Forest Ecology and Management 400 (2017) 181–198

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Water quality effects of short-rotation pine management for bioenergy feedstocks in the southeastern United States ☆

Natalie A. Griffiths [a,*], C. Rhett Jackson [b], Menberu M. Bitew [b,1], Allison M. Fortner [c], Kevin L. Fouts [b], Kitty McCracken [c], Jana R. Phillips [c]

[a] Climate Change Science Institute and Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[b] Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA
[c] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

ARTICLE INFO

Article history:
Received 9 March 2017
Received in revised form 1 June 2017
Accepted 5 June 2017
Available online 12 June 2017

Keywords:
Intensive silviculture
Short-rotation woody crops
Nitrogen
Concentrated flow tracks
Interflow
Surface water

ABSTRACT

Growing interest in renewable and domestically produced energy motivates the evaluation of woody bioenergy feedstock production. In the southeastern U.S., woody feedstock plantations, primarily of loblolly pine (*Pinus taeda*), would be intensively managed over short rotations (10–12 years) to achieve high yields. The primary differences in managing woody feedstocks for bioenergy production vs for pulp/-sawtimber production include a higher frequency of pesticide and fertilizer applications, whole-tree removal, and greater ground disturbance (i.e., more bare ground during stand establishment and more frequent disturbance). While the effects of pulp/sawtimber production on water quality are well-studied, the effects of growing short-rotation loblolly pine on water quality and the efficacy of current forestry Best Management Practices (BMPs) have not been evaluated for this emerging management system. We used a watershed-scale experiment in a before-after, control-impact design to evaluate the effects of growing loblolly pine for bioenergy on water quality in the Upper Coastal Plain of the southeastern U.S. Intensive management for bioenergy production and implementation of current forestry BMPs occurred on ~50% of two treatment watersheds, with one reference watershed in a minimally managed pine forest. Water quality metrics (nutrient and pesticide concentrations) were measured in stream water, groundwater, and interflow (i.e., shallow subsurface flow) for a two-year pre-treatment period, and for 3.5 years post-treatment. After 3.5 years, there was little change to stream water quality. We observed a few occurrences of saturated overland flow, but sediments and water dissipated within the streamside management zones in over 75% of these instances. Stream nutrient concentrations were low and temporal changes mainly reflected seasonal patterns in nitrogen cycling. Nitrate concentrations increased in groundwater post-treatment to <2 mg N L^{-1}, and these concentrations were below the U.S. drinking water standard (10 mg N L^{-1}). Applied pesticides were almost always below detection in streams and groundwater. Overall, these findings highlight that current forestry BMPs can protect stream water quality from intensive pine management for bioenergy in the first 3.5 years. However, groundwater quality and transit times need to be considered in these low-gradient watersheds of the southeastern U.S. that are likely to become an important location for woody bioenergy feedstock production.

1. Introduction

Forestry is a large part of the economy in the southeastern U.S. (Prestemon and Abt, 2002). Over half of the timber harvested in the U.S. comes from southern forests, and loblolly pine (*Pinus taeda*) is the dominant timber species in this region (Smith et al., 2009; Wear and Greis, 2002). Forest products are mainly used for sawtimber and pulpwood. However, due to the growing interest in renewable and domestically produced energy (e.g., the Energy Independence and Security Act of 2007), there is an increasing potential to utilize woody feedstocks for bioenergy (i.e., biofuels, biopower) (U.S. Department of Energy, 2016). There are two

☆ This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

* Corresponding author.
E-mail address: griffithsna@ornl.gov (N.A. Griffiths).
[1] Present address: USDA-ARS Southwest Watershed Research, Tucson, AZ 85719, USA.

http://dx.doi.org/10.1016/j.foreco.2017.06.011
0378-1127/© 2017 Elsevier B.V. All rights reserved.

silvicultural strategies for producing woody biomass for bioenergy: (1) the utilization of tree tops and branches that are not removed for sawtimber and pulpwood production, and (2) the production of short-rotation plantations where the whole tree is harvested and utilized for bioenergy. Under the latter scenario, trees would be grown on a short rotation (10–12 years; Munsell and Fox, 2010) with more intensive management (mechanical and chemical site preparation, multiple pesticide and fertilizer applications) than for sawtimber or pulpwood in order to achieve high yields (Fox et al., 2007; Hinchee et al., 2009; Scott and Tiarks, 2008; Zhao et al., 2016). Whole-tree harvest can result in lower residual forest floor biomass relative to roundwood harvest, but quantification is difficult, and the few quantitative studies suggest that the reduction in forest floor biomass can range from 18 to 81% (Fritts et al., 2014; Klockow et al., 2013). In the southeastern U.S., the native, fast-growing, and resilient loblolly pine is the primary candidate species for bioenergy feedstock production (Kline and Coleman, 2010) and could be grown on a short rotation followed by whole-tree harvesting. However, the environmental effects of intensive production of short-rotation loblolly pine for bioenergy have not yet been evaluated at the watershed scale.

Local water quality effects (i.e., increased concentrations and fluxes of nitrogen, phosphorus, suspended sediment, and pesticides) and associated downstream effects (i.e., eutrophication, habitat degradation, impacts to aquatic organisms, and increased water treatment costs) are primary concerns of forest management. The water quality effects of silvicultural operations primarily depend on the amount, connectivity, and duration of bare soils and on the coincidence of chemical application (fertilizers, pesticides) with the presence of bare soils. Harvest and site preparation equipment can expose and compact bare mineral soils, and the resulting surface runoff (i.e., Horton overland flow) can mobilize soil particles and potentially increase concentrations of suspended sediments, sediment-bound nutrients, dissolved nutrients, and pesticides in stream water (Binkley and Brown, 1993; Yoho, 1980). Forest roads, landings, and skid trails have been repeatedly identified as the dominant sources of sediment from silvicultural operations (e.g., Hoover, 1952; Megahan and Kidd, 1972; Rivenbark and Jackson, 2004). Dissolved stream water nutrient concentrations (primarily nitrate) can also increase following timber harvest (Blackburn and Wood, 1990; Likens et al., 1970; Swank and Webster, 2014; Wynn et al., 2000) due to a lack of vegetative uptake and warmer soil temperatures that accelerate residue decomposition and nitrification (Grace, 2005; Vitousek and Melillo, 1979). Fertilization can also increase stream water nutrient concentrations (Binkley and Brown, 1993; McBroom et al., 2008), especially if the fertilizers are applied on or near streams, in the form of ammonium nitrate, at frequent intervals, or shortly before storm events (Beltran et al., 2010; Binkley et al., 1999). Stream water nutrient concentrations that are elevated due to forestry practices tend to return to baseline conditions within months to a few years (Aust and Blinn, 2004; Boggs et al., 2016). As the newly planted forest grows, the expanding canopy and associated litter fall reduce bare soils. Thus, in the rapidly growing pine plantations of the southeastern U.S., overland flow and associated water quality issues are expected to occur during the first 2–3 years after harvest. These water quality effects can be minimized if forestry Best Management Practices (BMPs) are implemented (Anderson and Lockaby, 2011a, 2011b; Aust and Blinn, 2004; Cristan et al., 2016; Witt et al., 2013).

Forestry BMPs include leaving a vegetated streamside management zone (SMZ) between the field and the stream, and minimizing bare soils and soil compaction during silviculture activities (South Carolina Forestry Commission, 1998). Forestry BMPs are state-specific, and in the southeastern states, BMP implementation is voluntary, but adoption is very high (87% overall implementation) (NCASI, 2009). Many studies have evaluated the effectiveness of BMPs, and most have found beneficial effects on water quality compared to forestry without BMPs (Anderson and Lockaby, 2011a, 2011b; Aust and Blinn, 2004; Cristan et al., 2016; Witt et al., 2013). For instance, forestry BMPs are effective at minimizing herbicide transport to streams (Scarbrough et al., 2015), with <1–2% of applied herbicides reaching streams during storm events (McBroom et al., 2013). These SMZs can reduce the amount of nutrients transported to streams (Pratt and Fox, 2009; Secoges et al., 2013; Wynn et al., 2000), as nutrients can be taken up by vegetation or nitrate can be denitrified (Hill, 1996; Peterjohn and Correll, 1984; Sweeney and Newbold, 2014). However, SMZs are often not 100% effective at removing nutrients (Marchman et al., 2015; McBroom et al., 2008), especially if rain events occur shortly after fertilization (Beltran et al., 2010). Streamside management zones also reduce sediment inputs to streams (Carroll et al., 2004; Ward and Jackson, 2004) by minimizing the occurrence of overland flow such that the undisturbed soil of the SMZ can disperse and infiltrate flows before reaching the stream (Pinho et al., 2008; White et al., 2007). However, SMZs retain proportionally fewer small-diameter than large-diameter sediments (Sweeney and Newbold, 2014), and breakthroughs can occur, especially in gullies and areas of concentrated flow (Rivenbark and Jackson, 2004). While many studies have evaluated the effectiveness of forestry BMPs at mitigating effects on water quality, it is not known whether current forestry BMPs are adequate to protect water quality during short-rotation pine production or whether bioenergy-specific BMPs are needed (Shepard, 2006). Short-rotation silviculture involves more frequent ground disturbance, greater competition control with herbicides, and potentially higher fertilizer application. For these reasons, it is not clear if current forestry BMPs are sufficient to protect water quality in watersheds supporting short-rotation woody feedstocks.

Forestry BMPs minimize the movement of pollutants to streams by overland flow (Edwards and Williard, 2010). However, the effectiveness of BMPs in groundwater-dominated watersheds is not well known. For instance, in low-gradient watersheds of the Upper Atlantic Coastal Plain in the southeastern U.S., the source of streamflow and stream water nitrate is primarily groundwater (Du et al., 2016; Griffiths et al., 2016; Klaus et al., 2015). Shallow subsurface flow can be important, especially during storms (Du et al., 2016), but downslope travel distances are short (~10's of m), and thus stream flow contributing areas generally originate within the riparian zones (Jackson et al., 2014). Therefore, it is important to understand the effects of intensive forestry for bioenergy not only on stream water quality but also on groundwater quality in low-gradient, groundwater-dominated watersheds.

In this study, we used a watershed-scale experiment in a before-after, control-impact design to examine the effects of growing short-rotation loblolly pine for bioenergy on water quality in the southeastern U.S. We selected three watersheds with minimally managed loblolly pine in the Upper Atlantic Coastal Plain of South Carolina, and examined baseline water quality in groundwater, interflow (i.e., shallow subsurface flow), and stream water for two years. Over the next 3.5 years, water quality sampling continued as ~50% of two treatment watersheds were harvested, planted with loblolly pine seedlings, and managed for short-rotation pine production (including multiple fertilizer and pesticide applications). The third watershed was not manipulated and served as a reference. For the first 3 years after harvest, we also identified and characterized locations where overland flow was moving from the harvest/plantation units into the SMZs in sufficient quantity to mobilize the litter layer and sediments. All silviculture practices in the two treatment watersheds followed South Carolina Forestry BMPs (South Carolina Forestry Commission, 1998). We predicted that silvicultural practices for