

Sustainability of High Intensity Forest Management with Respect to Water Quality and Site Nutrient Reserves

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ABSTRACT

Ensuring sustainability of intensively managed woody crops requires determining soil and water quality effects using a combination of field data and modeling projections. Plot- and catchment-scale research, models, and meta-analyses are addressing nutrient availability, site quality, and measures to increase short-rotation woody crop (SRWC) productivity and site sustainability. Plot-scale (0.5 ha) research began in 1995 in MS, AL, and TN to compare woody and agricultural crops. In 1997, the plot scale expanded to catchment-scale SRWCs plantings (20-40 ha) on International Paper lands in South Carolina. Water quality, erosion, runoff, soil quality, and nutrient cycling are being quantified with production of SRWCs. Combined literature, meta-analyses, field data, and models (NuCM and WATRCOM) are identifying mechanisms to enhance soil carbon, fertilizer and water-use efficiency, and site sustainability, while minimizing nutrient and soil losses. Data and literature analyses demonstrate that soil cover, rates and timing of nutrient application, rainfall timing and intensity, and plant growth are keys to minimizing runoff, erosion, and nutrient transport while maximizing productivity. In SC, decreases in soil water potassium and phosphorus are indicative of previous agricultural fertilization; while increased extractable aluminum reflects increasing site acidification. Modeling simulations and water level management at the SC site are demonstrating mechanisms to enhance tree growth.

Keywords: soil quality, nutrient modeling, nutrient utilization, hydrologic modeling

INTRODUCTION

Dedicated short-rotation woody crops (SRWC) and perennial herbaceous crops, as well as residues, can provide significant feedstocks to support viable biomass to bioenergy and bio-products industries. Incorporating production of intensively managed biomass crops into agricultural systems can provide both economic and environmental benefits. Quantifying environmental benefits, risks and any mitigation measures that may be necessary to ensure sustainable establishment, management, and harvest of SRWC must occur if these benefits are to be realized. Growing perennial biomass crops on agricultural lands, particularly those producing marginal yields or established on more erosive soils, can provide soil and water quality benefits, dedicated feedstocks (Smith,

1995; Grigal and Berguson, 1998), and alternative economic return. The potential impacts from site preparation and production on more marginal lands are greater and the yields probably less than on more productive agricultural lands; however, the greatest gains in soil quality are expected on these lands. Determining management practices that can minimize on-site and off-site effects, e.g., erosion and chemical transport, and matching biomass crop types to appropriate sites, can maximize the environmental sustainability of biomass crop production for multiple end uses.

The combination of site-specific research, literature analysis, and modeling described here summarizes the ongoing research being supported by the U.S. Department of Energy's Offices of Transportation Technologies and Industrial Technologies. The goal of this research is to identify cost-effective management options to increase tree crop productivity while simultaneously enhancing site sustainability and long-term soil productivity. The combined approach evaluates measures to manage off-site movement of sediment and chemicals, develops water management approaches to increase productivity and reduce runoff, and evaluates nutrient budgets to assess nutrient use efficiency. The endpoint is to develop an integrated approach with user-friendly nutrient (NuCM) and water quality (WATRCOM) models that can be used to increase productivity and sustainability of short rotation woody crops. Thornton et al. (1998) and Tolbert et al. (1997, 1998) summarized some of the earlier surface water and nutrient transport results from the small field-scale studies that provided the first layer in identifying practices to increase sustainable SRWC production.

METHODS

Small-scale plantings have been used to quantify water and soil quality and productivity of sycamore compared with no-till corn for at a site in western Tennessee (TN), sweetgum with and without a cover crop compared with no-till corn at a site in northern Alabama (AL), and cottonwood in Mississippi (MS) since 1995. Earthen berm enclosures were used to exclude runoff from outside the plots and to quantify runoff, sediment, and nutrient transport from the individual plots. At the TN and MS sites the replicated plots were 0.5 ha and at the AL site 0.25 and 0.5 ha. This event-based monitoring will continue at least through 2001 at the TN and AL sites. Detailed descriptions of the plot-scale study methods are available in previously available publications (Joslin and Schoenholtz 1998, Thornton et al. 1998, Tolbert et al. 1997, 1998)

Catchment-scale (20-40 ha) plots and watershed scale (~500 ha) plantings were established on International Paper lands in SC to assess factors controlling off-site movement of nutrients, chemicals, and water, and long-term soil sustainability of larger scales. Replicated SRWC plantings [two using current management techniques for tree crop production (sweetgum with open drainage -SWO and sycamore with open drainage - SYO), and one incorporating agronomic water management practices for SRWC production (sycamore with controlled drainage structures - SYC)] were established in late 1996. The treatments represent commercially feasible systems of tree species, fertilization, weed control and water management regimes. The six catchments are instrumented to measure surface and subsurface water quality and surface water discharge. Soil nutrients, carbon, and tree productivity are measured annually. The combination of the small-scale, catchment-scale and two second-order watersheds (~500

ha) are providing the basis to evaluate the ability to use results from multiple scales to make predictions of effects of landscape-scale SRWC production. Field data from the SC site are providing input to the meta analysis on nutrient turnover and for models for hydrologic and nutrient cycling.

Existing information on nutrient reserves and nutrient amendments in short rotation biomass plantations is being compiled into databases for meta analyses using the method of Curtis (1996). These databases are being used to assess the factors affecting the sustainability of site nutrient reserves and the effects of nutrient amendments on water quality. Sources of information included are published reports obtained from literature searches and inquiries from forest scientists via the International Energy Agency.

Process-based hydrologic (WATRCOM) and nutrient based (NuCM) models are being used to develop an integrated modeling framework to assess the sustainability of SRWC with respect to water quality and site nutrient reserves. Data from the SC site are being used to parameterize the models to develop a user-oriented model platform for operational use by the forest products industry.

RESULTS AND DISCUSSION

Results from the plot-scale studies through 1997 have been reported in several publications (Bandaranayake et al. 1996, Thornton et al. 1998; Tolbert et al. 1997, 1998, Tolbert and Wright 1998). Establishing short-rotation tree crops on former agricultural sites has been shown to provide positive benefits for water and soil quality. At the AL research site establishing a 60-cm wide herbaceous cover crop centrally between tree rows significantly reduced sediment transport from the plots especially during the initial year of establishment (Green et al. 1996, Malik et al. 2000). Sweetgum productivity from 1995-97 did not show a competition effect of the 60-cm wide fescue cover crop.

Soil quality

Comparisons on small-scale plantings showed that soil organic carbon (SOC) increased by 19% in the upper 2.5 cm with conversion to cottonwood production; the total soil carbon mass (excluding stumps and coarse organic matter) was 15 Mg ha⁻¹. With stump and coarse roots included, the belowground biomass was approximately 18 Mg ha⁻¹ (Tolbert et al. 1998). At the TN site SOC increased by 27% and 34%, respectively, under no-till corn grown with a winter cover crop and sycamore. The increased SOC storage under the sycamore was approximately 1.3 Mg ha⁻¹ yr⁻¹. Soil carbon significantly increased ($p \leq 0.02$) under switchgrass, sweetgum with a cover crop, and no-till corn from 1995-1997 at the AL site. By contrast soil carbon under sweetgum without a cover crop decreased by 6% over the same period (Fig. 1). This carbon loss is consistent with Hansen's (1993) measurements showing soil carbon decreases during the initial years of tree crop establishment with use of cultivation.

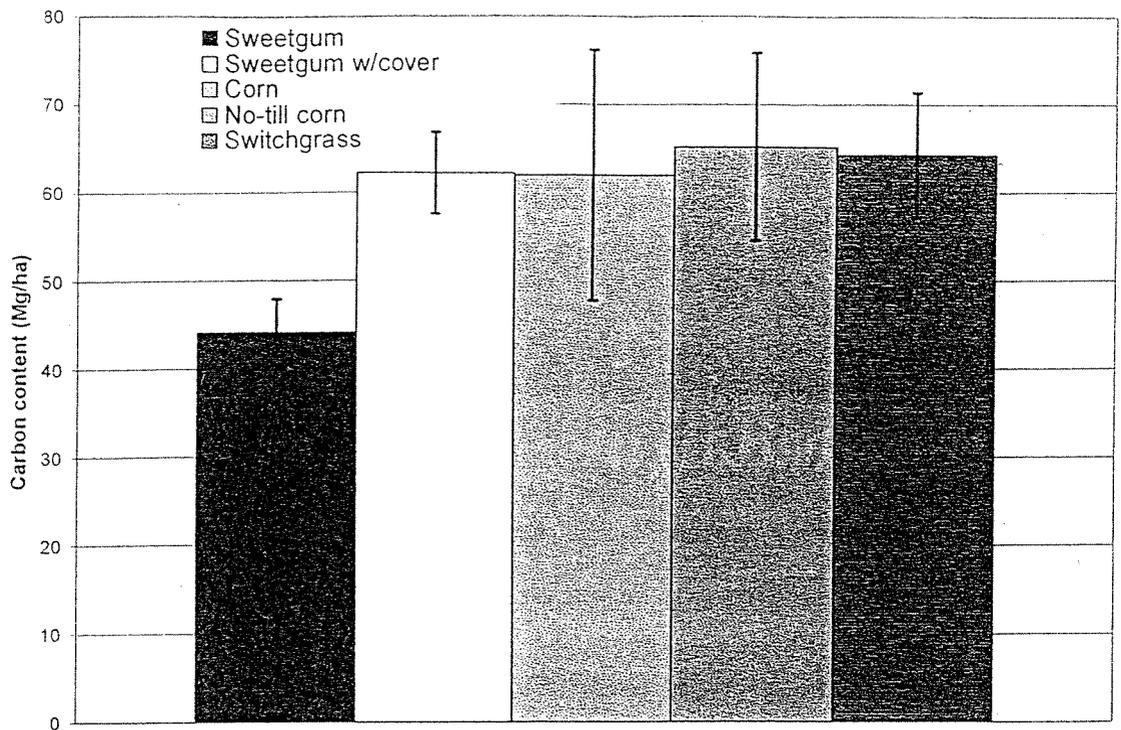


Figure 1. Mean soil organic carbon by treatment at the AL site after the fourth growing season.

At the South Carolina (SC) site, elevated extractable cation levels reflected differences in parent material and genesis between the Coxville and Goldsboro soils. Extractable K was greater in the upper 30 cm on the sweetgum plots than the sycamore plots. Phosphorus exhibited effects of past agricultural management, with the sycamore-open drainage catchments having significant higher levels than the other two treatments; all treatments had elevated levels in the upper 30 cm. Extractable K and P declined between 1997 and 1998 in the sycamore-open drainage treatment indicating a loss of P from the surface soil that is not being maintained by the current fertilization regime. Comparisons of carbon allocations into soil and aboveground components at the SC site show that there are dramatic differences in allocation between sycamore and sweetgum (Fig. 2) with sweetgum allocating significantly more carbon to the soil component over the first three years of growth.

At the TN site, soil samples taken from 1995 – 1998 showed the greatest changes in soil properties within the upper 30 cm. Initial comparisons showed bulk densities and penetration resistance to be lower under 13-year old sycamore than the newly established sycamore and no-till corn. Both penetration resistance and bulk density at 0-30 cm decreased significantly over time in the younger sycamore plots compared with the no-till corn plots. The hydraulic conductivity and infiltration rates in the cottonwood plots at the MS site were more than twice as great as in the continuous cotton plots (12.47 vs. 4.6 and 44.7 vs. 20.0 cm/hr, respectively (Tolbert et al. 1998). Bulk density in the upper 10 cm decreased over the 3-year cottonwood production (1.4 Mg m⁻³ in 1995 to 1.1 Mg⁻³ in 1998) as the result of increased incorporation of organic material and root penetration. Soil bulk density and infiltration at the SC site ranged from 1.42 Mg m⁻³ in the A horizon within the planting bed for treatment SYC to 1.79 Mg m⁻³ in the B- horizon, between

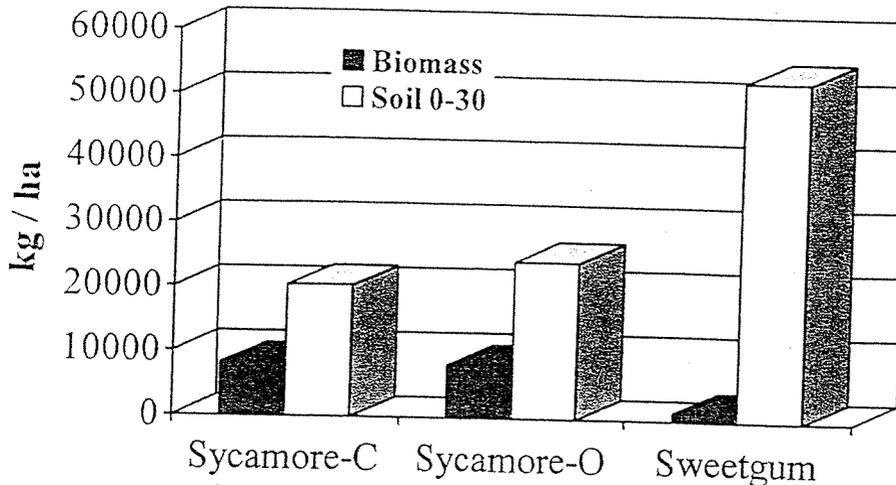


Figure 2. Allocation of carbon by sycamore (C – closed drainage, O – open drainage) and sweetgum at the SC site.

beds for treatment SWO. Sample infiltration rates ranged from 1.0-104.1 cm per hour.

Runoff was reduced with production of SRWC relative to agricultural crops. The reductions, which were greatest with eastern cottonwood, then sycamore, and finally sweetgum match the species growth and site occupation rates and show the effect of higher rainfall interception and evaporative losses by tree foliage (Mitchell 1997) and increased litter cover. At the AL site, sweetgum plantings with a cover crop produced 25% less runoff than the no-till corn plots.

Hydrologic data are currently being collected at the SC site and provide the opportunity to compare water availability with and without use of flashboard risers to retain water on the site and to determine water availability for comparison with plant growth responses. Water level simulations are contributing to the WATRCOM simulations of water level management at the SC site (Fig. 3).

Water quality

Water quality comparisons overall for the plot scale sites show that runoff transport of nitrate was greater from the row crops than from the tree crops (at the TN and AL sites). As would be expected, nutrient transport was greatest when runoff events occurred soon after fertilizer application.

Soil water at the SC site is acidic, averaging pH 5.39, 5.21, and 5.63 for the SWO, SYO, and SYC treatments, respectively. In 1997-98 there were significant differences in pH but little difference in Ca and Mg among the SRWC treatments during this period. Calcium and Mg levels in the SRWC plantings were greater than in soil water collected in the agriculture reference plot, presumably a result of past management practices. Potassium exhibited variation among treatments with no discernible treatment effects or temporal patterns. Elevated $\text{NH}_4\text{-N}$ following the spring 1998 application of fertilizer was evident in the soil water. The levels declined within a month, but remained elevated relative to the 1997-growing season. Overall, levels of $\text{NH}_4\text{-N}$ have consistently been below 1 mg l^{-1} . Nitrate levels, across all treatments, have been low during the winter

(Nov. - March) and then increased in the spring probably a result of fertilizer application and nitrification. The strong temporal pattern suggests that nitrification (of both organic and fertilizer $\text{NH}_4^+ \text{-N}$) is the primary mechanism. Nitrate levels in the SRWC plantings exceeded those in the agricultural reference at all times. The $\text{NO}_3^- \text{-N}$ levels in the SRWC plantings represents a mobile N pool, which is likely in excess of vegetation or microbial demand. This suggests that the N fertilization rates are too high for the present stage of stand development.

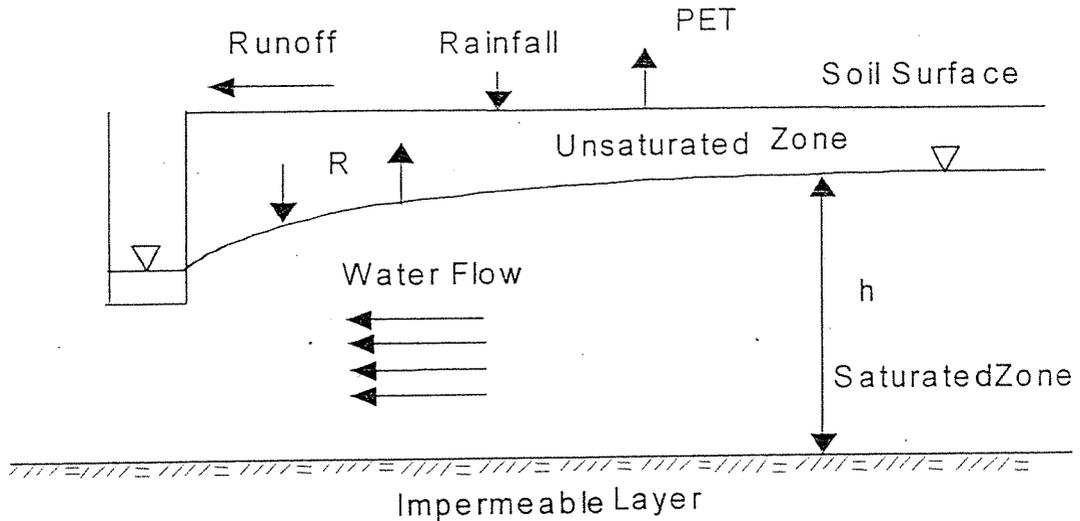


Figure 3. Schematic representation of the water flows simulated in the saturated zone along with linkages to the unsaturated zone for WATRCOM hydrologic model.

Literature Survey and Meta Analysis

Existing literature on nutrient losses and fertilizer recovery in forest systems has been compiled and summarized in separate databases on the effects of forest harvesting on soil carbon (Johnson and Curtis In press) and fertilizer nitrogen recovery. The meta analysis of the harvesting and soil C data base revealed no significant differences between whole-tree and sawlog harvesting, each producing an average soil C increase of approximately 22%. There were significant-time-since-harvest effects, where little differences in soil C (4-8%) were noted within the first five years of harvest and considerably more during years five to twenty. The analysis of depth effects revealed a perhaps spurious result: the greater accumulation of soil C in deeper horizons than in surface horizons. Further refinements of these analyses are being conducted.

The literature analysis of fertilizer recovery and allocation by trees was an update of a database previously reported by Johnson (1992). The developed database on fertilizer nitrogen recovery is being used to assess factors affecting the sustainability of site nutrient reserves, allocation of site available nitrogen, and effects of nutrient amendments on water quality. The comparisons to date of the fertilizer N recovery using the meta analysis show that the type of fertilizer applied effects the retention of the fertilizer applied (Fig. 4). For example, ammonium nitrate was retained approximately in equal proportions by soil, litter, and stem whereas applied urea was retained primarily in the soil and litter and NO_3^- primarily in the stem and soil. Data from multiple studies

show that single annual applications of fertilizer showed greater on-site retention of nutrients than from multiple fertilizer applications (Fig. 5). Application of less than 150 kg resulted in greater retention than 150-500 kg and particularly more than 500 kg. Linking these meta analyses with data from the catchment-scale studies, and nutrient models can begin to guide application of fertilizer to SRWC to maximize their productivity, environmental benefits for soil and water quality, and economic competitiveness.

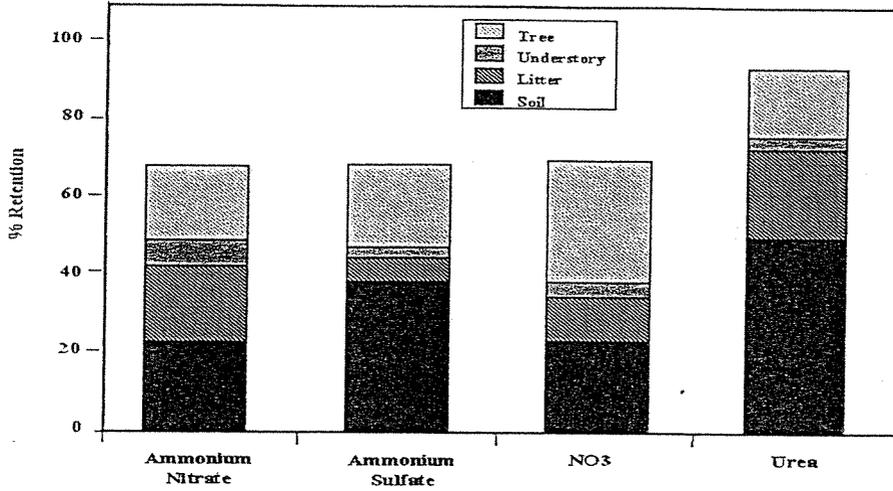


Figure 4. Comparison of retention of fertilizer show that the type of fertilizer applied influences the retention of fertilizer by forest components.

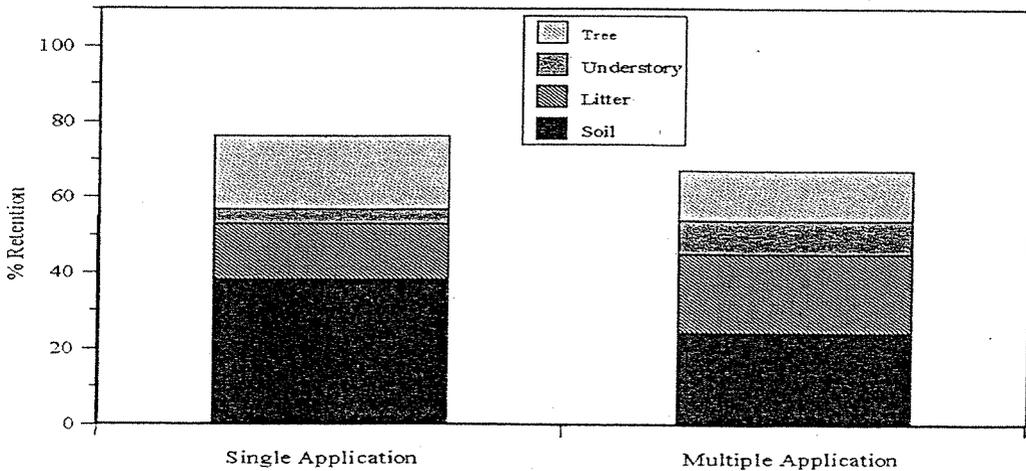


Figure 5. Comparisons of retention of fertilizer within different forest components based on single applications compared with multiple applications.

Calibration of the NuCM Model

The results of the meta analysis are currently being used along with the SC field data and the NuCM nutrient model to determine whether the timing of nutrient additions and their allocation within the system are reflected in the patterns of nutrient requirements and losses from intensively managed tree crops at the SC site. Meteorological data, including precipitation chemistry and air quality, and soils and vegetation data for the South Carolina site are currently being collected for calibration of the hydrological and chemistry sub-models of NuCM for the SC site.

SUMMARY

The combination of small field-scale and catchment-scale comparisons of productivity of woody crops in combination with hydrologic and nutrient models and databases summarizing information on SOC retention with different harvesting practices and nutrient management are providing powerful tools to help increase the sustainability of SRWC production. Conversion of agricultural croplands to SRWC production can have positive benefits for both soil and water quality. Production of SRWC on agricultural lands can also contribute to increased SOC. The combination of small- and catchment-scale research studies show that different SRWC respond to variations in soils and that nutrient requirements differ for different tree crops and different soil types.

Identifying appropriate management practices for nutrient additions can contribute to environmentally sustainable production of SRWC and to reducing economic costs for their production. Identifying changes in nutrient content and productivity with time and developing user-friendly models for nutrient and water use can also assist individual and operational scale growers to identify best management practices for nutrient content, application, and timing to maximize sustainable production. The combined projects will continue monitoring runoff, water quality, and soil chemistry, including SOC, at both small- and catchment- scales during the middle rotation years (5 – 8) of production cycles. Continuing to monitor these soil and water quality parameters will allow us to determine (and document) whether patterns change over time and whether the quantified benefits of cover crops for soil and water quality continue. At the AL site monitoring productivity and SOC over time will help determine whether SOC on the plantings with a cover crop will continue to outpace that of the sweetgum without a cover crop plantings. This has important implications for both soil and water quality with larger-scale production of woody crops. If productivity data from comparisons of the effects of different cover crops at the AL site show significant nutrient and productivity benefits for the tree crops from use of different cover crops, there could be increased interest and use of cover crops at production scales to increase sustainability and productivity. The AL and SC sites offer opportunities to determine if cover crop and water level management can provide enhanced nutrient availability and use efficiencies to enhance productivity. Management options under consideration for harvesting and replanting at the TN site can provide additional information for establishment, site management, and harvest to increase both yields and sustainable production. Monitoring changes, testing options, and documenting measures to increase economic and environmental potential of SRWC can increase their adoption for energy, bio-based products, and fiber.

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Proceedings of the Short-Rotation Woody Crops
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August 2001