Modeling Growth and Biomass Production in Willow Plantations in the Northeastern and Mid-Atlantic United States

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ABSTRACT

Since the mid 1980's, researchers at the State University of New York College of Environmental Science and Forestry (SUNY-ESF) have been involved in the research and development of willow (*Salix* spp.) biomass plantations. These plantations are being developed in the northeastern and mid-Atlantic United States (U.S.), for the commercial production of biomass feedstock to be used as a source of renewable energy and biobased products. Simultaneously, initiatives are ongoing to expand the scale of operations and deploy the technology on larger, more diverse sites, so as to further define the potential geographical range, and expedite the eventual commercialization of willow plantation technology. As the emphasis is moved from research and demonstration to a commercial scale, some critical needs that have strong bearing on the economic viability of the system become apparent. These are: the need for the successful establishment of high yielding plantations over large areas in a cost-effective manner; and the need for further yield enhancement through tree improvement. A process based dynamic growth and yield modeling approach represents an effective method of addressing these needs. We propose to use this approach to study growth and development as influenced by environmental factors and management practices in existing plantations in the northeastern and mid-Atlantic U.S. This paper reviews growth and production modeling in SRIC willow, describes existing models, studies recent trends in model simplification and proposes a direction for model improvement.

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INTRODUCTION

Willow (*Salix* spp.) is being established as an alternative agricultural crop under a short rotation intensive culture (SRIC) regime with great potential in the northeastern, north-central and mid-Atlantic regions of the United States (Volk et al. 1999). Wood biomass from willow is a renewable feedstock that can be converted into a variety of fuels (e.g. wood chips, ethanol and syngas) and biobased products (e.g., levulinic acid, graphitic carbon materials and biopolymers).

Research in SRIC willow was initiated at the State University of New York College of Environmental Science and Forestry (SUNY-ESF) in the mid 1980's (Abrahamson et al. 1990, White et al. 1992). Nearly a decade and a half of concerted research and development on all aspects of willow crop production, including production biology, ecology, system sustainability, economic viability and enterprise development, have helped to explore related fundamental issues and develop adequate solutions. Current state-of-the art features a demonstration scale, SRIC system complete with recommendations for planting, fertilization, weed control and harvesting. Mechanization for all stages of plantation establishment and management has either been finalized or is close to being finalized. Ongoing extension and outreach activities, spearheaded by SUNY-ESF[1], is helping to educate different stakeholders about the potential of the willow crop and garner grower support, as demonstrated by the more than 500 acres of commercial willow plantations established on private lands in western New York (NY) (Volk et al. 1999).

As willow production technology is scaled up from research and demonstration, to a commercial scale, some critical needs that have strong bearing on the economic viability of the system become apparent. These are: the need for successful establishment of high yielding plantations over large areas in a cost-effective manner; and the need for further yield enhancement through tree improvement. Both of the above needs can be effectively addressed by gaining a better understanding and integration of the patterns, processes and mechanisms associated with biomass production in willow plantations as influenced by environmental and cultural factors. This understanding will help identify the manner and degree to which environmental factors constrain potential site biomass productivity, help screen potential plantations sites and plan appropriate management practices, thereby increasing the success rate of new plantations. In addition, accurate prediction of site productivity and creation of large area productivity maps can be accomplished. Information on site capabilities, biomass production patterns and management practices lend themselves to the undertaking of physical and economic analyses of site specific treatments or investments, and addressing broad questions about environmental impact and sustainability.

As more resources are dedicated to genetic improvement, there is a greater need to understand the interaction between willow genotypes and the environment. This would help identify traits, the manipulation of which, can lead to yield enhancement, and also

[1] SUNY-ESF is a member of the Salix Consortium, a group of state, local and federal agencies, utilities, universities and private organizations, that have come together with the stated goal of commercializing a willow biomass energy enterprise in NY.

assess the extent to which desirable outcomes, both in terms of yield and product quality, are constrained by growing conditions - thus leading to "smart" tree improvement initiatives (Isebrands et al. 1996).

Similar objectives have been addressed effectively in agronomy using the systems based approach of crop growth and production modeling or crop modeling (Whisler et al. 1986; Boote et al. 1996). Crop models have been used to integrate research understanding about the genetic, cultural, physiological and environmental factors that influence growth and yield. Sensitivity analysis of genetic traits and subsequent genetic improvements has resulted in substantial yield increases in crops such as soybean and peanut (Wilkerson et al. 1983; Boote and Jones 1986). Additionally, crop models have proved invaluable in the education of growers and extension agents, and in providing in-season and season-to-season decision support in fertilizer and irrigation use.

Use of Empirical and Process Models in Forest Management

Differing objectives, amounts of data available and professional expertise of researchers have resulted in several different approaches to crop modeling. Based on the conceptual underpinning and internal structure of the model, one can broadly differentiate between empirical, and process or mechanistic models. Empirical models primarily use statistical analyses to collate and describe data on growth and biomass production in a large number of forest stands or plantations, using which, one can make predictions about other stands growing under similar conditions (Mohren and Burkhart 1994). Examples of such models in forestry include yield tables or yield curves, and regression models that predict the effects of management strategies such as fertilization and variation in planting densities, on plantation yield.

Process models, on the other hand, predict the behavior of a system such as a forest stand based on a set of functional components and their interactions with each other and the system environment (Bossel 1994). Instead of modeling the result of growth in terms of dimensional change, emphasis is on understanding the nature of processes of growth such as light interception, photosynthesis, respiration and evapotranspiration, and modeling these processes as a function of the physical environment as defined by ambient temperature, light, soil water and nutrient regime. The functional components are chosen at a specified level of hierarchy, usually at one level below the level of the entire system (Makela et al. 2000), and carbon (C), nitrogen (N), water and energy fluxes between the different components are simulated over the specified period with functional components being updated after each specified time step.

Both empirical and process approaches have advantages and limitations that have been the focus of several recent articles (Mohren and Burkhart 1994; Korzukhin et al. 1996; Makela et al. 2000). Empirical models are often characterized as being simple, requiring little data, extremely effective in addressing singular objectives such as prediction of stem volume production, well tested under actual field conditions as demonstrated by their long term continued use by forest managers. However, they are most effective in summarizing past data and interpolating within the range of past data, and tend to be insufficient for extrapolative prediction to other sites or environmental conditions, or for explanatory interpretation (cause and effect) of experimental results. These models often have site and year specific parameters that need to be calibrated to a new site and period. They are limited in terms of feedback mechanisms, in their ability to describe genotypic differences in growth and biomass production, and in their capacity to respond to a wide range of cultural management practices.

Process models, by virtue of being organized along generally accepted internal and external plant growth processes and relationships, are useful for the exploration of complex systems for which sparse data exists or studying system behavior under changing conditions (Landsberg and Waring 1997). They facilitate the understanding of cause-effect, feedback relationships and genotype X environment interactions. These models address multiple objectives and are thus relevant to the current philosophy of multiple-use forest management. On the other hand, these models have been criticized as being too abstract, difficult to understand, use and apply, requiring too much data and often times, advanced training in computers and tree physiology measurements, thereby rendering them impractical for wide use by field-based managers and practitioners. Prior to the mid 1990's, most process models were only used by research teams, and were rarely tested against field data - most of the evaluations involved checks to assess if model outputs fit a generally accepted "reference" mode and sensitivity analyses of input parameters. In real terms, it is difficult to delineate models as being entirely empirical or process based, it is more relevant to assign them to continuum between empirical and process models, as most models have been developed using elements of both empirical and process approaches (Korzhukin et al. 1997).

Relative to agronomy, historically, growth and yield models have found far less utility in forest management and plantation systems (Battaglia and Sands 1997; Makela et al. 2000). Recently, however, with advances in model simplification, greater efforts to integrate process models with empirical data, and attempts to validate model performance against real field level data has fostered much interest in the application of process models to forest management and plantation management. A heightened collaboration between model developers and intended users aimed at further simplification, technology transfer and providing decision support for plantation management is also being undertaken, primarily in even-aged stands (Sands et al. 2000). Ongoing work is aimed at developing stand development models that will address regional and national scale requirements through the use of remotely sensed data and GIS based analysis (Makela et al. 2000).

<u>Process Models in Short Rotation Intensive Culture of Willow</u>

Among the relatively few attempts at model development for SRIC willow crops, the ones made by Sievanen (1983) and Eckersten et al. (1983) are salient.

Sievanen (1983) developed the first complete stand growth model for short rotation willow crops. His model simulated growth of short rotation willow coppice under optimal soil water and nutrient regimes, on a per unit area basis. The model was intended to guide physiological research and provided an output of biomass accumulation in each of the stems, foliage and root components. Model performance was less than satisfactory in terms of prediction accuracy and quantification of environmental constraints on final production. The model is limited, as it was developed to address situations where water and nutrients are optimal, which is hardly the case in real life plantation situations. Additionally, the assumption of constant allocation coefficients is an over simplification as allocation coefficients are a function of stand environment and age.

Nilsson and Eckersten (1983) developed a simulation model for willow in Sweden. This model calculated annual production in young, irrigated and fertilized willow plantations as a function of radiation and temperature. This model which has since then undergone several modifications and improvements (Eckersten 1985; Eckersten 1991). In its latest form, the model called WIGO (Willow Growth), has the capability to simulate the effects of different harvest regimes, and account for the influence of soil water and nutrient conditions by including relevant submodules that simulate soil water and soil nutrients availability. While this is the most comprehensive model available for short rotation willow, the major limitation of this model is its complexity and large data requirements.

Recently, a class of process models developed using a simplified approach intermediate in character between empirical model and detailed process approaches have been developed for *Eucalyptus* spp. and *Pinus* spp. plantation systems in Australia and New Zealand. These models assume biomass production to be proportional to the amount of cumulative photosynthetically active radiation (PAR) absorbed by a plant canopy during the growing season (after Monteith 1977). The efficiency with which this intercepted radiation is converted to biomass is a function of environmental factors such as temperature, soil moisture and nutrients, weed competition and frost, the influence of which is modeled through the use of appropriate modifiers. Prominent models in this class include BIOMASS (McMurtie et al. 1994), PROMOD (Battaglia and Sands 1997), and 3-PG (Landsberg and Waring 1997).

BIOMASS has been used to model growth and production in Radiata pine (*Pinus radiata*) and *Eucalyptus* spp., and was able to successfully predict water use and carbon assimilation of stands, however nutrient dynamics were not modeled. PROMOD has been applied to model site productivity in *Eucalyptus globulus* in response to climate and site factors and quantify the extent to which environmental factors constrain productivity. 3-PG has been used to model environmental limitations on growth and final yield in Sitka spruce (*Picea sitchensis*) stands (Waring 2000), in addition to Radiata pine stands.

Although these models are simpler than process models, since they model basic plant growth processes as a function of the environment, they can be used to predict site-specific growth and final biomass production. Other than a few species-specific parameters, these models mostly use readily available site and climatic information and some generalizations about tree growth and production (Battaglia and Sands 1997; Landsberg and Waring 1997). While these models have been developed for longer rotation, evergreen species systems that are different from that of SRIC willow, some of the basic framework could well be adapted to serve the purpose of the proposed study.

In general, most of the SRIC models were adapted from those developed for forage crops or agricultural crops, few relate to trees (Isebrands et al. 1996). The next generation models will have to be developed specifically for the short rotation intensive culture system, include the unique aspects of coppiced trees, and be capable of handling, in addition to environmental influences on growth, influences of management practices such as irrigation, planting densities, weed control, and different harvest regimes. Rather than be extremely mechanistic and data demanding, these models should take advantage of the current trends of model simplification and generalization and lend itself eventually to a form that will be useful for growth and yield research, economic planning and management decision support.

PROPOSED STUDY

Much of the previous research and monitoring work with SRIC willow at SUNY-ESF has focused on silviculture, physiology, soil sustainability, genetic improvement and assessing production rates under a range of cultural treatments, spacing and rotation lengths. We propose to use a process-based crop modeling approach to collect and analyze new information, integrate with existing information about the production system, and eventually develop and test a willow growth and production model. The new information would come from existing plantings in the northeastern and mid-Atlantic United States (Table 1, Figure 1). The objectives of the study are as follows:

1. Integrate previous data from research at SUNY-ESF and published literature using existing crop production models.
2. Conduct focused research in existing plantations in New York, Delaware and Pennsylvania and under controlled conditions to obtain additional information that is required to build and test a growth and yield model.
3. Develop a growth and yield model for SRIC willow.
3. Validate model performance against field data collected from plantations in the northeast, mid west and Mid-Atlantic States.

<u>Analysis of historical data</u>

Published and unpublished data will be gleaned from the SUNY-ESF willow research program to help establish a historical bioassay of survivorship curves, site quality-productivity functions, and response to cultural practices such as fertilization, irrigation and weed management (Kopp et al, 1993; Kopp et al, 1997). Information would also be assembled on ecophysiological processes such as foliar development, foliar nitrogen dynamics, light interception and biomass partitioning patterns. External published literature would be also be researched to provide relevant information. This data would be used to parameterize some of previously discussed models and used to carry out a preliminary analysis of biomass production in willow biomass plantations. The models will be assessed in terms of their data requirements, accuracy in forecasting production on diverse sites, and ease of use and versatility in addressing SRIC crop management issues.

Field and laboratory experiments

The research would focus on three select clones, selected from four different species of willow: *Salix dasyclados*, *S. eriochephala*, and *S. miyabeana* or *S. sachalinensis*. These species are featured in SUNY-ESF's Willow Crop Development Center's breeding program. A *S. dasyclados* clone, SV1, has been the best biomass producer in small-scale trials and is planted across all clone-site trials as a reference clone. *S. eriocephala* is native to North America (Zsuffa 1988) and appears to have large potential for bioenergy production based on research completed in Ontario, Canada (Aravanopoulos and Zsuffa 1988). *S. miyabeana* and *S. sachalinensis*, both natives of Asia, appear to be promising for biomass plantation purposes in the Northeastern United States (Tharakan et al. 2000).

Observational field experiments will be conducted for 1-year (study year 1) in eight clone-site trials (Table 1). These eight trials, selected to represent the range of soil and site combinations across the Northeast and mid-Atlantic region, would be classified into intensive study sites (four sites), and extensive study sites (four sites). On intensive study sites, a wide range of growth and ecophysiological variables would be monitored in older plantations (1-3 years old, after first coppice). These would include length of growing season, initial biomass values, light interception, foliar dynamics, foliar nitrogen and biomass, biomass partitioning, and end of season survival and stem biomass. Stem biomass production will be estimated either by destructive sampling (end of rotation harvests) or by using regression equations.

These sites would also be monitored for environmental variables such as solar radiation, precipitation, temperature, soil moisture and soil nutrient status. Additional soil characteristics measured may include bulk density, depth to mottling, effective rooting depth, pH, texture, and coarse fragment content, and site factors such as landform, and landscape position. Information from these sites would mainly be used to provide parameters values and other empirical relationships that would be used in model development. If found to be necessary, controlled experiments in laboratory or greenhouse would be undertaken to obtain parameter values for detailed aspects of physiology such as light saturation curves.

The extensive study sites would be monitored in 1 year (study year-2) for peak leaf area, foliage nitrogen, end of season survival and stem biomass. In addition, environmental and soil-site variables as detailed above would be measured. These sites would be used for rigorous validation of model outputs from actual field based data.

Modeling approach

The lack of a large comprehensive database of growth and production, and the fact that most of the future plantations are going to be of new clones being planted on land that has been planted to willow before, implies that empirical models would not be very effective for modeling SRIC willow. In terms of detailed process models, the most evolved and relevant model is WIGO, however, it was designed to serve research objectives and can be considered to be too complex and data demanding to be of use in routine SRIC crop management.

Table 1. Willow clone-site trials established by SUNY-ESF from 1993 to 2000.

Site	Year planted	No. *Salix* clones	Cooperator or landowner
Tully, New York (NY)	1993	19	SUNY-ESF/NYSERDA
Massena, New York	1993	14	Reynolds Metals
King Ferry, New York	1995	13	New York State Electric & Gas
Somerset, New York	1995	6	New York State Electric & Gas
Burlington, Vermont (VT)	1997	6	Burlington Electric
LaFayette, New York	1997	13	Private landowner
Rhinelander, Wisconsin (WI)	1997	34	USDA Forest Service
Tully, New York	1997	34	SUNY-ESF/Oak Ridge Nat. Lab
Sheridan, New York	1998	11	Private farmer
Leon, New York	1998	15	Private farmer
Canastota, New York	1998	13	Private farmer
Wolcott, New York	1998	11	Wegmans Egg Farm
Easton, Pennsylvania (PA)	1998	13	LaFayette College//USDA Forest Service
East Lansing, Michigan	1998	16	Michigan State University
Peters Tract, Delaware (DE)	1999	13	Delaware Department Agriculture
Roaring Branch, Pennsylvania	1999	13	PA Farm Bureau//USDA Forest Service
Madison, Wisconsin	1999	10	Univ. Wisconsin/ USDA Forest Service
Rhinelander, Wisconsin	1999	10	USDA Forest Service
Montreal, Quebec	1999	12	Montreal Botanical Gardens
Raleigh, North Carolina (NC)	1999	13	North Carolina State University
Montour Preserve, Pennsylvania	2000	24	PP&L Inc./USDA Forest Service
Queenstown, Maryland (MD)	2000	15	Wye Res. & Educ. Ctr/E. Shore RC&D
Westfield, New York	2000	28	Private landowner
Jackson, New Jersey (NJ)	2000	11	NJ State Forestry Service

Currently, much of the tree crop modeling research is focused on the streamlining of existing process models to make them more useful for management purposes, or the development of simpler models that borrow from both empirical and process model approaches (Battaglia and Sands 1997; Landsberg and Waring 1997). The possibilities of adapting modern simplified models such as BIOMASS, PROMOD and 3-PG developed for longer rotation evergreen systems such as *Eucalyptus* spp does exist. However, fairly generic models such as 3-PG and PROMOD were developed for uncoppiced systems and assume complete canopy closure, a feature that would prevent these models from capturing the pre and post coppice dynamics of SRIC willow. Thus, it is most likely that existing short-rotation models would need substantial modification and streamlining as to be applicable to a coppiced willow system, growing conditions in the northeastern, north central and mid-Atlantic United States, and be able to make predictions of growth and production from a suite of easy to measure variables.

Based on analysis of existing information and new data from research and calibration trials, the relationships between growth processes and environmental factors would be assembled into mathematical relations that would then be used to streamline or modify existing models, or develop an entirely new model. In general, the modeling approach that would be used will be along the lines of that used in recent simplified stand level production models. According to this approach, the efficiency with which absorbed radiation is converted to biomass and allocated to different parts of the trees, is influenced by environmental and management factors, primarily, soil water and nutrient levels, atmospheric vapor pressure deficit, stand density and age (Figure 1). The specific characteristic of reserve biomass in the stool and root system stimulating a flush of new growth at the beginning of the growing season following coppicing will be explicitly modeled, as coppice vigor does influence growth in the following years.

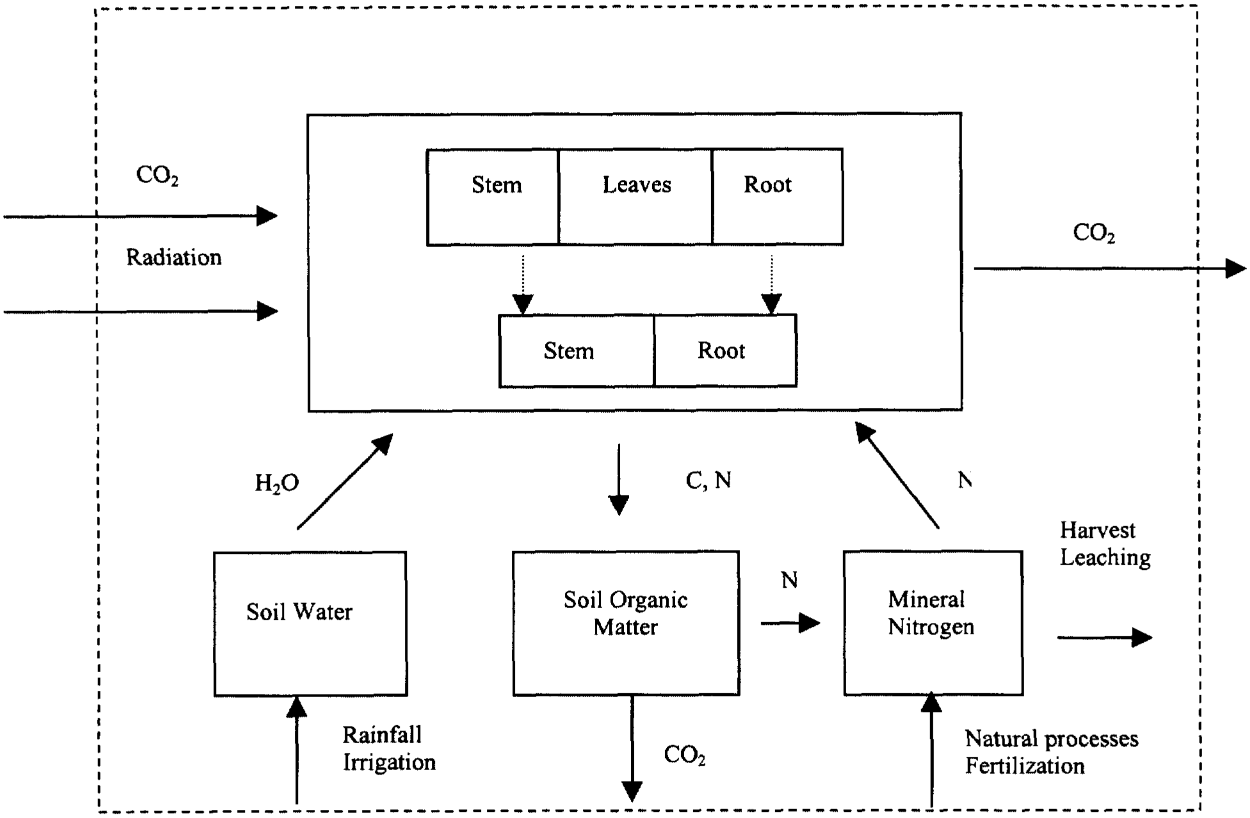

Figure 1. Compartmental flow diagram of the proposed willow production model

Stand growth would be divided into current year growth, differentiated as stem, leaves and roots components, and older tissue, in turn differentiated into stem and leaves. The model will link the important fluxes of energy, carbon and nutrients on one hand, and CO_2 and water on the other. Water balance as a function of precipitation, site water holding capacity, evapotranspiration, plant uptake and runoff, would be simulated as will also nutrient (nitrogen) availability as a function of plant uptake, loss during harvest, mineralization and litter decomposition.

CONCLUSION

The proposed study will result in the development of a dynamic process model that will be particularly useful for synthesizing research understanding and for integrating from a reductionist approach to studying growth and production in willow plantations. In terms of management applications, this modeling exercise will facilitate screening of potential sites for plantations, designing effective management practices including weed management and fertilization, and a study of environmental, genetic and cultural influences on rotation length production for willow plantations in the northeast and mid-Atlantic U.S. With model development will come opportunities for studying effects of coppicing on the growth vigor of these plantations across a wide range of environmental factors, and exploring small plots bias and other issues related to extrapolating small plot growth and development data to large plantations.

This is the first time that a study of this nature is being undertaken in coppiced SRIC systems in the U.S. In the future, following development and validation, the model can be further adapted to help evaluate economic costs and producer risk, and provide management decision support.

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