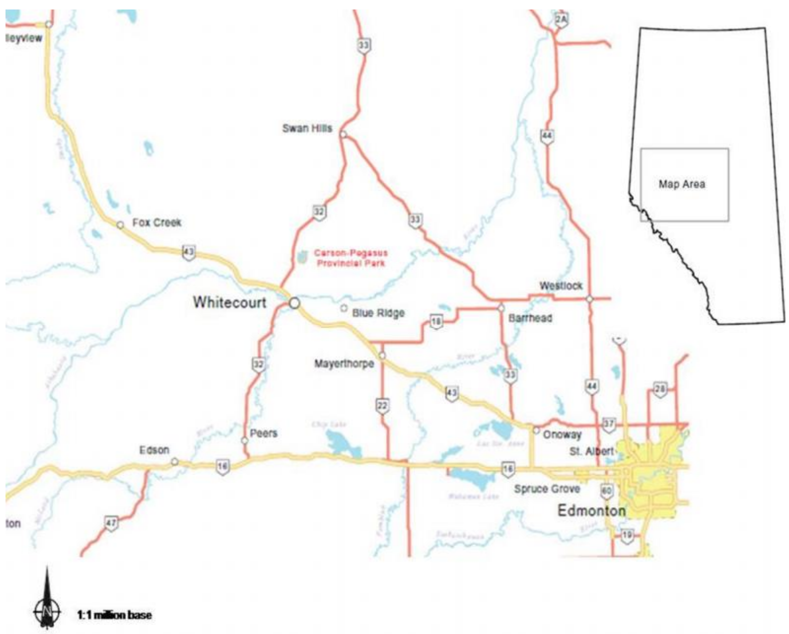


Figure 42. Map study site at Whitecourt, Alberta, in proximity to Edmonton (Gainer, 2012, p.48)

Prior to the establishment of a short-rotation woody crop at the site, the study site was an agricultural field planted with canola for at least 5 years (Gainer, 2012, p.28). Since 2006, seven clones have been planted as a trial. The five willow clones are Charlie, SX64 (S. myabeanna), SX61 (S. sachalinesis), SV01 (S. dasyclados) and Psuedo (S. alba). The two poplar species are Brooks 1 and

Green Giant. The results of 8 years of data collection by the Canadian Wood Fibre Centre of the Canadian Forest Service (CWFC-CFS) (M. Blank, CWFC, personal communication, 2014) indicate that willow SX64 has the highest and most stable yields (note the error whiskers) among those clones – see Figure 43ab. The SD model will therefore be parameterized with the SX64 clone data – Table 10 and Figure 44ab (note that the bars are for the ODT and height measures and are on the left-hand axis, while the dots are for the sample size, and are shown on the right-hand axis).

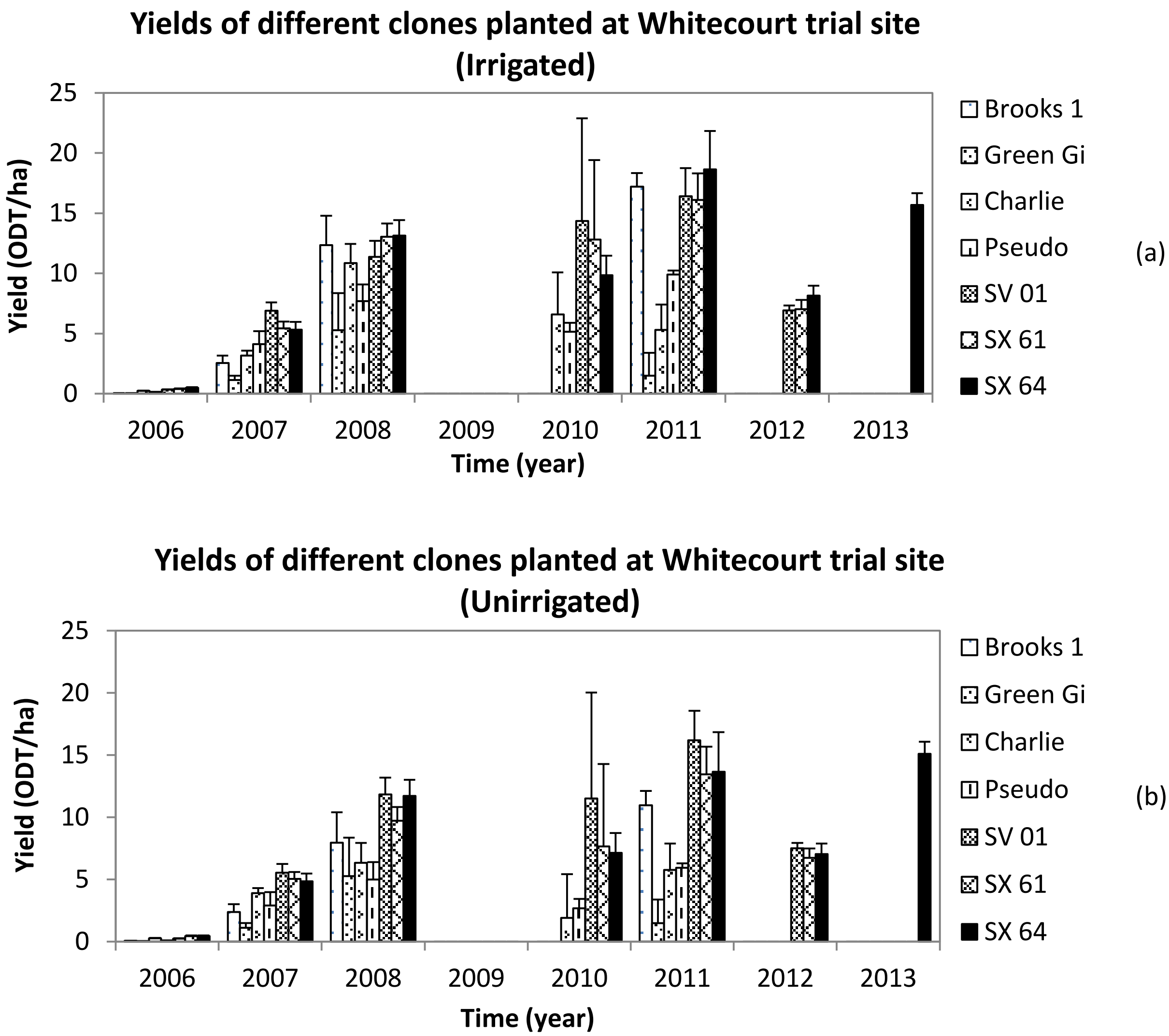
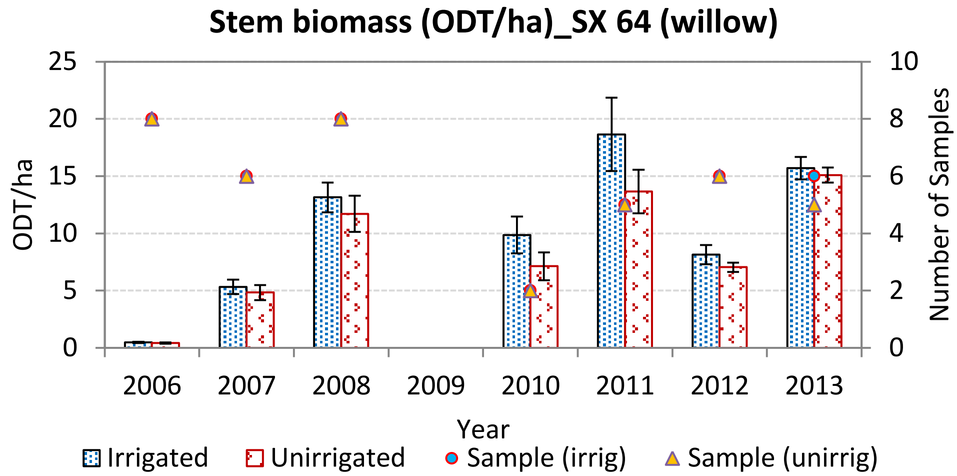
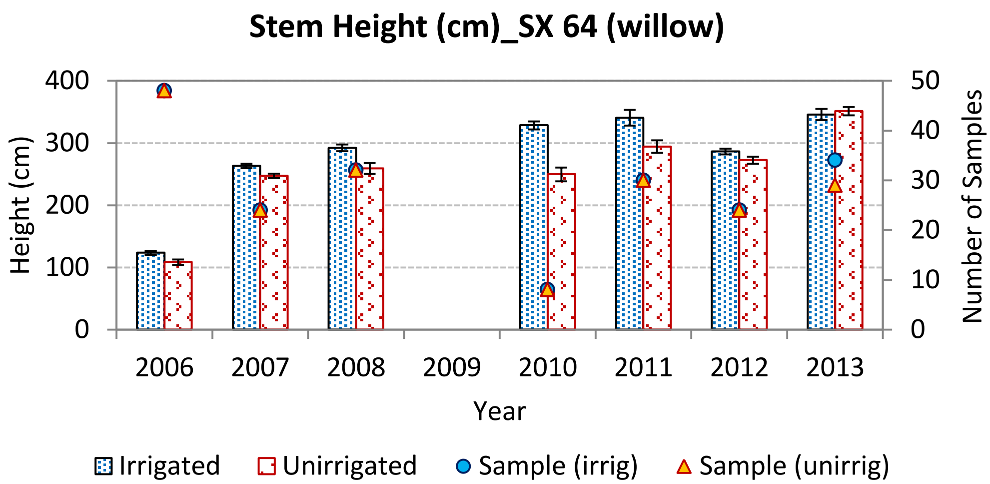


Figure 43. Compare the yields of different clones planted at the Whitecourt trial site from 2006 to 2013 for (a) irrigated and (b) unirrigated cases (Data source: CWFC – CFS)



(a)



(b)

Figure 44. (a) Stem biomass (ODT/ha) and (b) stem height (cm) of SX64 clone for the irrigation and unirrigated cases (Data source: CWFC – CFS)

Table 10. Data on stem biomass and height of SX64 clone (Data source: CWFC – CFS)

Year	Rotat.	Biomass production						Stem height					
		ODT/ha		Stderr		Sample		Height (cm)		Stderr		Sample	
		Irrig	Unirr	Irrig	Unirr	Irrig	Unirr	Irrig	Unirr	Irrig	Unirr	Irrig	Unirr
2006		0.49	0.43	0.06	0.05	8	8	123.4	108.6	3.6	4.4	48	48
2007	1st	5.33	4.83	0.62	0.66	6	6	263.2	247.2	3.6	3.8	24	24
2008		13.14	11.71	1.29	1.59	8	8	292.3	259.1	5.3	8.9	32	32
2009		-	-	-	-	-	-	-	-	-	-	-	-
2010	2nd	9.86	7.13	1.61	1.22	2	2	328.4	249.6	6.6	11.1	8	8
2011		18.65	13.65	3.19	1.90	5	5	340.6	294.2	12.5	10.1	30	30
2012	3rd	8.14	7.04	0.83	0.41	6	6	286.1	272.4	4.6	5.6	24	24
2013		15.70	15.09	0.97	0.66	6	5	345.8	351.2	9.1	6.6	34	29

4.2 Simulation of Whitecourt SRC system

Simulation of the SRC system at Whitecourt is presented in three parts as illustrated in Figure 45, (1) determination of simulation time and model inputs, (2) values used as the model parameter set, and (3) model performance and validation.

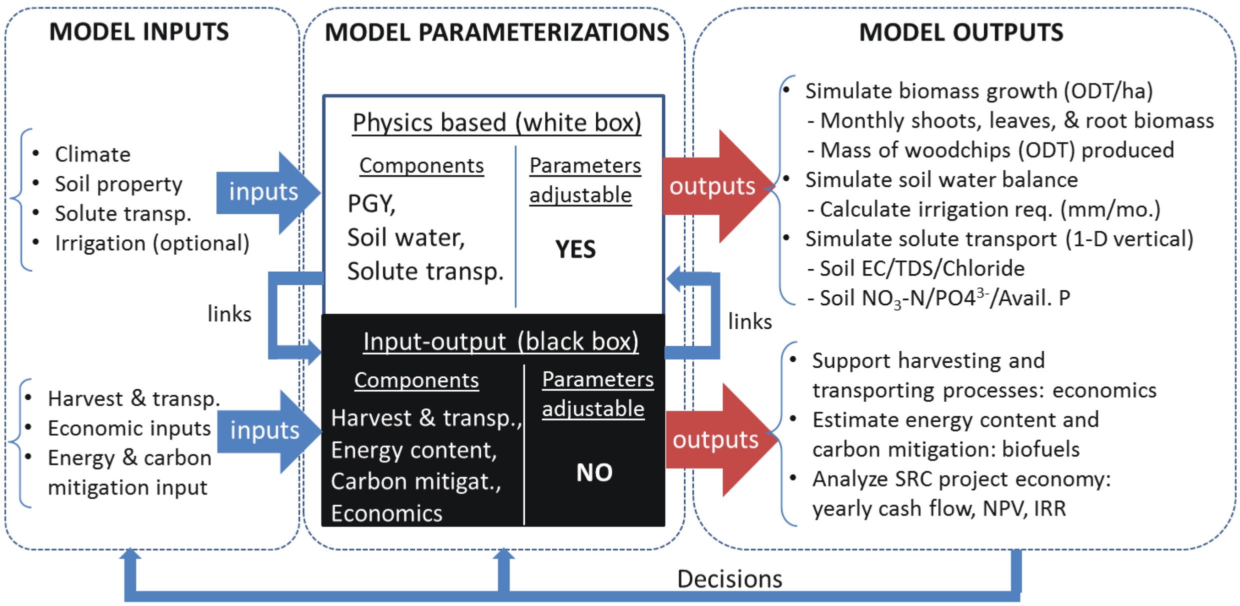


Figure 45. Simulation of SRC systems

The first step in simulation of a SRC system is to determine the simulation time and model inputs. To obtain the best model performance, the simulation time is chosen to replicate best the historical data. Further, the SD model requires inputs for each of the different aspects – biophysical, harvesting, economic, and so on – of the SRC system. The climate-driven-growth engine, the soil water, and the solute transport sub-models require climate data (including solar radiation, air temperature, precipitation, humidity, and wind speed), soil properties (including the soil moisture retention curve, permanent wilting point, field capacity, and saturation point), solute concentration in the wastewater irrigation (electrical conductivity, chloride, nitrate-nitrogen, and phosphate-phosphorus). In addition, to assist stakeholders and decision-makers in planning harvest and transport operations and estimating energy contents and the project economy, the SD model requires information on the field site, machinery information, the partial costs of harvesting sequences and other management operations, and the biomass sale price, that together contribute to the expenditures and revenues of a complete SRC project life cycle.

The second step is to parameterize the model components. This is compulsory for the physics-based or white-box sub-models in Figure 56, including plant growth and yield, soil water, and solute transport components, in order to obtain the best model calibration – or agreement between the model outcomes and observed data for variables of interest. The remaining components, which include harvest and transport, energy content, carbon mitigation, and economics, are considered as input-output or black box sub-models – for which users enter inputs and obtained outputs without parameterizing the model – this step is unavailable. However, it is important to know that several inputs of the black-box sub-models, such as biomass production, carbon offset, are connected to the outputs of white-box sub-models, and so their values do change as a result of user decisions.

The third step in SRC system simulation is to investigate model outputs. Results for different variables related to stem biomass production, stem height, irrigation requirements, soil electrical conductivity, soil nitrate-nitrogen, and so on, in both irrigated and unirrigated conditions are presented in this chapter. However, the results for SRC project economics will be illustrated in chapter 5, as project economics calculations are only relevant for a complete SRC lifecycle.

4.2.1 Simulation Time and Model Inputs

4.2.1.1 Simulation time

Since 3-year-rotation SRCs have been established in Whitecourt from 2006, the simulation period begins in 2006 and runs to the end of 2013 (i.e. eight years). The simulation period contains two harvests, at the ends of 2008 and 2011. To capture the primary feedbacks within and between model components, avoid excessive data input requirements, and still obtain useful simulation results, a monthly input interval was used.

4.2.1.2 Model inputs

a. Climate data input

In terms of climate data, nine meteorological stations were used, including the Whitecourt station and eight nearby stations – see Table 11 and Figure 47 (AARD, 2014b).

Table 11. Climate data and station information (Source: AARD,2014b)

No	Station Information							
	Station	**Climate ID**	**WMO ID**	**TC ID**	**Lat (°)**	**Lon (°)**	**Elev (m)**	**Data type**
1	WhiteCourtA	3067372	71930	YZU	54.1439	-115.7867	782.4	Precip. (mm) Temp. (°C) Humid. (%)
2	High Prairie	3063165	71226	XHP	55.3958	-116.4795	591	Total incoming solar radiation (MJ m^{-2} d^{-1})
3	Valleyview	3076680	71277	XVW	55.0978	-117.1987	694	
4	Evansburg	3062475	71481	PEB	53.5732	-115.1236	819	
5	Dapp AGDM	3061975	71340	XDP	54.329	-113.9345	619	
6	Oliver AGDM	3014921	71351	ZOL	53.6466	-113.3546	665	
7	Breton Plot	3010816	N/A	WOV	53.0893	-114.4428	853	
8	Wind fall	3067586			54.1900	-116.2400	830	Wind speed ($m\ s^{-1}$)
9	Twin lake	3066FME	N/A	TWL	54.0589	-114.7947	655	

All of the climate data from the nine stations are plotted in Figure 48-52. Note that Windfall wind speed data is only available from Jun 2011. Therefore, to obtain homogeneous data series from 2006 to 2013, the Twinlake wind speed was scaled to reproduce Windfall data, as Windfall has a high correlation with Twinlake (see appendix C for more details).

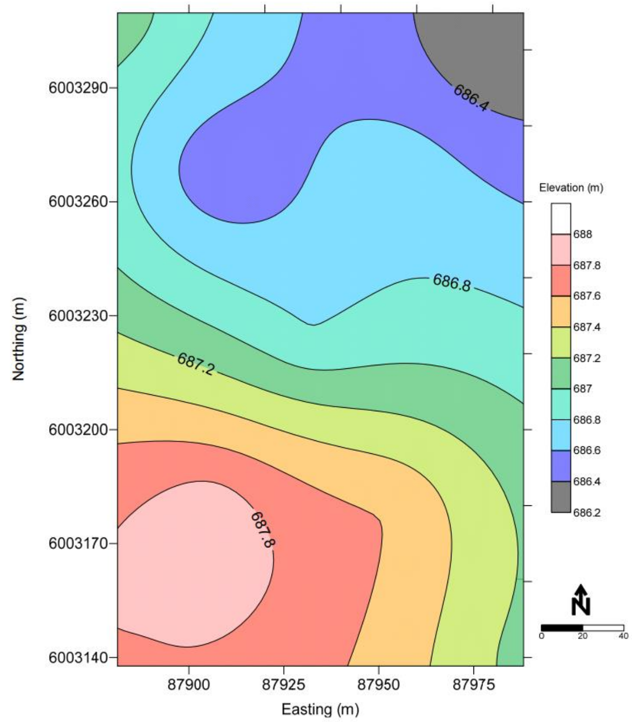


Figure 46. Topographic map of SRC plantation with wastewater irrigation project at Whitecourt, Alberta (source: Gainer, 2012)

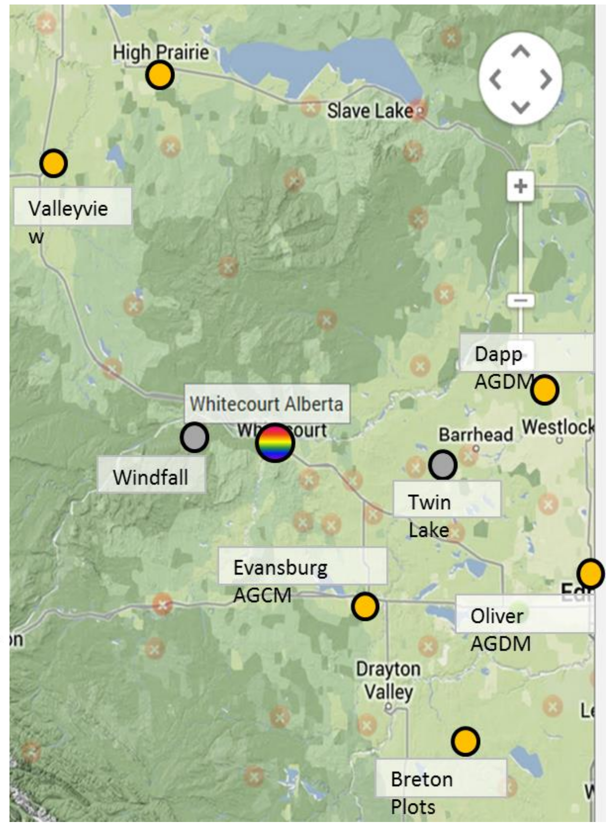


Figure 47. Location of 9 climate stations at Whitecourt and surrounding area, each station color represents a type of climate data (source: AARD, 2014b)

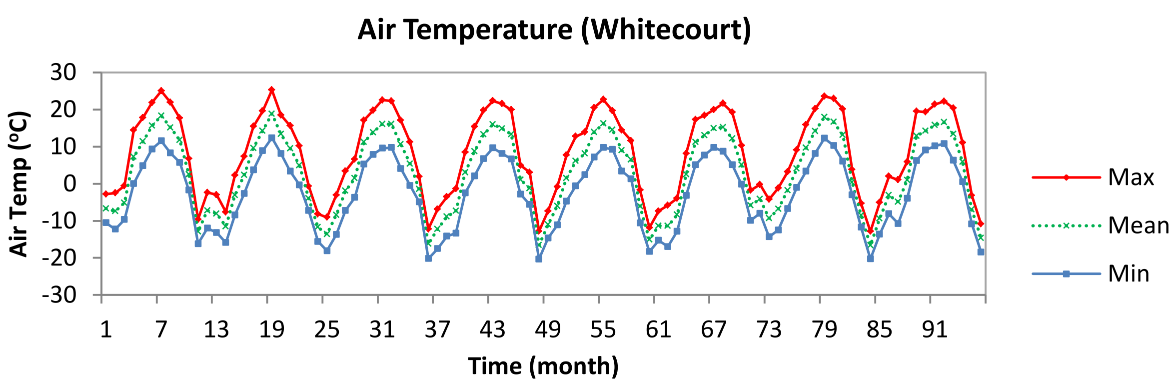


Figure 48. Monthly air temperature (max, mean, and min) from 2006 to 2013 at Whitecourt station

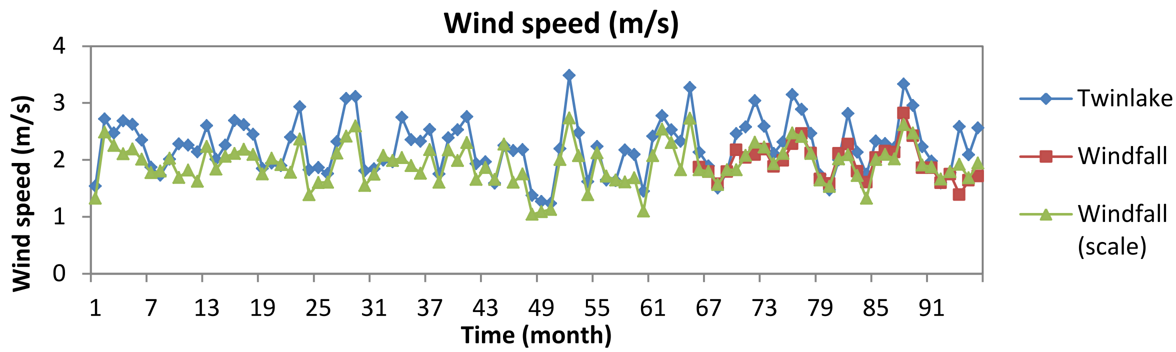


Figure 49. Monthly wind speed (m/s) from 2006 to 2013 at Twinlake and Windfall stations

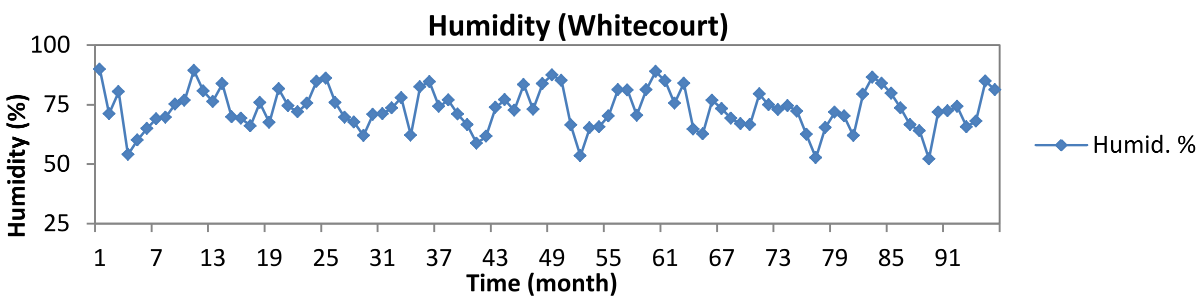


Figure 50. Monthly humidity from 2006 to 2013 at Whitecourt stations

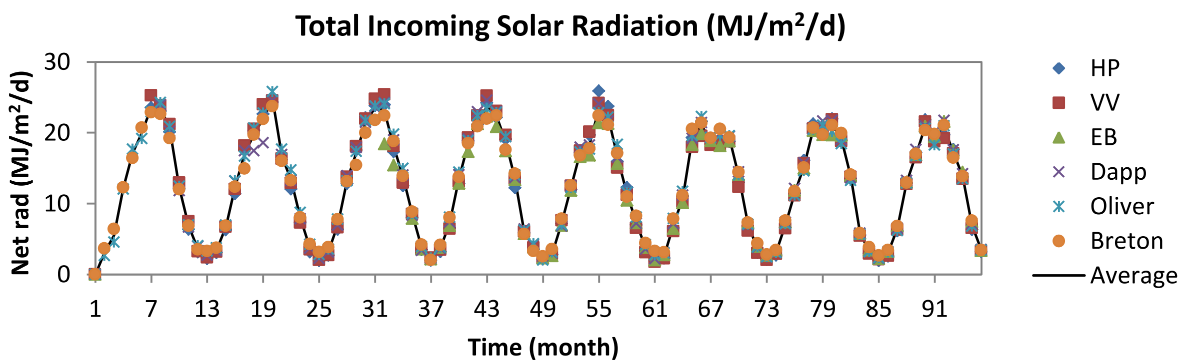


Figure 51. Monthly solar radiation (MJ $m^{-2}d^{-1}$) from 2006 to 2013 at High Prairie (HP), Valleyview (VV), Evansburg (EB), Dapp, Oliver, and Breton stations

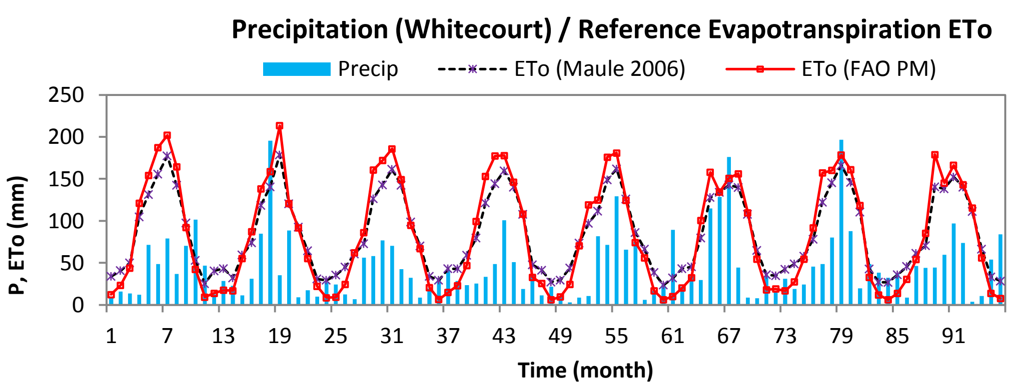


Figure 52. Monthly measured precipitation P (mm) and calculated ET_o (mm) from Maule et al. (2006) and FAO Penman-Monteith (PM; Allen et al., 1998) from 2006 to 2013 at Whitecourt

b. Soil property and solute transport inputs

In terms of soil properties, the moisture retention curve (MRC) provided by CWFC – CFS (M. Blank, CWFC, personal communication, 2014) provides water content at field capacity (FC) and at permanent wilting point (PWP) values of $\theta_{FC} = 0.37$ and $\theta_{PWP} = 0.16$ respectively. There are no data for water content at the saturation point (SAT) from field experiments. However, to be able to determine the onset of runoff, it is assumed that the saturation point is $\theta_{SAT} = 0.5$. Note that the assumption of SAT will have no influence on the irrigation requirement calculations.

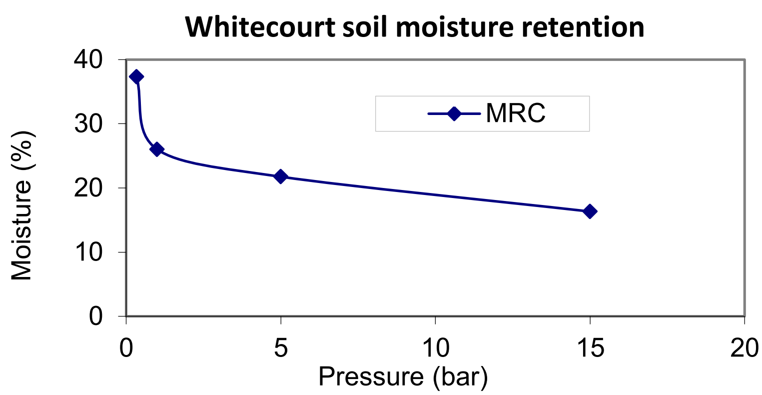


Figure 53. Whitecourt soil moisture retention (Data source: CWFC – CFS, 2013)

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 12.

Table 12. Electrical conductivity (EC), chloride, nitrate-nitrogen (NO_3-N), and phosphate-phosphorus (PO_4-P) concentration in waste water irrigation (Data source: CWFC – CFS, 2013)

Solute type \ Year	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Wastewater EC (dS/m)	0.77	0.76	0.81	*0.81**	0.82	0.89	*0.81**	*0.81**
Chloride (mg/L)	*81.9**	*81.9**	*81.9**	*81.9**	85.90	77.90	*81.9**	*81.9**
NO3-N (mg/L)	19.24	17.07	20.48	*29.8**	20.5	71.9	*29.8**	*29.8**
PO4-P (mg/L)	1.58	0.83	2.04	*1.3**	0.88	1.10	*1.3**	*1.3**

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

c. Harvest and transport inputs

To assist with harvest and transportation planning, data on the Whitecourt site, characteristics of different harvesters (JF 192, Claas HS-2, and bio-baler), and the partial costs of the harvesting sequence have been entered as shown in Table 13 - Table 15.

Table 13. General inputs of the harvest and transport component (Source: CWFC – CFS)

Field description	Symbol	Value	Unit
Link to plant growth and yield decision	YES/NO	YES	
Area to be harvested	Length L=	0.16	km
	Width W=	0.044	km
Number of single row in total	N=	110	
Biomass to be harvested	**Auto link/Input**	Auto	(ODT/ha/rota)
Initial moisture content (assumed)	H=	50	(%)
Wet chip density	ρ=	0.3	(T/m^3)
Bale weight (if bio-baler is selected)	W_bale=	308	(kg/bale)

Table 14. Machinery information of different harvesters utilized for SRC harvest, based on Phillips (n.y.) and Buchholz and Volk (2010)

Harvester type / Harvester info		1 JF 192	2 Claas HS-2	3 Bio-baler
Row number harvesting ability		1	2	2
Harvesting speed	(km/h)	2-5	6.4-9.7	-
	(bales/hr)	-	-	15-40
Turning time	(hr)	$20^{s}/3600^{s/hr}$	$20^{s}/3600^{s/hr}$	$20^{s}/3600^{s/hr}$
Maintenance time	(%)	5	10	6

Table 15. Details of cost input for harvesting sequence processes of different harvesters, based on Phillips (n.y.) and Buchholz and Volk (2010)

Harvesting sequence process	Decision/ Unit	Method		
HARVESTING (cutting + chip/bale)		**1** **JF 192**	**2** **Claas HS-2**	**3** **Bio-baler**
Harvesting equipment decision	BUY/RENT	-------------------- BUY --------------------		
Number of harvester	(unit)	1	1	1
Ownership	(C$/hr)	24.81	75.31	41.4
Rental cost	(C$/hr)	0	0	0
Delivering cost	(C$)	0	0	0
Fuel	(C$/hr)	48.3	48.3	45.08
Wage	(C$/hr)	36.53	36.53	36.53
Maintenance	(C$/hr)	23.7	57.77	37.81

Harvesting sequence process	Decision/ Unit	Method		
ON-SITE TRANSPORT		**1 Tractor**	**2 Tractor**	**3 Fr. Loader**
OST equipment decision	BUY/RENT	-------------------- BUY ---------------------		
Time for fully loading a dump cart	(hr)	0.333	0.167	-
Dump cart operates (0) behind (1) parallel with harvester		0	1	-
Number of frontend loader (user input)	(unit)	-	-	2
On-site speed (average)	(bale/hr)	-	-	60
	(km/hr)	20	20	-
Transport distance (1-way)	(km)	1	1	-
Ownership	(C$/hr)	10	10	10
Rental cost	(C$/hr)	0	0	0
Delivering cost	(C$)	0	0	0
Tractor fuel	(C$/hr)	7	7	2.8
Wage	(C$/hr)	20	20	20
Maintenance	(C$/hr)	5	5	5
FIELD STORAGE		**1**	**2**	**3**
Field storage decision	YES/NO	-------- NO ---------		-
Storage duration	(month)	0	0	-
Storage cost/month	(C$/month)	0	0	-
Reloading cost	(C$/hr)	0	0	-
Reloading time	(hr)	0	0	-
HIGHWAY TRANSPORT		**1**	**2**	**3**
		--------- **Tractor-trailer (Truck)** --------		
Maximum volume capacity	(m^3)	108	108	108
Maximum weight capacity	(tons)	35	35	35
Tractor-trailer (truck) cost	(C$/km)	0.3	0.3	0.3
Tractor-trailer (truck) Fuel	(C$/km)	0.280	0.280	0.280
Transporting distance (1-way)	(km)	10	10	10
Transporting speed (average)	(km/hr)	50	50	50
Labor (Driver + Indirect labor)	(C$/hr)	33.75	33.75	33.75
Loading time + dumping time	(hr)	0.333	0.333	0.300
SUBSEQUENT PROCESS (GRINDING)		**1 -**	**2 -**	**3 Grinding**
Grinding volume flow rate	(m^3/min)	-	-	2.67
Grinding equipment cost	(C$/hr)	-	-	30
Grinding labor cost	(C$/hr)	-	-	20

d. Economic inputs

In order to analyze the project economics (such as net cash flow, cumulative cash flow, and so on) for the Whitecourt site, data on different component costs including soil preparation and establishment, planting, maintenance, re-cultivation, and fixed- and indirect costs, as well as the biomass sale price and the value of carbon trading permits, and the discount rate have been entered as shown in Table 16.

Table 16. Data inputs for component costs and revenues of a SRC project

Item	Unit	Value	Reference / Comment	Country
DISCOUNT RATE	(%)	4	Buchholz and Volk (2010), Allen et al. (2013)	USA, Canada
EXPENDITURES				
Soil preparation and establishment			Marron et al. (2012, p. 98) [a]	Europe
Soil prep.+ establ. costs	(C$/ha/yr)	160		
Planting			Buchholz and Volk (2010)	USA
Operation + equipment cost				
Number of planter	(unit)	1		
Planter speed	(ha/hr)	0.667		
Ownership	(C$/hr)	50		
Rental cost	(C$/hr)	0		
Delivering cost	(C$)	0		
Fuel	(C$/hr)	28		
Wage	(C$/hr)	36.53		
Maintenance	(C$/hr)	30		
Supplies				
Planting stock	(C$/cutting)	0.12		
Planting density	(cutting/ha)	15000		
Stock delivery	(C$)	250		
Other supplies	(C$/ha)	5		
Maintenance			Marron et al. (2012, p. 98) [b]	Europe
Maintenance cost	(C$/ha/yr)	80		
Harvest, on-site transport, storage, and highway transport	**Link to the harvest and transport component** Table 15)		Phillips (n.y.), Buchholz and Volk (2010)	Canada
Re-cultivation			McKenney et al. (2011)	Canada
Stock removal	(C$/ha/yr)	400		
Irrigation system	YES/NO	NO	[c]	
System setup				
Irrigation system setup	(C$/ha)	-		
System operation				
Hours of irrigation	(hr/yr)	-		
Irrigation system operation	(C$/hr)	-		
Fuel	(C$/hr)	-		
Maintenance	(C$/hr)	-		
Rent, fixed- and indirect costs			Buchholz and Volk (2010)	USA
Land cost and Insurances	(C$/ha/yr)	85		

Item	Unit	Value	Reference / Comment	Country
Administration	(C$/ha/yr)	12		
REVENUES			Allen et al. (2013, p. 70)	Canada
Revenues from the sale of biomass production	(C$/ODT)	85		
Benefits from carbon mitigation and capture	(C$/T $_{CO2e}$)	10		

Note:
[a] The preparation cost is about 2% of the total cost, while the planting cost is about 21% (Marron et al. 2012, p. 98)
[b] The maintenance cost is about 1% of the total cost, while the planting cost is about 21% (Marron et al. 2012, p. 98)
[c] No reference is available for irrigation cost, to the best of my knowledge. However, the WISDOM model is structured to take into account the irrigation cost. Currently, its value is zero or "NO" because price details are lacking.

e. Energy and carbon mitigation input

To estimate the energy produced from biomass combustion, as well as the carbon emissions captured, it is necessary to enter the boiler efficiency and the amount of CO2 sequestered per year. These values are presented in Table 17.

Table 17. Data input for estimation of energy and carbon mitigation

Item	Unit	Value	Reference/Comment
Energy conversion			
Boiler efficiency	(%)	75	McKenney et al. (2011) (section 2.5.2)
Higher heating values at 0% MCw	(GJ/ODT)	19.5	Default (section 2.5.3)
and 50-55% MCw	(GJ/ODT)	9	Default (section 2.5.3)
Hydrogen content	(%)	6	Default (section 2.5.3)
Carbon mitigation and capture			
Amount of CO2 sequestered by SRC	t C/ha/yr	0.25	Volk et al. (2004) (section 3.3.7)
Offset calculation	Fuel displace: Diesel/Residual oil/Coal/Natural gas		

4.2.2 Model parameterization

The second step in simulation Whitecourt SRC system is to parameterize the model constants. This is compulsory for the physics based or white-box sub-models, including plant growth and yield, soil water, and solute transport components in order to obtain the best model behaviour.

The PGY sector, as explained in section 3.3.2, is built based on the 3-PG model which simulates plant growth as a function of light-use efficiency – plants convert solar radiation to NPP through the processes of photosynthesis and respiration – and partitions the resulting biomass production to the biomass pools of stems, foliage, and roots (Landsberg & Sands, 2011). Although these underlying principles are similar for all tree species, solar radiation utilization efficiency, plant growth characteristics (for example, growth increments, biomass allocation, and canopy structure), and wood properties differ among tree species (Amichev et al., 2010, 2011). Such species-specific properties and features are controlled in the PGY sub-model by parameters categorized into five main groups – see Table 18. As proposed by Amichev et al. (2010, 2011), these groups include 1) canopy structure and processes (GPP and NPP determination), 2) biomass partitioning and turnover (root, stem, and foliage allocation), 3) growth modifiers, 4) stem mortality and self-thinning, and 5) wood and stand properties (the stem-height allometric relationship). Note that the stem mortality and self-thinning group is unavailable because of the model simplifications described in section 3.3.2. For the soil water and the solute transport sub-models, choosing ETo methods, irrigation application methods (user-defined or irrigation requirement), leaching fraction, crop coefficient, soil distribution coefficient, and plant uptake parameters are all elements of parameterization – see Table 18.

The sub-model parameters and their values for the simulation of the Whitecourt SRC system are presented in Table 18. Note that these sub-models are parameterized for the willow SX64 clone, as mentioned in section 4.1. For other clones, these values provide a good reference point, but they need modification to properly represent different clones (for instance, the specific leaf area, light extinction coefficient, stem and foliage allocation, and so on, vary among clones).

Table 18. Willow SX64 clone-specific model parameter values

Item	Symbol	Value	Unit	Reference /Comment	City/ Country
1. PLANT GROWTH AND YIELD					
GPP & NPP determination					
Constant carbon use efficiency	Y	0.5	Dmnl	Landsberg and Sands (2011)	
Max canopy quantum efficiency	α_{cx}	0.023	$G.MJ^{-1}$	[a] Green et al. (2001)	Southern Wisconsin, USA
Light extinction coefficient	k	0.7	Dmnl	Green et al. (2001); Headlee et at. (2012)	Southern Wisconsin; Minnesota and Wisconsin, USA
Specific leaf area	SLA	21.06	$m^2.kg^{-1}$	Pellis et al. (2004), Afas et al. (2005)	Antwerp, Belgium
The fractional ground cover of the canopy β_{gc} =f (L/L_{gc})					
Critical canopy LAI	L_{gc}	4.6	Dmnl		
Bare ground L=0	β_{gc0}	0.025	Dmnl		
Full canopy cover $L=L_{gc}$	β_{gc}	1	Dmnl	Default	
Virtual leaf biomass					
Initial virtual leaf biomass		0.37	$T.ha^{-1}$		
Plant functional type dependent constants $k_{virtual}$	$k_{virtual}$	1.72	Dmnl	Arora and Boer (2005)	Canada
Plant functional type dependent constants $\varepsilon_{virtual}$	$\varepsilon_{virtual}$	6.63	Dmnl	Arora and Boer (2005)	Canada
Root allocation					
Root allocation under the most limiting conditions	η_{Rx}	0.8	Dmnl	Headlee et al. (2012)	Minnesota and Wisconsin , USA
Root allocation when neither site fertility nor soil water availability are limiting	η_{Rn}	0.1	Dmnl	Headlee et al. (2012)	Minnesota and Wisconsin , USA
Stem and foliage allocation					
Stem allometric scale factor	a_{S_1}	0.01	Dmnl	Amichev et al. (2011) [b]	Saskatchewan, Canada;
Stem allometric power	n_{S_1}	1.5	Dmnl		
Foliage to Stem ratio for sapling tree (DBH=2cm)	P_{FS2}	0.6	Dmnl		
Foliage to Stem ratio for mature tree (DBH=20cm)	P_{FS20}	0.1	Dmnl		
Foliage re-allocation		0.8	Dmnl		
Stem re-allocation (leaf-out)		0.2	Dmnl		
Root re-allocation (leaf-out)		0	Dmnl		
MODIFIERS					
Soil water modifier (or soil-water-dependent growth modifier)	$f_\theta(\theta_r)$				

Item	Symbol	Value	Unit	Reference /Comment	City/ Country
The soil water constant parameter (Sw_{const})	c_θ	2	Dmnl	[c]	
The soil water power parameter (Sw_{power})	n_θ	16	Dmnl	[c]	
Temperature modifier	f_T				
- Cardinal temperatures for growth	T_{min} T_{opt} T_{max}	5 15 40	^oC ^oC ^oC	Amichev et al. (2010); Amichev et al. (2011); Headlee et al. (2012)	Saskatchewan, Canada; Minnesota and Wisconsin , USA
Salinity modifier					
- Shape-determined power	n_{CS}	1	$dS.m^{-1}$	linear	
- Electrical conductivity of the soil at which salinity begins to affect and stop growth: C_{S0} and C_{S1}	C_{S0} C_{S1}	3 10	$dS.m^{-1}$ $dS\ m^{-1}$	Hangs et al. (2011)	Saskatchewan, Canada
Site fertility modifier					
- Shape-determined power	n_{fN}	1.5	Dmnl		
- Value of F_{FR} when $F_R = 0$	f_{N0}	0.25	Dmnl		
Stand age modifier					
Maximum age expected for a stand of this species t_x	t_x	22	Year	Allen et al. (2013)	Ontario, Canada
The relative age (t/t_x) at which f_{age} = 1/2	r_{age}	1	Dmnl	No effect [d]	
Power of relative age in fage (use n_{age}=0 to set f_{age}=1)	n_{age}	0	Dmnl	No effect [d]	
Height and diameter relations					
Process-based method (3-PG)					
The scale factor	a_H	0.7	Dmnl		
The allometric power	n_{HB}	0.5	Dmnl		
	n_{HN}	0	Dmnl		
Crop / Tree density	N	15000	$Stem.ha^{-1}$	Kitchen (2012)	Alberta, Canada
Empirical method (using logarit form)					
Log empirical value A=	A_{height}	1.21	Dmnl		
Log empirical value B=	B_{height}	-0.377	Dmnl		
Shortest tree height	H_{min}=	0	m		
2. SOIL WATER BALANCE					
Irrigation switch	IrrReq / UserDef				
Required leaching fraction	LF	0.3	Dmnl	Gainer (2012)	Alberta, Canada
Irrigation adjustment parameter (K_i is only valid in case of user-defined irrigation)	K_i	0	Dmnl	No irrigation [e]	
Percent of SWE infiltration into soil		0.7	Dmnl		
Snowmelt duration		1	Month	Default	
Runoff duration		1	Month	Default	
Crop coefficient - LAI function					
K_c = A. Ln(LAI) + B	A_{crop} B_{crop}	0.7 0.7	Dmnl Dmnl	Guidi et al. (2008); Pellis et al. (2004); Afas et al. (2005)	Pisa, Italy; Antwerp, Belgium

Item	Symbol	Value	Unit	Reference /Comment	City/ Country
3. SOLUTE TRANSPORT					
Distribution coefficient for soil nitrogen $K_{d,N}$ and phosphorus $k_{d,P}$ (rootzone layer)	$K_{d,N}$ $K_{d,P}$	0 0.8	Dmnl Dmnl	Default	
Plant uptake parameter for nitrogen a_N and phosphorus a_P	a_N a_P	1.27 1.38	Dmnl Dmnl	Gainer (2012) Gainer (2012)	Alberta, Canada Alberta, Canada

[a] The light use efficiency ε_g=f (α_{cx}) ranges from 1.06-2.22 (dmnl), the maximum canopy quantum efficiency is chosen so that the LUE falls in this range (Green et al., 2001),

[b] The empirical values for willow SV1 clone from 3 years of observed data in the first crop rotation were a_s=0.11 and n_s=1.89 (Amichev et al., 2011). These values have been adjusted in this study to obtain the best result with 8 year observed data of 3 rotations.

[c] The soil water modifier parameters are used to calibrate the stem biomass production in case of non-irrigation based on the result from the irrigation case.

[d] The stand age modifier parameters are set in a way that they have no effect. In other words, the stand age modifier value f_{age}=1 for the entire simulation time.

[e] The irrigation adjustment parameter K_i is used to alter the amount of irrigation application treated as input in case of user determination. K_i=0 means no irrigation.

4.2.3 Model Performance and Validation

This section presents the model performance and validation for simulations of the Whitecourt SRC system. Two different cases are examined: irrigated and unirrigated SRC systems. In both cases, stem biomass production is among the key model variables, as it directly affects project economics and energy production plans. Further, soil quality and solute transport results with irrigation using pre-treated wastewater effluent are also important. These results are the subject of this section.

4.2.3.1 Model performance in irrigated case

In the irrigated case, a comparison between model-predicted and observed values for eight years of simulation showed that the decision-support tool matched biomass production (R^2_{irr} = 0.98), tree height (R^2_{irr} = 0.92; see Table 19 and Figure 54) and soil EC (R^2_{irr} = 0.90; see Figure 56) data well. The model also predicted summer-season irrigation requirements at a monthly scale acceptably well (R^2_{irr} = 0.72; see Figure 55). At a seasonal scale, the differences between model-predicted and observed irrigation were 46%, 14%, and <1% in 2007, 2008, and 2010 respectively.

Table 19. Comparison between the predicted and observed stem biomass (ODT/ha) and stem height (m) of the irrigated case

No.	Year		Stem biomass (ODT/ha)			Stem height (m)			Note
			Model (ODT/ha)	Observed (ODT/ha)	Difference (%)	Model (m)	Observed (m)	Difference (%)	
1	2006	Irrigated	1.44	0.49	-	1.45	1.23	-	
2	2007		4.69	5.33	-	2.40	2.63	-	
3	2008		13.56	13.14	3.2	3.26	2.92	11.4	Harvest
4	2009		4.97	-	-	2.45	-	-	
5	2010		11.06	9.86	-	3.09	3.28	-	
6	2011		18.73	18.65	0.4	3.52	3.41	3.2	Harvest
7	2012		6.71	8.14	-	2.69	2.86	-	
8	2013		15.71	15.70	-	3.38	3.46	-	

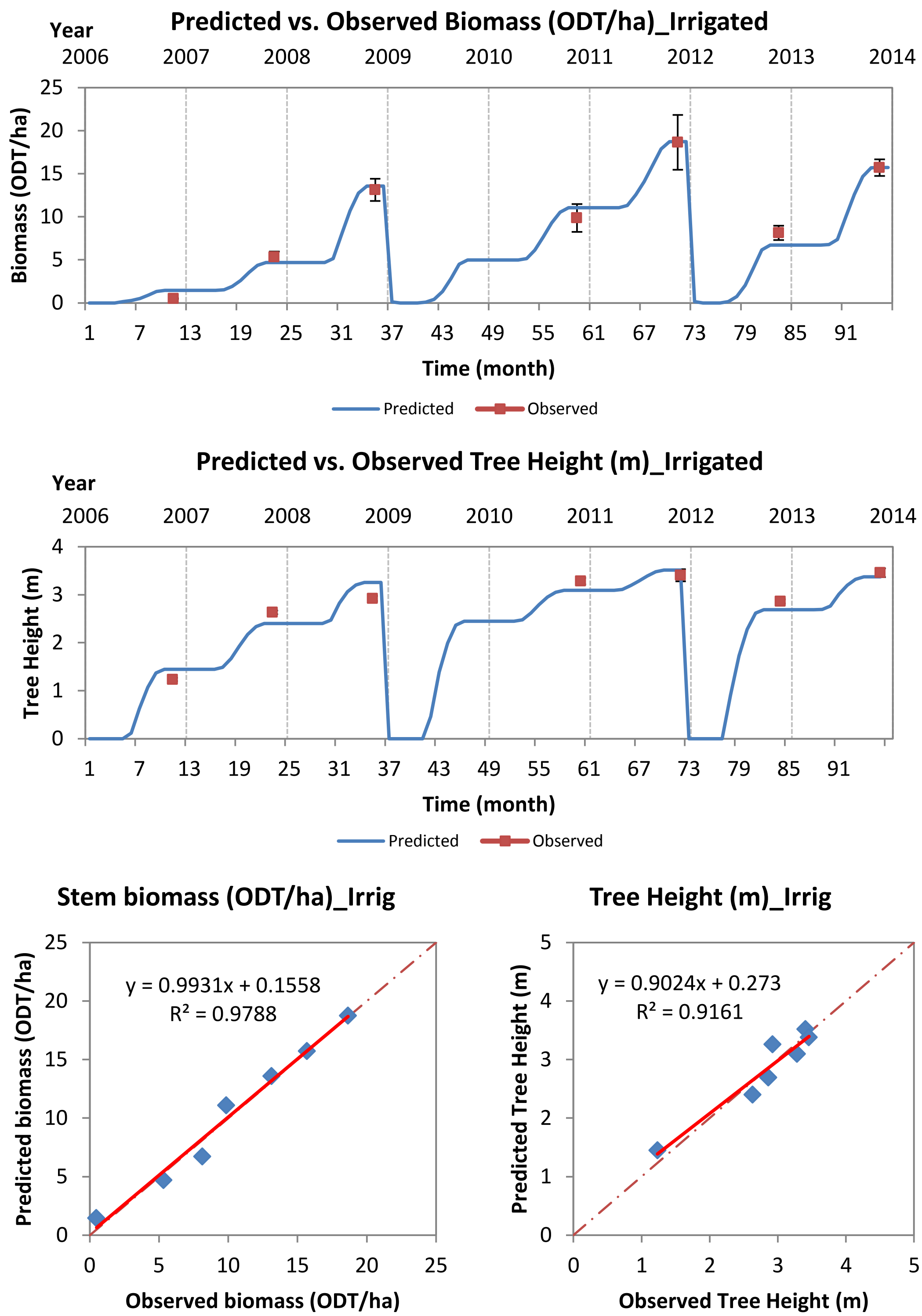
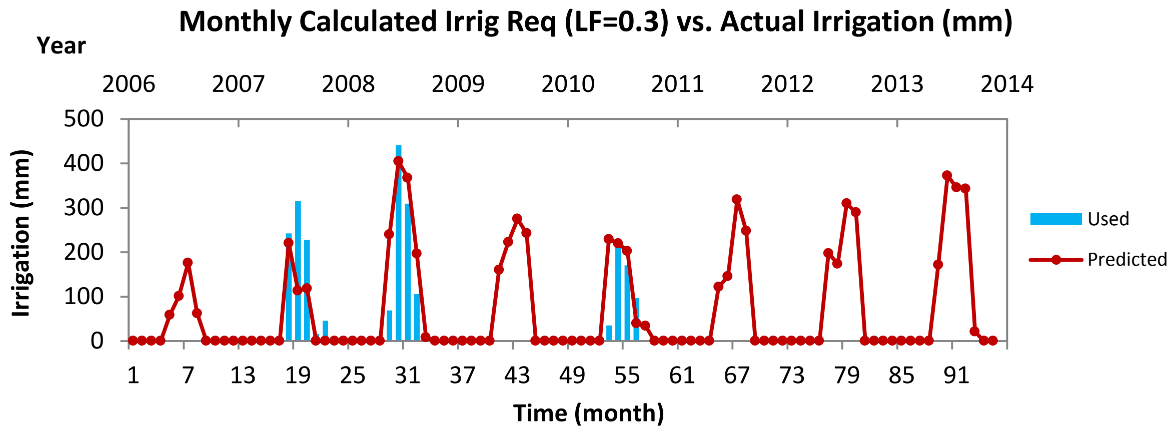


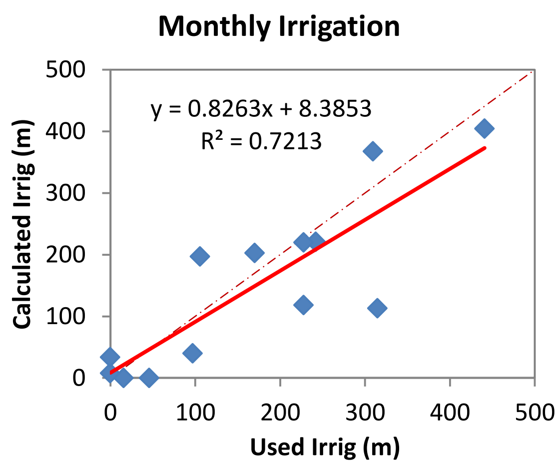
Figure 54. Plant growth – yield (ODT/ha) and stem height (m) outputs and validations (irrigation case)

The difference between predicted and observed irrigation at both monthly and seasonal scales may have a variety of sources. Firstly, the approaches used to calculate irrigation amounts were different between the real irrigation system operation and the system model. The real irrigation system estimated irrigation requirements by measuring daily real-time soil moisture content (M. Blank, CWFC, personal communication, 2014), while the irrigation applications calculated by the system model was based on a monthly soil water balance. Secondly, the leaching fraction or drainage required to leach cumulative salt in the root zone to deeper layers may differ between the real irrigation system and the model. Indeed, for convenience, the system model used the same leaching fraction values for every simulated month and year, while this could be different for real operations. Thirdly, the difference may be a result of irrigation equipment malfunctions – the system was actually broken in 2009 and 2011 (M. Blank, CWFC, personal communication, 2014).

To make the problem clearer, the seasonally predicted and observed irrigation values for 2007 and 2010 – the second year of the first and second rotations – are investigated here, with results shown in Figure 55c. The seasonal rainfalls for the two years are slightly different, at 345.7mm and 341.8mm for 2007 and 2010, respectively – see Table 20. The ETa for 2010 is higher than for 2007, although the ETo of 2010 is lower because its crop coefficient is higher; note that the biomass production in 2010 is higher than in 2007, as shown in Table 19 and Figure 54. Therefore, applying the soil water balance approach, with the same leaching requirement or leaching fraction, the irrigation requirement for 2010 will be higher than for 2007, as shown in Figure 55c for the model prediction. However, the observed data from the real irrigation showed an opposite result, with the 2007 irrigation much higher than in 2010. This problem might be a result of one of the listed reasons above. In this case, if leaching fraction of 2007 is set higher than that of 2010, then a higher predicted irrigation requirement of 2007 can be produced.

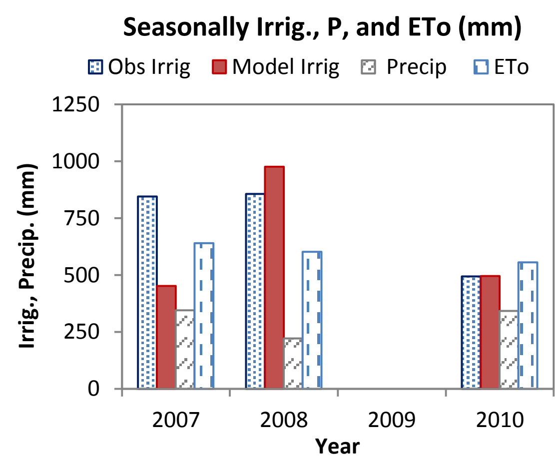


(a)



Note: May of each year is excluded

(b)



(c)

Figure 55. Irrigation requirement output and validation

Table 20. Comparison between observed and predicted monthly and seasonally irrigation

Year	Month	Monthly Irrigation (mm)		Seasonally Irrigation (mm)			Precip (mm)	ETo (mm)
		Observed	Model	Observed	Model	Differ.(%)		
2007	6	242.02	220.51	845.78	451.78	46.6	345.7	639.5
	7	314.85	113.10					
	8	227.73	118.17					
	9	15.59	0.00					
	10	45.59	0.00					
2008	6	440.89	404.45	856.09	976.11	14.0	221.4	601.9
	7	309.37	367.18					
	8	105.83	196.71					
	9	0.00	7.77					
2010	6	227.64	219.68	494.57	496.1	0.3	341.8	555.4
	7	170.04	202.53					
	8	96.89	40.00					
	9	0.00	33.89					

For soil EC, a comparison between the predicted and observed values is shown in Figure 56. The model results match the observed soil EC with R^2_{irr}=0.9, and show that the model can predict conservative solutes well. Another way to determine the value of the model predictions is to compare the simulated soil EC with values from the analytical solution of Rose et al. (1979) when the volumetric water content is at field capacity, as follows:

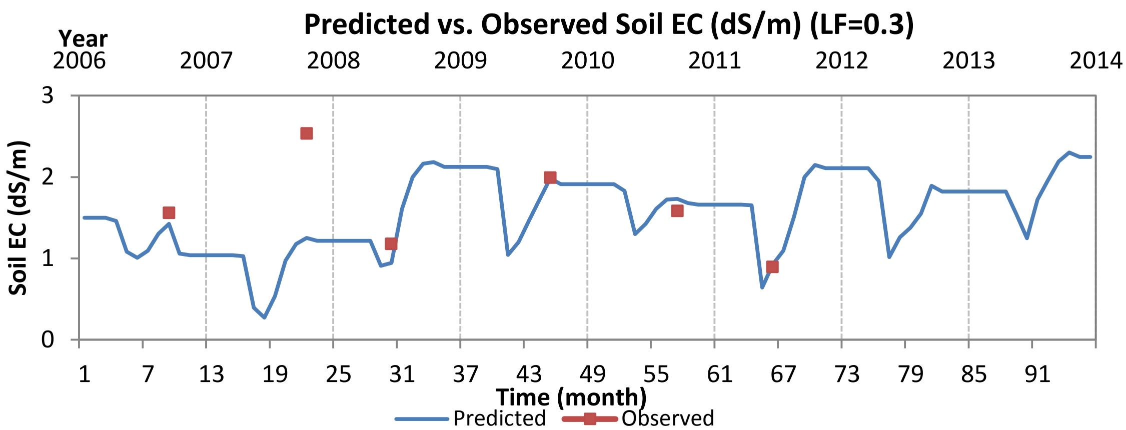
$$\bar{s} - \overline{s_o} = (Ic / D\lambda - \overline{s_o})(1 - \exp\left\{-(D\lambda / z\overline{\theta_{FC}})\,t\right\}) \tag{21}$$

Equation (21) predicts average soil EC concentrations in the root zone over time $\bar{s}$ (dS/m), where $\overline{s_o}$ is the initial average EC concentration in soil (dS/m), I is irrigation (mm), c is EC concentration in irrigation (dS/m), D is drainage estimated from the soil water balance under the assumption that no significant runoff occurs, or D=P+I-ET (mm), λ is a non-dimensional parameter, where $\lambda = s_z / \bar{s}$ in which s_z is the soil EC concentration at depth z (it is assumed here that if there is no difference in vertical distribution of the root-zone soil EC, then $\lambda = 1$), z is rooting depth (m), and $\overline{\theta_{FC}}$ is the average field capacity (cm^3/cm^3).

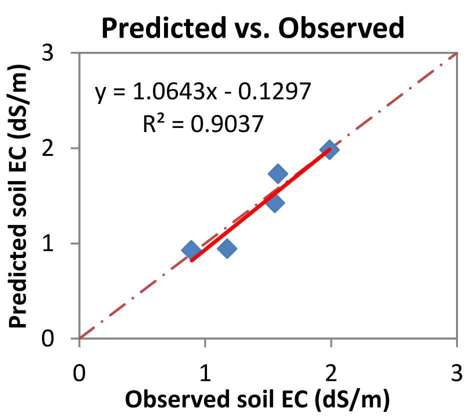
It is obvious that equation (21) is explicit since most of its parameters are known: I (mm) is the irrigation requirement, D (mm) is estimated from the soil water balance approach, c (dS/m) is wastewater EC, $\lambda = 1$, z = 0.5m is rooting depth, $\overline{\theta_{FC}}$ =0.37 is volumetric water content at field capacity, and $\overline{s_o}$ can be chosen. Note that both Rose et al. (1979) and the system model used the same approach to determine the drainage flux – the soil water balance approach D=P+I-ET. With the same inputs, P and I (mm), and output, ET (mm), the drainage value from the two models will be the same. Thus, drainage D (mm) can be borrowed from the system model. The main purpose here was to compare the soil EC predicted by the system model (solving numerically the mass balance equation (14), section 3.3.4) with that calculated from the explicit analytical solution – eq. (21) above.

Note that equation (21) is in continuous form; therefore, depending on the time scale (for example t=1 month, 0.5 month, 0.25 month and so on), the equation's roots may be discrete and approximate the continuous form, with smaller time scales resulting in a closer match to the continuous form. The results were plotted in Figure 57 with time scales of 1 month and 0.25 month for the approximation of Rose et al (1979)'s continuous analytical solution, while the system model was run at a much smaller time scale of 0.0078 month to ensure that the numerical solution converged.

Figure 57 shows that the predicted soil EC from Rose et al. (1979)'s solution and from the WISDOM model converged when the time steps used for the simulation were small enough: $t < 0.25$ month. These results along with the comparison between observed and model predicted soil EC above demonstrate that the solute transport sub-model simulates a conservative solute well.



(a)



Note: 2007 data point is excluded

(b)

Year	Soil EC (dS/m)		Difference (%)
	Observed	Model	
2006	1.55	1.42	8.5
2007	2.53	1.25	-
2008	1.18	0.94	19.8
2009	1.99	1.98	0.3
2010	1.58	1.73	9.5
2011	0.89	0.93	3.7
2012	-	1.82	-
2013	-	2.30	-

(c)

Figure 56. Soil EC output and validation

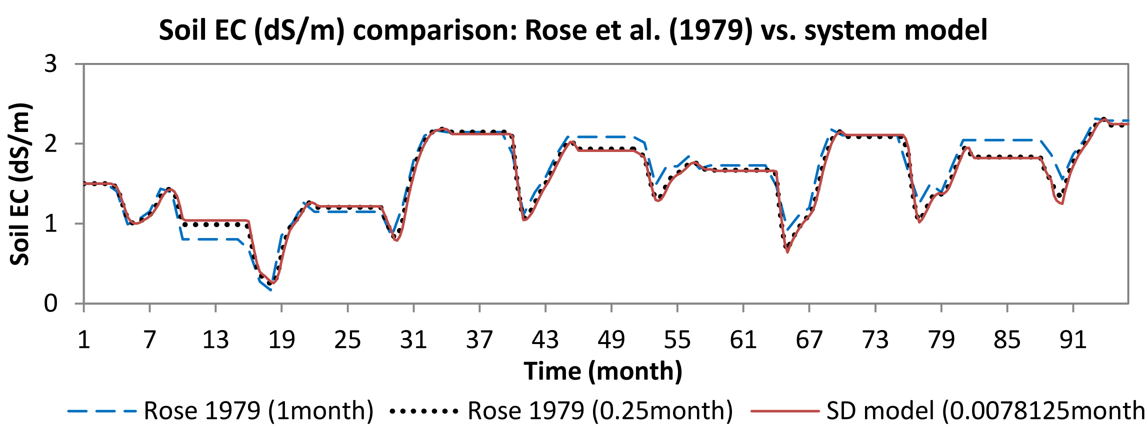


Figure 57. Comparison of soil EC between the approximations of Rose et al. (1979)'s analytical solution (time step = 1 month and time step = 0.25 month) and the WISDOM model result.

For the soil chloride values, the match between model-predicted and observed values for each month could not be directly compared, as shown in Figure 58. However, it is possible to compare the model-predicted trend with the limited observations. These observed values were measured from May-October 2010 (six values), while the time-varying wastewater-chloride values required for the system model to simulate annual soil chloride in 2010 was measured only once, in August (M. Blank, CWFC, personal communication, 2014).

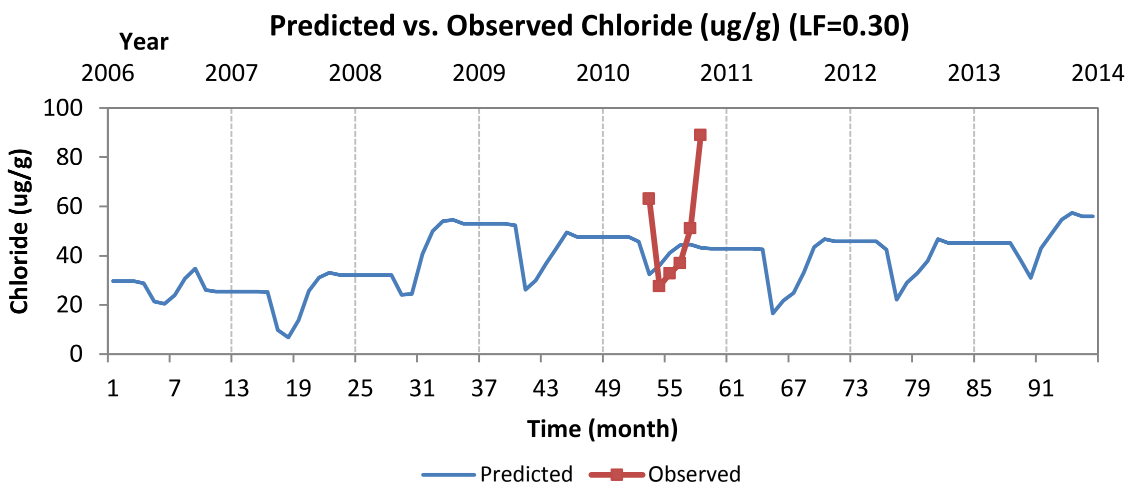


Figure 58. Comparison between soil chloride output and observed data (Data source: Gainer, 2012)

For a non-conservative solute, a comparison of soil NO_3-N and available P between predicted and observed values – plotted respectively in Figure 59 and 60 – showed that the SD solute transport sub-model underestimates the non-conservative solute in several years. This was because the model did not take into account complex interactions of different chemical processes that occur in soil such as nitrification, denitrification, mineralization, immobilization, and so on which are subject to soil organic matter.

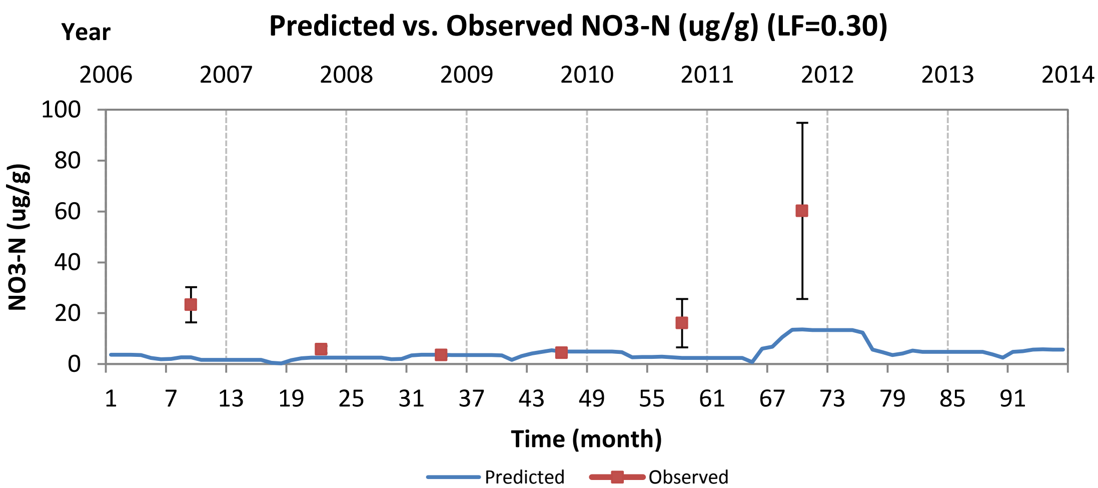


Figure 59. Comparison between predicted and observed soil NO3-N

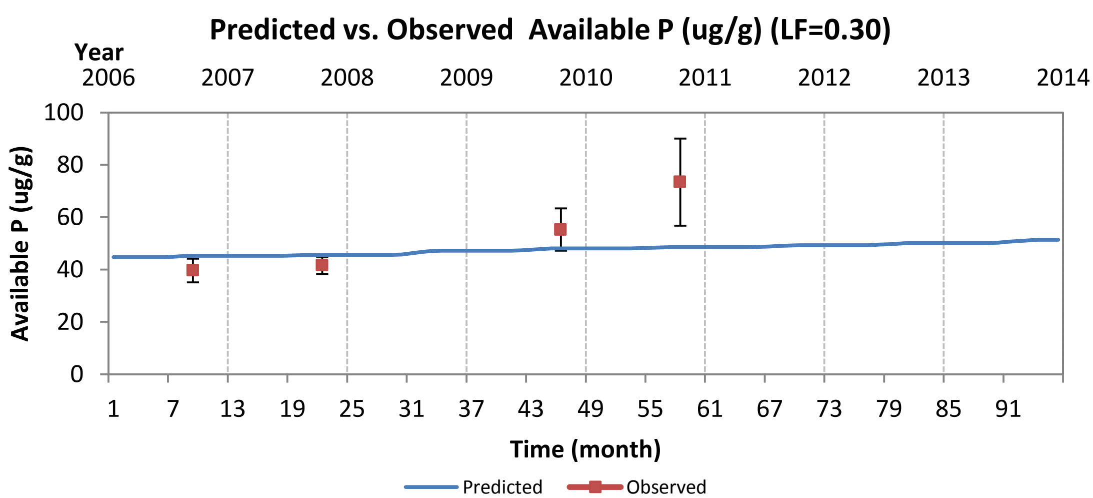


Figure 60. Comparison between predicted and observed soil available P

4.2.3.2 Model performance in unirrigated case

In the unirrigated case, the model continued to match the biomass production well ($R^2_{non\text{-}irr} = 0.92$), while the predicted tree height in this case was acceptable ($R^2_{non\text{-}irr} = 0.78$; see Table 21 and Figure 61). This was because the results for the unirrigated case differed from the irrigated case only by the modification of the water stress parameter – in other words, the model did not take into account the absence of nutrients provided by the wastewater and the consequent nutrient stress.

Table 21. Comparison between the predicted and observed stem biomass (ODT/ha) and stem height (m) of the unirrigated case

No.	**Year**		**Stem biomass (ODT/ha)**			**Stem height (m)**			**Note**
			Model (ODT/ha)	**Observed (ODT/ha)**	**Difference (%)**	**Model (m)**	**Observed (m)**	**Difference (%)**	
1	2006	Unirrigated	1.32	0.43	-	1.38	1.09	-	
2	2007		4.23	4.83	-	2.32	2.47	-	
3	2008		11.76	11.71	0.5	3.14	2.59	21.2	Harvest
4	2009		3.96	-	-	2.26	-	-	
5	2010		9.03	7.13	-	2.93	2.50	-	
6	2011		15.43	13.65	13.1	3.36	2.94	14.2	Harvest
7	2012		5.46	7.04	-	2.52	2.72	-	
8	2013		13.21	15.09	-	3.24	3.51	-	

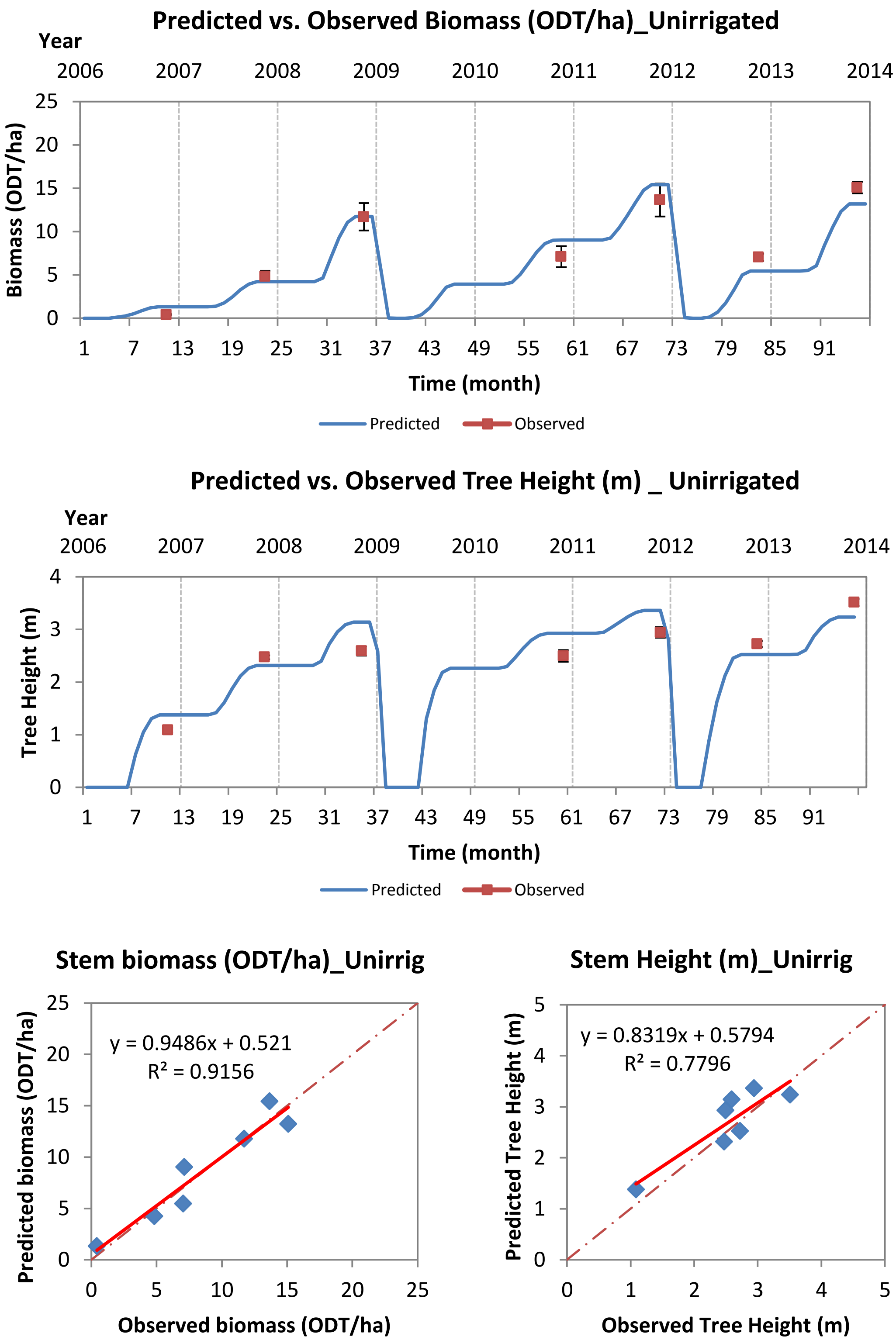


Figure 61. Plant growth – yield (ODT/ha) and stem height (m) outputs and validations (unirrigated)

5 INSIGHTS INTO WHITECOURT SRC PLANNING AND MANAGEMENT

System dynamics models are used to answer “what if?” questions, rather than for optimizing policies (Davies & Simonovic, 2011). For example, what happens if the leaching fraction or amount of irrigation requirement is increased or decreased? What if harvest occurs in a 4-year rather than 3-year rotation cycle? What if yield is lower than expected? If we use 8-year-average data to simulate a 22 year complete cycle of SRC, what would potential yields be? What happen to the harvesting process if the harvester does not perform as effectively as the producer’s standard? 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? And so on.

This chapter illustrates how the WISDOM model can be used as a powerful and useful instrument in the sustainable planning and management of SRC system. By playing with the WISDOM model to discover the answers for the above, and similar, questions, model users can learn insights into various aspects of SRC plantation and management as presented in the following sections. Further, users can update and run the model with observed and experimental data to achieve the most realistic scenarios.

5.1 Leaching Fraction Effects

Gainer (2012) investigated the deep drainage flux and water quality of SRCs irrigated with treated municipal wastewater at the Whitecourt site and suggested that the leaching fraction (LF) should be between 0.2 and 0.5 as explained in section 2.3.3. 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. Therefore, four scenarios of leaching fraction were simulated at intervals of 0.1 (the simulations thus used LF = 0.2, 0.3, 0.4, and 0.5). The influence of LF changes on the irrigation requirement, root-zone drainage, and soil EC are plotted in Figure 62.

The simulations revealed that the differences in the drainage and irrigation requirement between the four scenarios could be up to 250mm as in 2008 and 2013, for instance. The higher the leaching fraction or irrigation requirement was, the lower the resulting soil EC. With the irrigation requirement differences among the four scenarios, the maximum soil EC – which occurred in 2013 – decreased from 3 dS/m to 1.5 dS/m. Of course, the WISDOM model is intended as assistance for decision makers in addressing “what-if” statement rather than in optimizing the problem; therefore, the final choice of the leaching fraction is the farmers’ and decision-makers’, depending upon the acceptable salinity level, and the acceptable costs for irrigation, which are produced by the economic sector of the model.

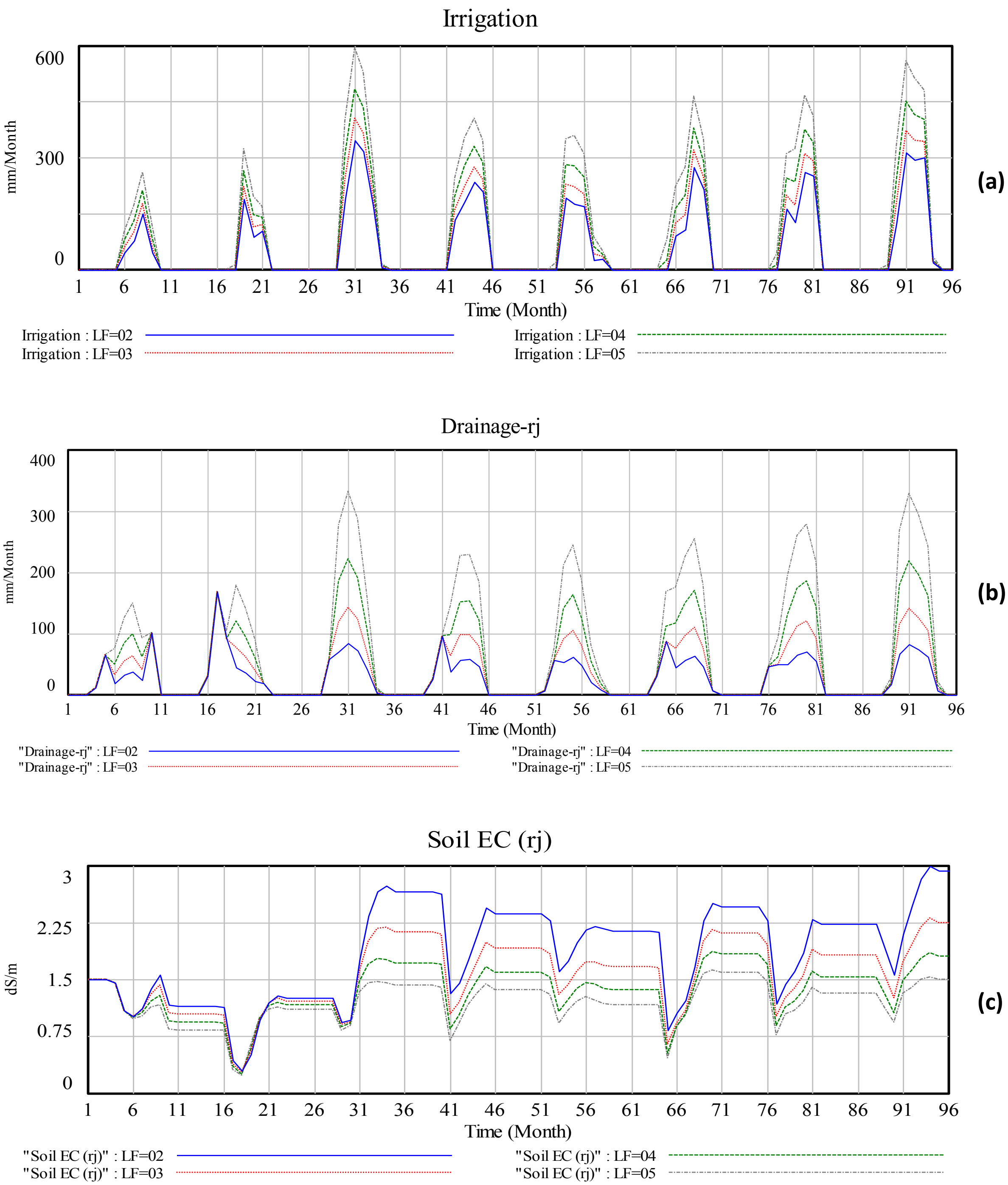


Figure 62. Effect of variation of leaching fraction to a) irrigation requirement, b) root-zone drainage, and c) soil electrical conductivity

5.2 Whitecourt SRC Plantation Growth and Yield

An important question in management of SRC plantations is whether biomass production for future years, and particularly a complete cycle which is 22 years – including 21 years or 7 rotations plus a year of preparation and establishment, can be predicted accurately by the WISDOM model. In essence, the yield, on one hand, determines the economic benefit of the project. On the other hand, SRCs are planted as a green energy source that is intended as a substitute for fossil fuel energy, and therefore its value in this regard is also important. This section portrays potential yields of an entire SRC project lifespan at the Whitecourt SRC trial site based on different yield-climate scenarios.

5.2.1 Yield Scenario Design and Simulation Data for a Complete SRC Life Cycle

As mentioned in section 3.3, the plant growth and yield sub-model is climate-driven; therefore, the simulation of a complete life cycle – 21 years – requires climate data for the full period. The key problem, of course, is that the input data for those years are uncertain. Climate data could be generated from climate generator software with a reasonable level of uncertainty, depending upon the length of historical data series.

Normally, long historical records of precipitation, air temperature, humidity, and wind speed are available. However, data on net radiation are rare and hard to obtain in the vicinity of Whitecourt, and are only available from 2006. For the sake of illustration here, data used for predicting biomass production into the future were generated from eight years of historical data (see section 4.2.1) using optimistic, average, and pessimistic scenarios, which correspond to maximum, average, and minimum yield. It is important to note that because the growth engine in the plant growth and yield sub-model is developed based on the light use efficiency principle (see section 3.3.2), it incorporates no water and salinity stresses, although these may be relevant factors in the case of irrigation requirements. In addition, as irrigation quantity or nutrient content varies between the scenarios (see Table 23 and the explanation below), the nutrient stress would differ for each case. However, the assumption here is that any nutrient deficiency can be corrected by fertilization, which means that nutrient stress can be neglected. The yield-dominating elements in this case are solely total incoming solar radiation and the remaining stressor, air temperature, as presented in Table 22 as follows:

Table 22. Scenarios for potential yield of future years

No	Scenario	Yield case	Net rad. Rn ($MJ/m^2/d$)	Air Temperature (oC)			Comment
				T_{max}	T_{min}	T_{mean}	
1	Optimistic	max	max	min	max	mean	Irrigation requirement case:
2	Average	avg	avg	avg	avg	avg	No water, nutrient, and salinity
3	Pessimistic	min	min	max	min	mean	stresses $f(\Theta_r)=1$, $f(FR)=1$, $f(S)=1$

The other climatic factors, including precipitation, humidity, and wind speed, only influence irrigation requirements through evapotranspiration, but will not affect the plant yield because the water deficiency between ET, drainage, and precipitation is offset by the irrigation applications. Therefore, if the irrigation cost is omitted because data are unavailable (as was assumed in section 4.2.1), the consideration of different irrigation scenarios is unnecessary. In contrast, climatic inputs are required for model simulation, and so the factors used in the three cases are shown in Table 23.

Table 23. Scenarios for irrigation correspond to the scenarios for yield

No	Scenario	Irrigation case	Precipitation (mm)	Humid (%)	Wind speed (km/hr)	Corresponding Yield case
1	Optimistic	min	max		min	max
2	Average	avg	avg	$f(\Delta T) = f(T_{max}-T_{min})$	avg	avg
3	Pessimistic	max	min		max	min

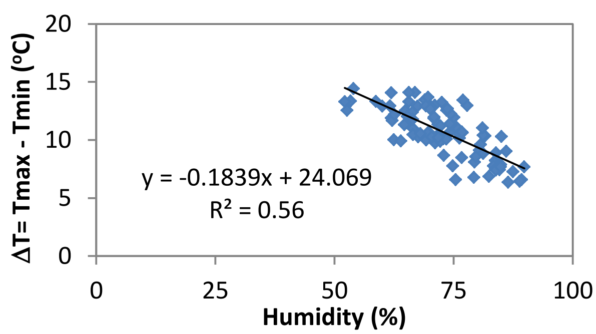


Figure 63. Correlation between humidity (%) and monthly air temperature difference $\Delta T= (T_{max}-T_{min})$ based on eight year historical data

The relationship between climatic factors is complex. To simplify the simulation, one variable is made to depend on the values of other variables; for example, humidity is obtained from the relationship between air temperature differences $\Delta T = (T_{max}-T_{min})$ as shown in Figure 63. Simulation data for the three scenarios are plotted in Figure 64.

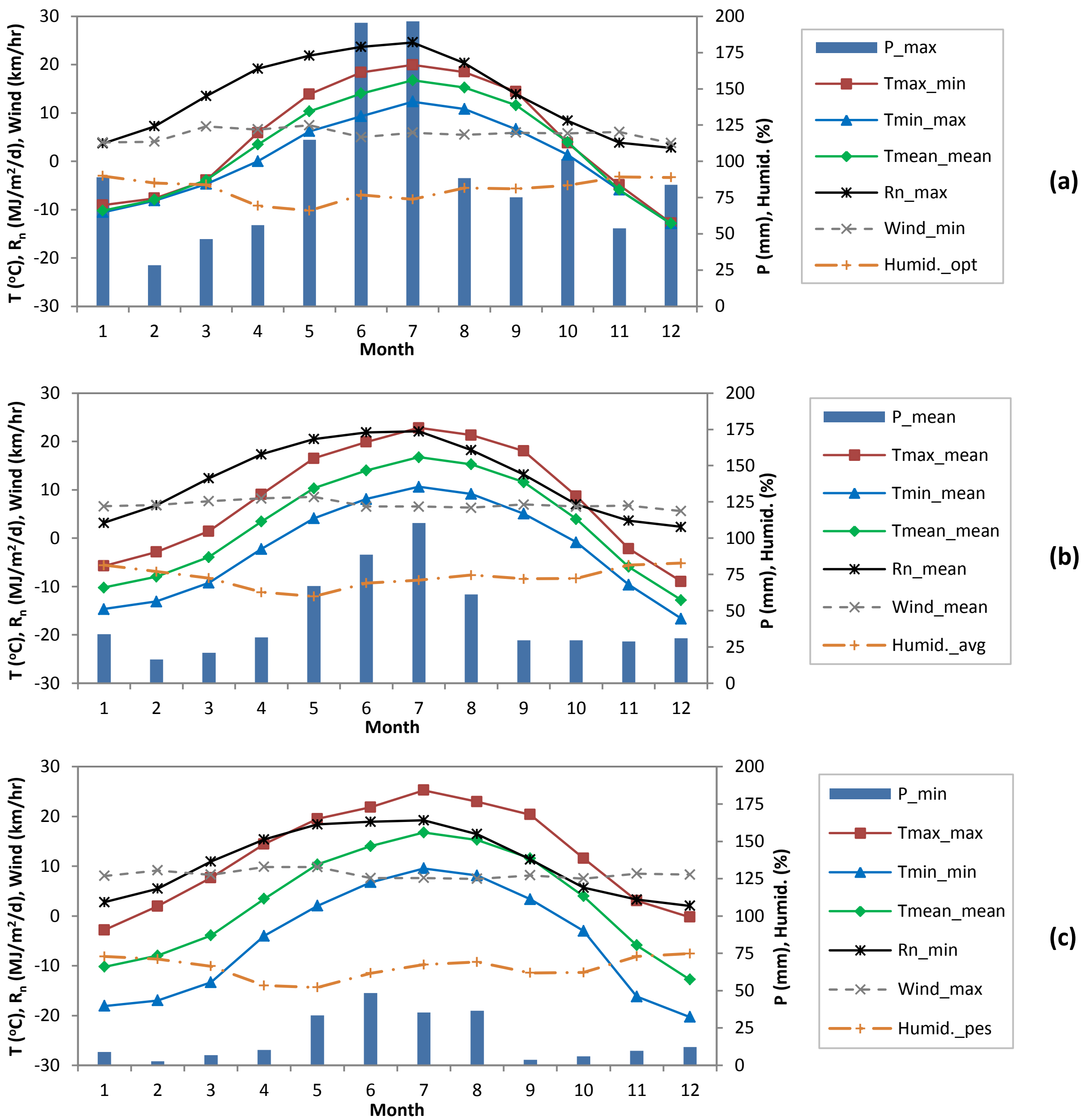


Figure 64. Simulation data for the a) optimistic, b) average, and c) pessimistic scenarios based on eight years (2006-2013) of data

5.2.2 Simulation Results for Whitecourt SRC Growth and Yield

The WISDOM model indicated only slight differences in the 2014 yields, with a range of approximately 22-25 ODT/ha. 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 24 and Figure 65.

Table 24. Predicted biomass production at different harvesting points of the three yield scenarios: optimistic, average, and pessimistic

Biomass (ODT/ha)	Rotation / Harvest Year	1st 2008	2nd 2011	3rd 2014	4th 2017	5th 2020	6th 2023	7th 2026
Observed		13.14	18.65	-	-	-	-	-
Predicted	Optimistic	13.56	18.73	25.44	28.97	29.69	30.13	30.20
	Average	13.56	18.73	23.94	24.56	25.23	25.72	25.87
	Pessimistic	13.56	18.73	21.91	18.36	19.16	19.60	19.96

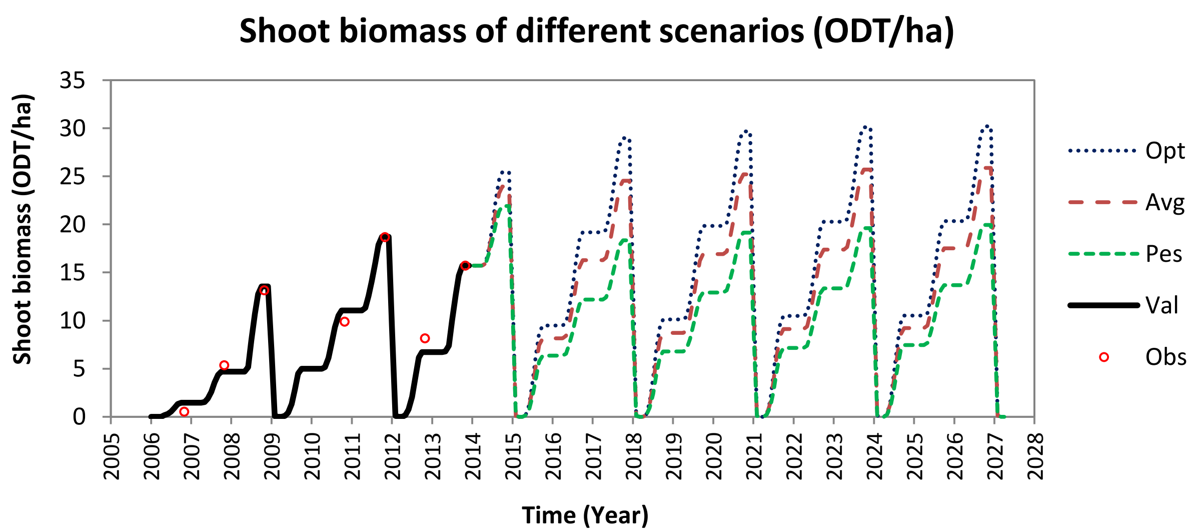


Figure 65. Prediction of biomass production for a complete 7-rotation cycle of the three scenarios: optimistic (opt), average (avg), and pessimistic (pes) based on validated (val) results and yearly observed (obs) values from 2006-2013.

Compared with the observed data from the first and second rotation, the anticipated yield in the average case increased by 88% and 36% respectively, and those of the optimistic case were 120% and 60%. With the 8-year pessimistic data, future yields after the next harvest in 2014 decreased to 19.5 ODT/ha/3-year-rotation or 6.5 ODT/ha/year.

Together, the pessimistic and optimistic scenarios showed future Whitecourt SRC yield ranges of 6.5-10 ODT/ha/year, a reasonable result compared with the range of 5-11 ODT/ha/year from North American field-scale studies conducted by Samson and Chen (1995), and others (Kenney et al., 1991; Heller et al., 2003; Volk et al., 2006, 2011).

5.3 Whitecourt SRC Plantation Economics

The biomass production predictions above relate to potential project revenue. Further, biomass energy content can be estimated based on the predicted biomass production, and thus an appropriate energy supply can be planned. However, to assess the project profit and other economic criteria such as the internal rate of return (IRR), and the net present value (NPV), either at a specific point in a SRC lifecycle or over the entire lifecycle, it is critical to investigate the effects of different expenditures on the SRC planting and harvesting cycle. As explained in section 2.6 (SRC expenditures) and section 3.3.8 (economic assessment), compared with the one-time preparation, planting, management, and re-cultivation (PPMR) costs and the relatively-stable yearly fixed- and indirect costs, the harvesting, transporting, drying, and storage (HTDS) costs occur several times over the SRC project lifespan and can be up to 30% of the total project expenditure. Moreover, the HTDS costs vary significantly between different harvesting equipment options, or even in the same harvesting method, for example using the bio-baler and differences in operating factors such as harvesting speeds, bale compactions, turning time, maintenance time.

This section investigates differences in the overall project economy caused by different harvesting methods and different harvesting speeds – the most important element of the harvesting operation (Phillips, n.y.) – in the same selected harvesting method.

5.3.1 Economic Scenario Design

The influences of different harvester selections and operations on the overall project economy were explored through twenty seven scenarios as shown in Table 25.

Table 25. Design of twenty seven economic scenarios

No.	Scenarios	Yield	Harvesting methods	Harvesting speeds (km/hr; bales/hour)		Assumption
1	Opt_JF_max	Optimistic	Harvest 1 (JF 192)	max	5.0	* General assumption (for all three harvesters): - Initial moisture content=50% - Wet chip density ρ=0.3T/m^3 * Specific assumption: - JF-192 and HS-2: the harvesting speed modifier k_{speed}=1 if fresh yield < 30 T/ha, k_{speed}=0.6 if fresh yield > 60 T/ha, and k_{speed} is interpolated linearly if fresh yield is in the middle of that range. - Bio-baler: Bale weight=308 kg/bale
2	Opt_JF_avg			average	3.5	
3	Opt_JF_min			min	2.0	
4	Opt_HS_max		Harvest 2 (Claas HS-2)	max	9.7	
5	Opt_HS_avg			average	8.1	
6	Opt_HS_min			min	6.4	
7	Opt_BB_max		Harvest 3 (Bio-baler)	max	40.0	
8	Opt_BB_avg			average	27.5	
9	Opt_BB_min			min	15.0	
10	Avg_JF_max	Average	Harvest 1 (JF 192)	max	5.0	
11	Avg_JF_max			average	3.5	
12	Avg_JF_max			min	2.0	
13	Avg_HS_max		Harvest 2 (Claas HS-2)	max	9.7	
14	Avg_HS_avg			average	8.1	
15	Avg_HS_min			min	6.4	
16	Avg_BB_max		Harvest 3 (Bio-baler)	max	40.0	
17	Avg_BB_avg			average	27.5	
18	Avg_BB_min			min	15.0	
19	Pes_JF_max	Pessimistic	Harvest 1 (JF 192)	max	5.0	
20	Pes_JF_avg			average	3.5	
21	Pes_JF_min			min	2.0	
22	Pes_HS_max		Harvest 2 (Claas HS-2)	max	9.7	
23	Pes_HS_avg			average	8.1	
24	Pes_HS_min			min	6.4	
25	Pes_BB_max		Harvest 3 (Bio-baler)	max	40.0	
26	Pes_BB_avg			average	27.5	
27	Pes_BB_min			min	15.0	

These twenty seven scenarios were designed based on the combination of the three yield scenarios of section 5.2.1 with the three harvester options (JF-192, HS-2, and bio-baler) and three harvesting speeds (including maximum, average, and minimum speeds). The harvesting speeds were obtained from Phillips (undated) and manufacturer’s manuals – see Table 2, section 2.3.6. Note that the general assumption for all three harvesters about the initial moisture content was approximately 50% and the wet chip density was approximately 0.3T/m^3. For the bio-baler, the bale weight was assumed to be 308 kg/bale, based on the bio-baler real operation data from CWFC-CFS – a much smaller value than the 500-600 kg/bale from the manufacturer's manual. For the JF-192 and the Claas HS-2, the harvesting speed modifier was k_{speed}=1, if the fresh yield was less than 30 T/ha, and k_{speed}=0.6 if the fresh yield was greater than 60 T/ha; if the fresh yield was in the middle of the range, then k_{speed} was interpolated linearly.

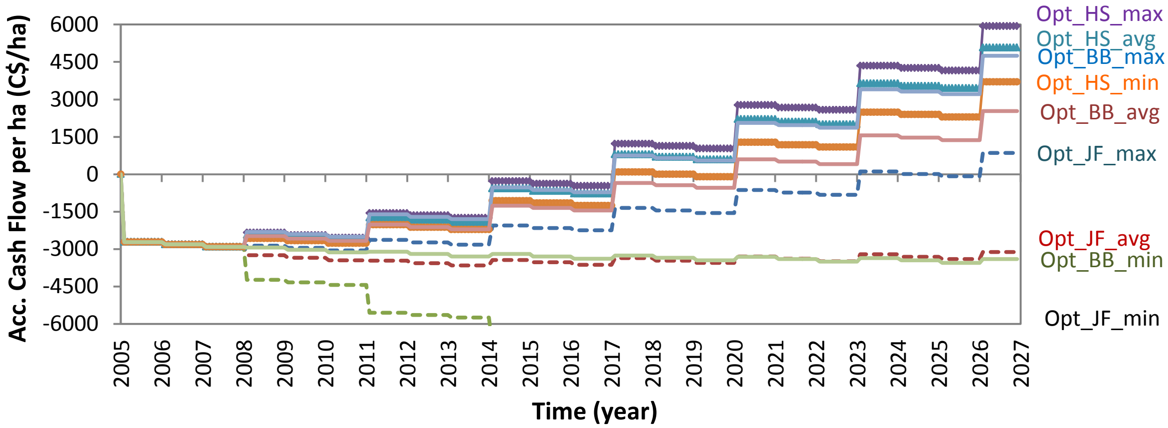
5.3.2 Whitecourt SRC Economic Scenario Results

Simulation results of the twenty-seven economic scenarios – based on the inputs described in section 4.2.1 (Table 13-Table 17) and in the previous section – are plotted in Figure 66. Note that changes in any input or assumed values will lead to different results, as discussed below, and could change the order of the results shown in the graphs.

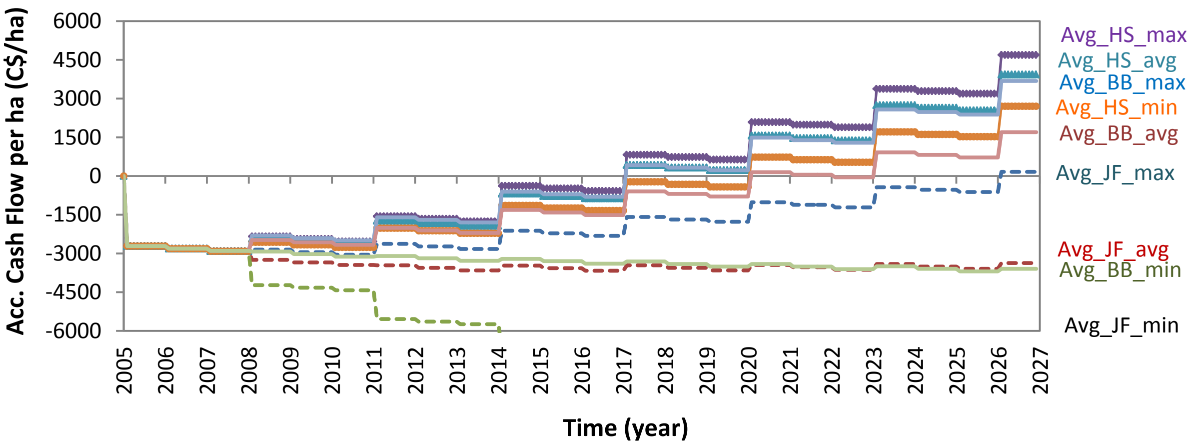
The WISDOM model results indicated that the selection of the Claas HS-2 harvester with the maximum operating speed would bring the project owners the highest profits in all three scenarios at the end of a complete life cycle. The optimistic, average, and pessimistic scenarios produced approximately $6000, $4700, and $2800 per hectare, respectively, compared with the other harvester options. In addition, the results permitted an interesting comparison: the operation of the bio-baler at the maximum speed of forty 300 kg bales/hour resulted in similar profits to the Claas HS-2 harvester operating at the medium speed of 8 km/hr, adjusted by the assumed speed modifier. Of course, such comparisons are imperfect, since (as explained in section 5.3.1), the bale weight differs between the real operation – about 250-350 kg/bale (M. Blank, CWFC, personal communication, 2014) – and the manufacturers' manual, which gives a bale mass of about 500-600 kg (AndersonGroup, 2013). Further, the actual harvester speed can be lower than the minimum speed provided in the manufacturer's manual – for example, an experiment with the Claas HS-2 produced an average harvesting speed of 5.3 km/hour (Phillips, n.y.). Thus, this research aimed to provide a wide range of plausible results to assist decision makers in managing SRC systems and improving project economics.

Use of the JF-192 harvester, even at the maximum operating speed, resulted in break-even economics at the end of the lifecycle in both the optimistic and average yield cases, and negative results in the pessimistic yield case. The probable cause was that the harvesting time was longer than for the Claas HS-2 and bio-baler harvesters, since the JF-192 can handle only one SRC row at a time. Thus, although the JF-192 unit ownership cost (C$/hour) was relatively low compared with the Claas HS-2 and bio-baler costs, which were $24.81, $75.31, and $41.4 per hour respectively, the JF total harvesting cost was much higher because of the much-longer harvesting time. To use the JF-192 more efficiently for harvest, it is necessary to minimize ownership and other equipment operating costs (fuel, wage, and maintenance costs), as well as the turning, hydraulic arm adjustment, and maintenance times – and to test the results in the model. Inefficient JF-192 or bio-baler use through, for instance, slow harvesting speeds coupled with high ownership and operating costs could results in zero or negative profits on each harvest years as the shown in Figure 66 (see specifically the Opt, Avg, Pes_BB_min; the Opt, Avg, Pes_JF_avg; and the Opt, Avg, Pes_JF_min lines).

The results also indicated, importantly, that it took at least four rotations (12 years) in all situations to start making a profit – shown as a positive cumulative cash flow.



(a)



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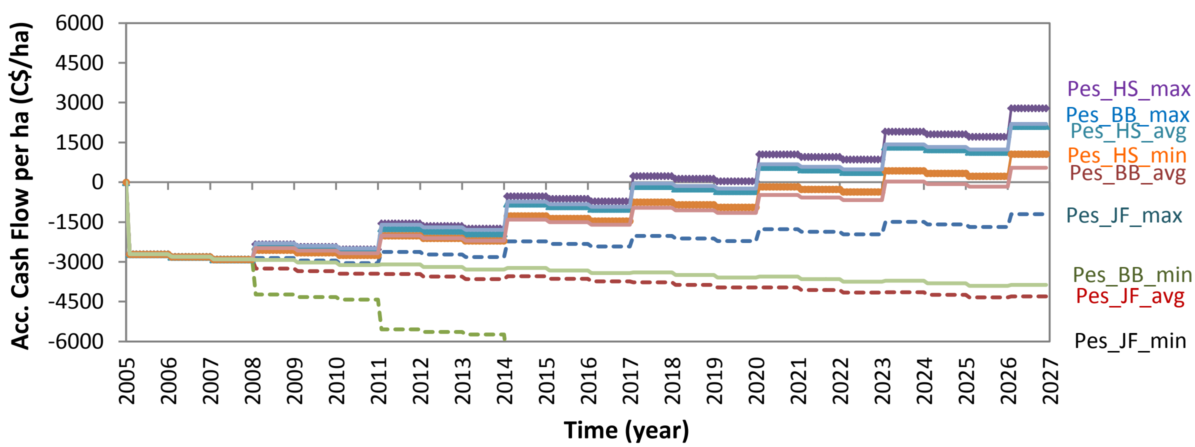


(c)

Figure 66. Prediction of the overall project economy under the case of (a) optimistic yield, scenarios 1-9, (b) average yield, scenarios 10-18, and (c) pessimistic yield, scenarios 19-27 in the Table 25, using different harvesters (JF-192, claas HS-2, and bio-baler) combining with different operating speeds (max, average, and min)

Instead of using cumulative cash flow, an alternative way to assess the results of different economic scenarios is through the net present value (NPV) and the internal rate of return (IRR). NPV, sometimes referred to as present value (PV), present worth (PW), or net present worth (NPW), is “the equivalent value at time 0 of a set of cash flows”(Eschenbach, 2011, p. 120). A project that has positive NPV is good, while a project with a negative NPV should not receive investment, based on the definition of NPV above. IRR, sometimes referred to as economic rate of return (ERR), is “the interest rate that makes both the present worth and equivalent annual worth equal zero” (Eschenbach, 2011, p. 176). Note that the equivalent annual worth is “the uniform dollar amounts at the ends of periods 1 through N that are equivalent to a project’s cash flows” (Eschenbach, 2011, p. 147). Normally in project management, assuming that there are many projects and all other factors are equal among the various projects, the project with the highest IRR would be considered the best and would probably be undertaken in preference to the others.

The formula for NPV is (adapted from Eschenbach, 2011):

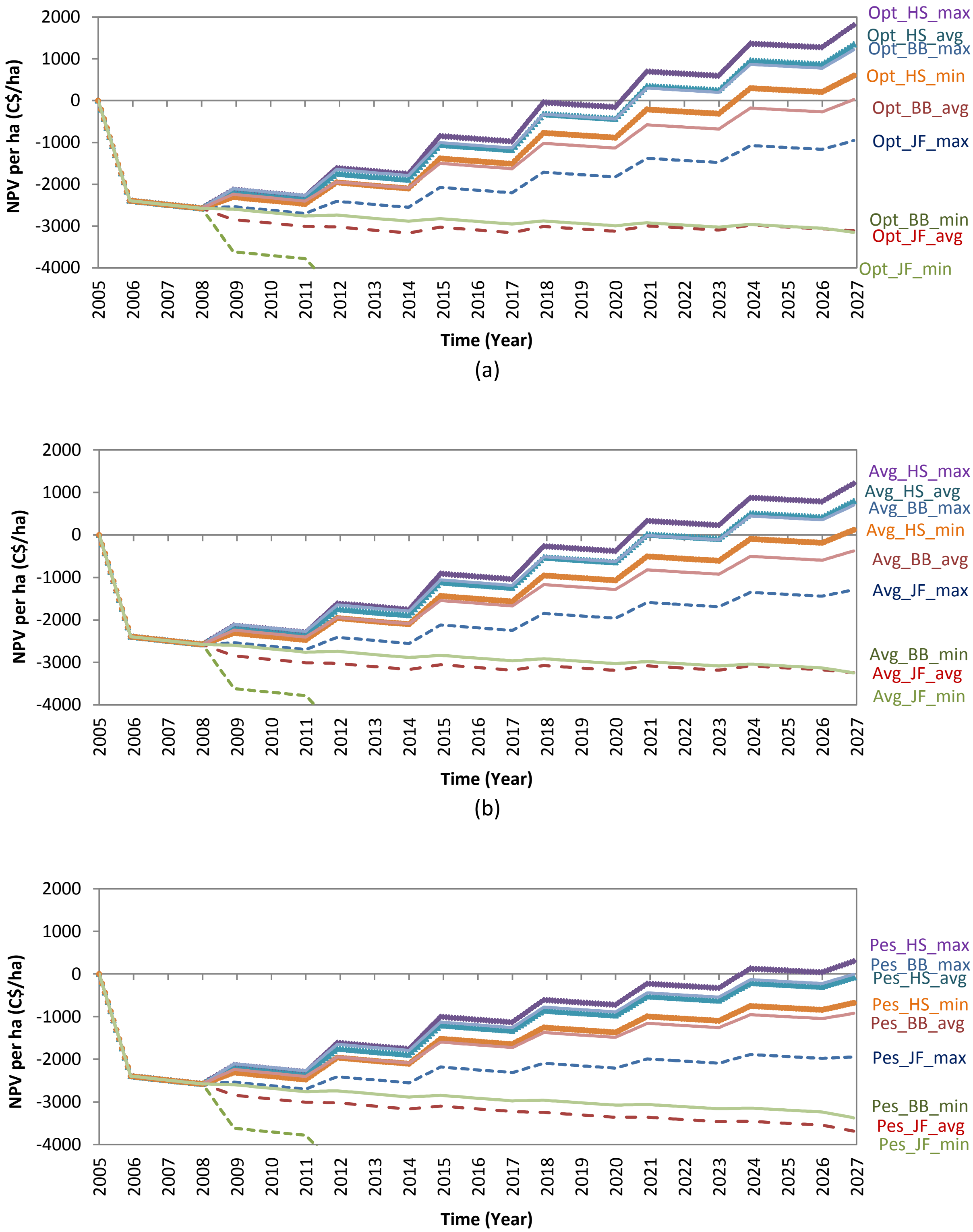
$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o$$

where C_t is the net cash inflow during the period ($/time), C_o is initial investment ($), r is discount rate (%), and t is number of time periods.

The net present values (NPVs), based on a discount rate of 4% (see Table 16, section 4.2.1), and internal rate of returns (IRR) of the twenty-seven scenarios under the optimistic, average, and pessimistic yields were plotted in Figure 67 and 68.

The results showed that with the discount rate of 4%, only several scenarios had positive NPVs at the end of a complete life cycle. For optimistic and average yields, Figure 67 shows that using Claas HS-2 harvester and operating at any speed brought a positive NPV, but that the bio-baler must operate faster than the medium speed to produce a positive NPV at the end of the life cycle. For the pessimistic yield to achieve a positive NPV, the Claas HS-2 harvester had to operate at higher than medium speed, while the bio-baler had to operate at the maximum speed, as shown in Figure 67c. In all three yield scenarios, using the JF-192 harvester could not bring positive NPVs at the end of the lifecycle, even operating at maximum speed as illustrated in Figure 67.

In addition to NPV, IRR was used to compare the results of different economic scenarios. Like the NPV graphs, the IRR graphs (Figure 68) indicate that using the Claas HS-2 harvester at the maximum speed brought the highest IRRs: 8.7, 7.4, and 5% for optimistic, average, and pessimistic yield scenarios respectively. Harvesting with the biobaler at maximum speed produced the same IRRs at harvesting with the Claas HS-2 at medium speed, which were 7.6, 6.3, and 3.7% respectively, as shown in Figure 68.



(c)

Figure 67. Net present values (NPV) per ha (C$/ha) under the case of (a) optimistic yield, scenarios 1-9, (b) average yield, scenarios 10-18, and (c) pessimistic yield, scenarios 19-27 in Table 25.

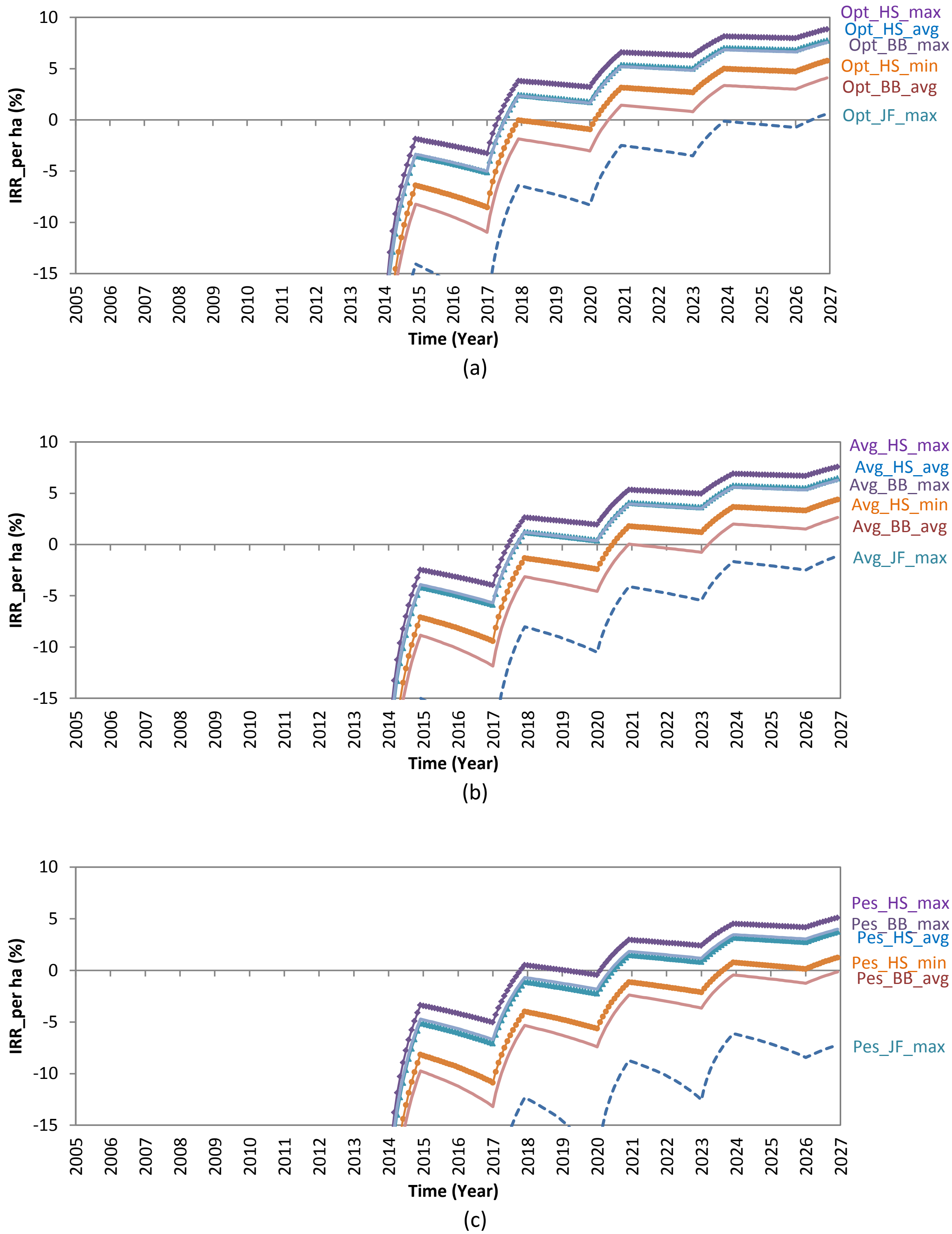
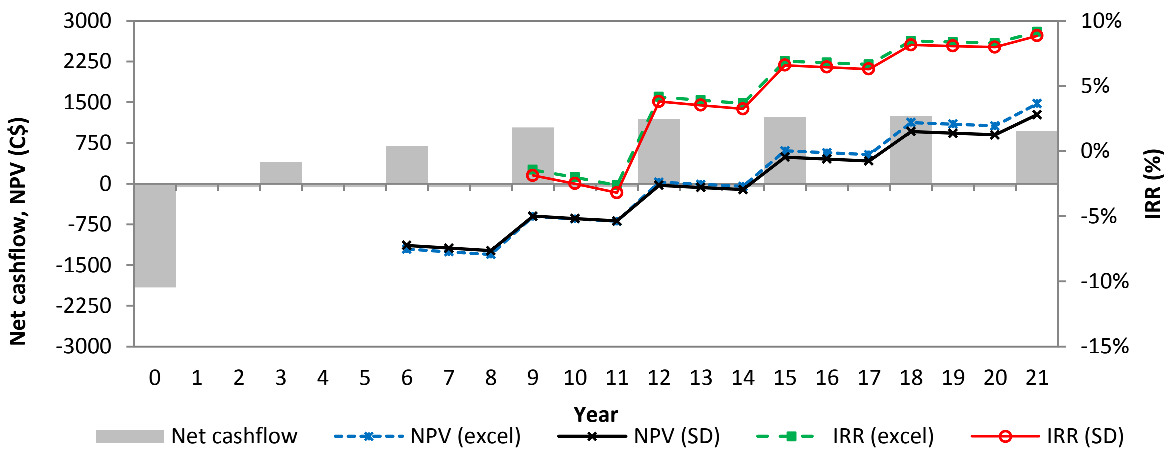
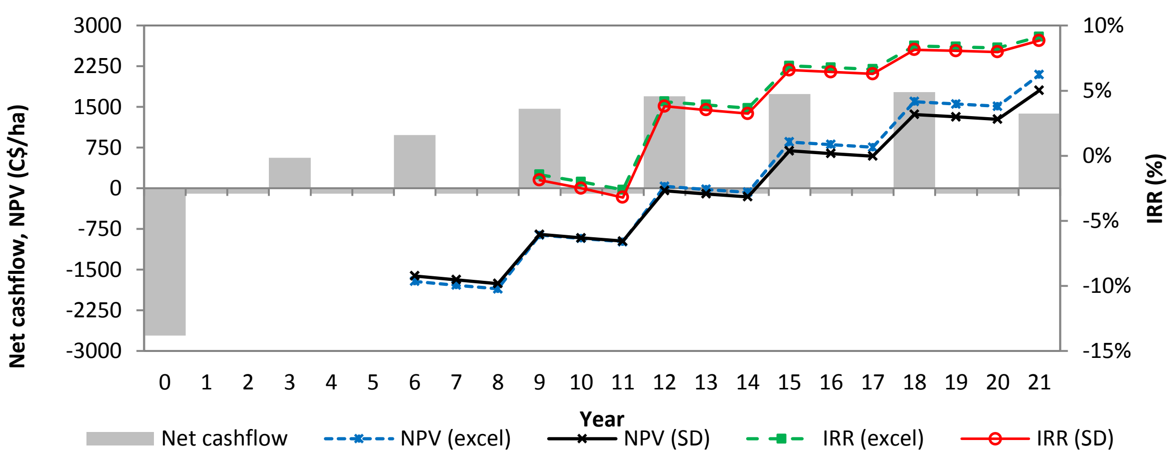


Figure 68. Internal rates of return (IRR) per ha (%) under the case of (a) optimistic yield, scenarios 1-9, (b) average yield, scenarios 10-18, and (c) pessimistic yield, scenarios 19-27 in Table 25.

Finally, with a known net cash flow, the net present value (NPV) and the internal rate of return (IRR) can also be determined using Microsoft Excel. A comparison between the NPV and IRR values calculated by the WISDOM model and Microsoft Excel are shown in Figure 69. These results demonstrated that the WISDOM model was conservative in both the IRR and NPV calculations, with approximately a 0.5% difference from the Microsoft Excel results in the IRR calculation.



(a)



(b)

Figure 69. Comparison of NPV (C$, C$/ha) and IRR (%) calculated by the WISDOM model and Microsoft Excel for (a) total area and (b) per ha for the case of Opt_HS_max as a demonstration

6 CONCLUSIONS and FUTURE RESEARCH

This chapter addresses the four research questions from the introduction and provides a list of recommendations for future work.

6.1 Application of System Dynamics to Short-Rotation Coppice System

The first questions asked whether short-rotation coppice (SRC) plantations are "systems", and whether systems modelling is applicable to decision-making for SRCs. Clearly, the answers to both questions are 'yes'. System dynamics is a well-established system modelling methodology and has been applied successfully in a broad range of fields, from natural to social sciences, in economics, engineering, education, management, ecology, public health, and sociology (Forrester, 2007a, 2007b; Sterman, 2000). System dynamics has been employed successfully for SRC systems as described in chapter 3, from the construction of SRC system maps, or "causal loop diagrams", to the development of stock and flow diagrams and the WISDOM simulation model. Further, the model has been tested through application to the SRC plantation at Whitecourt, Alberta, with good simulation results, as shown through close matches between simulation results and observations with R^2=0.98 for biomass production, R^2=0.92 for tree height, R^2=0.9 for soil EC, and so on, as described in chapter 4 and 5.

6.2 SRC System and Importance of Intersectoral Feedbacks

The second question dealt with the significance of inclusion, or integration, of "intersectoral feedbacks" – a key component of systems analysis – as compared with more traditional single-disciplinary approaches. Indeed, according to Parson and Fisher-Vanden (1997, p. 590), "most useful assessment is integrated to some degree, since few real policy issues or decisions can be usefully advised by drawing only on the knowledge of a single research community". As explained in chapter 2, SRCs are complex systems that involve interactions and feedbacks between biological-chemical-physical and socio-economic aspects. These linkages and feedbacks were represented in a general CLD and seven sectoral CLDs mentioned in chapter 3 and appendix A, including:

1. Biomass production: *SRC Growth-Soil-Water*
2. Irrigation supply: *SRC Growth-Wastewater Treatment-Irrigation Supply*
3. Environmental quality: *SRC Growth-Irrigation Water Quality-Soil Quality-Water Quality*
4. Bioenergy: *SRC Growth-Bioenergy-Climate Change*
5. Land use: *SRC Growth-Producers-Land Use-Biodiversity*
6. Production cost: *SRC Growth-Production Costs and Profits*
7. SRC policy: *SRC Growth-Local Economy-Government Policy*

The inclusion of intersectoral feedbacks is important. Feedback linkages allow stakeholders and decision-makers to trace effects caused by changes in variables throughout the system – in other words, using causal loop diagrams to see how a change is transferred from one variable to others in the system. In addition, using the stock and flow diagrams and particularly the simulation model – both based on the causal loop diagrams – stakeholders and decision-makers can explore the effect of different policies and their unintended consequences acting not only on the selected element and component, but also on other different elements and components of SRC system through the system feedbacks. Therefore, the identification of feedbacks helps to improve the understanding of SRC systems and planning for SRC plantation management. This systems view may become more important as SRC-cultivated areas expand. For instance, from an economic perspective, SRCs are attractive because they can bring profit both from growing biofuels and from treating wastewater. However, does a larger SRC area necessarily bring higher profits, and does a much larger SRC area provide much higher economic profits? In reality, SRC plantations are affected by trade-offs also involve other considerations, such as wastewater treatment requirements and the available irrigation supply, regulation and management of soil and water quality, land use, and so on.

6.3 Development of the WISDOM model

The third question concerned the incorporation of modified existing models of SRC sectors into WISDOM, along with newly-constructed model sectors. As WISDOM contains many different components that simulate biological-chemical-physical and socio-economic components of SRC system and their linkages, this approach not only saves time and effort, but also helps to combine strengths of these models to produce a reliable, useful decision-support tool.

As described in chapter 3, WISDOM contains seven interconnected components. Four of these components were newly constructed as system dynamics models, including 1) soil water, 2) solute transport, 3) energy content, and 4) carbon mitigation, while three were developed based on existing, validated models, including 5) plant growth and yield, 6) harvest and transport, and 7) economic assessment.

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 dissolve solid, 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, which has been proved successful in simulating SRC biomass production in the US and Canada (Amichev et. al., 2010, 2011, 2012; Headlee et al., 2012; Nair et al., 2012). 3-PG is a well-known, process-based, forest growth modelling, and free-of-charge software developed by CSIRO (Landsberg and Sands, 2011). There were two major simplifications and one major adaption of the original 3-PG in the PGY model, including simplification of the basic stand-level sub-model, simplification of the growth modifiers for site and environmental effects, and modification of plant functional types in 3-PG. The harvest-transport component of WISDOM was developed based mainly on the "KUP-Ernteplaner", a German harvest-support tool (CREFF, 2012) with two major improvements: use of the detailed cost calculations presented in the "Ecowillow" model (Buchholz & 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 & Volk (2010), with two improvements: using the concept of SRC process chain expenditures presented in Marron et al. (2012), and replacing the static harvest-transport cost calculation in Ecowillow with a more detailed version in the WISDOM harvest-transport component.

6.4 The Application of WISDOM

The fourth question asked whether the WISDOM model can be used as a decision-support tool to improve understanding of interactions and feedbacks between the various system components to help stakeholders and decision-makers to plan the establishment of environmentally- and economically-sustainable SRC plantations.

Again, the answer is 'yes'. As illustrated in chapter 4, WISDOM was used to simulate successfully many components of an SRC system at the Whitecourt site, such as stem biomass and height under both irrigated and unirrigated cases, irrigation requirements, soil electrical conductivity (EC), chloride, soil nitrogen and phosphorus, and other model variables with very good results. In chapter 5, WISDOM was utilized to understand the effects of alternative decisions on system behaviour through "what-if" scenarios. The simulation of different leaching fractions was provided as an example. Further, three climate scenarios run for Whitecourt SRC provided yield predictions, and twenty seven yield-harvest-combined scenarios illustrated 20-year economic forecasts over a complete SRC life-cycle. Together, these sorts of scenarios can provide insight into the establishment and management of the Whitecourt site into future years.

6.5 Recommendations for Future Research

Future model development could occur in two directions: improving the current components of WISDOM, and developing and incorporating new components into WISDOM.

6.5.1 Component improvements

The current version of WISDOM performed well; however, several sectors of WISDOM should be improved to get better results or broader application.

- Plant growth and yield: this sector was developed based on 3-PG, a forest-growth model, and two major simplifications were made in the PGY model. To improve the PGY component of WISDOM, all the key parameters of 3-PG could be incorporated. This would make WISDOM applicable not only to SRC plantations (willow or poplar) in particular, but also to short-rotation forestry (such as eucalyptus, nothofagus, poplar, sycamore, and ash plantations) in general. Note that harvest of short-rotation coppices often takes place on a regular cycle of approximately two to four years with the trees are cut back to stools to promote the growth of multiple stems, while that of short-rotation forestry occurs only once between eight to twenty years when the tree diameters at breast height reach 10-20 cm, depending upon the tree species (McKay, 2011).

- Solute transport: the solute transport component of WISDOM underestimated the non-conservative solutes, such as soil nitrogen and phosphorus, because the model did not include the complex interactions between chemical processes that occur in soil, including nitrification, denitrification, mineralization, immobilization, and so on, which are affected by soil organic matter.
- Economic assessment: WISDOM analyzes SRC economics by accounting for the sale of biomass production as the main source of profit. However, in some regions, SRCs are not cultivated purely for commercial purposes. For example, in the Camrose County, Alberta, SRC plantations combined with a wood biomass-fuel heating-system is non-commercial, and benefits municipally-owned and public buildings. In this case, the economic analysis becomes more complex because the profit of biomass production is zero and the expenditures of the heating-system set-up and operation have to be taken into account. An integrated economic assessment between wastewater treatment costs, SRC wood-biomass energy, and fossil fuel energy displacement should be conducted at the local-economy scale.

6.5.2 Component development

The current version of WISDOM contains seven interconnected components and can represent and simulate linkages, feedbacks, and results of different natural and socio-economic aspects of SRC plantations. However, outside the current model boundary presented in chapter 3 (see Figure 27), there are problems related to SRC plantations that are described in the general CLD (Figure 26), including environmental regulations, social effects, the local economy, and government policies. In the longer term, depending upon user demands and the level of available data, the entire simulation model could account for all these components. Specifically, the potential components include,

- Irrigation supply and demand: it is important to balance irrigation supply and demand to maximize the use of available municipal wastewater and the corresponding biomass production, while minimizing the treatment cost. As presented in section 2.7, Hurdle (2012) developed a wastewater treatment decision-support tool for SRC plantations. This tool should be incorporated into WISDOM.
- Environmental regulations: this component should be developed to reduce stakeholders' and decision-makers' time and effort in evaluating environmental impacts of SRC cultivation. Instead of manually checking and comparing model outputs with standard permissible levels, such as those related to nutrient leaching, this sub-model would simulate values for relevant variables and notify users of any exceedances. However, as environmental regulations/laws vary from region to region and country to country, this component should be developed in a flexible way so that users can enter the relevant regulations.
- Land-use: the economics and energy supply of SRC plantations may cause their area to expanding quickly, as mentioned in chapter 2. The expansion of SRC sites also requires larger supporting facilities, such as wastewater storage ponds. Together, these expansions may result in significant changes in land use between SRC plantations, agricultural cropland, and forests, and may affect biodiversity and the regional landscape. A land-use component should be developed to estimate the land use required for SRC sites, wastewater storage ponds, and other supporting facilities.
- Local economy: as mentioned above, when SRCs are planted for non-commercial purposes, the project economics should be viewed in an integrated sense that balances wastewater treatment costs, SRC biomass energy production, and fossil-fuel energy displacement. For instance, the use of SRC biomass energy will substitute the use of fossil fuels, costs of fossil fuel consumptions should therefore turn into profits.

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APPENDIX A: SEVEN SECTORAL CAUSAL LOOP DIAGRAMS

This appendix presents the seven sectoral causal loop diagrams (CLDs) mentioned in the system map for SRC section of chapter 3, these sectoral CLDs include,

1. Biomass production: *SRC Growth-Soil-Water*
2. Irrigation supply: *SRC Growth-Wastewater Treatment-Irrigation Supply*
3. Environmental quality: *SRC Growth-Irrigation Water Quality-Soil Quality-Water Quality*
4. Bioenergy: *SRC Growth-Bioenergy-Climate Change*
5. Land use: *SRC Growth-Producers-Land Use-Biodiversity*
6. Production cost: *SRC Growth-Production Costs and Profits*
7. SRC policy: *SRC Growth-Local Economy-Government Policy*

Each CLD contains many variables with their distinct colors, the meanings of them can be found in Table A-1.

Table A-1. The meanings of distinct colors in the CLDs

Variable Type	Meaning
Red variables	These variables are very important in the CLD.
<Blue variables>	These "shadow variables" are not very important in the current view CLD, but can be found and are important in other CLDs where they appear as bold black or red variables. These variables link different CLDs.
Orange variables	As parameters or exogenous variables, they affect other variables in the CLDs, but they themselves are not affected by any variables.
Green variables	There are significant uncertainties with the linkages, as well as changes in variable values. These variables need more attention.
Bold black variable	These variables are more important than black variables, but less important than the red ones.
Purple variable	These variables are assumed to be in an ideal or "optimal" state, and could be either ignored or omitted from the CLD.

A1. Biomass production CLD (SRC Growth-Soil-Water)

The biomass production CLD – Figure A-1,2,3 provides the details for one of seven sectors of the large-scale CLD, and is related to that larger CLD through five main variables which play important roles in SRC plantation and growth: irrigation, SRC growth, soil nutrient, soil water and salinity in the root-zone.

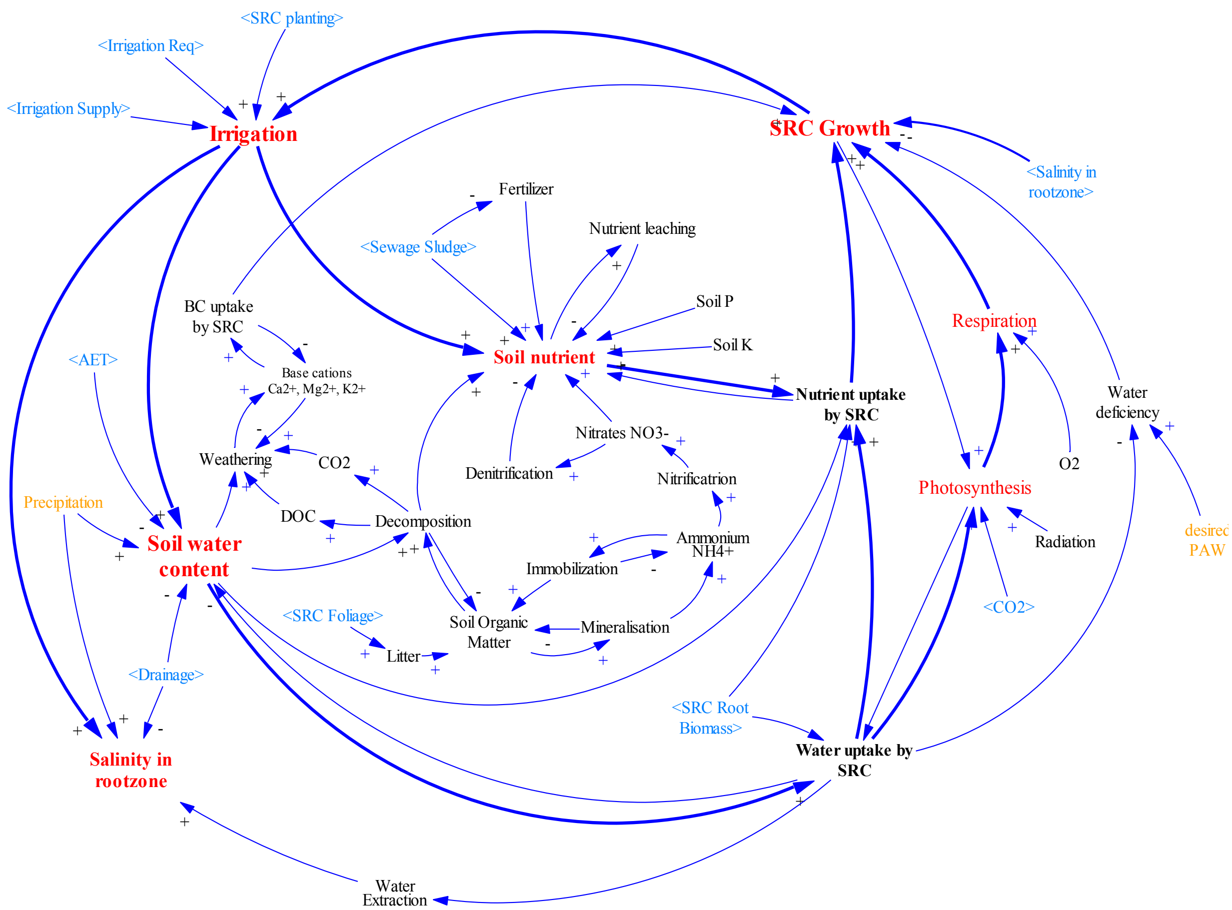
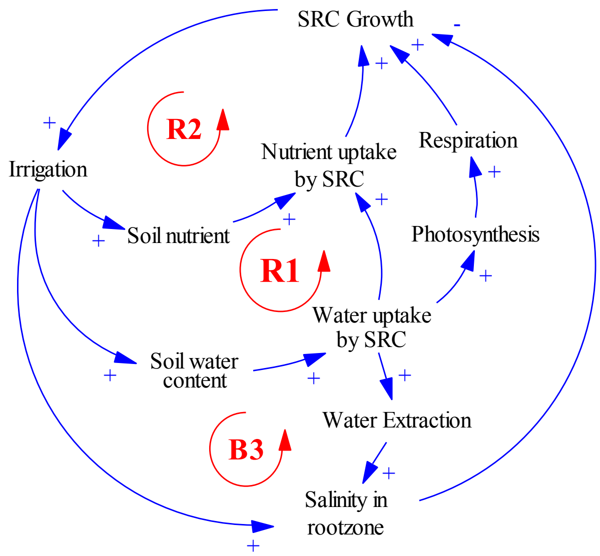


Figure A-1. Full biomass production CLD



- loop (R1), the “soil water reinforcing feedback loop”
- loop (R2), the “soil nutrient reinforcing feedback loop”
- loop (B3), the “yield-reduction balancing-feedback loop”

Figure A-2. Simplified biomass production CLD

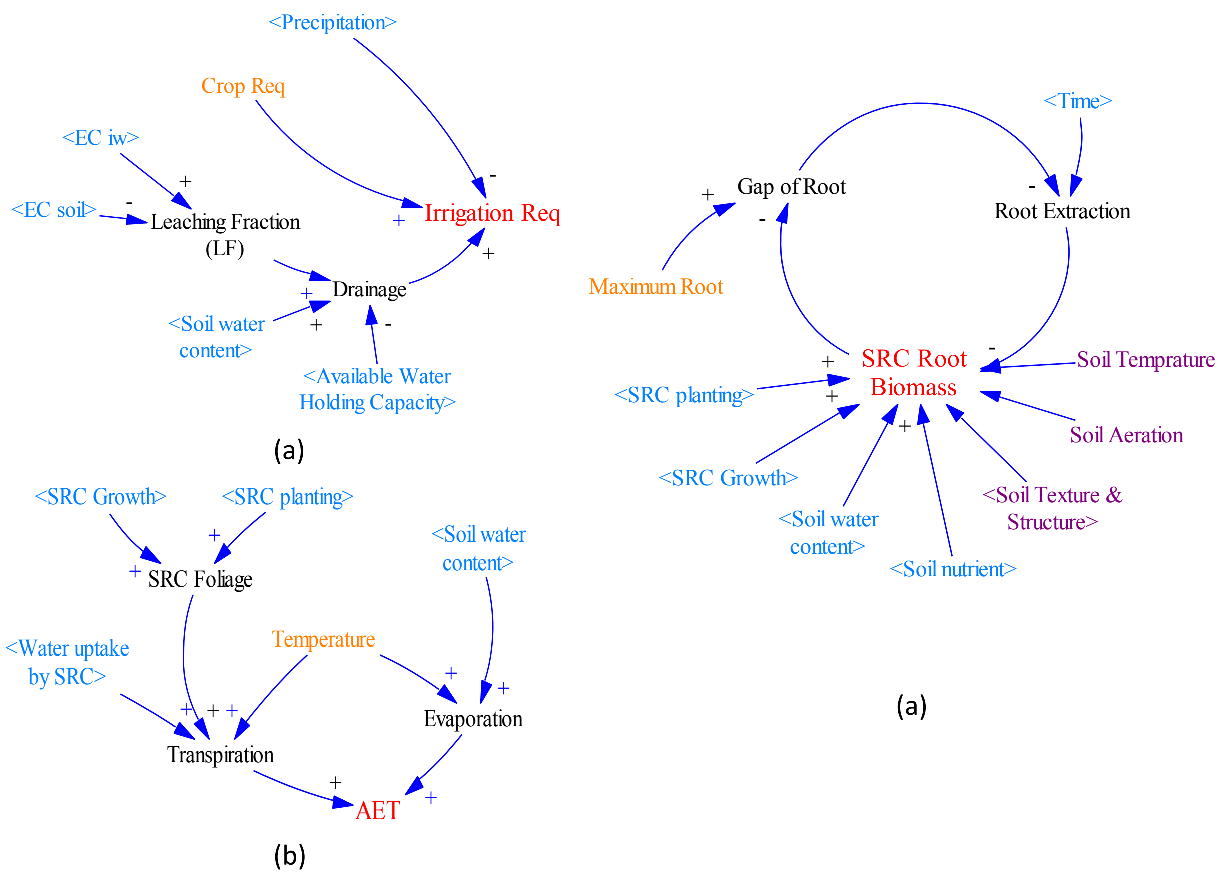


Figure A-3. Plant Growth CLDs
a. Irrigation Requirement, **b.** Actual Evapotranspiration, **c.** SRC Root biomass sub-CLD

A2. Irrigation Supply CLD (SRC-Wastewater Treatment-Irrigation Supply)

The irrigation supply CLD, as part of the large scale CLD, affects other sectors like biomass production through the irrigation variable, or local economy through the wastewater treatment cost. Increases to the irrigation application also affect the environmental sector in terms of soil quality and water quality through both the nutrient and effluent contents – Figure A-4.

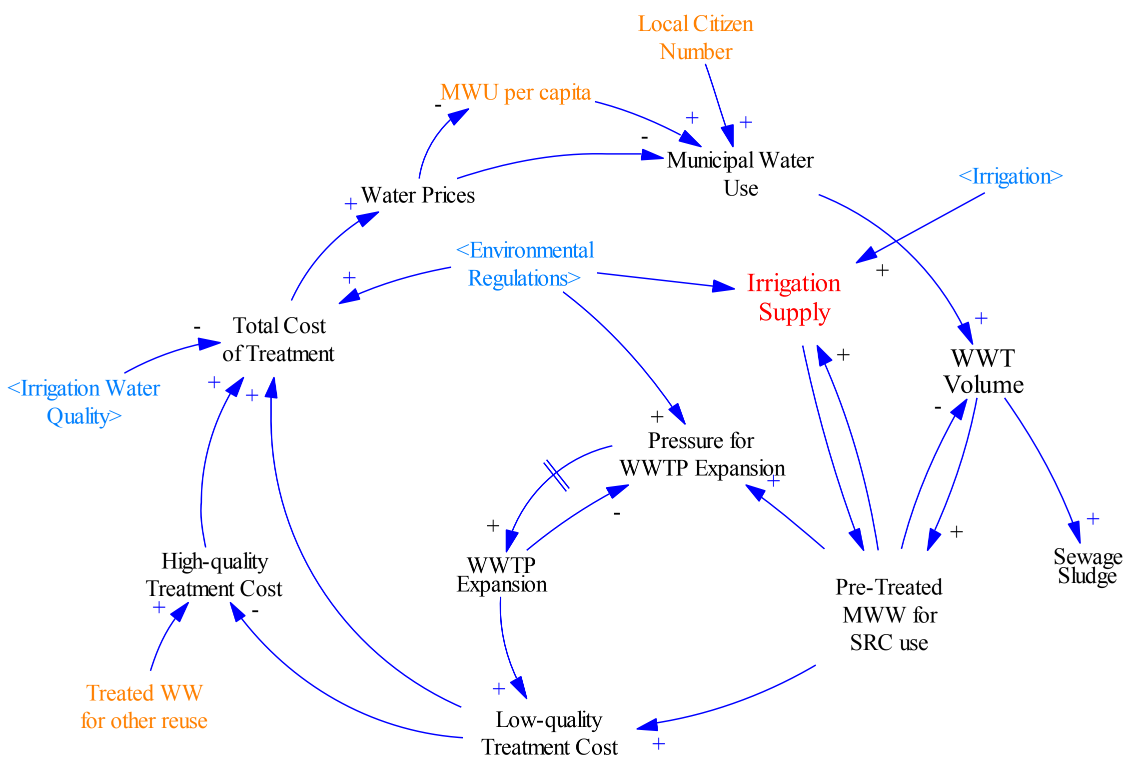


Figure A-4. Irrigation Supply CLD

A3. Environmental Quality CLD (SRC-Irrigation-Soil-Water)

This CLD focuses on the irrigation water quality and its influence on soil quality, and ground and surface water. When evaluating the irrigation water quality, there are numerous factors that must be included (see Figure A-5); however, it is possible to categorize water quality according to groups based on 1) general chemical parameters, including electrical conductivity (EC), sodium adsorption ratio (SAR), total suspended solid (TSS), total dissolved solid (TDS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD), 2) excess nutrients, such as nitrogen, nitrate, and phosphorus, 3) major cations and anions, and 4) pathogens. Note that, for each site in Alberta, these factors must satisfy the standard regulations from Alberta Environment *AENV (2000)*, like the guidelines for municipal wastewater irrigation in Alberta.

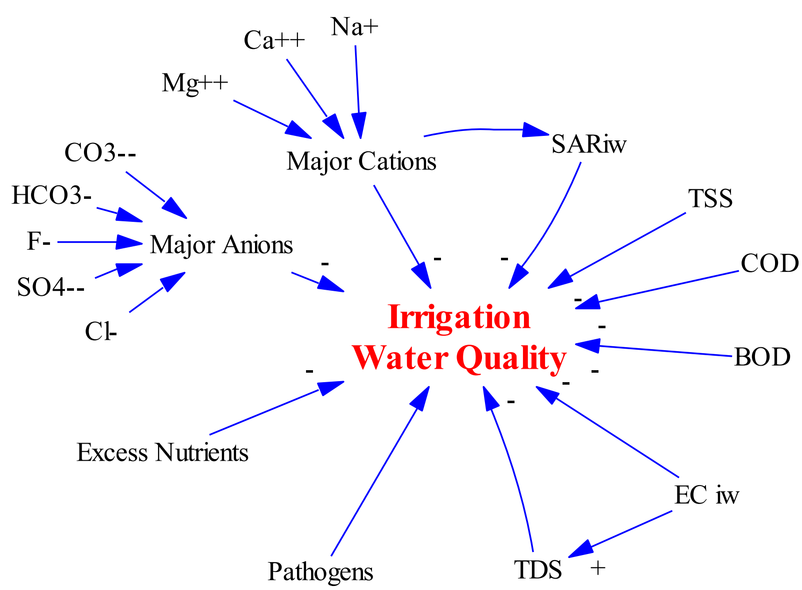


Figure A-5. Irrigation Water Quality CLD

The application of treated wastewater and sewage sludge provides nutrients to the soil, and thus helps to improve the soil quality. However, the contaminants and heavy metals contained in both also reduce soil quality. In addition, the cultivation of SRC can enhance the soil quality as it can play the role of phyto-remediation or phyto-extraction to help reduce the toxic elements in soil. However, during the cultivation process, herbicide use for weed control poses a risk for soil quality, and later on for ground and surface water quality. Figure A-6 represents the linkages amongst the various factors stated above, especially the dynamic links with other sub-CLDs like irrigation water quality, or with other sector, such as biomass production through the SRC planting and irrigation variables.

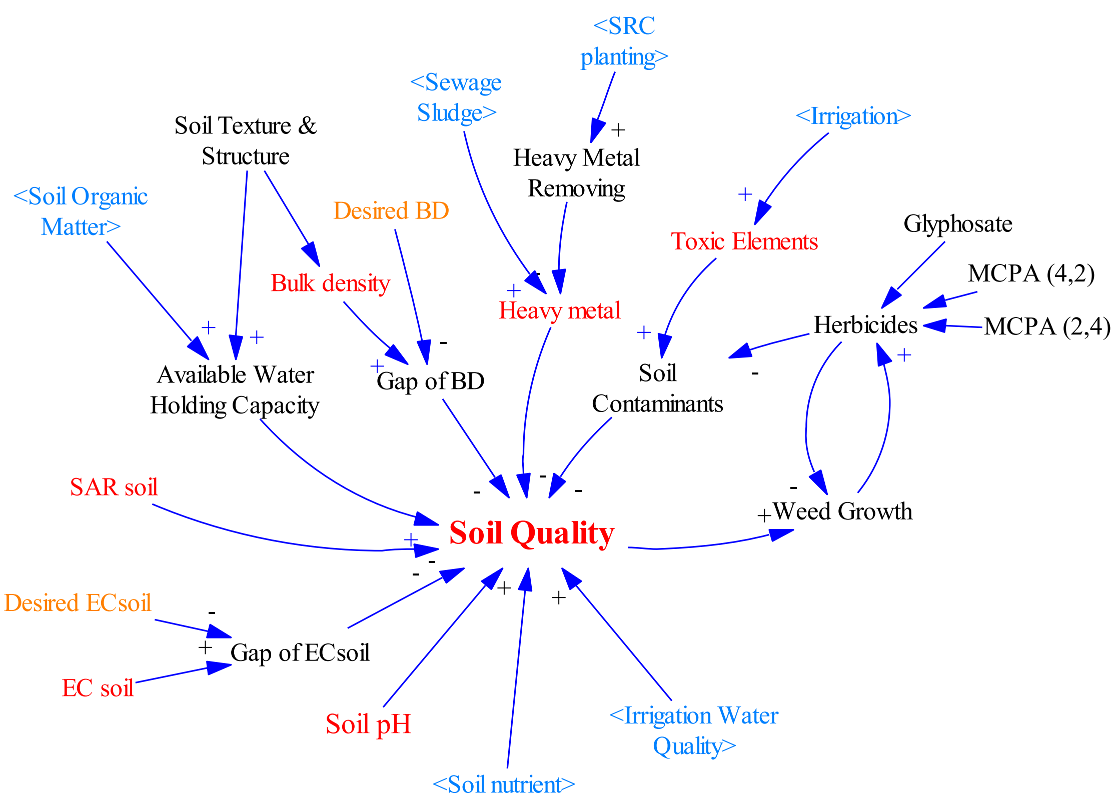


Figure A-6. Soil Quality CLD

Water flow through the soil may leach the contaminants, nutrients and pathogens in soil derived from the irrigation water quality to the groundwater. Depending on the phyto-extraction capability of SRC and the concentrations of contaminants in soil, the contamination level of groundwater can differ significantly. Further, the ground water quality is affected by the salt leached from the root-zone during soil salinity control. The SRC plantation and its root system also affect water percolation to groundwater, which may lead to an impact on the groundwater table and contribute to the threat of groundwater pollution. All of the pollutants in the groundwater may then be transported to the nearby streams or rivers. Depending on the pollutant concentration in the groundwater and the pollutant carrying capacity of the stream or river, the surface water can become polluted. If such pollution occurs, then surface water use can threaten public health and aquatic life, and cause changes to existing environmental regulations, or cause promulgation of new regulations. All of the causal links described above are shown in the ground-surface water quality CLD of Figure A-7.

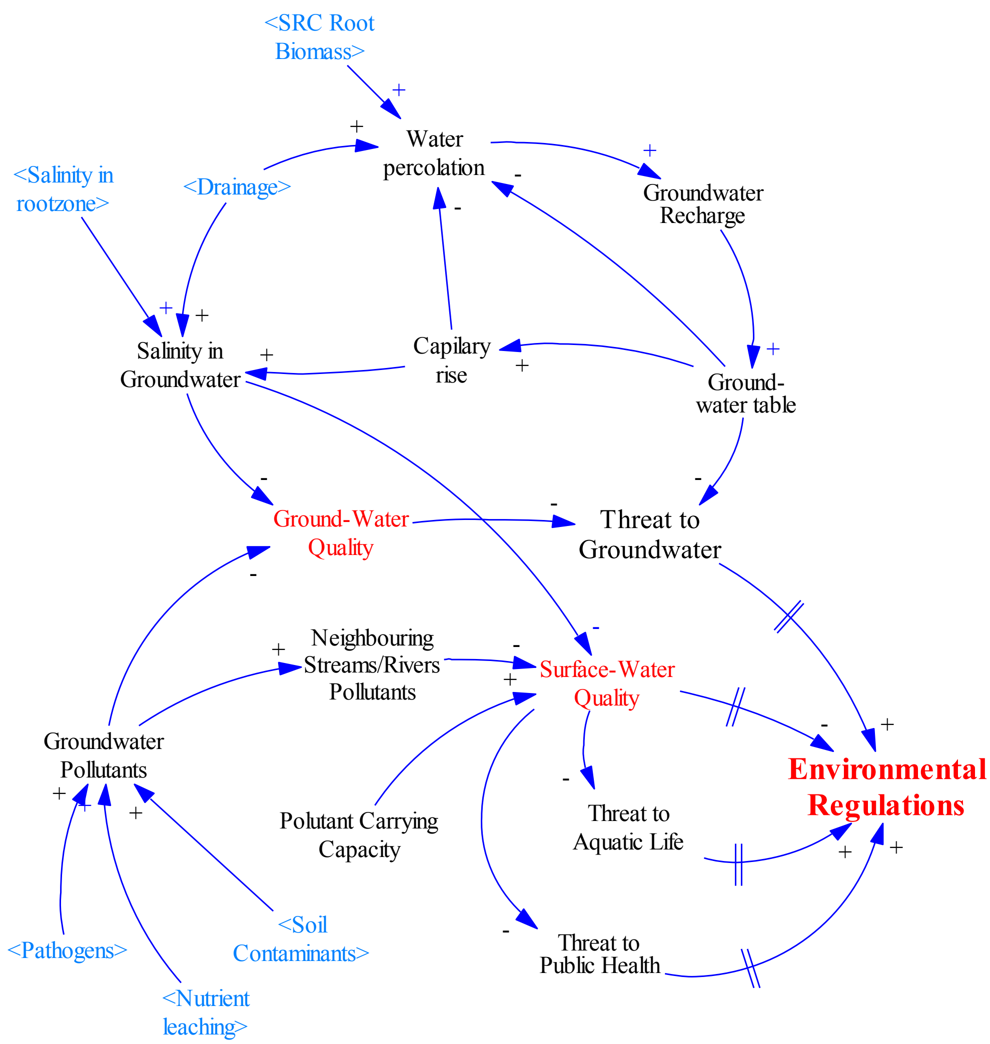


Figure A-7. Ground and Surface Water Quality CLD

A4. Bioenergy CLD (SRC Growth–Bioenergy–Climate Change)

The bioenergy CLD – Figure A-8 is a crucial sector of the large-scale CLD, as it affects and is affected by a variety of sectors, such as SRC policy and biomass production. The bioenergy CLD links to the climate change factor in the large-scale CLD through the reduction of greenhouse gas (GHG) emissions, which comes from the substitution of bioenergy for fossil fuels and from the carbon sequestration that occurs as the crop grows.

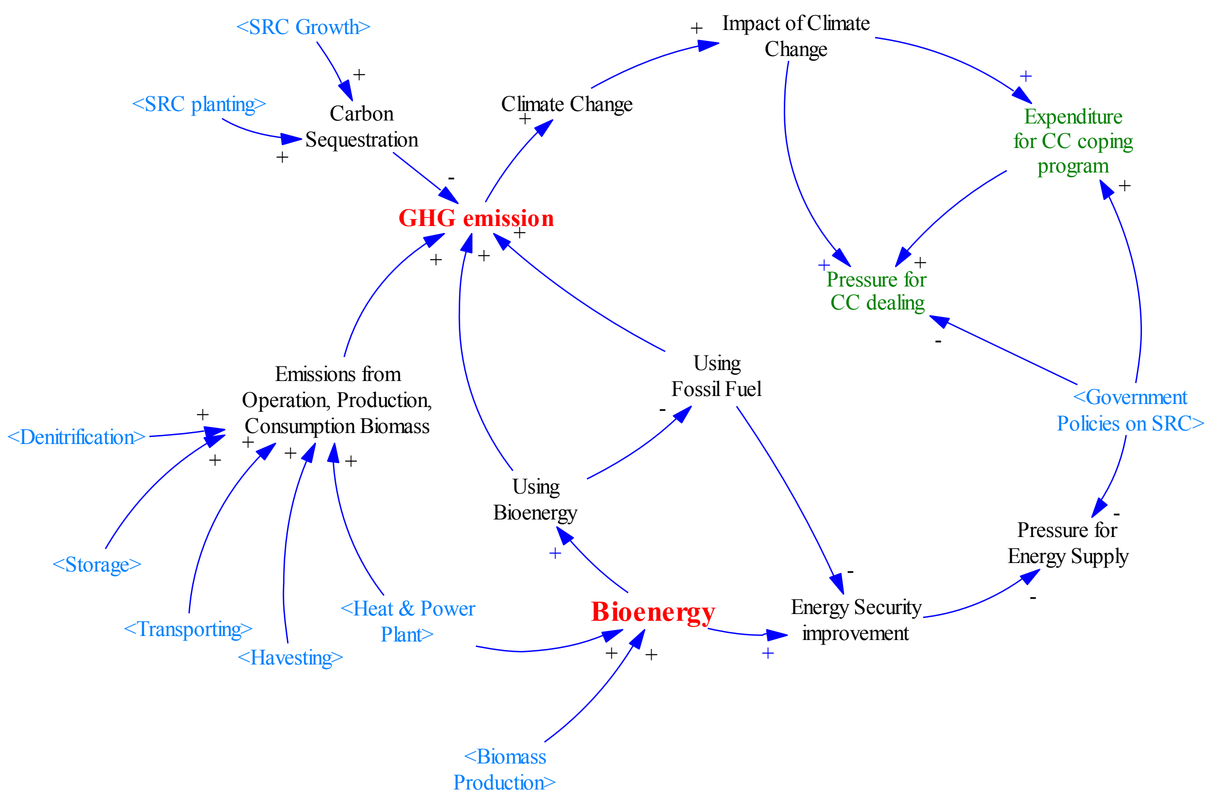


Figure A-8. Bioenergy CLD

A5. Land Use CLD (SRC-Producer-Land Use-Biodiversity)

In Canada, the SRC plantation area is still relatively small. Nonetheless, several nations in Europe, such as France, Sweden, Germany, and UK have cultivated SRC extensively. Thus, the problem of balancing land use for agriculture and SRCs is of concern, especially if SRC plantations continue to expand because of the benefits and profits that they can bring to their stakeholders and the public. The land use CLD shown in Figure A-9 accounts for the various SRC land use processes: SRC planting and growth, wastewater storage, and displacement of agricultural crops.

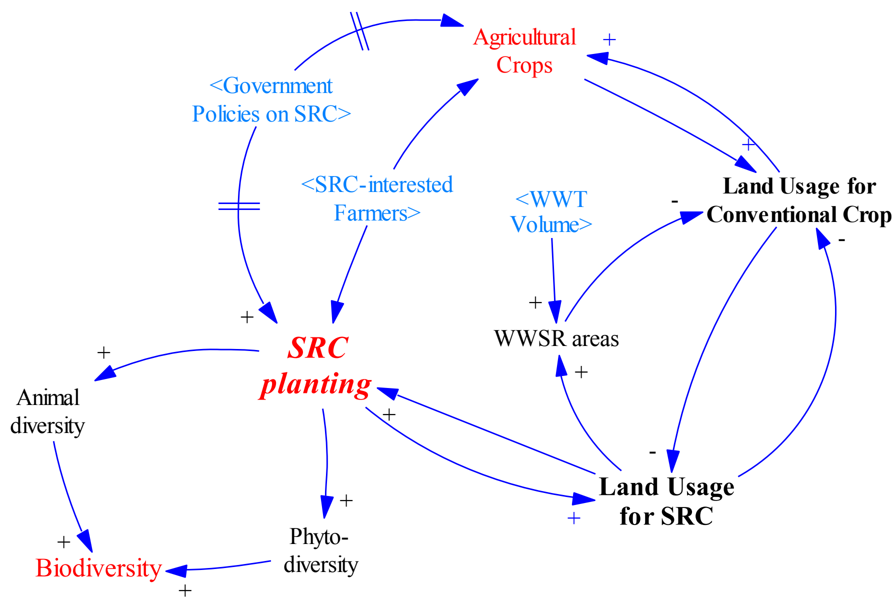


Figure A-9. Land Use CLD

A6. Production Cost CLD (SRC Growth-Production Costs-Profits)

The production cost CLD is shown in Figure A-10, which accounts for the various processing costs that can affect the total production cost, as well as the many factors from other CLD sectors that can impact the profit, such as the fertilization budget and wastewater treatment costs.

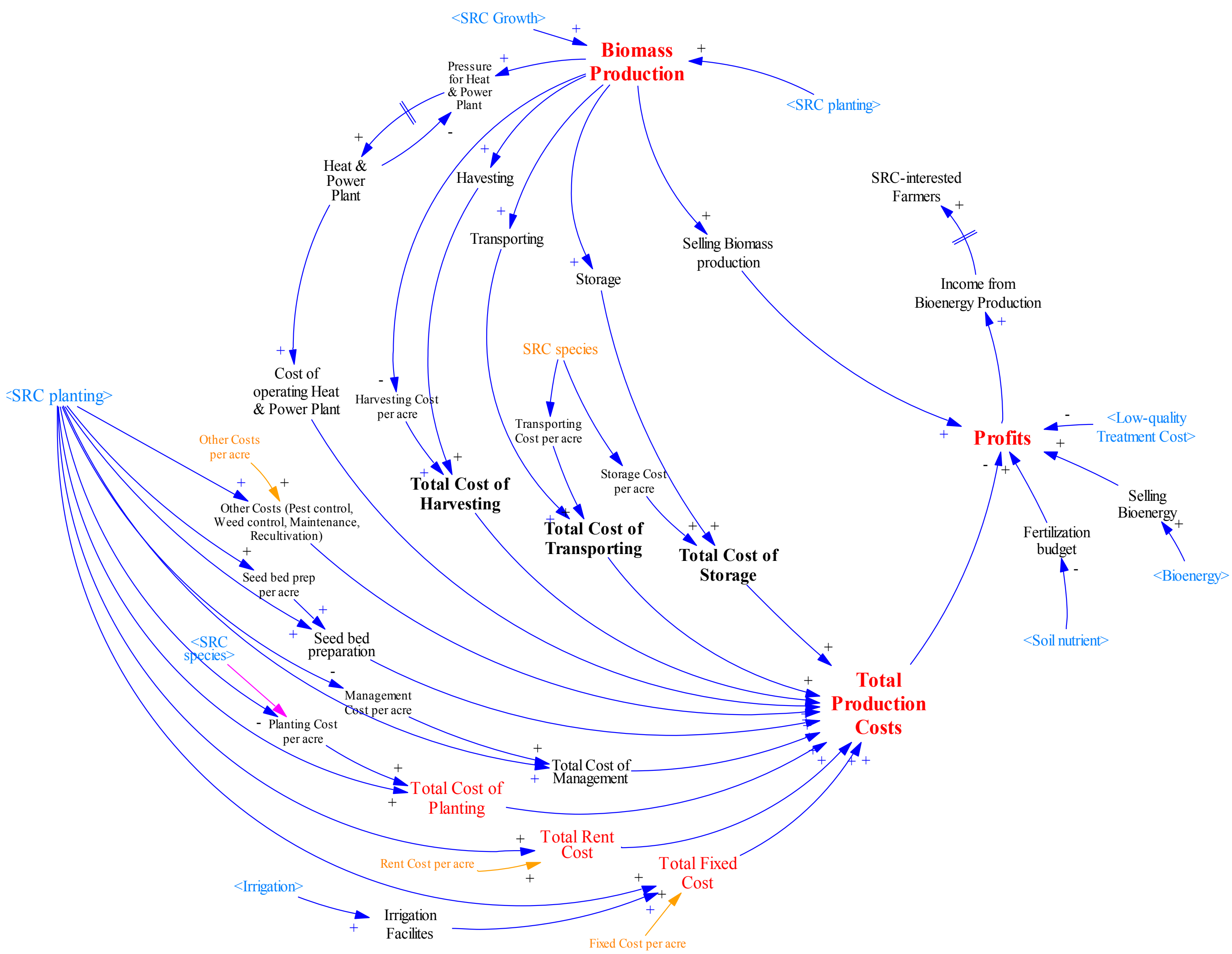


Figure A-10. Production Costs

A7. SRC Policy CLD (SRC Growth-Local Economy-Government Policy)

As shown in the large-scale CLD, the plantation of short-rotation coppices may significantly affect various aspects of the local economy, energy, agriculture, environment and society. All of these changes should ideally affect the development and implementation of government policies for SRC plantations. Figure A-11 represents potential links amongst these factors.

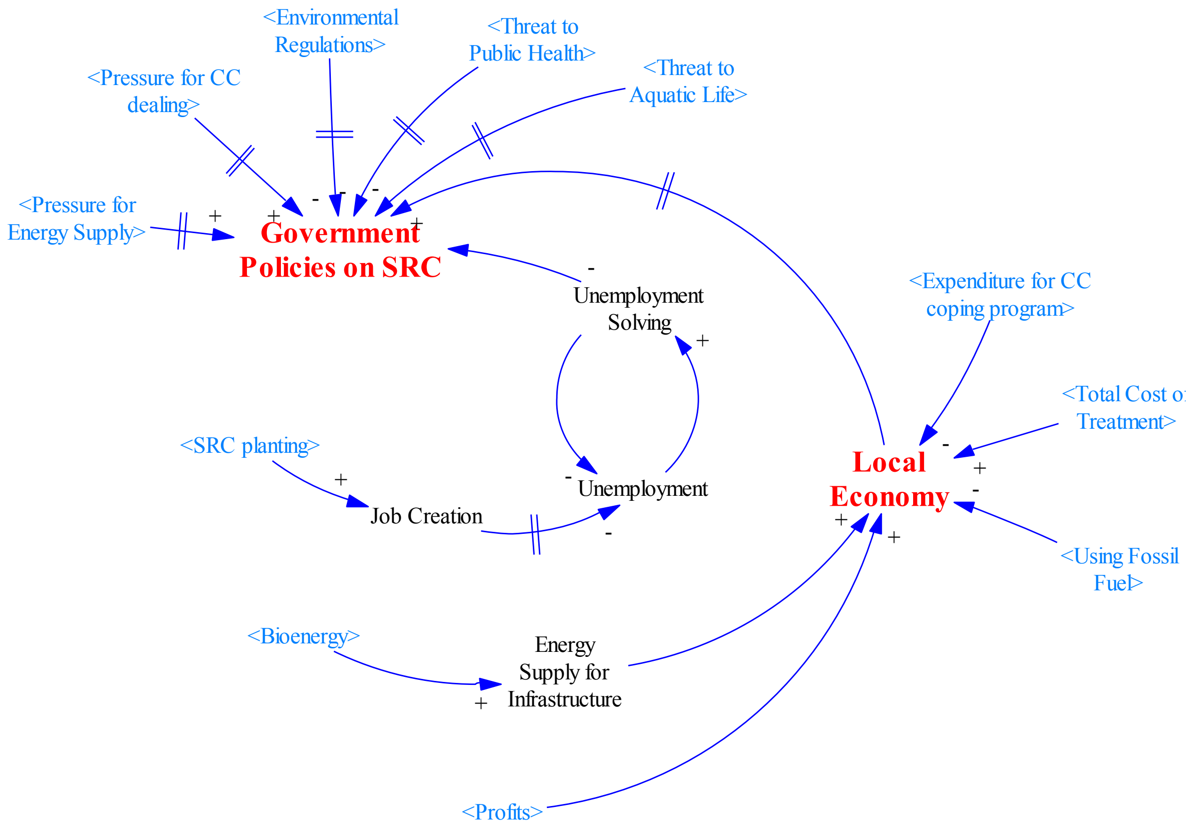


Figure A-11. SRC Policy

APPENDIX B: 3-PG GROWTH ENGINE

This appendix describes in details the parameters of the 3-PG growth engine based on Landsberg and Sands (2011) mentioned in the plant growth and yield (PGY) sub-model of WISDOM (section 3.3.2), including 1) determination of net primary production (NPP), 2) growth modifiers for site and environmental effects, and 3) biomass allocation and turn over.

B1. Determination of net primary production (NPP)

NPP in 3-PG is calculated using a light-use efficiency method, with respiration taken into account by a constant carbon use efficiency. Radiation intercepted by the canopy is given by Beer's law, and takes into account the fact that the canopy might not be closed.

GPP is converted into NPP using a constant carbon use efficiency Y:

$$P_n = YP_g, \qquad (22)$$

Where Y is constant carbon use efficiency Y = 0.47 $\pm$0.04 (this is a species-specific parameter), and P_g is monthly gross primary production by the canopy on a dry matter basis (T/ha/month).

$$P_g = 0.01 d_m \varepsilon_g \phi_{abs}, \qquad (23)$$

Where 0.01 is constant which converts from g/m^2 to t/ha, d_m is the number of days in the month, ε_g is light-use efficiency (the efficiency of conversion of absorbed photo-synthetically active solar radiation into dry matter, g/MJ), and $\Phi_{abs}$is absorbed photo-synthetically active solar radiation (MJ/m^2/d)

Light-use efficiency, ε_g (g/MJ) is determined as:

$$\varepsilon_g = M_{DM} q_{MJ} \alpha_C \qquad (24)$$

Where M_{DM} = 24 g_{DM} mol^{-1} converts moles of plant matter into grams of dry matter (assuming dry matter is 50% C), q_{MJ} = 4.6 mol/MJ converts moles of PAR into MJ of PAR, and α_C is equivalent canopy light-use efficiency (mol C mol^{-1} photons).

Absorbed photo-synthetically active solar radiation (PAR), Φ_{abs} ($MJ/m^2/d$) is determined as:

$$\phi_{abs} = 0.5\left(1 - e^{-kL/\beta_{gc}}\right)\phi_0\beta_{gc}, \quad (25)$$

Where 0.5 is constant which converts total radiation into PAR, k is the light extinction coefficient (dmnl), Φo is the monthly average daily incident total solar radiation ($MJ/m^2/d$), β_{gc} is the fractional ground cover of the canopy, and L is the canopy leaf area index (dmnl)

Canopy leaf area index, L (dmnl) is calculated as:

$$L = 0.1\sigma_F W_F \quad (26)$$

Where 0.1 is constant which converts T/ha to kg/m^2, σ_F is the specific leaf area (this is a species-specific parameter, m^2/kg), W_F is leaf biomass (T/ha).

B2. Growth modifiers for site and environmental effects

The temperature-dependent growth modifier, $f_T(T_{av})$, is:

$$f_T(T_{av}) = \left(\frac{T_{av} - T_{min}}{T_{opt} - T_{min}}\right)\left(\frac{T_{max} - T_{av}}{T_{max} - T_{opt}}\right)^{(T_{max}-T_{opt})/(T_{opt}-T_{min})} \quad (27)$$

Where T_{av} is the (monthly) average daily temperature (°C), and T_{min}, T_{opt}, and T_{max} are the cardinal temperatures for growth respectively (°C).

The soil-water-dependent growth modifier, $f_\theta(\theta_r)$, is:

$$f_\theta(\theta_r) = \frac{1-(1-\theta_r)^{n_\theta}}{1+[(1-\theta_r)/c_\theta]^{n_\theta}} \quad (28)$$

Where θ_r is the relative plant-available soil water (dmnl), and c_θ and n_θ determine the shape of the modifier (dmnl).

The fertility-dependent growth modifier, $f_{FR}(F_R)$, is:

$$fFR(F_R) = 1-(1-f_{N0})(1-F_R)^{n_{fN}} \quad (29)$$

Where F_R is the site fertility rating (dmnl), f_{N0} is the value of f_{FR} when FR=0 (dmnl), and n_{fN} is a power determining the shape of the response (dmnl).

The age-related growth modifier, $f_{age}(t)$, is:

$$f_{age}(t) = \frac{1}{1+[(t/t_x)/r_{age}]^{n_{age}}} \quad (30)$$

Where t is stand age (years), t_x is the maximum age expected for a stand of this species (years), r_{age} is the relative age (t/t_x) at which f_{age}=1/2 (dmnl), and n_{age} determines the strength of the response (dmnl).

The salinity-dependent growth modifier, $f_S(C_S)$, is:

$$f_S(C_S) = \begin{cases} 1 & C_S \le C_{S0} \\ 1-\left(\frac{C_S - C_{S0}}{C_{S1}-C_{S0}}\right)^{n_{Cs}} & C_{S0} < C_S < C_{S1} \\ 0 & C_{S1} \le C_S, \end{cases} \quad (31)$$

Where C_S is the electrical conductivity of the soil, C_{S0} and C_{S1} are the conductivities at which salinity begins to affect and stops growth respectively (dS/m), and n_{CS} is a power that determines the shape of the response (dmnl).

B3. Biomass allocation and turnover

Root allocation ratio, η_R, is determined as:

$$\eta_R = \frac{\eta_{Rx}\eta_{Rn}}{\eta_{Rn} + (\eta_{Rx} - \eta_{Rn}) * \zeta} = f(site\ fertility, soil\ water\ status) \tag{32}$$

Where η_{Rx} is root allocation under the most limiting conditions (dmnl), η_{Rn} is root allocation when neither site fertility nor soil water availability are limiting (dmnl), ζ determines the degree of site limitation.

$$\zeta = (m_o + (1 - m_o)F_R)\varphi \tag{33}$$

Where m_o is a potentially species-specific parameter but is usually assigned the value of zero, F_R is the site fertility rating (dmnl), φ is the physiological modifier (dmnl).

Stem and foliage allocation ratios, η_S and η_R are determined as:

$$\eta_S = \frac{1 - \eta_R}{1 + P_{FS}} \tag{34}$$

$$\eta_F = P_{FS}\eta_S \quad (35$$

Where η_R is the root allocation ratio, and P_{FS} is the ratio of foliage allocation to stem allocation and is the allometric function of diameter at breast height (DBH) and stem number. The ratio P_{FS} is an important quantity determining allocation, and is conveniently parameterized by its values P_{FS1} and P_{FS2} at two distinct values of DBH corresponding to saplings and mature trees.

APPENDIX C: WINDFALL WIND SPEED DATA SCALE

This appendix presents how the Twinlake wind speed data was scaled to obtain homogeneous data for the Windfall station.

The wind speed data for the Twinlake station was available from 2006 to 2013, while that of Windfall station was only available from the second half of 2011 to 2013. Using the corresponding data from both stations in three years (see Figure C-1), the scale factors of each month can be determined as follow:

$$Scale\ factor_{month\ i} = \frac{Windfall\ wind\ speed_{month\ i}}{Twinlake\ wind\ speed_{month\ i}}$$

Where: Scale factor$_{month\ i}$ is the scale factor of month I (1-12), and Windfall and Twinlake wind speed$_{month\ i}$ are the wind speed value of month i in the year.

The values are shown in Table C-1 and Figure C-2.

The average values of the scale factors of each month are then applied to scale the data for the Twinlake station. The wind speed data of Windfall obtained from the Twinlake scale are shown in Figure C-3 and the comparison between the observed and measured Windfall data in 2011-2013 is plotted in Figure C-1 with a high correlation.

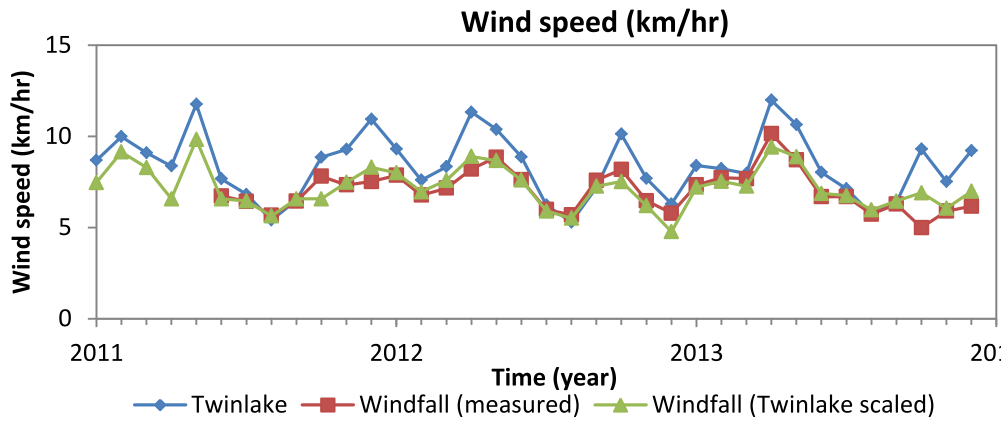


Figure C-1. Corresponding wind speed data for the Twinlake and Windfall stations in 2011-2013 and Twinlake wind speed data after scaling.

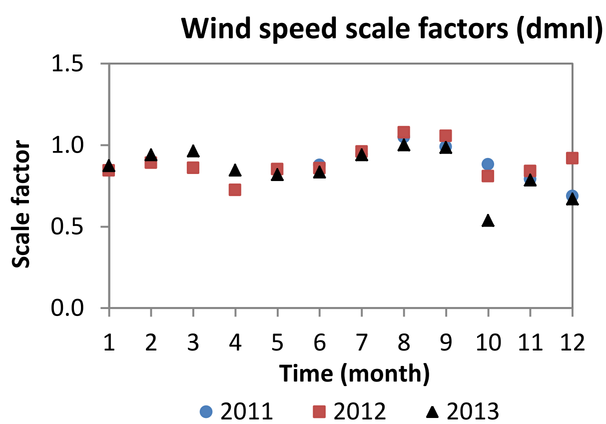


Figure C-2. Values of the wind speed scale factor

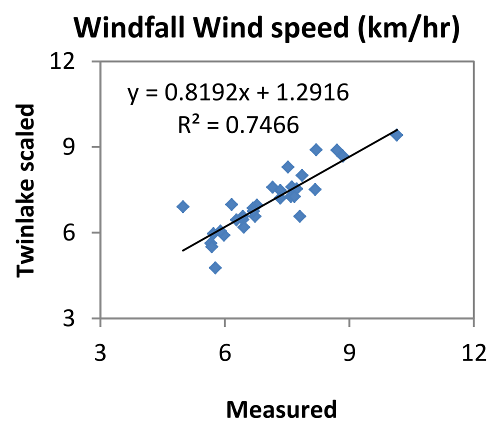


Figure C-3. Comparison between measured and scaled Windfall wind speed (km/hr)

Table C-1. Wind speed scale factor R=(Windfall wind speed / Twinlake wind speed)

Month Year	1	2	3	4	5	6	7	8	9	10	11	12
2011						0.88	0.94	1.05	0.99	0.88	0.79	0.69
2012	0.84	0.89	0.86	0.72	0.85	0.86	0.96	1.08	1.06	0.81	0.84	0.92
2013	0.87	0.94	0.96	0.85	0.82	0.83	0.94	1.00	0.98	0.54	0.78	0.67
Average	0.86	0.92	0.91	0.79	0.84	0.86	0.95	1.04	1.01	0.74	0.81	0.76

APPENDIX D: MODEL USER'S GUIDE

This appendix serves as an instruction to the use of WISDOM with a system-dynamics-modelling software-package named Vensim (Ventana Systems, 2014). WISDOM uses Vensim DSS, which is available for purchase from the Ventana Systems, Inc. website at http://www.vensim.com. WISDOM works best when simulated with Vensim DSS software.

Ventana Systems also offers a free-of-charge 'Vensim Model Reader', which can simulate a complete model and can be used to read datasets from previous model runs, but does not permit model modification. Note that data derived from simulations using the Model Reader differ slightly from the data produced by the Vensim DSS version because of a difference in numerical precision: although both the Model Reader and Vensim DSS use automatic Runge-Kutta 4 (RK4 auto) to run the model, Vensim DSS has double the numerical precision of the Model Reader – see below for more details on numerical integration.

In terms of modelling software, note too that an introductory modelling package, called Vensim PLE, is also available from Ventana Systems at no cost; however, because the model uses subscripts (or arrays), it cannot be run using Vensim PLE.

Appendix Outline

This appendix first outlines the user-friendly interface of WISDOM, then it presents the basic steps to work with WISDOM, including how to open the model from a blank page, enter inputs, set up "switches", run a new simulation, view the results, and finally how to use "synthesim" – one of the advanced functions of WISDOM (supported by Vensim environment) to assist stakeholders and decision-makers in SRC plantation and management. Other advanced functions of WISDOM including "sensitivity analysis" and "optimization" (supported by Vensim environment) that are very powerful in supporting decision-makers will not be illustrated here due to limited time and space, users can figure out these functions using the Vensim user's manual once they familiarize themselves with the basis of WISDOM.

WISDOM user interface

The main user interface for WISDOM is shown in Figure D-1 with the four categories on the right hand side, including: 1) inputs and model parameters, 2) outputs and decision support tool, 3) stock and flow diagrams (SFDs), and 4) causal loop diagrams (CLDs). Each categorization contains their sub-categories that can be accessed from the main interface by a mouse click. The sample interfaces of these sub-categories are illustrated below from Figure D-2 to Figure D-9, while details on how to use WISDOM is presented in next section.

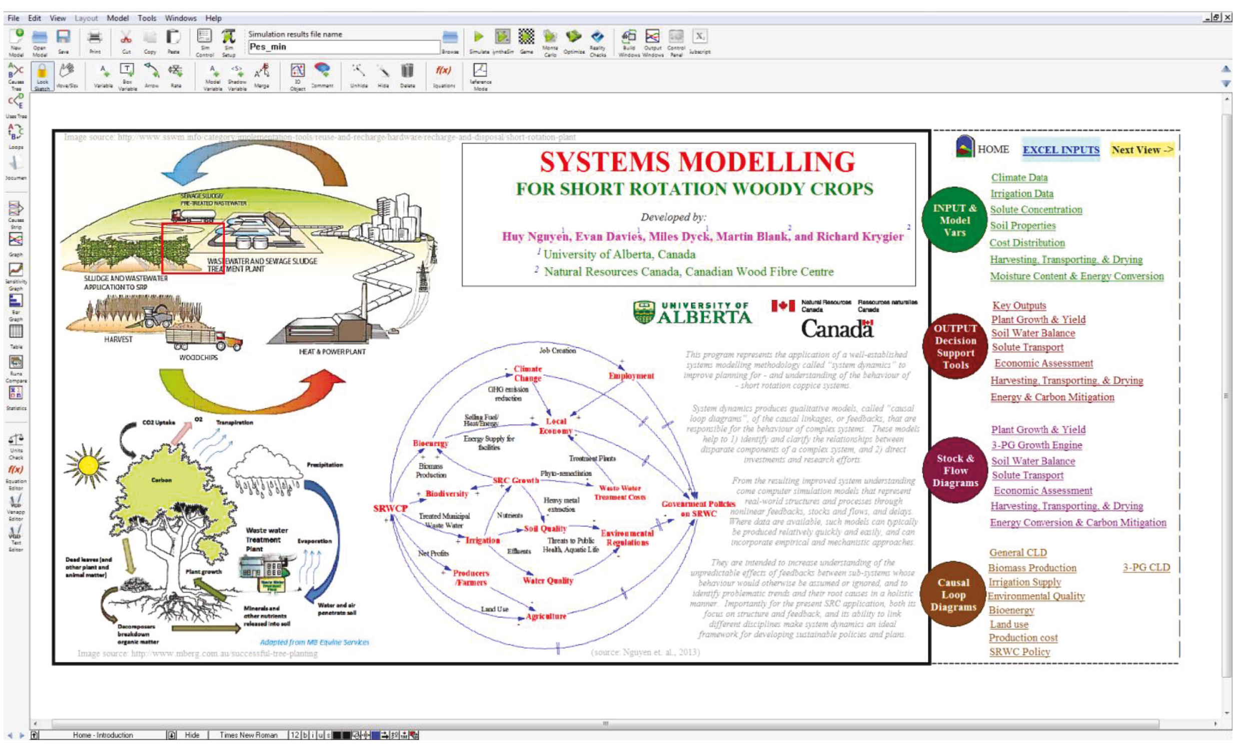


Figure D-1. The main user interface of WISDOM

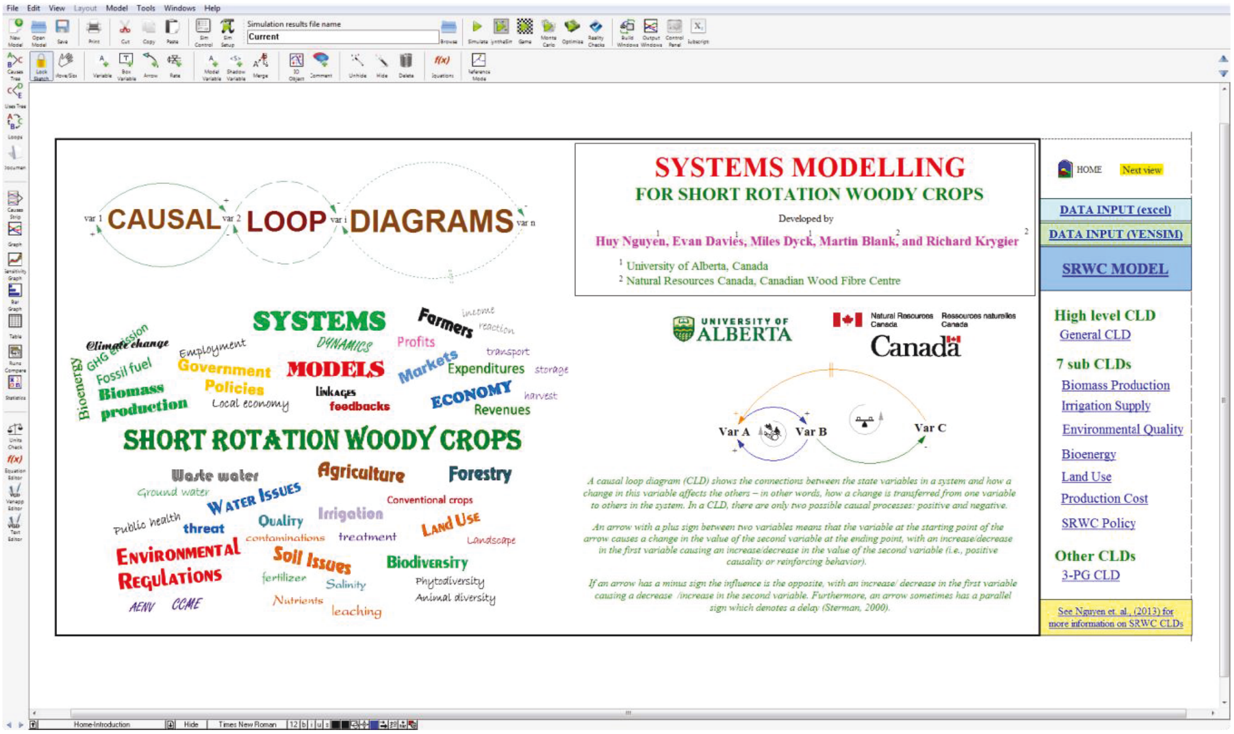


Figure D-2. WISDOM-"Causal loop diagrams" interface

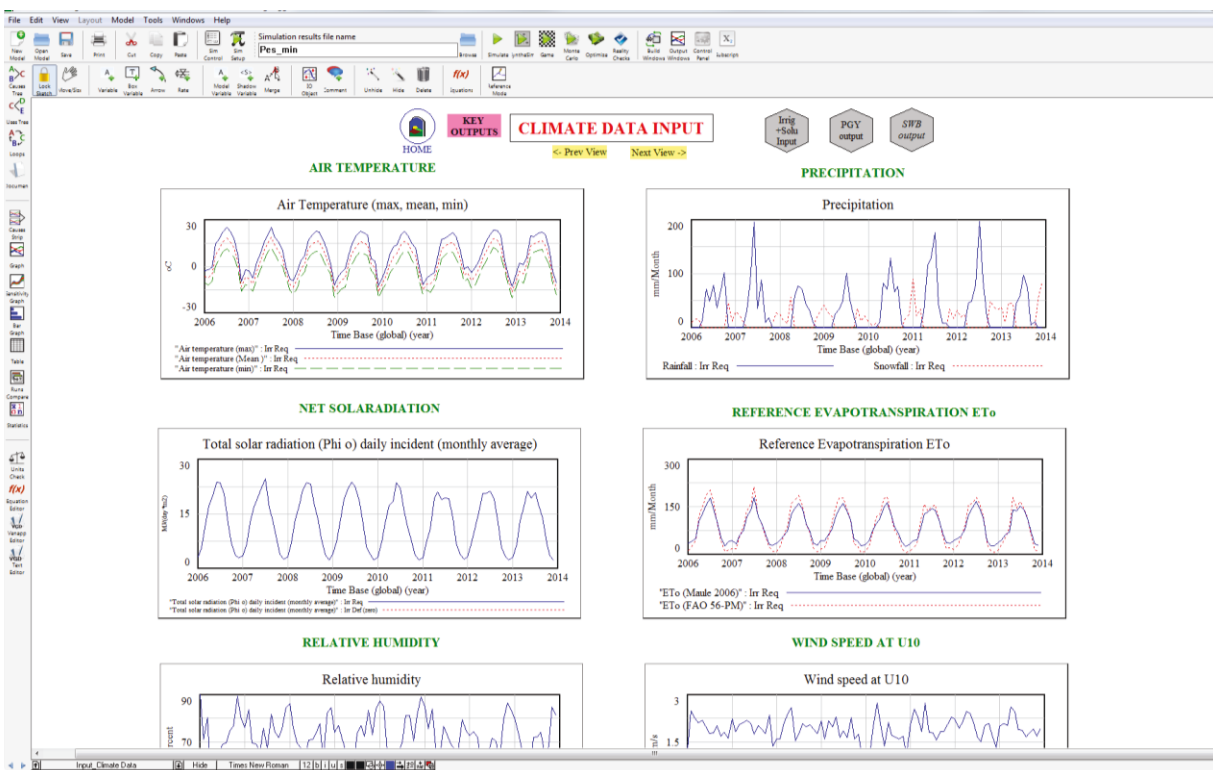


Figure D-3. WISDOM-"climate data input" interface

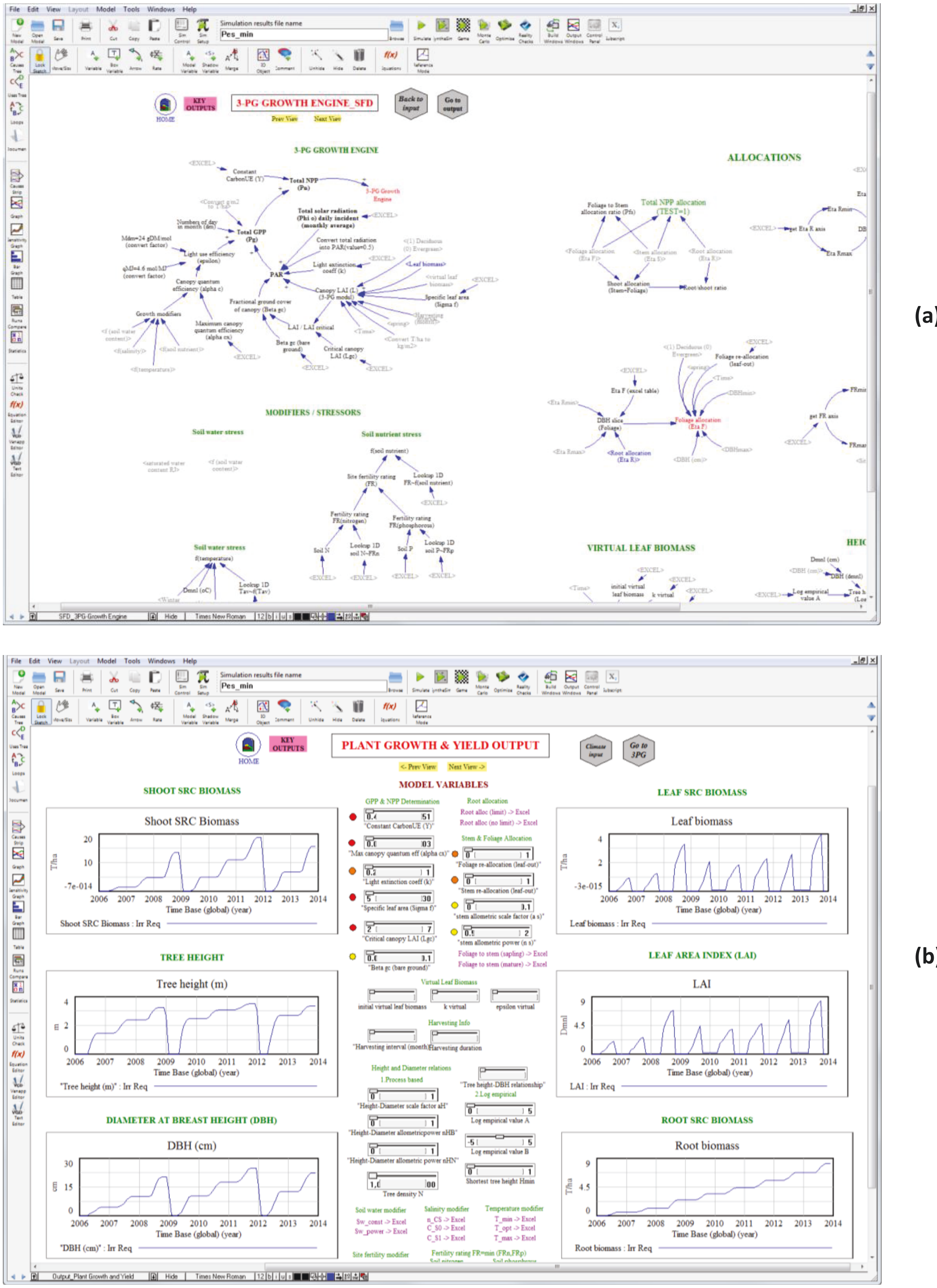
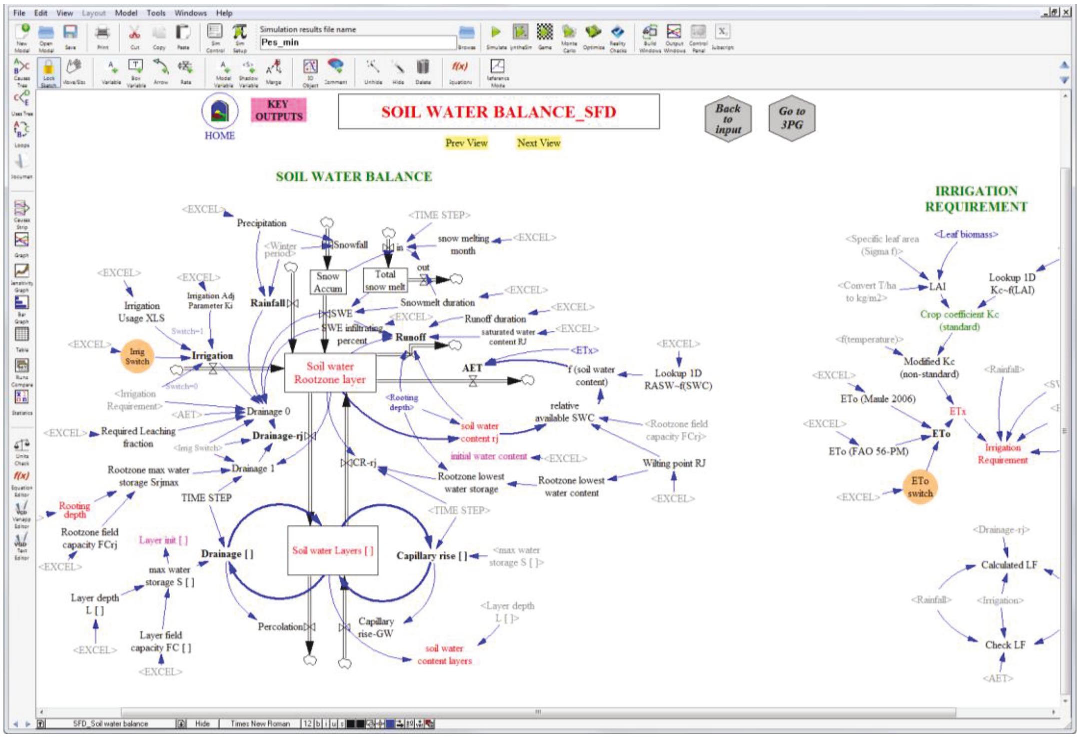


Figure D-4. a) "3PG growth engine-SFD" and b) "plant growth and yield-outputs" interfaces



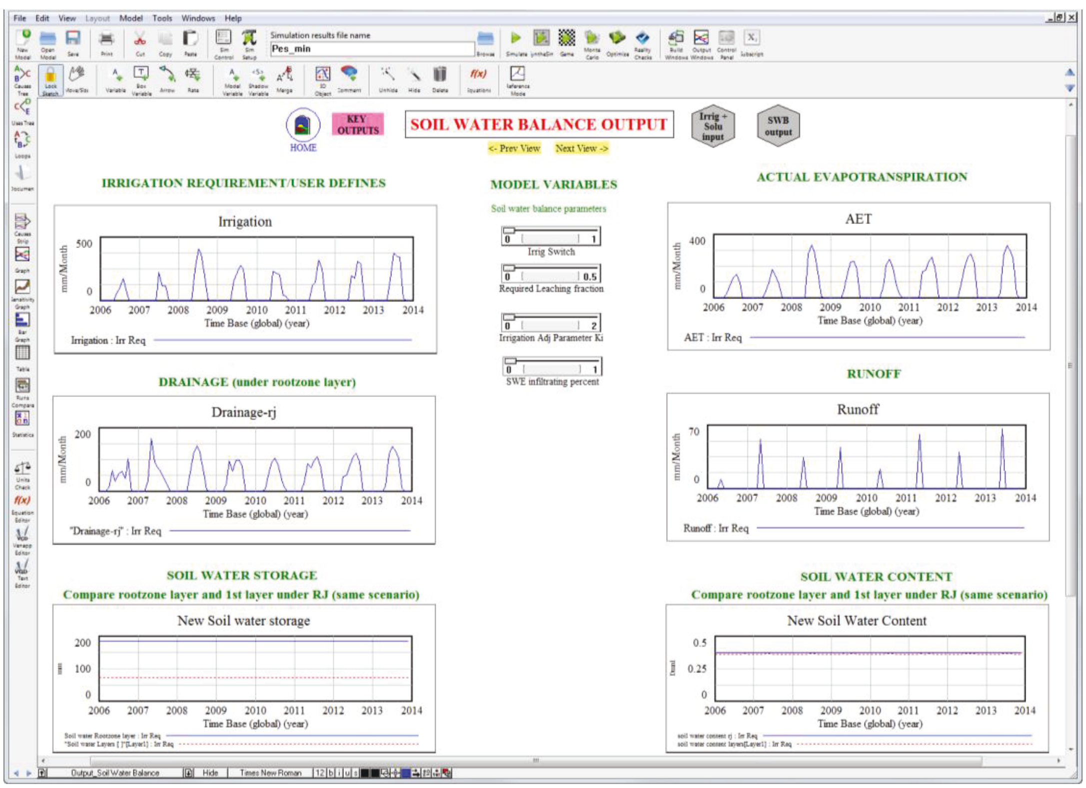
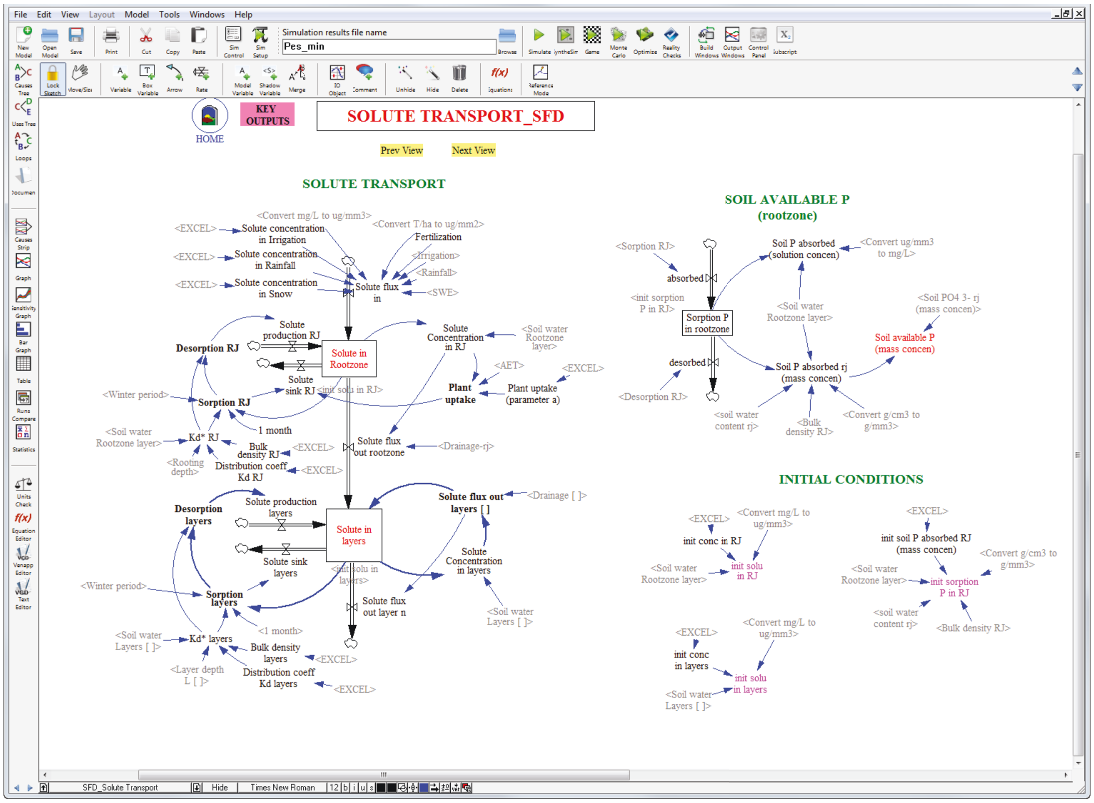
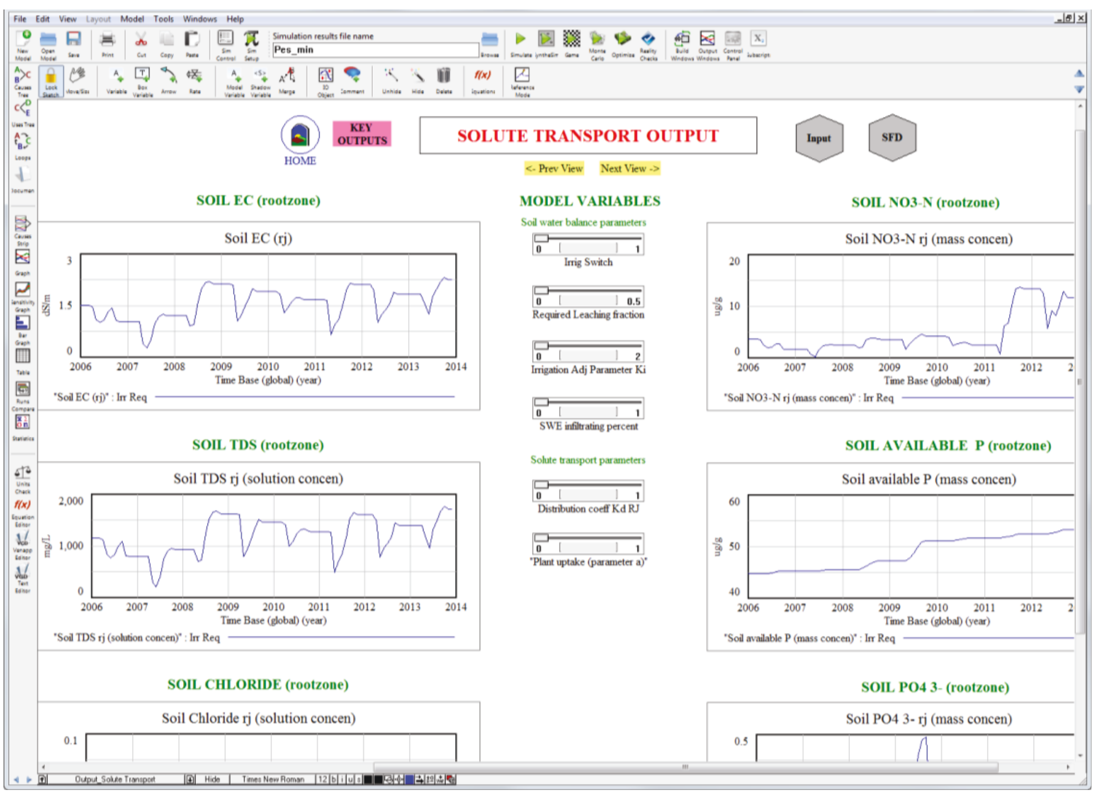


Figure D-5. a) "Soil water balance-SFD" and b) "soil water balance-outputs" interfaces

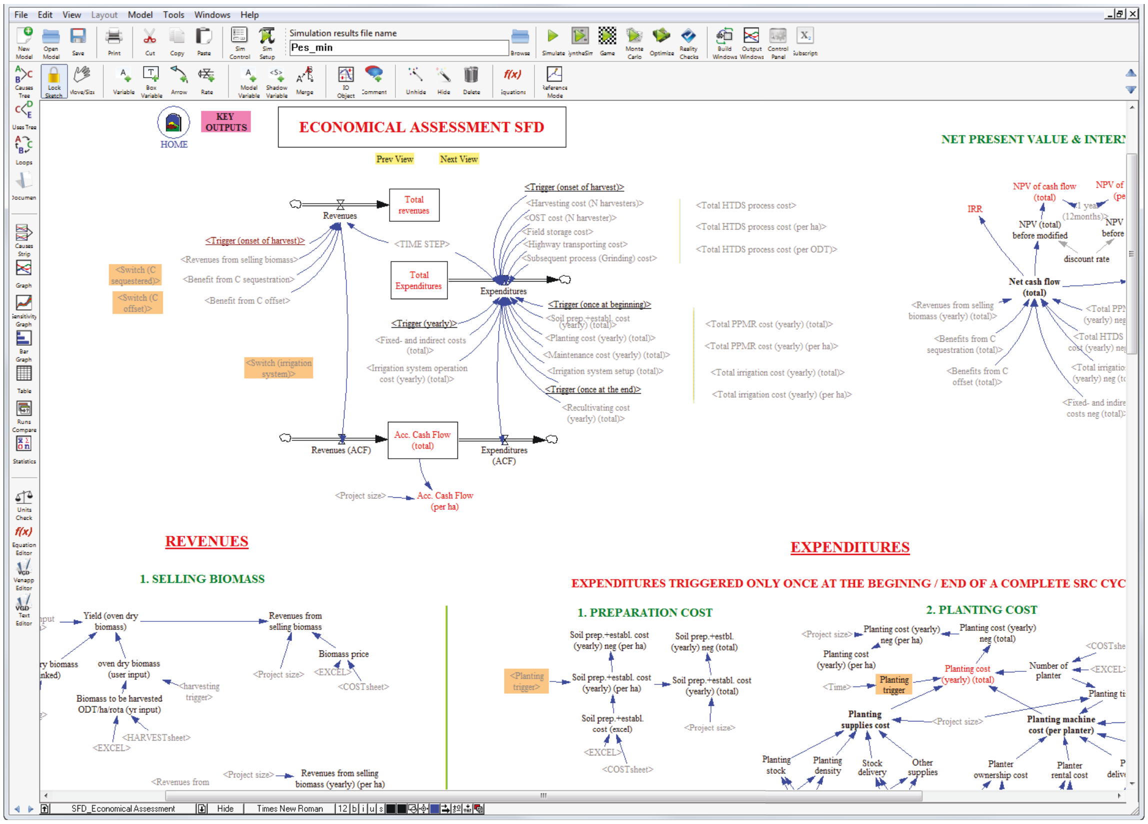


(a)

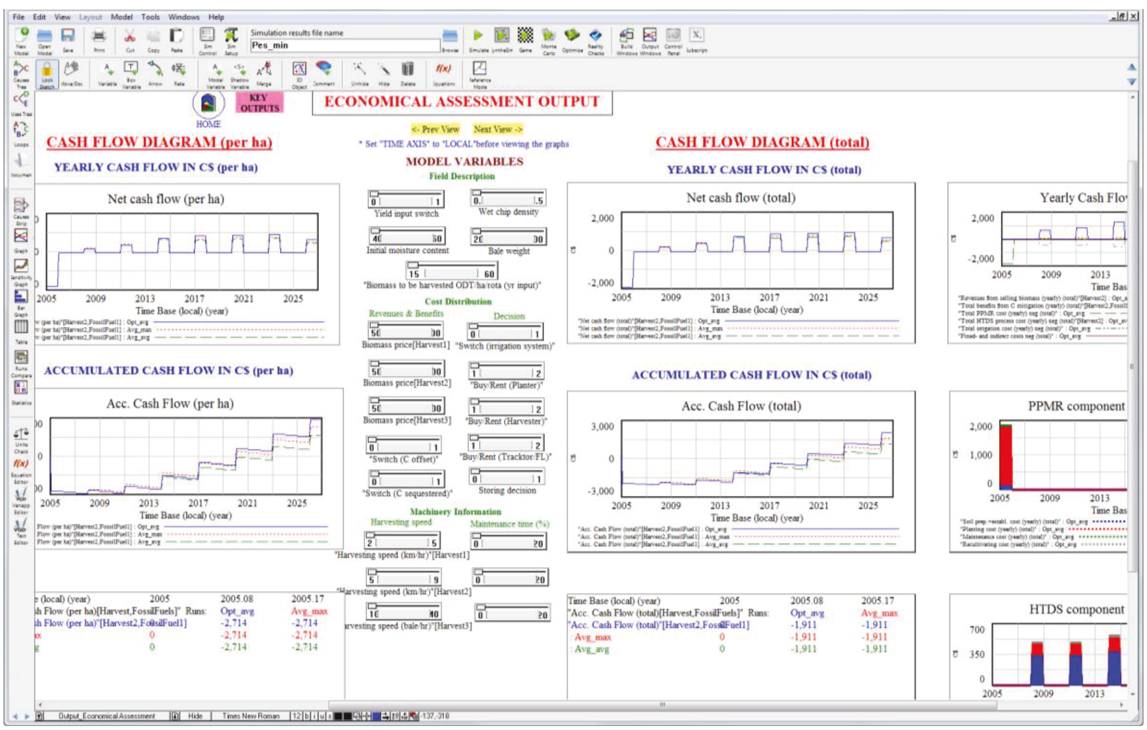


(b)

Figure D-6. a) “Solute transport-SFD” and b) “solute transport-outputs” interfaces

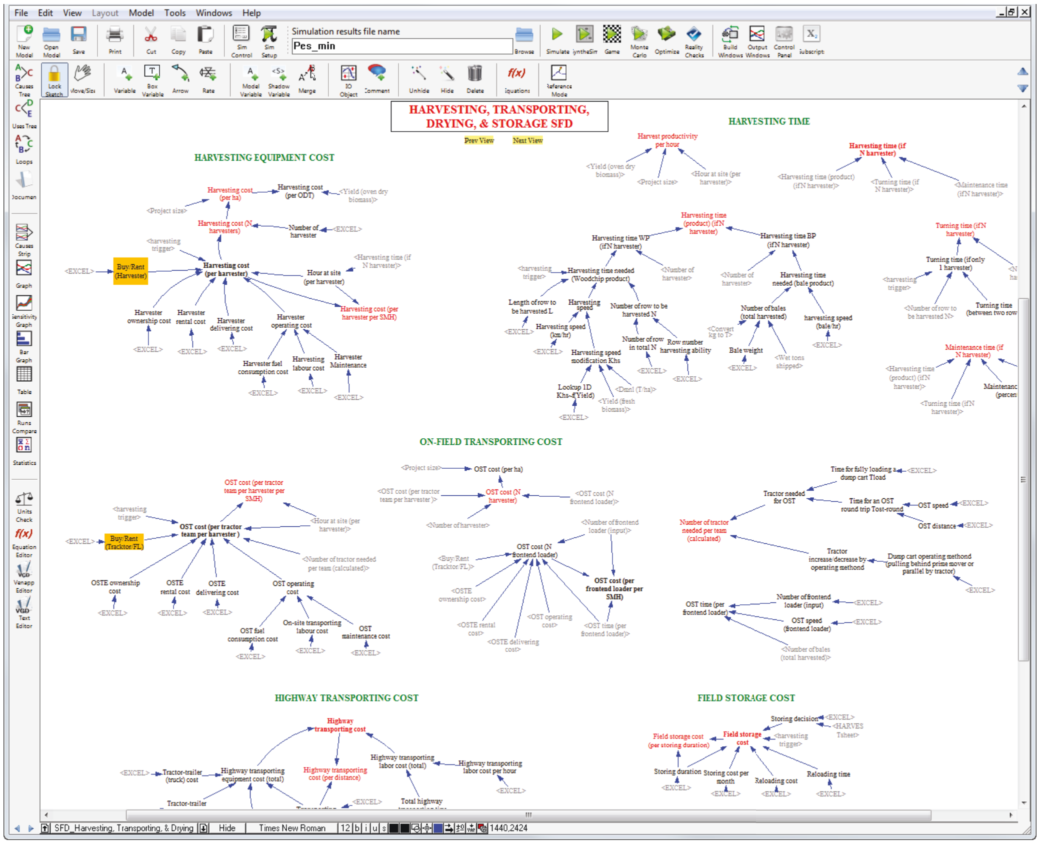


(a)

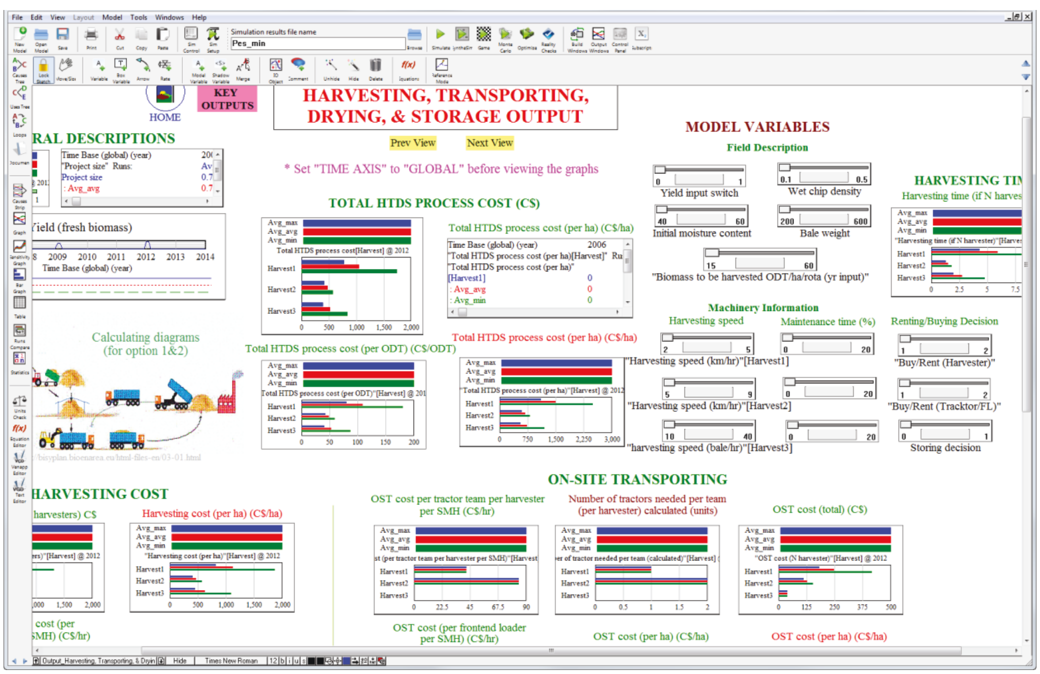


(b)

Figure D-7. a) “Economic assessment-SFD” and b) “economic assessment-outputs” interfaces

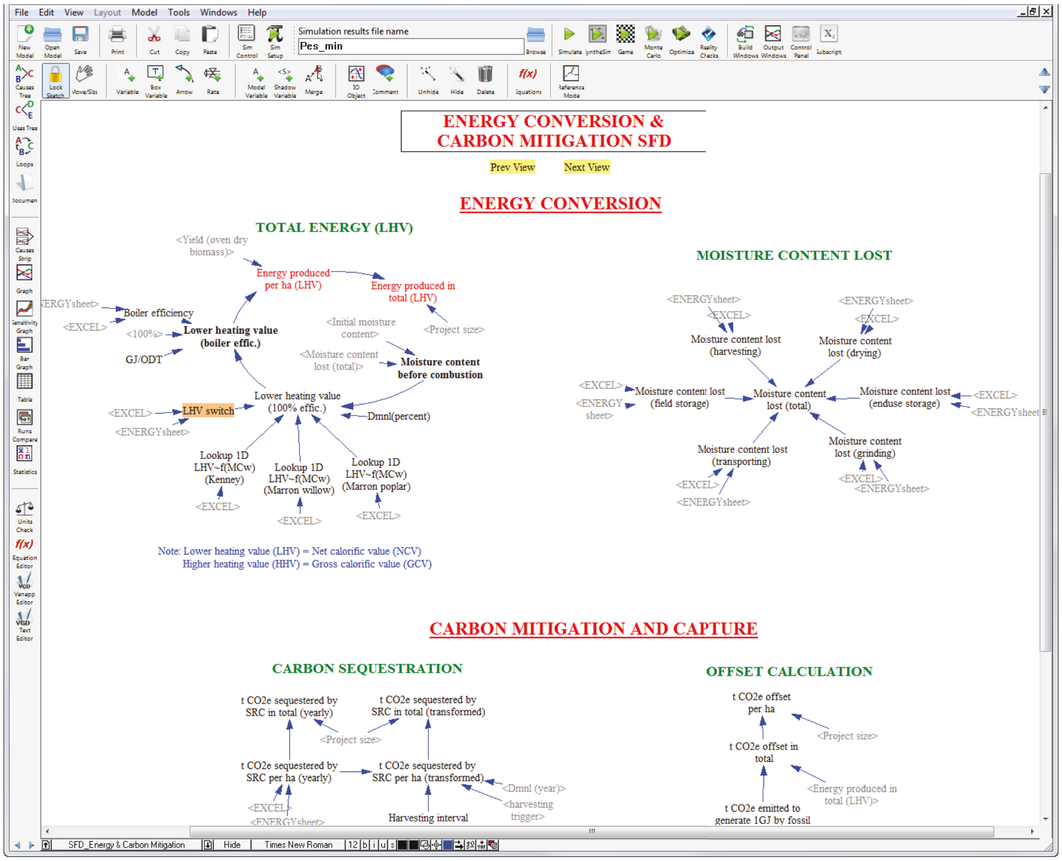


(a)

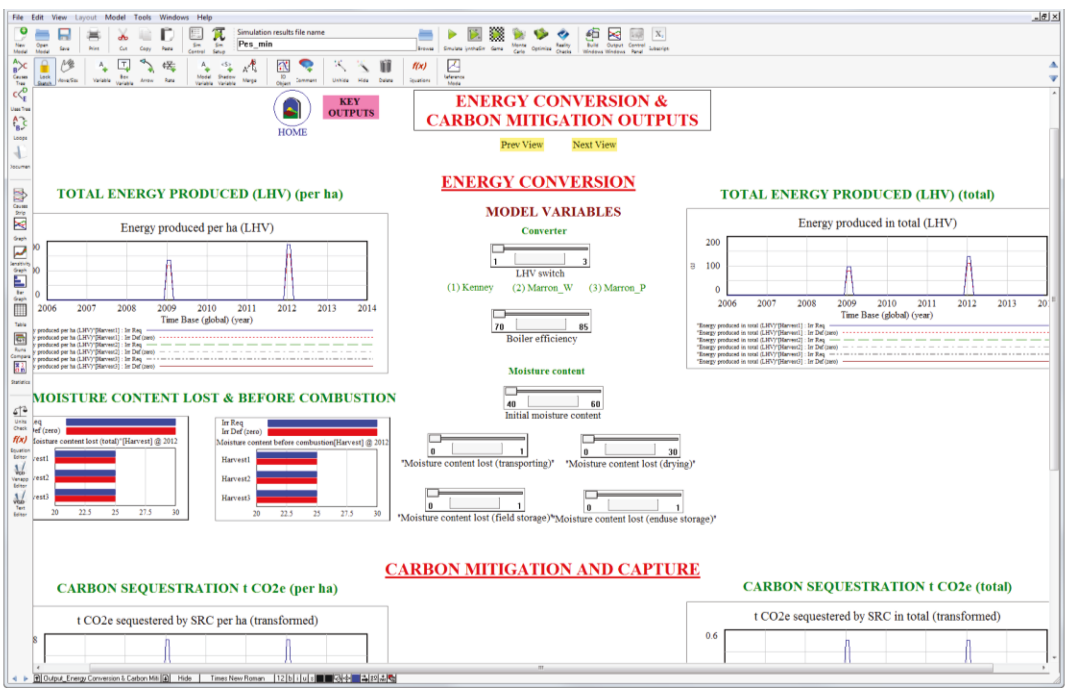


(b)

Figure D-8. a) "Harvest and transport-SFD" and b) "harvest and transport-outputs" interfaces



(a)



(b)

Figure D-9. a) "Energy conversion-SFD" and b) "energy conversion-outputs" interfaces

WISDOM – basic working things

How to open the WISDOM model

To open WISDOM, first double-click on the Vensim icon on your computer desktop to start a new blank-page model as shown in Figure D-10. Then go to File -> Open model …, or choose the icon on the main toolbar and browse to the folder where the file “WISDOM.mdl” is located as presented in Figure D-10. Double-click on the file and it will open both the WISDOM model and the data input excel file “full.xlsx” simultaneously – see Figure D-11.

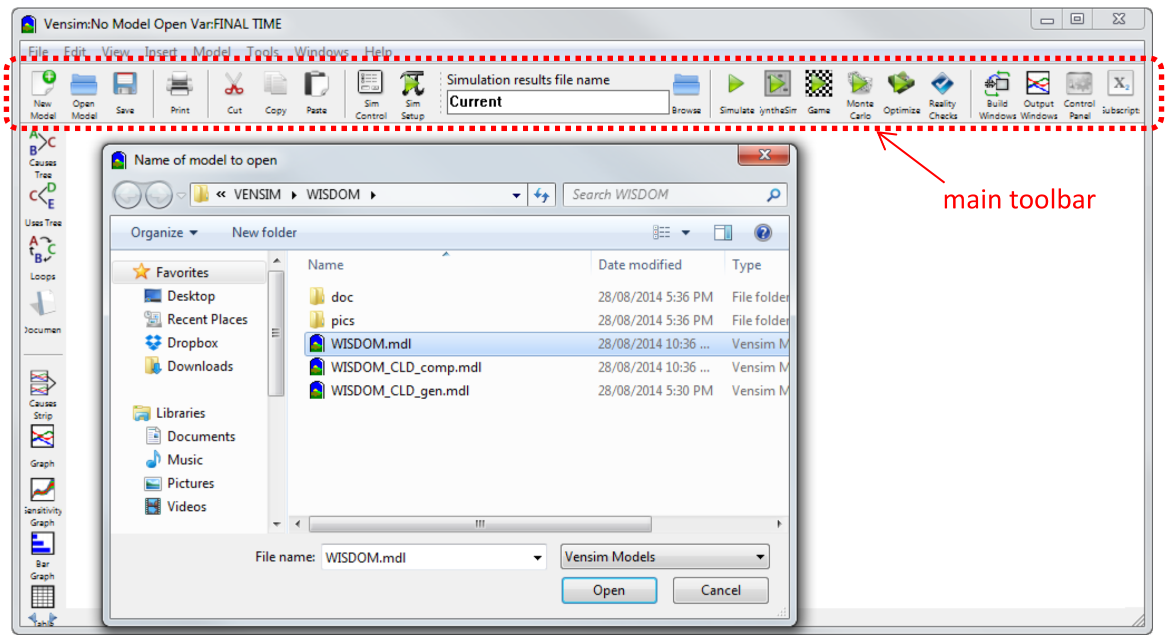


Figure D-10. Open WISDOM by starting a new model

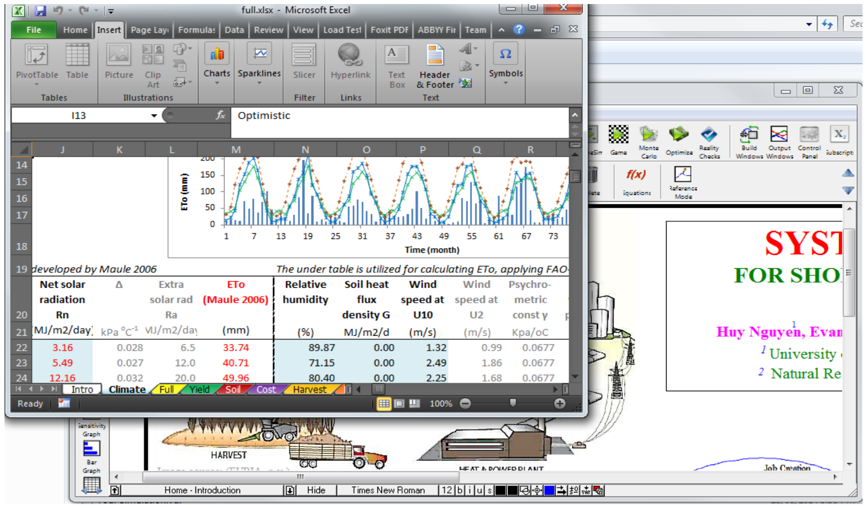
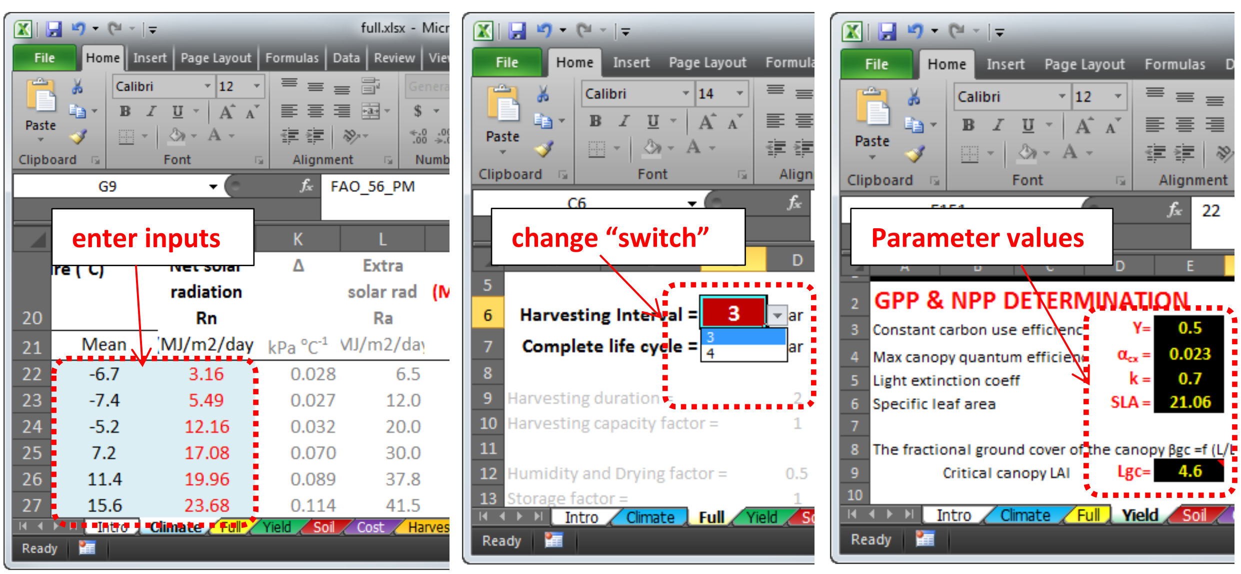


Figure D-11. The input excel file and WISDOM main interface

How to enter input data for, select "switch" values, and parameterize WISDOM

All of the input data is collected in the input excel file named "full.xlsx". All of the cells in the file are locked, except the blue cells or "input cells", where users can enter input data; the red cells or "switch cells", where users can select available values but cannot enter data; and the black cells or "parameter cells", where users can enter species-specific parameters to adjust the outputs (Figure D-12).



(a) (b) (c)

Figure D-12. a) enter input pf, b) change "switch" value of, and c) parameterize WISDOM

How to run a new simulation

To run a new simulation, first enter inputs, change switch values, and enter parameter values described above, then type the name of the simulation in the "simulation results file name box" located on the main toolbar, and finally click the icon next to the "simulation name box" to activate the simulation with the selected name – see Figure D-13.

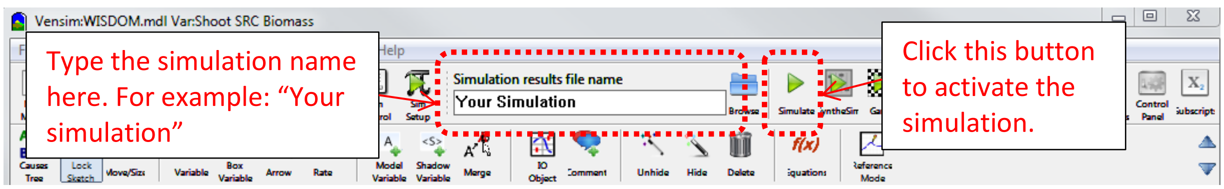


Figure D-13. Simulation name box and simulation activating button

How to view outputs

There are different ways to view outputs, using the default output interfaces of WISDOM, or using Vensim support tools to view all potential outputs of stock and flow diagrams (SFDs) and simulation models. The default output interfaces provide common or interesting results from different WISDOM components, such as stem biomass production, irrigation requirements, soil electrical conductivity, cumulative cash flow, harvest and transport, energy content, and so on. Users can view these default outputs by clicking on the sub-categories of the "outputs and decision support tools" category on the main interface of WISDOM as shown in Figure D-1 above. The other way to view all the potential outputs of SFDs and simulation models is to use Vensim's built-in tools, namely "graph" and "table", which are located at the left hand side of the Vensim interface, by first clicking on an model parameter of interest and then choosing "graph" to open the graphs, or selecting "table" to open the table values of the selected parameter.

How to compare or view different simulations on the same graph

Users may want to run different simulations and then compare their results. To compare or view different simulations on the same graph, click the control panel icon  on the main toolbar and then load as many simulations as they want on the left hand side (Figure D-14a), into the right hand side (Figure D-14b), of the control panel pop-up window. Finally, view the output results as mention above – see Figure D-14c.

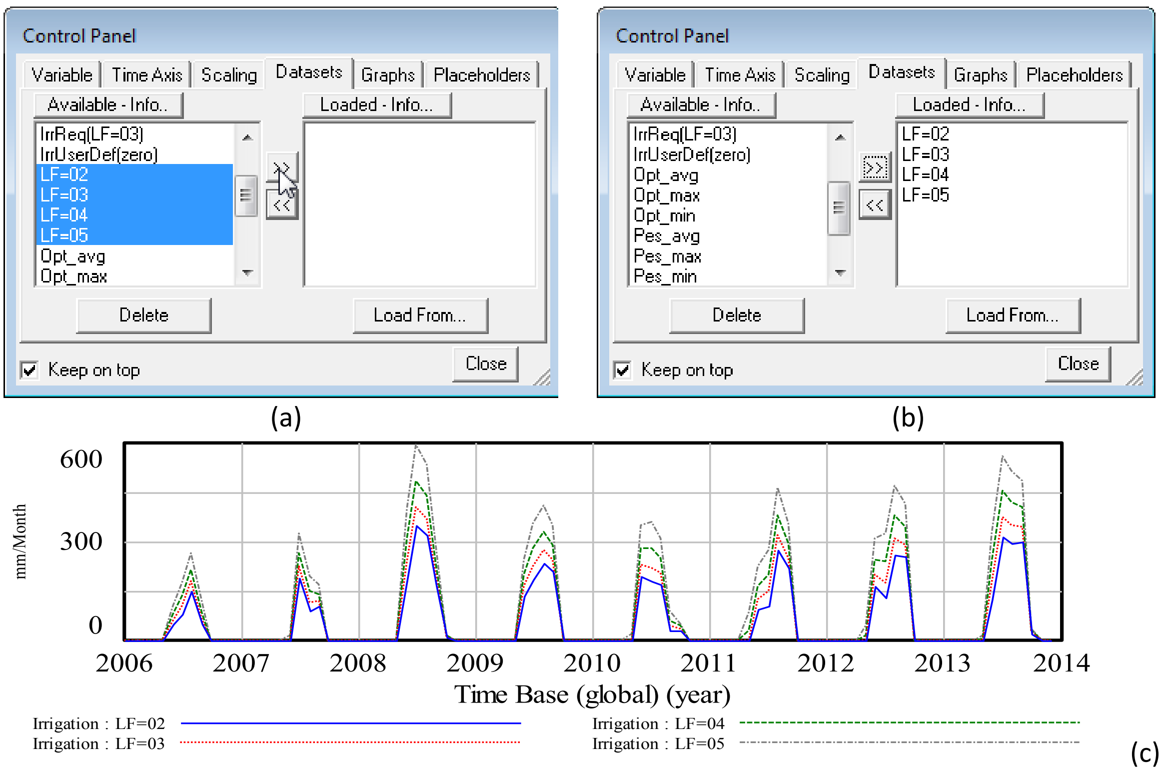
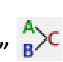
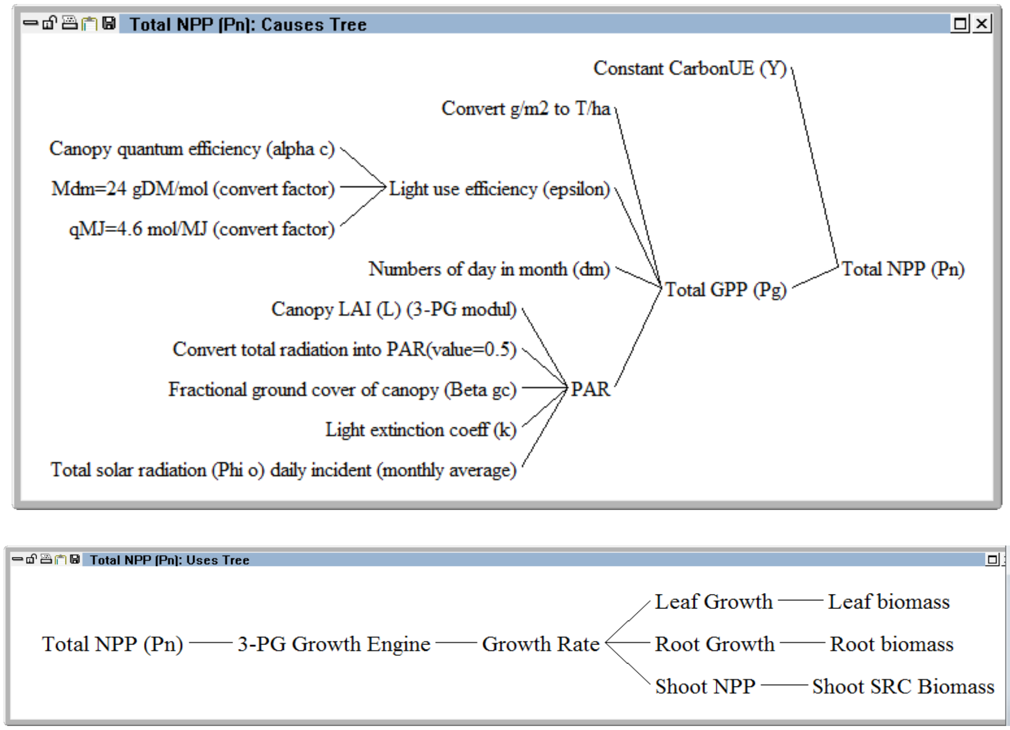


Figure D-14. Viewing different simulation on the same graph

How to track causes and effects

WISDOM is a complex model, as its systems involve many variables, components, and linkages and the feedbacks between them. Therefore, to analyze and understand simulation results, two powerful tools are available to assist users in tracing causality – or the causes and effects related to any element in the system. These tools named “causes tree”  and “uses tree” , are located at the left hand side of Vensim interface. An example of tracking causality of total NPP in the plant growth and yield component of WISDOM is illustrated in Figure D-15.



(a)

(b)

Figure D-15. How to track a) "causes" and b) "effects of a model element

How to run a "SyntheSim" simulation and change "slider" values

"Synthesim" is one of the advanced functions of WISDOM (supported by Vensim environment) that assist stakeholders and decision-makers in planning SRC plantation and management. Synthesim allows users to view the effects of different "decisions" through changing WISDOM "slider" values on different system elements and components immediately. The synthesim icon  is located at the main toolbar next to the simulation icon , while WISDOM sliders  are provided on the interfaces of each sub-categories of the "outputs and decision support tools" category.

To run a synthesim simulation, first name the simulation by typing into the simulation name box, and then click on the synthesim icon . As this point, the main toolbar disappears and is replaced by a new toolbar that supports synthesim simulation – see Figure D-16, also all the sliders provided on each interfaces appear, and their values can then be changed – see Figure D-17.

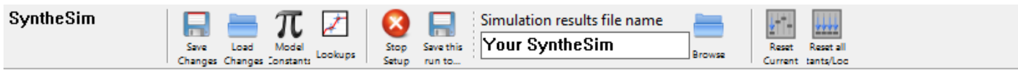
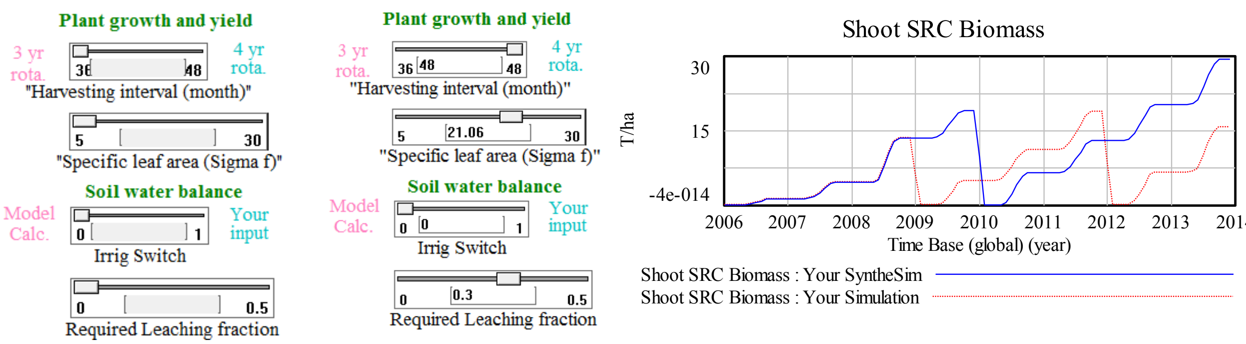


Figure D-16. The synthesim toolbar



(a) (b) (c)

Figure D-17. a) Sliders before and b) after activating synthesim, c) an example of effect of changing "harvesting interval" slider from 3 to 4-year-rotation on "stem biomass"

How to change the time axis

Two time axes are provided in WISDOM, the global and local. The global time axis is used to view the majority of simulation results, including plant yield, soil water, solute transport, harvest and transport, energy content, except the economic results which must be viewed with a local time axis.

To change the time axis, go to control panel window , then click on the time axis tab. Two options are available in the drop-down menu of time base, as shown in Figure D-18.

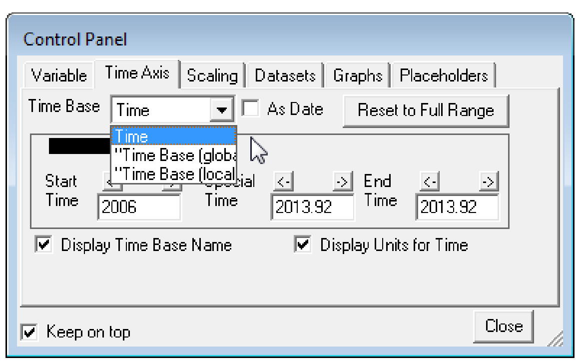


Figure D-18. How to select different time axis values

APPENDIX E: CONTENTS OF MODEL CD-ROM

The CD-ROM attached with this thesis contains a set of models that can be used to reproduce the results illustrated in Chapter 4 and 5, the data input themselves, and the Vensim software required to run the model. Refer to Appendix D for more information on how to use Vensim DSS and the Vensim Model Reader – although Appendix D focuses on Vensim DSS, most of the commands and tools presented there apply to the Model Reader as well. Refer to chapter 4 and 5 for the description of model inputs, and the parameter modifications involved.

CD-ROM Layout

The CD-ROM contains a hierarchy of folders, as listed below:

- Vensim Installation Software
    - Model Reader
    - Vensim PLE
- Complete Models and Data sets
    - For use with Model Reader
    - For Use with Vensim DSS
    - Models for results in chapter 4 and 5

Vensim Model Reader software is included so that users can open and explore the provided data and run the models supplied here. Installation instructions are provided in the 'Vensim installation software" folder.

Vensim PLE is included so that users can familiarize themselves with the basic functionality of Vensim – and system dynamics-based – software. The user guide included with Vensim PLE is comprehensive and many different example models are included in the software. Installation instructions are included in the ‘Vensim installation software’ folder. Note that the use of Vensim PLE software is free-of-charge for academic use. I suggest, however, that readers who plan to make more extensive use of the software register with Ventana Systems, Inc., at http://www.vensim.com.

Otherwise, most of the folder contents are clear from the titles. Clearly, readers without a licensed copy of Vensim DSS should install the Model Reader and then focus only on the ‘Model Reader’-related folders, while readers with Vensim DSS should use the folders intended for Vensim DSS users. The contents of these version-specific folders are identical except for the version of Vensim required in their use.