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SUSTAINABLE AND RENEWABLE FUELS (M WU, SECTION EDITOR)

Sustainable Production of Bioenergy Feedstock from the Industrial Forest: Potential and Challenges of Operational Scale Implementation

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Abstract There is increasing interest in energy from woody biomass as fossil fuel replacement, yet environmental and economic limitations have reduced feedstock available for bioenergy. Supply could likely be substantially increased with intensive forest management for productivity and utilization as well as forest-based dedicated energy crops. This paper discusses the role of industrial forests in sustainable bioenergy feedstock production and the lessons learned in an operational scale project. Catchlight Energy, LLC, a Chevron|Weyerhaeuser joint venture, evaluated intercropping switchgrass (*Panicum virgatum*) in loblolly pine plantations for liquid transportation fuel, with the goal of full-scale production. Within Weyerhaeuser, sustainability and operational research were conducted simultaneously. While the environmental research is non-proprietary and being published as it is completed, operational trials were internal. To understand lessons learned, staff responsible for management, planning, logistics, and field operations were interviewed, and perceived and actual barriers to production described. Ongoing environmental research is showing that carefully planned field operations can be conducted sustainably, but energy crop production fell below levels needed for economic feasibility.

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Introduction

Increasing concern over impacts of elevated concentrations of greenhouse gases (GHG) in the atmosphere on climate has generated interest in replacing energy from fossil fuels with energy from forests, with woody biomass possibly accounting for 18 % of global energy consumption by 2050 [1]. However, it is likely that this value could be substantially increased by developing and implementing forest management measures to enhance biomass productivity and utilization and also grow dedicated energy crops.

While woody biomass may be defined as "all forest plant and forest-plant-derived materials" [2], not all woody biomass is grown in a forest nor is it the only potential feedstock from the forest. Forest-based bioenergy crops can come from increased management and use of trees grown for traditional forest products or from dedicated feedstock grown specifically for bioenergy. Short-rotation woody crops are an important source of biomass but are typically grown agriculturally.

Recent efforts have focused on innovations to make second-generation biofuel technically and economically feasible. Initial estimates showed adequate feedstock to meet the Renewable Fuel Standard [3], but models over-allocated woody biomass to bioenergy uses [4] and environmental and economic limitations make actual supply much lower than potential availability [5, 6]. Capital for investment in conversion was limited by the economic recession, energy costs dropped, and high-profile failures in wood-based biofuel conversion facilities [7] reduced willingness of growers to plant bioenergy-specific feedstock.

However, there are still US wood-based cellulosic biofuel planned and in place, although only one is ready for commercial scale production [7]. European markets will depend on US woody biomass to meet renewable fuel targets [8]. With careful landscape planning, industrial forestry could source a large, stable source of biomass without affecting food supply, bring experience in large-scale sustainable land management, and provide a balanced economic and market portfolio of products.

Forest-Based Feedstock

Increased Management and Use of Forests Grown for Traditional Forest Products

While there was initial concern that a market for forest-based sources of biomass would cause conversion of forest to more intensive land uses, bioenergy production need not lead to deforestation [9], and demand could lead to increased forest area [10]. More intensive biomass removal from public forests could work within fuel load reduction and pest management plans to remove understory and manage stand density [11]. For small private landowners, increased utilization of existing forest biomass requires less investment and risk than dedicated plantings. More intensive management could include fertilization, denser plantings, more frequent thinning of non-crop trees, or understory harvest. Forest residues could be an important bioenergy feedstock, making up 13 % of the US potential biomass [12] and displacing about 3 % of electricity sector carbon (based on 1997 FIA and energy data) [13]. Figure 1, produced by the National Renewable Energy Laboratory based on US Forest Service data, shows residues available for biomass removal.

Increased residue usage is most easily accomplished by whole-tree harvest, with natural understory vegetation harvested mechanically [14–16]. Periodic natural understory vegetation would be more variable than a dedicated crop, causing potential conversion issues. Increased residue use and understory removal would be subject to applicable regulatory forest practice rules, state Best Management Practices, certification guidelines, and other environmental regulations, such as the Clean Water Act. Participation within forest certification systems, such as the Sustainable Forestry Initiative® (SFI®), Programme for the Endorsement of Forest Certification (PEFC), American Tree Farm System® (AFTS), and Forest Stewardship Council® (FSC) [17], has expanded rapidly over the last decade, and many standards associated with these certification programs are applicable to forest biomass production.

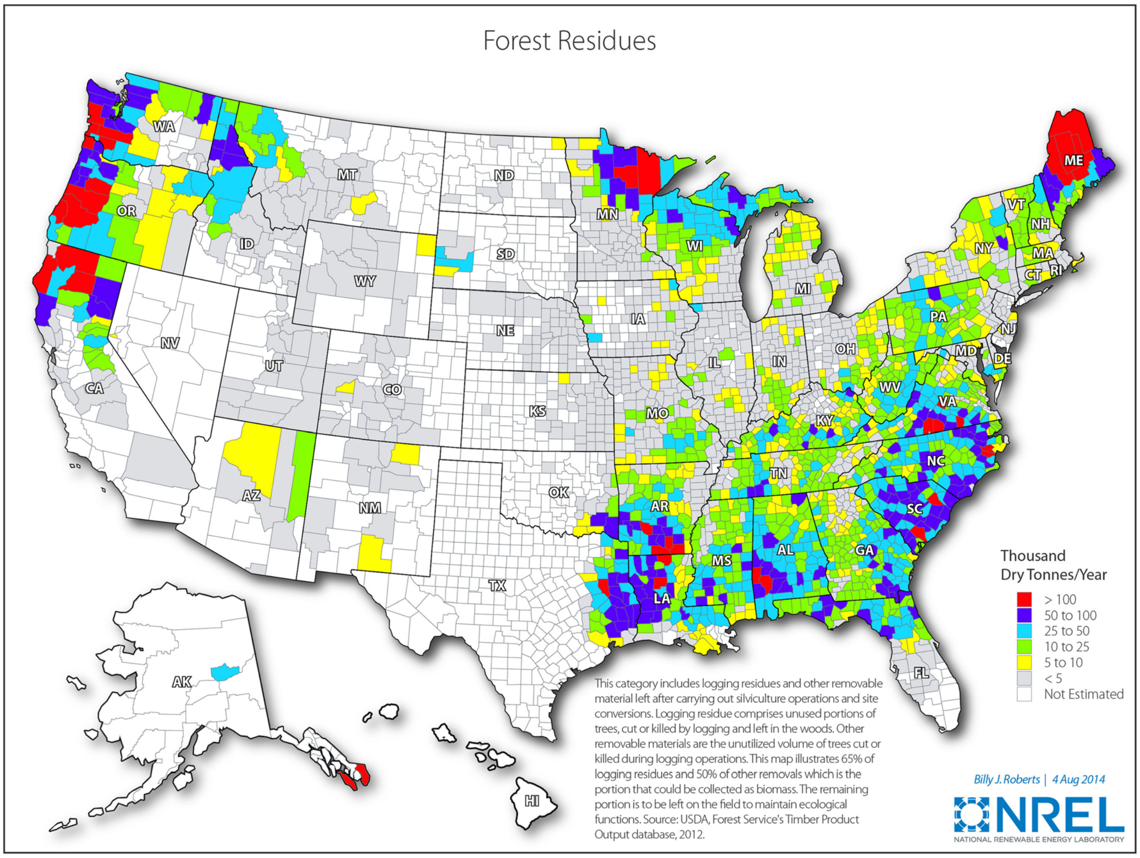
Sustainability of intensive removals from forests depends on the specific practice and site. Eisenbies et al. [12] synthesized study data on biomass left after current stem-only harvest and found that whole-tree harvest could remove 20–50 % of material now retained after harvest. They cite conflicting evidence as to which sites are most resilient, but that it is possible to remove residue without depleting nutrients and reducing site productivity. Many studies have found little to no effect of these types of removals on soil quality [18–20], though aggressive biomass removal may impact soil productivity. On poorer loblolly pine (*Pinus taeda*) sites, often with coarse-textured soils, intensive biomass removal is more likely to reduce productivity [21–24], and higher slope areas are more susceptible to erosion from biomass removal [25]. Removal of harvest residues on sites that are already deficient in organic matter/soil carbon may remove a higher proportion of available C and nutrients from the site than would occur on sites with higher levels of organic matter.

Dedicated Forest-Based Feedstock Grown Specifically for Bioenergy

There are many hurdles to growing a purpose-grown bioenergy crop on forest land, but future scenarios may require more bioenergy feedstock than is available from existing agriculture and forest landscapes. These crops could include low-value trees or perennial energy crops, either intercropped in or grown in a mosaic with traditional plantations. However, much of what we know comes from plot-scale trials or agricultural studies. Weyerhaeuser Company installed, to our knowledge, the only purpose-grown bioenergy crop at operational scale within a forested system.

Weyerhaeuser's bioenergy project was initiated in 2008 as part of Catchlight Energy, LLC, a Chevron|Weyerhaeuser joint venture, to evaluate intercropping switchgrass (*Panicum virgatum*) in loblolly pine plantations for liquid transportation fuel. Switchgrass is a native C4 grass, and there is a large body of research and guidance in growing it for bioenergy in agricultural settings [26–28], including a full-scale, integrated bioenergy system through the University of Tennessee [29]. Pine intercropping is also not new; the literature includes examples of plot trials, for example intercropping with low-value trees [30] and switchgrass [31, 32].

The Catchlight joint venture brought together expertise in natural resources from Weyerhaeuser and energy from Chevron and worked to fill technology gaps. We, the authors, were primarily involved in feedstock supply and sustainability research. While our sustainability research is being published, many of the planning decisions and operational trial results were not public. To capture the important lessons from these and gain additional insight into project history, we interviewed others in management, planning, operations, and logistics, and the following reflects our experience and that of those we interviewed. As part of the bioenergy project scoping, planners from Weyerhaeuser, Chevron, and the joint venture



This category includes logging residues and other removable material left after carrying out silviculture operations and site conversions. Logging residue comprises unused portions of trees, cut or killed by logging and left in the woods. Other removable materials are the unutilized volume of trees cut or killed during logging operations. This map illustrates 65% of logging residues and 50% of other removals which is the portion that could be collected as biomass. The remaining portion is to be left on the field to maintain ecological functions. Source: USDA, Forest Service's Timber Product Output database, 2012.

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Fig. 1 Forest residues beyond that needed for ecological function [72]

evaluated barriers to bioenergy supply. Major barriers were overall demand including energy and feedstock markets; government policy, mandates, and incentives; environmental effects on biodiversity, water, and soil; carbon fate and accounting methodology; seed source and availability; planting methods and establishment success; switchgrass productivity; competition between pine and switchgrass; equipment and contractor availability; harvesting logistics and efficiency; and transportation costs. Plans were put in place to simultaneously address the major research gaps and scale up sustainable feedstock production. Seventeen bioenergy plants were planned by 2029, with the first commercial plant on line in 2014.

Operational tracts and studies were installed in 2008 and continued until 2012 when it became clear that with dropping energy prices, reduced policy imperatives, and no breakthroughs in scaled conversion technology efficiency, pine/switchgrass intercropping was economically infeasible except under the most productive conditions. As Alan Shaw, former CEO of Codexis advanced biofuel company, said about cellulosic conversion, it is "not a promising place to start producing commodity chemicals and fuels where 80 percent of the cost is feedstock."[33]. Where research into engineered system components can occur rapidly, research and development of feedstock cannot move faster than crop establishment and growth, and perennial, forest-based systems face additional challenges. Competition between pine and switchgrass is a major component of the economic [34] and sustainability equation, yet switchgrass does not reach maturity for 3 years. Site preparation and sowing of switchgrass were expected to cause high erosion initially [35], yet once established, switchgrass is a very effective sediment control [36] and has even been shown to be effective in mitigated gully erosion [37]. Biodiversity and water quality components of sustainability research required a pre-and post-treatment period, further increasing length of time needed for results. However, results can be extrapolated to many intensive forest-based biofuel practices, and although the operational studies concluded, sustainability work has continued and is yielding useful insights.

Operational studies included in-field operations, logistics, plant and system productivity, and effects on soil quality and carbon stocks. Trials examined switchgrass species optimization, provenance, spacing and configuration, fertilization rates and timing, herbicide prescriptions, shading effects, planting equipment and methods, harvest timing and frequency, site preparation, pine/switchgrass competition, and ash content. The intercropping system was patented [38], and while some studies were proprietary, others overlapped sustainability work and were published (e.g., [39–44]). Many trials were conducted in Lenoir County, NC, an experimental site established in 2008 for soil and carbon sustainability work [45]. Other field trials, environmental research sites, and approximately 30 full-scale operational tracts were installed across Weyerhaeuser's ownership in Mississippi, Alabama, and North Carolina. These to-scale trials revealed several barriers to economically viable and environmentally sustainable feedstock production.

Site Planning

Although multiple row spacings were studied, switchgrass was operationally planted between pine spaced in rows 6 m apart (Fig. 2). Plot studies demonstrate lower switchgrass height and productivity on edges nearest to pine, due to competition and shading [39, 40]. Effect magnitude increases with pine age and competition for resources, including light. Although a shading effect is not apparent early in the intercropping cycle [40] and has been hypothesized to help young switchgrass outcompete other grass [46], it greatly limits productivity as switchgrass matures [39].

Correlated with row spacing, age of pine at switchgrass planting has implications for switchgrass productivity and site erosion. Delaying switchgrass site preparation and planting until 2 years after plantation establishment leaves residuals time to decay, providing more uniform ground conditions, improving establishment efficiency and success. Preliminary results also found desynchronized planting reduced water quality response to switchgrass site preparation [47, 48] comparison to simultaneous planting. However, switchgrass loses significant productivity under a shading equivalent of 6–8-year-old pine [39], moving switchgrass production to a 4–6-year window in a 25-year pine rotation.

These sites, like all Weyerhaeuser US plantations, were managed under SFI requirements, and state Best Management Practices (BMPs) for forestry were followed. Forested riparian buffers and non-riparian buffers, common in steeper slopes and wet areas, reduced operable area. Steeper sites and sites with broken microtopography were also excluded. Trees were planted on contour, and in sites with steep and dissected relief, planting rows became broken and also intersected, making operations less efficient. While these practices provided soil and water quality protection, areas left in trees shaded switchgrass and reduced and fragmented planting area. Other best practices, such as sinuous contour planting, limited equipment type and maneuverability and required more fuel.

Operations

Establishing an agricultural crop on forest land proved to be challenging, requiring equipment and experience not typical of forest operators. Although intercropped sites were limited to lower slopes, operators used their judgment and experience to further restrict operations within a tract to limit erosion, reducing the area site prepared for switchgrass by approximately 25 % in upland areas [49].

After plantation harvest, but before planting pine or switchgrass, sites were cleaned with a brush rake, an expensive and slow process. The ground had to be dry enough to support a large bulldozer, but still have enough moisture for optimal sowing. Intercropped areas had to be further cleared so that

Fig. 2 An intercropped site in Greene County, Alabama, with bales from previous year harvest

the seeds were sown in mineral soil, while avoiding erosion. Even with additional clearing, considerable forest residue remained, slowing site preparation considerably. Planting areas, while very smooth by forestry standards, were much rougher than agricultural sites.

The first attempts at sowing used a seed drill designed for row crops. However, in many sites, slope, ground undulations, and rills led to large variations in seed placement, with some sown too deeply and other dropped on the soil surface. Experiments led to improved techniques, and in subsequent attempts, soil was disked three times with a tractor and seed was broadcast followed by a light harrowing using an all-terrain vehicle with a chain bar. This produced more optimal soil moisture conditions and seed depth leading to much more successful germination.

Loblolly pine prefers soil pH from 4.5–7.0 [50] but switchgrass prefers a pH of 5.5–6.5 [28], and productivity is reduced in lower pH soils. Pine plantations are fertilized at low average annual rates, and additional fertilization was needed for switchgrass. Pine, planted as seedlings, are not affected by localized standing water, but this reduced productivity of or killed switchgrass. Competition from diverse seed reservoirs, not present in highly cultivated agricultural land, required site-specific herbicide prescriptions.

Agricultural equipment and techniques had to be modified for mowing and baling. Pine rows closed over time, and switchgrass growth hid obstacles. Contour plantings, efficient in preventing erosion, require much more equipment maneuverability and slowed each equipment pass. Costs per bale were approximately double those from an agricultural field.

Sustainability

To understand sustainability of intercropping, research was conducted for carbon balance and environmental effects; environmental research included biodiversity, soil quality, and water resources. Biodiversity studies covered plants, herpetofauna, and large and small mammals [51–59]. Soil quality, GHG, and carbon life cycle analyses were conducted. [31, 40–42, 44].

In research watersheds, switchgrass was planted into a young pine stand or co-planted during with pine along with stands of mid-rotation pine, young pine, and switchgrass only. Early switchgrass success was low, and the sites were replanted and overseeded, delaying the project by a year and extending the final growing season to 2015. Publications to date evaluate methods and models, reference site dynamics, plot trials, pre-treatment or site preparation periods, and early data [47, 60–66]; however, general observations can be made. A visual survey confirmed water quality analysis [47] that erosion associated with site prep and sowing was minimized by existing pine rows, which stopped almost all sediments. Co-planted stands were clear of vegetation for a longer time and had none of the litter accumulation associated with even young pine. Water use has been a major concern in biofuel feedstock [67, 68], but early estimates show intercropping would use slightly less water than pine plantations they replace [50, 69]. The final analyses are not complete, but properly implemented pine/switchgrass intercropping appears to maintain ecological functions of the forest.

Conclusions

To make a significant contribution to renewable fuel supply, forest-based biomass must be grown and harvested sustainably and efficiently. Intense management of a high-productivity crop must be done in a way that maintains ecosystem services of managed forests. Operational plantings across feedstocks show much less yield than plot trials predict [70]; this discrepancy between modeled and actual supply could harm food and bioenergy markets and threaten plans for renewable fuel [71]. Identifying and addressing the benefits and challenges of forest-based biomass feedstock systems will help ensure renewable fuel supply for our future.

Compliance with Ethical Standards

Conflict of Interest Jami Nettles, Peter Birks, Eric Sucre, and Robert Bilby declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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