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Interactions of Woody Biofuel Feedstock Production Systems with Water Resources: Considerations for Sustainability

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Abstract. Water resources are important for the production of woody biofuel feedstocks. It is necessary to ensure that production systems do not adversely affect the quantity or quality of surface and ground water. The effects of woody biomass plantations on water resources are largely dependent on the prior land use and the management regime. Experience from both irrigated and non-irrigated systems has demonstrated that woody biofuel production systems do not impair water quality. Water quality actually improves from conversion of idle or degraded agricultural lands to woody biomass plantations. Site water balance may be altered by cultivation of woody biomass plantations relative to agricultural use, due to increases in evapostranspiration (ET) and storage. Incorporation of woody biomass production plantations within the landscape provides an opportunity to improve the quality of runoff water and soil conservation. Given the centrality of water resources to the sustainability of ecosystem services and other values derived, the experience with woody biofuels feedstock production systems is positive.

Keywords. Short rotation woody crop, forest hydrology, water quality, hardwood plantation.

Introduction

Water resources are an essential consideration for the production of woody biofuel feedstock. From a silvicultural perspective, woody crops vary in their water demand, hence it is necessary to ensure that the site has sufficient water supply. Correspondingly, the production systems should not adversely affect the quantity or quality of surface and ground water. The effects of converting to woody biomass plantations on water resources are largely dependent on the prior land use and the management regime. Experience from both irrigated and non-irrigated systems has demonstrated that short-rotation woody crop (SRWC) production systems can be operated without adverse affects to water resources. However, there are only a few hydrologic studies on the SRWC production systems. Here, we provide a basis for considering intensively managed woody crop production systems by synthesizing hydrologic and water quality responses from forest plantations

Effects of SRWC Production on the Water Cycle

Most SRWC production systems are developed on agricultural lands, hence the basis for evaluating the effects on the water balance. The contrast between these cropping systems yields generally positive effects of woody crop plantations (Fig. 1). A major difference between woody crop and agricultural crop production systems is that the former don’t require annual tillage; this change in tillage regime is a major factor affecting the hydrologic response (e.g. infiltration, subsurface flow and surface runoff). The cumulative effect of increasing the amount of forest land within a watershed is to reduce runoff (i.e., yield) (Fig. 2), primarily as a result of increased evapotranspiration (ET) and storage. Each of the component responses are discussed below.

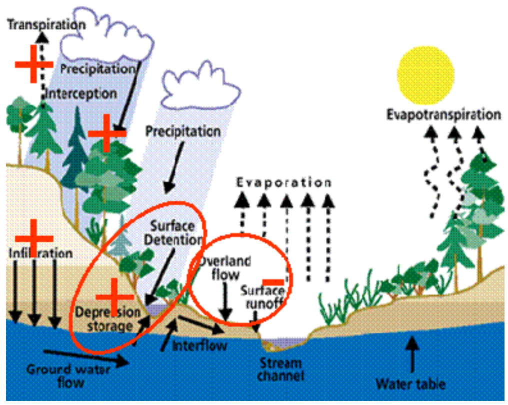

Figure 1. Schematic of the water cycle, with the signs (+ / -) indicating the effect of woody crop production systems on the individual components. Components without signs are generally not affected by SRWC management.

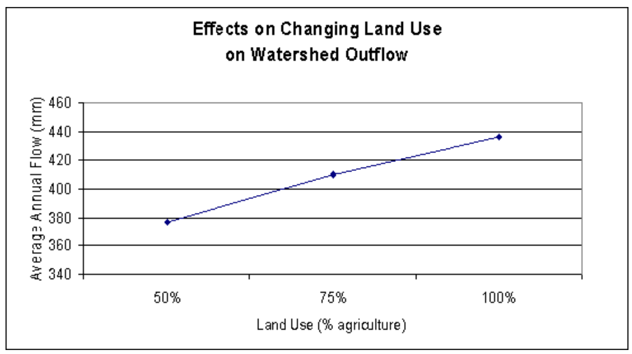

Figure 2. Changes in annual yield as the proportion of watershed used for agriculture increases relative to forested landscape (Fernandez et al. 2007).

Interception

Interception is generally larger in forest plantations than agricultural fields due to the greater leaf area and above-ground biomass. The perennial nature of woody crops is also an important factor, yielding interception throughout the year. Interception by both pine and hardwood species increases with stand age, with pine generally yielding larger amounts (Rutter etal. 1975). Helvey (1967) reported that during the dormant season, calculated monthly interception loss from mature hardwoods and white pine exceeded potential evapotranspiration calculated by the Thornthwaite method.

Evapotranspiration

On an annual basis, transpiration loss is greater in both hardwood and pine plantations than in agricultural fields, as a result of larger leaf area, deeper rooting depth, and longer growing season (Fig. 3). Skaggs et al. (2004) studied effects of land use on hydrology of drained soils on agricultural cropland, forested land (managed pine), and an undrained forest wetland in the lower coastal plain of North Carolina. The authors reported that higher ET demand on the forested site resulted on reduced water outflow and deeper water tables compared to the agricultural site. Amatya et al. (2002) found average annual ET, calculated as difference of rainfall and outflow, as 922mm, 714 mm, and 727 mm for forested, agricultural and mixed land use watersheds, respectively and were consistent with the results obtained by using the Zhang et al. (2001) method. The evapotranspirational loss also changes through the development of the stand, with rapidly increasing rates in the first 4-6 years, following canopy closure the rate of increase slows being a function of the leaf area and sap wood area (Wullschleger et al., 1998; Delzon and Loustau, 2005; Samuelson et al., 2006; Calder et al., 1993). As an example, annual ET, calculated as difference of rainfall and outflow, for a pine forest in eastern North Carolina increased from as low as 660 mm, on average, in 1996 (soon after harvest) to as high as 1,100 mm, on average, in 2004 when the trees were 7 years old (Amatya et al., 2006). The authors reported that the hydrology had recovered to pre-harvesting levels seven years after planting for regeneration, which corresponded with canopy closure.

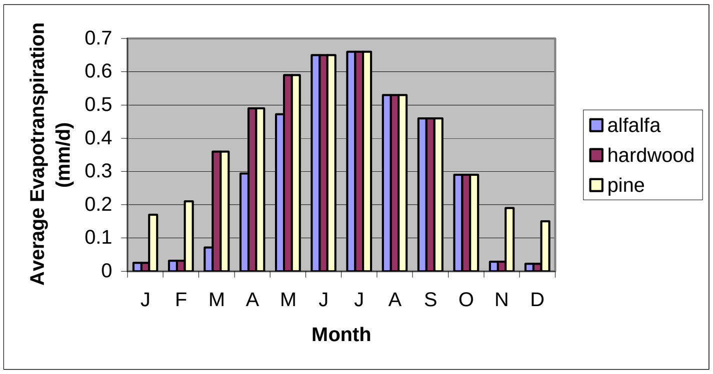

Figure 3. Comparison of evapotranspiration among forest plantations and agricultural crop.

Infiltration

The soil infiltration rate is generally higher in forest plantations than agricultural fields as result of reduced compaction and the porous litter layer at the surface. Since forest crop plantations do not require the same degree of tillage practices, compaction is lessened as a result of reduced trafficking. Compacted agricultural fields with a "plow-pan," may require ripping in the tree planting line, to allow for deeper root penetration which is characteristic of most tree species.

Storage and Detention

Storage in the surface soil is larger in forest plantations than agricultural fields, due the development of surface micro-topography that yields increased depressional storage. Subsurface soil storage is also effectively increased as a result of improvements in water infiltration and reduced compaction.

Surface Runoff

The cumulative effect of increased interception, evapotranspiration, and storage is in reduced runoff from the woody crop plantation as compared to the agricultural field (Amatya et al., 2002; Shelby et al., 2005; Skaggs et al., 2004). The improvement in subsurface drainage conditions (e.g., increased infiltration and storage) yields a significant effect on the timing and volume of runoff (Fig. 4). Amatya et al. (2002) compared water balance of a 2,950 ha forested, a 710 ha agricultural sub-watershed and a 8,140 ha watershed comprised of agricultural, forested, and riparian lands. They found that the average annual runoff/rainfall ratio for the managed pine forest watershed was the lowest compared to two other watersheds. In their recent modeling study using a SWAT (Arnold et al., 1998) watershed model on hydrologic effects of afforestation of a grassland in Uruguay, von Stackelberg et al (2007) predicted a 30 % reduction in mean annual water yield from the afforested catchment.

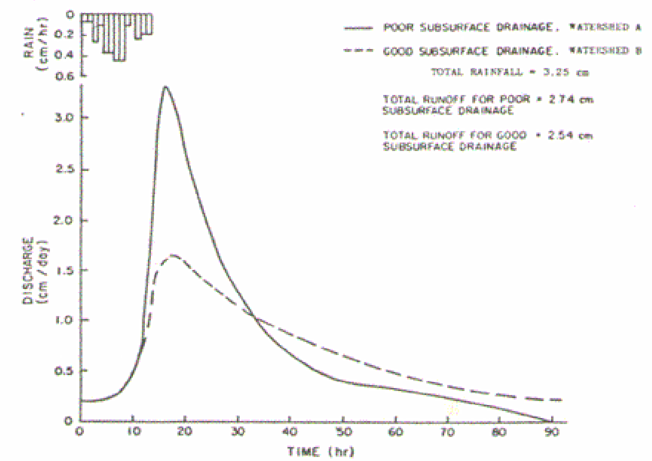

Fig. 4. A storm hydrograph illustrating the effect of subsurface drainage conditions on runoff (from Skaggs et al. 1991).

Effects of SRWC Production on the Water Quality

Although there are relatively few studies on the effects of SRWC production on water quality, both catchment-scale field studies and simulation studies demonstrate positive water quality benefits as a result of SRWC management. Updegraff et al. (2004) simulated the effects of catchment conversion from agriculture to SRWC; those results showed positive reductions for both sediment and total nitrogen in runoff (Fig. 5). Studying the conversion of an agricultural field in southwest Georgia on SRWC, Williams and Gresham (2002) reported that NO_3-N in the ground water remained high (> 10 mg l^{-1} NO_3-N) for two years following conversion, and that it had declined only slightly after five years. At the same time on that site, the soil water NO_3-N concentration at 1.4 m below the surface was less than 0.5 mg l^{-1}. The contrast between the soil water and ground water suggests that there is lag in the recovery of the shallow ground water following the agricultural cropping. We studied ground water quality on fields that had been converted from agriculture to SRWC plantations in the upper coastal plain of South Carolina. Monitoring over four years showed that the NO_3-N concentrations were relatively constant following establishment of the plantations (Fig. 6).

Typically forest management practices do not degrade water quality; accordingly, the same performance should be expected of SRWC plantations as long as Best Management Practices (BMPs), and herbicide and fertilizer labels are followed. The Georgia study (Williams and Gresham, 2002) highlights the relevance of background conditions inherited from the past agricultural practices. Accounting for that legacy effect is important to interpreting monitoring response data, and it could be important in designing the SRWC plantation to mitigate runoff or shallow ground water.

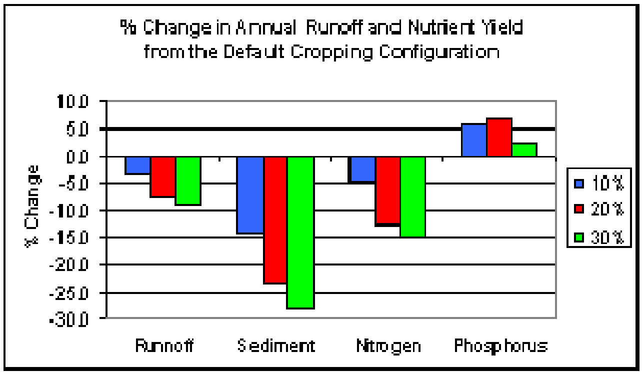

Figure 5. Changes in runoff and water quality associated with watershed conversion to short rotation woody drops (From Updegraff et al. 2004).

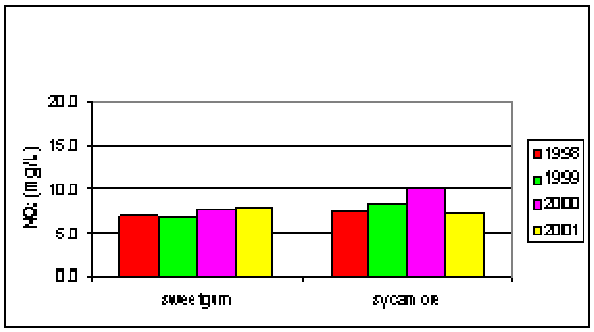

Figure 6. Annual mean NO_3-N concentration in shallow ground water (5 m) following conversion of an agricultural field to sweet gum and sycamore plantations in the upper coastal plain of South Carolina.

Conclusion

Conversion of agricultural lands to woody crop production systems will cause significant changes in the water balance of the site, and alter the runoff characteristics of the watershed. Reduced tillage associated with woody crops results in improved infiltration and soil storage. As a result of the improved soil drainage conditions, peak storm runoff is dampened, effectively reducing the high flow stage. The establishment of woody crops will increase the evapotranspiration from the site or watershed, effectively yielding less available water for runoff. Accordingly, as the proportion of a basin is converted to forestry from agriculture, there will be a corresponding decrease in stream outflow. SRWC production systems should not degrade surface water quality, and improvements should be expected on sites with high NO_3-N levels from agriculture.

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