Environmental effects of short-rotation woody crops for bioenergy: What is and isn’t known

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Abstract
Logging and mill residues are currently the largest sources of woody biomass for bioenergy in the United States, but short-rotation woody crops (SRWCs) are expected to become a larger contributor to biomass production, primarily on lands marginal for food production. However, there are very few studies on the environmental effects of SRWCs, and most have been conducted at stand rather than at watershed scales. In this manuscript, we review the potential environmental effects of SRWCs relative to current forestry or agricultural practices and best management practices (BMPs) in the southeast United States and identify priorities and constraints for monitoring and modeling these effects. Plot-scale field studies and a watershed-scale modeling study found improved water quality with SRWCs compared to agricultural crops. Further, a recent watershed-scale experiment suggests that conventional forestry BMPs are sufficient to protect water quality from SRWC silvicultural activities, but the duration of these studies is short with respect to travel times of groundwater transporting nitrate to streams. While the
effects of SRWC production on carbon (C) and water budgets depend on both soil properties and previous land management, woody crops will typically sequester more C when compared with agricultural crops. The overall C offset by SRWCs will depend on a variety of management practices, the number of rotations, and climate. Effects of SRWCs on biodiversity, especially aquatic organisms, are not well studied, but a meta-analysis found that bird and mammal biodiversity is lower in SRWC stands than unmanaged forests. Long-term (i.e., over multiple rotations) water quality, water use, C dynamics, and soil quality studies are needed, as are larger-scale (i.e., landscape scale) biodiversity studies, to evaluate the potential effects of SRWC production. Such research should couple field measurement and modeling approaches due to the temporal (i.e., multiple rotations) and spatial (i.e., heterogeneous landscape) scaling issues involved with SRWC production.

KEYWORDS
aquatic macroinvertebrates, best management practices, bioenergy, carbon/water tradeoffs, hydrologic modeling, soil organic carbon, southeastern United States, terrestrial biodiversity, water quality, woody feedstocks

1 INTRODUCTION

Many countries across the globe are turning toward bioenergy. As part of the effort to reduce volatility in fuel prices, dependence on foreign oil supplies, and greenhouse gas emissions, the US Congress passed the Energy Independence and Security Act (EISA) of 2007. The act mandates the use of 36 billion gallons of renewable fuels by 2022, including conventional and advanced biofuels (EISA, 2007). European nations aim to obtain 20% of their energy from renewable sources by 2020 to mitigate climate change and increase energy security (European Parliament & EU Council, 2009), and by 2030, Brazil plans to have bioenergy comprise 18% of their total energy production (Bacovsky, Ludwiczek, Pointner, & Verma, 2016). Currently, a significant portion (~20%) of the US renewable energy portfolio comes from residues derived from wood product processing (i.e., wood chips and wood pellets) (US Energy Information Administration, 2018). However, there is a call to include cellulosic ethanol in future (US Department of Energy, 2016). In addition to domestic consumption, the United States is also the world’s largest global exporter of wood pellets (US Energy Information Administration, 2014). Policy-driven European demand for this product has created a market for woody biomass in North America (Dale, Kline, et al., 2017; Dale, Parish, Kline, & Tobin, 2017; Parish, Dale, Kline, & Abt, 2017; Wang, Dwivedi, Abt, & Khanna, 2015). Nearly 60% of US wood products originate from managed forests in the southeast where climate, topography, and land ownership are favorable for wood production (Wear & Greis, 2012). From a global perspective, the southeast United States produces 18% of the world’s industrial timber and 25% of global pulp products (Kantavichai, Gallagher, & Teeter, 2014; McKeand, Mullin, Byram, & White, 2003; Munsell & Fox, 2010; Wear & Greis, 2012). Woody bioenergy feedstocks can be supplied as residues from processing traditional wood products and otherwise unmerchantable material (i.e., small diameter trees, limbs, and treetops removed in conjunction with harvesting operations; Vance et al., 2018) or as short-rotation woody crops (SRWCs; Dwivedi & Khanna, 2014). The environmental effects of removing forest harvest by-products for bioenergy have been recently reviewed (Vance et al., 2018); however, very little research has addressed the environmental effects of SRWC production for bioenergy, with one study synthesizing potential environmental effects of Eucalyptus and Poplar as SRWCs (Vance, Loehle, Wigley, & Weatherford, 2014).

While similar in some respects, SRWC silviculture is different enough from typical management for pulp or sawtimber and from agricultural production that the associated environmental effects should be considered separately. SRWC systems are designed to achieve high productivity by capitalizing on silvicultural treatments that expedite production and shorten harvest cycles relative to typically less-intensive pulpwood and sawtimber rotations. Although SRWC rotation lengths can range from 1 to 15 years (Dickmann, 2006), they are typically 3–4 years under high-density coppice plantings where subsequent harvests
originates from resprouting root systems, such as willow (Volk, Verwijst, Tharakan, Abrahamson, & White, 2004), and 8–12 years under relatively lower density plantings for eucalypts (US Department of Energy, 2011) and where subsequent harvests originate from new plantings, such as loblolly pine (Coyle, Aubrey, & Coleman, 2016). Short-rotation woody crop silviculture involves more frequent harvests and associated ground disturbance, potentially greater competition control through herbicide application, and potentially greater fertilizer application over the same time interval as typically less-intensive pulpwod and sawtimber management (Srestha, Stainback, & Dwivedi, 2015). Therefore, SRWC production spans the continuum between agricultural and forestry production systems. For example, woody crops grown on a shorter rotation (e.g., 3–4 years) with frequent fertilizer and herbicide applications may be more similar to agricultural production, while woody crops grown on a longer rotation (e.g., >8 years) with less-frequent fertilizer and herbicide applications may be more similar to forestry. In the literature, SRWC effects are reported relative to agriculture or forestry as a reference scenario depending on the study. Therefore, in our review, we report effects relative to forestry or agriculture consistent with the comparisons carried out in the previously published papers.

If SRWCs are to provide a substantial component of bioenergy feedstocks, it is critical to reduce the uncertainty regarding environmental effects of SRWCs across spatial scales and assess whether additional policies or SRWC practice guidelines are needed. Here, we describe the following: (a) SRWC silvicultural techniques, (b) forestry best management practices (BMPs) and their application to SRWC production for bioenergy, and (c) environmental effects with respect to water quality, carbon (C) fluxes, soil quality, watershed hydrology, and biodiversity. This review is primarily focused on SRWC production in the southeastern United States where loblolly pine has been identified as a primary candidate species for SRWCs (Kline & Coleman, 2010), with rotation lengths ~8–12 years. Therefore, loblolly pine production for bioenergy will likely be more akin to forestry except for more frequent entry, potentially higher competition control, and potentially more frequent fertilizer inputs. We also identify priorities and constraints for monitoring and modeling environmental effects of SRWCs. Lastly, this review proposes strategies for assessing environmental impacts that may result from SRWC production.

2 | SILVICULTURAL TECHNIQUES

Short-rotation woody crop cultivation employs a variety of silvicultural techniques that allow for rotations of 1–15 years (Dickmann, 2006; Drew, Zsuffa, & Mitchell, 1987). The two most fundamental considerations which influence all subsequent silviculture decisions are selection of the planting site and selection of the crop (i.e., tree species and variety). Sites of particularly low quality do not support levels of productivity that warrant the expense of intensive management, and sites with extremely wet soils or steep slopes do not facilitate mechanized stand management and harvest (Dickmann, 2006). On the other hand, high-quality, easily accessible sites are preferred for the production of more profitable agronomic crops. Therefore, most available sites suitable for SRWC production are marginal (Aubrey, Coyle, & Coleman, 2012; Ghezehei, Shifflett, Hazel, & Nichols, 2015; US Department of Energy, 2016), a term describing land that is of low economic value for the production of agricultural crops and, as a result, it is often not used for agricultural production (Gopalakrishnan, Negri, & Snyder, 2011). Tree species can be broadly delineated into narrow- and broad site-adapted functional groups based on physiological requirements (Aubrey et al., 2012). Narrow site-adapted species may exhibit higher biomass production potential than broad site-adapted species, especially early in their rotation (Coyle & Coleman, 2005; Coyle et al., 2016; Coyle, Coleman, & Aubrey, 2008), but only under adequate resource (i.e., water and nutrient) availability. Under suboptimal resource availability, biomass production of narrow site species can be substantially suppressed (Coyle et al., 2016; Coyle, Aubrey, Siry, Volkovicz-Leon, & Coleman, 2013). Silvicultural treatments (as described below) can effectively increase the quality of a marginal site to that of a high-quality site and thus support high productivity of both broad- and narrow site-adapted species.

Proper site preparation is essential to successful SRWC production (Dickmann, 2006; Stanturf, Oosten, Netzer, Coleman, & Portwood, 2001). The extent of site preparation will depend on the crop, but typically involves mechanical and chemical treatments that create bare mineral soil (Dickmann, 2006; Kline & Coleman, 2010). Mechanical treatments begin with the removal of debris and are often followed by plowing and discing. In locations where excess moisture poses a problem for seedling success, raised beds are established. Under some circumstances, mechanical treatments may not be necessary. Chemical treatments often, but not always, follow mechanical treatments. When necessary, treatments include improving soil pH through the application of lime and the elimination of competing vegetation via mechanical removal or through the application of herbicide(s) already commonly used for forestry site preparation. Planting occurs manually or mechanically, but both the timing and the approach are influenced by the crop species. Competing vegetation is then controlled through repeated herbicide applications beginning at site preparation and continuing.
until the canopy shades the ground. Herbicides eliminate fast-growing vegetation competing for light, and such competition control is often considered the most critical silvicultural treatment in the first year (Davis & Trettin, 2006; Kline & Coleman, 2010; Schuler, Robison, & Quicke, 2004; Stanturf et al., 2001). Herbicides also limit uptake of soil resources by herbaceous and woody competition and ensure that belowground resources remain available only to the SRWC.

Fertilizers (primarily urea and diammonium phosphate) are frequently used to enhance site quality and increase SRWC productivity (Figure 1a). Nitrogen is often considered the most limiting nutrient for temperate forest production (Binkley & Reid, 1984; Fisher & Garbett, 1980; Sword Sayer et al., 2004), and fertilization can increase the availability of nitrogen to the crop. All species have specific nutrient requirements, so there is no single approach to maximizing production while minimizing inputs. Fertilization is often a major expense among silvicultural treatments in SRWC stands, so it is important that fertilization is optimized to meet, but not exceed, the maximum demand by the plant. When fertilization is insufficient, maximum productivity is not realized. When fertilization exceeds uptake capacity, nutrients are lost through leaching (Lee & Jose, 2006; van Miegroet, Norby, & Tschaplinski, 1994) with negative economic and environmental impacts. It is therefore critical to consider site-specific nutrient availability along with requirements of the particular crop species to maintain economic and environmental viability. Ammonia can also be lost via volatilization, with emissions

![Figure 1](image-url)
dependent on fertilizer type and soil characteristics (Harrison & Webb, 2001; Heller, Keoleian, & Volk, 2003).

Many species are grown in SRWC production systems of North America, and the preferred species differ according to region. Most SRWC species are hardwoods, particularly in the north and northwestern United States where *Populus* (either cottonwood, black or hybrid) is the preeminent species and in the northeast where willow (*Salix*) dominates production (Volk et al., 2006; Willebrand, Ledin, & Verwijst, 1993). However, forestry practitioners agree that loblolly pine (*Pinus taeda* L.), a conifer, is a primary candidate for bioenergy production in the southeast United States and a benchmark from which to compare the productivity of other potential woody crop species in the region (Kline & Coleman, 2010; Figure 1b). Loblolly plantations for pulpwood and timber production have dominated the southeast United States due to the high production potential that has been realized through decades of genetic and silvicultural research and application (Carter & Foster, 2006). Although *Populus* production potential can be high on high-quality sites or when receiving resource amendments, their site requirements, particularly with respect to moisture availability, are too narrow to allow planting broadly in the southeast. Willow may also have potential for SRWC production in the southeast, but has received relatively little research attention thus far (Kline & Coleman, 2010; Rousseau, Gardiner, & Leininger, 2012). American sweetgum (*Liquidambar styraciflua* L.) is currently the best hardwood option for most of the southeastern region as it tolerates a range of site conditions (Adams, Lingbeck, Crandall, Martin, & O’Bryan, 2015; Nelson, Switzer, & Shelton, 1995) and demonstrates fairly consistent production rates (Kline & Coleman, 2010). However, sweetgum exhibits relatively slow early growth rates that can be similar to loblolly pine (Davis & Trettin, 2006). Eucalypt species offer high potential for SRWC productivity in the future (Dale, Langholz, Wesh, & Eaton, 2013; Vance et al., 2014); however, susceptibility to frost currently limits its range to the coastal zone. Regardless of SRWC species, genetic improvements can greatly influence the productivity of SRWC systems and a major goal is to identify genetic material that maximizes productivity while also minimizing nutrient and water use (i.e., increasing water and nutrient use efficiencies) and improving resistance to pests and pathogens (Tuskan, 1998). Overall, intensively managed SRWCs can yield 10–20 Mg of aboveground biomass per year (Kline & Coleman, 2010).

### 3 BEST MANAGEMENT PRACTICES

Each US state and Canadian province with commercial timberlands promotes and implements forestry best management practices (BMPs) designed to protect water quality and minimize silvicultural nonpoint source pollution. Forestry BMPs include a suite of harvest and management guidelines to reduce the mobilization of sediments, nutrients, and pesticides, and protect riparian-stream processes. BMPs can vary across jurisdictions, but all forestry BMPs share common guidance: (a) minimize soil compaction and bare ground exposure; (b) locate roads and landings on ridges away from surface waters (Figure 1c); (c) separate fertilizer and herbicide applications from surface waters; (d) inhibit hydraulic connections between bare ground and surface waters; (e) provide forested buffers around streams (Figure 1c); (f) engineer stable road surfaces, skid trails, and stream crossings; and (g) minimize landslide initiation risks (Olszewski & Jackson, 2006). BMPs have been tested and refined for decades (see reviews by Anderson & Lockaby, 2011; NCASI, 2012; Cristan et al., 2016), and this adaptive management loop has resulted in at least two major revisions of most state BMP documents since the first guidelines were published around 1980. Nevertheless, there is continuing debate about the efficacy of BMPs; this is especially true as forest production evolves (e.g., Jackson, 2014; MacDonald & Coe, 2014). The effectiveness of forestry BMPs at minimizing environmental effects of SRWC production for bioenergy has not been thoroughly evaluated at operational scales.

Best management practice implementation is motivated by a variety of mechanisms, with some jurisdictions mandating compliance through a regulatory permit system and others using so-called voluntary or quasiregulatory systems, with no significant compliance differences among the program types (Cristan, Aust, Bolding, Barrett, & Munsell, 2018). Under any of these systems, the US Environmental Protection Agency can fine a landowner for causing water quality problems if BMPs are not implemented. Large timber landowners and mills now participate in forest certification programs that require BMP compliance regardless of state regulatory systems, and most logging contractors must also be trained in BMP implementation to deliver wood to certified mills. As a result, BMP compliance has climbed steadily over the last few decades and was recently reported at ~91% in the United States (Cristan et al., 2018; Ice, Schilling, & Vowell, 2010; SGSF, 2012).

One potential issue not addressed by current BMPs, but is relevant to SRWCs, is long-term soil compaction due to higher frequencies of mechanical entry. Soil compaction from logging operations has been well studied, and is often cited as a critical concern, as compacted soil may limit infiltration of water and inhibit root growth (Page-Dumroese, Jurgensen, & Terry, 2010). However, many studies from repeated thinning and harvest operations indicate no significant decrease in productivity from soil compaction, and others report increases in soil water holding capacity...
and productivity, particularly on coarse-grained soils (Powers, Sanchez, Scott, & Page-Dumroese, 2004). Soil compaction can be minimized by limiting operations during wet periods, carefully placing skid trails to minimize repeated traffic, and utilizing equipment with low ground pressures (Page-Dumroese et al., 2010).

4 WATER QUALITY EFFECTS

There is a paucity of studies evaluating water quality effects from SRWC production. Therefore, we review the effects of typically less-intensive pulpwood and sawtimber silviculture, especially those that incorporate forestry BMPs, on water quality, and end by reviewing the few studies that have examined effects of SRWC production on water quality.

Traditional silvicultural practices can affect water quality during planting, harvest, site preparation, and the application of pesticides and fertilizers. In general, most recent studies conclude that current forestry practices coupled with BMPs have small and short-term effects on stream water quality (Fraser, Jackson, & Radcliffe, 2012; Grace, 2005; Keim & Schoenholtz, 1999; McBroom, Beasley, Chang, & Ice, 2008; Witt, Barton, Stringer, Bowker, & Kolka, 2013; Wynn et al., 2000). Timber harvesting can increase dissolved nutrient concentrations, particularly nitrate (Aust & Blinn, 2004; Gravelle, Ice, Link, & Cook, 2009; Marchman et al., 2015), due to reduced nutrient uptake by vegetation and increased soil temperatures that accelerate mineralization (Bormann, Likens, Fisher, & Pierce, 1968; Fox, Buger, & Kreh, 1986; Kreutzweiser, Hazlett, & Gunn, 2008). Soil disturbance during harvest can increase sediment concentrations in streams (Grace, 2005); although most increases in sediment inputs are associated with the construction or use of roads (Anderson & Lockaby, 2011; Croke & Hairsine, 2006; Sheridan & Noske, 2007). Elevated dissolved nutrient and suspended sediment concentrations are often temporary and concentrations return to baseline within months to a few years (Aust & Blinn, 2004; Boggs, Sun, & McNulty, 2016; Gravelle et al., 2009; Wang, Burns, Yanai, Briggs, & Germain, 2006). Harvests can also increase nutrient and sediment fluxes due to increases in stream runoff associated with reduced evapotranspiration (Boggs et al., 2016; Grace, 2005). Changes in water quality after harvests are not always observed (Clinton, 2011; Terrell, Summer, Jackson, Miwa, & Jones, 2011), and sometimes effects are not consistent across the landscape (Grace, 2005).

The effects of forest fertilization on water quality can be greatest when fertilizers are applied: (a) repeatedly; (b) as ammonium nitrate; (c) to nitrogen-saturated forests; (d) directly to streams; or (e) shortly before rainfall events (Beltran et al., 2010; Binkley, Burnham, & Allen, 1999; McBroom et al., 2008). Streamside management zones (SMZs) can reduce nutrient inputs to adjacent water bodies (Perrin, Shortreed, & Stockner, 1984; Secoges, Aust, Seiler, Dolloff, & Lakel, 2013), but SMZs may be less effective at retaining nutrients traveling via subsurface flow paths than overland flow (Edwards & Willard, 2010), and stream water nutrient concentrations can increase after fertilizer application even when SMZs are implemented (McBroom et al., 2008).

The potential contamination of stream water with pesticides is greater with aerial or broadcast applications than stem injection or soil application (Michael, 2004). Forested SMZs can retain pesticides being transported in overland flow via sorption to soils or organic matter, infiltration of water and dissolved pesticides, or retention of pesticides bound to sediments (Lowrance, Vellidis, Wauchope, Gay, & Bosch, 1997; Neary, Bush, & Michael, 1993; Pinho et al., 2008; Vellidis, Lowrance, Gay, & Wauchope, 2002). Despite SMZs, pesticides can still enter streams, but transport is generally limited to the first few storm events after application (McBroom, Louch, Beasley, Chang, & Ice, 2013; Michael & Neary, 1993; Neary et al., 1993; Scarbrough et al., 2015) and concentrations are low relative to levels of concern (Tatum et al., 2017). Pesticides are usually not detected during baseflow (McBroom et al., 2013; Scarbrough et al., 2015, but see Neary & Michael, 1989).

Most studies evaluating the effects of forestry on water quality are focused on surface (stream) water, with few studies evaluating the effects on groundwater quality, although leaching of nutrients below the rooting zone is commonly measured. Potential impacts of silviculture on groundwater can be important, especially in regions where groundwater flow paths dominate, such as the Coastal Plain of the southeast United States (Griffiths et al., 2016; 2017; Klaus, McDonnell, Jackson, Du, & Griffiths, 2015). A study in Texas found increased nitrate concentrations in groundwater in clear-cut watersheds (Messina et al., 1997), while a study in Alabama found no effect of harvest on groundwater nutrients (Lockaby, Thornton, Jones, & Clawson, 1994). Pesticides are generally immobile in soils (Michael, 2004) and were not detected in groundwater in the Coastal Plain of Florida (Neary & Michael, 1989) or South Carolina (Griffiths et al., 2017).

The effects of SRWC production on water quality may differ from current forestry practices as SRWC production may involve more frequent fertilizer and pesticide applications to increase SRWC yields (Neary, 2013; Shepard, 2006), and more frequent disturbance from harvesting. In fact, of the few studies that have evaluated water quality impacts of SRWC production for bioenergy, most compare results to agricultural rather than forestry production. Plot-scale studies in the southeast found that short-rotation sweetgum production with a fescue cover crop reduced nitrate,
ammonium, and sediment yields compared with maize and switchgrass (Nyakatawa, Mays, Tolbert, Green, & Bingham, 2006). Modeling of a watershed in Minnesota found that conversion of a portion of the landscape from agriculture to SRWCs reduced sediment, nitrogen, and phosphorus loads (Updegraff, Baughman, & Taff, 2004; Updegraff, Gowda, & Mulla, 2004). A watershed-scale study in the southeast United States examined the effect of growing and managing short-rotation loblolly pine for bioenergy with BMPs and found no changes in stream water nitrate concentrations in the first 3.5 years after planting; however, nitrate concentrations increased in groundwater (Griffiths et al., 2017; Figure 1). Thus, this study suggested that BMPs may be short to adequate to protect stream water quality in the first years after planting, but also highlighted the need for longer-term studies that focus on quantifying lagged effects (e.g., groundwater travel times) (Griffiths et al., 2017).

The small number of watershed-scale studies evaluating water quality effects of SRWCs, especially those that run through multiple rotations, or that evaluate effects of harvests, highlights a future research need. Due to financial constraints, watershed-scale field studies evaluating the effects of multiple rotations on water quality may be difficult. As of this time, we mainly rely on short-term, plot-scale studies, and modeling from which to evaluate effects. However, modeling efforts (e.g., Amaty et al., 2013) paired with shorter-term field studies (e.g., Griffiths et al., 2017) may be a powerful tool to evaluate the effects of SRWC production for bioenergy on surface and groundwater quality over large spatial and temporal scales.

5 | CARBON FLUXES AND SOIL QUALITY EFFECTS

The effects of SRWCs on C fluxes and soil quality have not been well documented, and most of the available information comes from traditional silviculture or European SRWC systems (Baum, Leinweber, Weih, Lamersdorf, & Dimitriou, 2009; Guo & Gifford, 2002; Janowiak & Webster, 2010; Johnson & Curtis, 2001; Mann & Tolbert, 2000). The effects of SRWCs on all environmental variables, including C fluxes and soil quality, are relative to the starting point. When SRWC plantations displace agricultural production, there are likely positive effects on biomass C stocks, soil organic C (SOC), nitrogen retention, and erosion rates; however, the impacts may be neutral or negative if pasture or native forests are cleared for SRWCs (Guo & Gifford, 2002; Janowiak & Webster, 2010). The effects of woody bioenergy production on C budgets (Schlesinger, 2018) must be weighed against the starting point assumption. At this time, most woody biomass is generated from harvest residues on land already dedicated to forestry (Hanssen, Duden, Junginger, Dale, & Hilst, 2017) and SRWC plantations are not common enough to analyze the distribution of pre-SRWC land uses.

Total ecosystem C storage is relatively high in forested production systems when considering standing biomass, SOC, net ecosystem exchange of C, or net ecosystem production (Bracho et al., 2012; Clark, Gholz, & Castro, 2004; Lai et al., 2002). However, these metrics do not necessarily account for the operational impacts of producing biomass. It is necessary to take into consideration the entire “cradle to grave” life cycle of the production system when assessing C storage. This includes, but is not limited to, the legacy of land which has been converted for SRWC production, the intensity of management during production, the C cost of inputs (e.g., the production of fertilizer and herbicide applied), the time since conversion to biomass production, and the harvest and transport of the product to the end user (e.g., biorefinery for power generation).

Land conversion creates a C debt, which refers to the C lost by removing existing vegetation (Lamers & Junginger, 2013). When agricultural lands are converted to forest or SRWCs, the C debt is readily offset as C storage in aboveground biomass typically increases (Haberl, 2013). The conversion of forested systems to SRWCs often comes at a larger C cost; therefore, the C debt will take longer to repay (Haberl, 2013). Rotation length may also influence C debt as shorter rotations can reduce the retention of recalcitrant C (Smith et al., 2012). Based on the legacy of land use with more degraded lands, the ability of the system to alleviate this debt increases from a single rotation (decades) to multiple rotations (centuries; Lamers & Junginger, 2013).

Factors that confound the effects of SRWCs on C budgets include site preparation prior to planting, fertilizer used to reduce resource limitation on marginal lands, and competition reduction associated with herbicide applications (Melillo et al., 2009). A significant amount of C is required to produce and apply fertilizer and herbicide. In addition, the reduction in fossil fuel use which is replaced using SRWCs as an energy source and the overall retention time of C in the crop (e.g., is C returned to the atmosphere a year or decades after it is sequestered in vegetation?) should be considered. Without taking these factors into account, estimates of C debt recovery may be incorrect for a system or region which could lead to misguided policies and regulations (Melillo et al., 2009).

Although aboveground biomass is the most visible C pool, 30 to >50% of total ecosystem C may be stored belowground as roots and SOC (Schlesinger, 1997). In addition to mitigating greenhouse gas emissions, SOC serves several key functions in ecosystems, such as improving soil structure, reducing runoff, increasing waterholding capacity, providing a food source for macro- and micro-organisms, and facilitating nutrient cycling.
Short-rotation woody crops such as pine or hardwood coppice systems have inconsistent effects on SOC depending on the previous land use (Baum et al., 2009; Guo & Gifford, 2002; Mann & Tolbert, 2000). When annual cropping systems are converted to SRWCs, SOC tends to increase significantly, due to reduced tillage and increased organic inputs from leaf litter, fine root turnover, and fungal mycelium (Boman & Turnbull, 1997; Godbold et al., 2006). However, the results vary depending on climate and soil mineralogy, and SRWC systems rarely approach the SOC levels measured in comparable native forests (Boman & Turnbull, 1997; Guo & Gifford, 2002). Conversely, native forests and even pastures tend to lose SOC when converted to SRWC systems; particularly when converted to intensively managed pine plantations, and in regions with rainfall >1,500 mm/year (Guo & Gifford, 2002). When native forests or pastures are converted to hardwood coppice systems or hardwood plantations, there appears to be little impact on SOC (Guo & Gifford, 2002).

In addition to the role that soils have in C storage, soil fertility can have a significant influence on site productivity, and nutrients (particularly nitrogen) are often limiting in forest ecosystems. Nitrogen (N) and other nutrients including phosphorus (P), potassium, and calcium are more prevalent in foliage than in woody tissue, and so the results of traditional forest and SRWC harvests on soil nutrients often mimic those described for SOC. In SRWC systems, N fertilizer is often added to increase productivity and reduce rotation intervals, and although N fertilization generally increases soil A-horizon N content over time, it may also lead to nitrate leaching early in a rotation if the timing and amount of N fertilizer is not carefully matched to tree uptake (Mann & Tolbert, 2000). To date, there have been very few studies that track P and cations in SRWCs, but it has been suggested that because harvests will typically occur after leaf fall in hardwood production, the removal of these nutrients should be minimal (Heilman & Norby, 1998). However, removal of nutrients may be higher in evergreen species.

Soil erosion can reduce productivity by removing organic matter and soil nutrients. Erosion rates from forested watersheds are typically a fraction of those observed in agricultural watersheds (Fox, Allen, Albough, Rubliar, & Carlson, 2007). However, erosion rates can increase significantly after harvesting, particularly when clear cutting, and site preparation techniques such as subsoiling, stump shearing, and windrowing are utilized (Stednick, 2010). Erosion losses from SRWC systems can be similar to losses from agricultural production in the first season after planting, but tend to decline over time (Kort, Collins, & Ditsch, 1998; Thornton et al., 1998). Cover cropping can significantly reduce erosion rates during the establishment phase and throughout the life cycle of SRWCs (Kort et al., 1998). To assess the long-term changes in soil chemical, physical, and biological properties and maintain productivity, it will be necessary to continue monitoring changes in soil resources over time and adjust inputs if necessary.

6 | CARBON/WATER TRADEOFFS AND HYDROLOGIC FLUXES

Assessment of the hydrologic effects of SRWCs can be accomplished at the stand scale using eddy covariance measurements (Baldocchi et al., 2001), at the catchment scale through paired-watershed studies (Bosch & Hewlett, 1982), or at multiple spatial and temporal scales using ecosystem budgets and models (Andrèassian, 2004) (Figure 2). At the stand level, forest productivity is tightly coupled to water availability (Noormets et al., 2008; Starr et al., 2016), and evaportranspiration (ET) rates increase with increasing leaf area (Gonzalez-Benecke, Martin, Jokela, & Torre, 2011) assuming adequate soil moisture availability. Pines grown in conventional pulpwood plantations use less water during early stand development when the canopy has a lower leaf area (Clark et al., 2004; Gonzalez-Benecke et al., 2011). Empirical measurements of ET have been made in a few young pine and eucalyptus plantations (S. George, C.L. Staudhammer, H.W. Loescher, S. Wiesner, G. Starr, unpublished data; D.P. Aubrey, P.V. Caldwell, M.J. Dix, C.R. Jackson, J.J. McDonnell, C.R. Miniat, S.E. Younger, unpublished data). Therefore, while we currently lack empirical measures of ET across a variety of SRWC stands, the expedited growth and development should result in maximum leaf area and ET years earlier than a conventional stand. Indeed, current research on SRWC stands of loblolly pine has shown that development and physiological activity is approximately 2–10 years ahead of conventional stands for a site entering its fifth growing season (S. George, C.L. Staudhammer, H.W. Loescher, S. Wiesner, G. Starr, unpublished data). Evapotranspiration dynamics will also depend on the duration that a SRWC stand is in bare soils. SRWC stands will be in bare soils more frequently than traditional forestry due to the rapid canopy development of SRWCs, the period of bare soils may be less when the trees are growing. Therefore, it remains unclear how ET, and thus water use efficiency, across multiple SRWC rotations will compare to that of conventional forest stands. In their sentinel paper, “Trading Water for Carbon,” Jackson et al., (2005) provided strong evidence that high rates of C sequestration do not account for the additional environmental outcomes which occur by growing timber at rapid rates. One of these potential outcomes is a reduction in streamflow in regions with SRWC plantations that could result from increased transpiration.
At a larger spatial scale, numerous paired-watershed studies have quantified the effects of harvest and forest regeneration on water quantity; however, few have specifically examined responses to SRWCs. Bosch and Hewlett (1982) summarized 94 paired-watershed studies which indicate that streamflow increases substantially for several years after harvest due to reduced canopy interception and transpiration (e.g., Swank, Vose, & Elliott, 2001; Terrell et al., 2011; Boggs et al., 2016). Climate, tree species, and silvicultural techniques all affect the rate of forest regrowth and thus the rate at which water use returns to preharvest conditions, which can take as little as four years (Swank, Knoepp, Vose, Laseter, & Webster, 2014) or as long as 20 years in the Pacific Northwest (Hicks, Beschta, & Harr, 1991; Perry & Jones, 2016). These findings from the paired-watershed literature indicate that the hydrologic effects of SRWCs are likely to be contextual and need to be evaluated over several rotations and considered relative to some baseline condition, whether it be forestry or agricultural crop production. Given the challenges associated with whole-watershed manipulations that incorporate multiple rotations, and recognition that over larger areas, a patchwork of forest practices and other land use types will interact to influence water resources, watershed simulations are needed to evaluate impacts across larger regions and longer timescales (Andréassian, 2004).

Computer simulation strategies have been used to represent forested ecosystems for many years (Running & Coughlan, 1988; Shugart & West, 1981) and can be applied to silvicultural SRWC systems. These models focus on a variety of elements relevant to managed forest ecosystems, including economics, lifecycle assessment, and biodiversity. Hydrologic responses to forest management activities can also be evaluated using simulation tools (Running & Coughlan, 1988; Sun, Rickerk, & Comerford, 1998; Tague & Band, 2001). Elements of these watershed hydrology models typically include soil moisture, groundwater, and stream water responses to weather, climate, and disturbance. Ecosystem and watershed hydrology models are often combined and could be used to estimate the impacts of SRWCs on both water quality and water quantity.

Most bioenergy feedstock analysis modeling used to assess potential impacts on water yield and water quality
has focused on herbaceous feedstocks rather than SRWCs (Engel et al., 2010). Such modeling efforts have indicated that larger-scale adoption of bioenergy crops may have positive (Chen, Ale, Rajan, & Munster, 2017; Cibin, Trybula, Chaubey, Brouder, & Volenc, 2016) or negative (Babel, Shrestha, & Perret, 2011; Love & Nejadhashemi, 2011) water quality impacts, and result in modest changes to the hydrologic budget. The direction of the changes will depend upon land management decisions, feedstock selection (e.g., perennial grasses vs. maize stover), and crop establishment rate (Sarkar & Miller, 2014; Wu & Liu, 2012).

Only a small number of modeling studies have been developed to explore impacts of SRWCs on water quantity and quality. A variety of challenges have been identified in the use of models to evaluate SRWCs. Primary among these is that models that have been developed for evaluations of herbaceous crops [e.g., Groundwater Loading Effects of Agricultural Management Systems (GLEAMS), National Agricultural Pesticide Risk Analysis (NAPRA), Environmental Policy Integrated Climate Model (EPIC), Agricultural Policy/Environmental eXtender Model (APEX), and the Soil and Water Assessment Tool (SWAT)] will not necessarily translate to silvicultural crops. The processes that govern hydrologic and ecosystem responses in agricultural landscapes are distinct from those operating in forested landscapes. Beckers et al., (2009) reviewed about 30 hydrologic models for potential use in operational forest management in British Columbia and indicated the need to improve the existing models or the need to recognize tradeoffs between model functionality, processes representation, and complexity in the application of the current models to answering forest management questions. Similarly, Amatya et al., (2013) reviewed the ability of five ecohydrology models to evaluate water quality effects associated with fertilizer applications to southeastern forests and found that none of the models had the capabilities needed to fully assess the fate of N fertilizers at the watershed scale. In recognition of some of these challenges, recent work has focused on the development of tools that are appropriate for use in the evaluation of SRWCs. For instance, there is a need for detailed projections of growth curves defining highly managed and fast-growing SRWCs. Guo et al. (2015) developed growth parameterizations for leaf area index, biomass yield, and biomass partitioning in hybrid Populus using the Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) model. They suggest that this type of model could be explicitly included in agricultural models like SWAT and APEX, replacing the seasonally focused herbaceous growth model with a more appropriate silvicultural model. This is clearly one mechanism to improve estimates from traditionally agricultural models like SWAT and APEX as they are applied to silvicultural crops. Overall, improvements to watershed-scale models are needed to evaluate hydrologic and water quality effects of SRWC production, but these efforts hold promise in furthering understanding of SRWC effects over larger spatial and temporal scales than achievable from stand-level and watershed-scale field studies.

### 7 BIODIVERSITY EFFECTS

Intensive land uses such as SRWCs and agriculture can have implications for biodiversity conservation (or any taxa of interest) and can also provide important ecosystem services (Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005). Increases in global demand for wood products challenge forest and wildlife managers attempting to balance consumer needs while also promoting conservation of biological diversity. Any changes to the demand for and production of wood products could affect diversity within stands (alpha diversity) and at larger spatial scales (beta and gamma diversity). Ecosystems are resilient to the loss of some species, as some redundancy exists in how species function within the environment, but the reduction in species and function at the local level must be mitigated at a larger spatial scale or diversity and function are lost (Folke et al., 2004). Generalities are difficult to make, but two patterns arise including the loss of alpha diversity as forest management intensity (i.e., disturbances) increases within a stand (e.g., Miller & Miller, 2004) or at least follows curvilinear response (i.e., intermediate disturbance hypothesis; Roberts & Gilliam, 1995). In particular, in pine forests of the southeast United States, forest canopy cover is a major driver of diversity (Greene et al., 2016).

Management actions associated with SRWCs (e.g., competing vegetation control, high fertilization rates, and high wood utilization) typically lead to a simplification of vegetation structure that as a rule reduces biodiversity (Greene et al., 2016). A meta-analysis of eight studies found that SRWC stands of Populus spp. were lower in avian diversity, avian guild richness, and mammalian guild and species richness relative to unmanaged forest stands (i.e., not conventionally managed forest stands; Riffell, Verschuyl, Miller, & Wigley, 2011). However, Gottlieb et al. (2017) indicated that SRWC pine would support more bird species than maize fields but less than reference forest stands.

Little is known about SRWC effects on aquatic wildlife (McKay, 2011; Riffell et al., 2011; Tolbert et al., 1997). A research approach was developed by Joslin and Schoenholtz (1997) to evaluate environmental effects of converting cropland to SRWCs, including measurements of erosion, runoff, groundwater quality, soil chemistry, soil biology, and wildlife. However, wildlife monitoring only consisted of birds and mammals, and not aquatic wildlife.
such as fish and aquatic macroinvertebrates, despite the fact that aquatic taxa can be affected by activities in the surrounding landscape (Carignan & Steedman, 2000). The approach of assessing terrestrial organisms has persisted, as literature searches reveal little consideration of SRWC effects on aquatic organisms.

Given the lack of studies examining the effects of SRWC production on aquatic biodiversity, we briefly review the effects of traditional silviculture on aquatic organisms. Harvest can increase suspended sediment loads in streams, which can negatively impact aquatic macroinvertebrate communities (Campbell & Doeg, 1989). In addition, increased nutrient concentrations in streams may affect macroinvertebrate communities due to nutrient-induced changes to primary producer communities, on which some macroinvertebrates feed (Gafner & Robinson, 2007). However, when appropriate BMPs are established, macroinvertebrates are usually not greatly impacted by disturbance, and streams generally recover in 2–5 years (Aust & Blinn, 2004; Cristan et al., 2016). Because of the duration that aquatic macroinvertebrate immature stages are exposed to the environmental conditions in a waterbody, they are excellent organisms to assess ecosystem health and water quality at the stream reach scale (Barbour, Gerritsen, Snyder, & Stripling, 1999; Bonada, Prat, Resh, & Statzner, 2006; Karr, 1991). Aquatic macroinvertebrates have been used to determine the effectiveness of forestry BMPs (Adams, Hook, & Floyd, 1995; Adkins, Barton, Grubbs, Stringer, & Krolka, 2016; Boggs et al., 2016; Carroll, Schoenholtz, Young, & Dibble, 2004; Holmes, Armanini, & Yates, 2016; Vowell & Frydenborg, 2004) and would be an ideal indicator to assess SRWC BMP effectiveness. Overall, there is currently limited understanding of the effects of SRWCs on biodiversity, particularly for aquatic organisms. Future research efforts should focus on examining terrestrial and aquatic organism effects throughout the SRWC rotation.

8 CONCLUSIONS

The environmental effects of SRWCs for bioenergy may be inherently more difficult to study than those of herbaceous crops due to the typically longer rotation lengths and the need for longer-term funding and consistent land ownership/management to study several rotations or even a single rotation. However, the importance of SRWCs motivates research to quantify these effects. In the bioenergy literature, woody crops receive less attention than herbaceous crops as feedstocks for bioenergy production. However, wood is currently one of the largest sources of biomass in the United States (US Energy Information Administration, 2018), and it is expected that woody crops will continue to support a large portion of biomass demand. Mill waste and residues (tops and limbs) from traditional silvicultural operations provide most of the current woody biomass demand (Vance et al., 2018), but SRWC contributions to the market are substantial and may grow as market conditions and policies dictate.

Short-rotation woody crops are economically viable on lands marginal for row-crop production. However, they differ from typical traditional intensive silviculture in terms of potentially greater competition control, potentially higher levels of fertilization, and more frequent ground disturbance (Figure 3). Thus, the environmental effects of SRWCs may be compared to forestry or agricultural production, depending on characteristics of the SRWC species and silvicultural techniques. Because the short rotation lengths of SRWCs are still long with respect to the duration of most scientific studies, the effectiveness of current forestry BMPs at minimizing environmental effects of SRWCs is only starting to be evaluated. More long-term studies across a variety of SRWC systems are needed to evaluate questions of environmental effects.

The tradeoffs between water use and quality, C dynamics, soil quality, and biodiversity inherent to SRWCs are dynamic and vary over the rotation cycle. Quantifying these tradeoffs requires multiple tools for evaluating net effects relative to appropriate baselines, and over multiple rotations within large, mixed-used watersheds (Figure 3). However, direct field evaluations of the environmental effects of woody biomass production have been practical only at stand and small watershed scales and in limited numbers. Studies thus far have indicated that the effects of SRWC production on the site C budget depends on the starting point for analysis. If a mature forest is converted to SRWC production, net C sequestration is negative, but if traditionally managed commercial forests or croplands are converted to SRWCs, C sequestration may be positive (Guo & Gifford, 2002; Janowiai & Webster, 2010). SRWCs are highly productive by design, and C sequestration is commensurately high during the growth period (Bracho et al., 2012). This high productivity also increases water usage, but over the rotation cycle, higher water use in some periods may be balanced by low water use in the first year after harvest and in the first few years of a new plantation (Jackson et al., 2005) as stand-level transpiration is positively correlated with leaf area (Sun, Alstad, et al., 2011; Sun, Caldwell, et al., 2011). Over several rotations, water usage by SRWCs may be more, less, or the same as a forest managed for sawtimber or pulpwood production; we currently lack empirical data from which to draw conclusions on SRWC water use.

The effects of SRWCs on water quality are not well studied. Plot-scale experiments and watershed-scale modeling suggest that SRWCs result in improved water quality compared to agricultural crops (Nyakatawa et al., 2006;
A recent watershed-scale study of water quality responses to loblolly pine SRWC production indicated that current forestry BMPs are sufficient to protect stream water quality, but the study was not underway long enough to see whether and how much nitrate might reach streams after leaching from SRWC plantations (Griffiths et al., 2017). Further, groundwater travel times to the stream can span years to decades, so stream nitrate concentrations may not respond to SRWC production within a single rotation. Groundwater quality has not traditionally been measured in silvicultural systems, but potentially higher fertilization rates in SRWCs suggest the need for long-term monitoring of nitrate concentrations in both groundwater and stream water in SRWC plantations. Appropriate hydrologic models can help elucidate the likelihood, timing, and magnitude of nitrate contamination of groundwater and receiving streams.

Diversity of birds and mammals decreases in SRWC stands relative to longer rotation forestry and unmanaged forests, but less so than agriculture (Gottlieb et al., 2017; Riffell et al., 2011). However, in general there is a dearth of published literature on long-term effects of SRWCs at the stand scale or over the scale of mixed-used watersheds. There is also a lack of studies evaluating the direct and indirect effects of SRWCs on aquatic invertebrates despite their utility as indicators of ecosystem health and water quality.

Because of the temporal and spatial scaling issues involved with SRWC effects, we propose a coupled field measurement and modeling approach to evaluate environmental effects. As models are further developed to represent SRWCs, they may be used to take findings from short-term site and small watershed-scale studies and extrapolate them over space and time to evaluate landscape-scale effects for plausible woody biomass production scenarios. Models inherently include errors, but they are the only practical tool to generate relevant insights before multirotation studies are completed. Woody biomass production will exist in a mosaic of traditional silviculture, food, and fiber production, and the landscape-scale characteristics of this mosaic will depend on unpredictable economic, legal, and social factors overlain on the environmental template.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

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