Biomass, spacing and planting design influence cut-and-chip harvesting in hybrid poplar

Mark H. Eisenbies (corresponding author)[1], Timothy A. Volk[1], Jesus Espinoza[2], Carlos Gantz[2],

Austin Himes[2], John Posselius[3], Rich Shuren[2],Brian Stanton[2], Bruce Summers[2]

1- State University of New York, College of Environmental Science and Forestry.1 Forestry Dr., Syracuse, NY 13210, USA

2- Greenwood Resources Inc. 1500 SW 1st Ave Suite 1150, Portland, OR 97201

3- CNH America LLC, P. O Box 1895, ms 640, New Holland PA 17557-0903, USA

Contact information for corresponding author - mheisenb@esf.edu, Ph. 315-470-4850, Fax 315-470-6934

Abstract

Hybrid poplar is a woody crop grown for the production of bioenergy, biofuels and bioproducts. Harvesting is often the largest single cost in the production system and the development and optimization of equipment is evolving. The objective of this study was to evaluate the performance of a single-pass, cut-and-chip harvesting operation in commercial plantings that included four cultivars, two spacing treatments, and two coppice planting designs (dedicated, and interplanted with sawtimber). Approximately 15 hours of harvesting using a New Holland 9080 forage harvester equipped with a purpose-built coppice header was monitored over four days. Stand biomass ranged between 34 and 78Mg ha^{-1}of fresh biomass and effective material capacity (C_m) of the harvesterranged from 10 to 78 Mg h^{-1}of fresh biomass excluding headland activities. Tree spacing had a significant effect on C_m but cultivar and planting design did not. The treatments did not have discernible effects on machine fuel consumption (mean 83 L h^{-1}; σ 16.4) or crop-specific fuel consumption for fresh biomass (mean

1.34 L Mg^{-1}; σ 0.31). Crop-specific fuel consumption was positively correlated with engine load, and negatively correlated with standing biomass; this result was statistically significant but negligible (< 1%) in terms of liters of fuel used for each additional Mg ha^{-1} of stand biomassfor engine loads ranging between 30% and 110%.

HIGHLIGHTS

- Harvesting operations are among the largest single costs in SRWC production systems
- Planting design affected poplar yield and harvester throughput by over 25%
- Higher plant density affected poplar yield and harvester throughput by over 10%
- The effect of planting design and spacing on fuel use may be minor at small scales
- There may be risks delaying harvests where trees sizes approach machine capacity

Keywords: Short-rotation Woody Crops; Biomass Harvesting;Hybrid Poplar; Fuel Consumption; Effective Material Capacity; Effective Field Capacity

Abbreviations

C_m, Effective Material Capacity; C_f, Effective Field Capacity; GPS, global positioning system; LLC, limited liability company; SPCC, single pass cut and chip; SRWC, short-rotation woody crop

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1. Introduction

Sources of biomass for bioproducts and bioenergy include forests, agricultural crops, various residue and waste streams, and dedicated woody or herbaceous crops [1,2]. However, an important challenge is to createsupply systems that are cost effective and efficiently deliver large quantities of biomass while maintaining quality [1]. Additionally, there are concerns about the environmental impact of these sources, their sustained performance, the technical constraints for conversion, as well as a stable and predictable policy environment [3–6]. It is unlikely that any one source of feedstock will dominate since supplies of dedicated crops as well as agricultural and forest residuals are subject to a variety of market forces and prices [1]. Short-rotation woody crops (SRWC) have had some commercial successin the United States [7,8], and they have the potential to provide ecosystem and environmental benefits in addition to energy production [9–11].

SRWC are managed using a combination of techniques and knowledge from both agriculture and forestry. These systems typically have higher planting densities and more intensive management than most forest systems. In many cases, stands are regenerated by coppice rather than planting [12]. The reported range for above-ground yield for short-rotation poplar ranges between 2 and 19 Mg ha^{-1} $yr^{-1}$of oven dried biomass depending on site characteristics, soil properties, climate, and cultivar, but most yields range between 9 and 13 Mg ha^{-1} yr^{-1} [7,13,14]. Although SRWC systems might include agronomic practices such as irrigation, management strategies are still grounded on silvicultural practices used in forestry.

The timing of weed control and fertilization rates are similar to forest plantation systems, and growth, yield, and stem form can be highly influenced by spacing [12,15,16].

The Northwestern United States is an important region with substantial lands and infrastructure devoted to the production of wood and wood fiber [1]. One potentially important crop includes dedicated *Populus* grown as SRWC [17]. One of the principal advantages of poplar is the ability to vegetatively propagate from hardwood cuttings and coppice under field conditions [18]. This meth od of crop establishment takes full advantage of clonal selection and substantially reduces nursery and establishment costs. Clonal plantings create uniform stands that are favorable for machine operations during harvesting.

Harvesting of SRWC can be accomplished with a variety of machines and systems [19,20]. Dedicated systems have been in development since the early 1980's [21–24], and continue to be refined and improved [25–28]. There are two general approaches to harvesting in these systems. The first is cutting and chipping the material with a piece of equipment in a single pass across the field (Single Pass Cut and Chip – SPCC). The second is harvesting the material as whole stems and chipping or processing it as a separate operation. Both systems have advantages and disadvantages, but due to their efficiency completing multiple steps in one process, SPCC systems have generally been shown to minimize harvesting costs [29]. Newer cut-and-chip systems address many of the hurdles faced by previous equipment; namely slower machine and material harvesting rates in the field, lower durability, inconsistent feeding and cutting, and quality issues associated with shredded or oversized chips [30]. The vision of advanced uniform feedstock supply systems is to incorporate needed preprocessing steps in advance of the biorefinery gate; the goal to deliver feedstock with consistent quality characteristics and cost advantages that allow easier integration with other woody biomass supply ch ains [31]. Additionally, improvements in providing feedstock that meet end-user specifications could lead to cost improvements elsewhere in the system [32,33]. These SPCC systems have been deployed on a range of short-rotation woody crops in many countries [32,34–36].

Harvesting operations are one of the largest single costs in most of these production systems due to the cost of equipment and amount of fuel used during operations. Properly matching harvesting equipment to a production system can significantly impact costs and efficiency of a production system [37,38]. Given competitiveness of the energy market, and the frequent occurrence of harvesting operations, especially in systems using coppice management, finding ways of optimizing them is critical [39,40]. Furthermore, there is a need to understand the sources of uncertainty in the harvesting process and removing variation associated with bioenergy production systems and crops so that efficiency can be improved and costs can be reduced [41,42].

Although there are some examples in the literature evaluating aspects of SPCC cut-and-chip, harvester performance, variability is common. Generally, maximum observed effective material capacity (C_m) for fresh biomass has increased steadily with advances in machine technology from about 20 Mg h^{-1} two decades ago to over 60 Mg h^{-1} in recent years; however, even among contemporary studies minimum C_m has not increased appreciably [36]. The variation in harvester performance (i.e. C_m and effective field capacity (C_f)) is related to a v ariety of factors (machine configuration, operator experience, crop and site conditions, etc.) [32,34]. In SRWC the variability due to these factors becomes particularly important from a planning perspective given how potential interactions could impact harvesting. For example, in crops with a high standing biomass there is a need for most of the machines power to be used for cutting and chipping but power might be diverted to compensate for poor soil conditions or an inexperienced operator [43]. The influence of cultivar selection, spacing and planting design in SRWC, and in particular poplar, on harvester performance is not well understood. The objective of this study is to evaluate the performance ofa single-pass, cut-and-chip harvesting operation in hybrid poplar plantings managed on two year coppice cycles, and to relate performance to cultivar and silvicultural prescriptions while controlling, to the degree possible, machine setup, operators, weather, and site conditions.

2. Materials and Methods

2.1. Site description

The study site was located at the former Boardman Tree Farm (45°45'12. 43"N, 119°37'4.32"W), a 10,000 ha facility established in the 1990's in Morrow County, OR, USA and operated by GreenWood Resources LLC (GWR) to grow poplar for products including bioenergy and sawtimber. The sandy sites reside on rolling, excessively drained grassland soils of the Columbia Plateau about 230 km east of Portland, OR on the east side of the Pacific Coast Ranges. The soils are mapped as Quincy loamy fine sands, which are categorized as mixed mesic Xeric Torripsamments [44]. In order to successfully grow trees on the site, GWR maintaineda dripirrigation system that supplied water to individual trees.

The SRWC trees were planted in the spring of 2010 and harvested the first time after the 2011 growing seasons so the plants in this 2014 trial were two years old on a four-year-old root system. The 15 ha research area included three factors: poplar cultivar (four levels), planting design (two levels), and spacing (two levels). The crop consisted of threeproprietary hybrid poplar cultivars from *P.* x*generosa* (TD) (PC4 and BC78) and *P.* x*canadensis* (DN) (BC79), and one nonproprietary cultivar from *P. xcanadensis* (DN) (OP367) on 390 m long rows. For each cultivar, planting designs included (1) a dedicated short-rotation poplar and (2) interplanted short-rotation poplar alternating with rows of sawtimber. Spacing for the dedicated rows were 3.05 m between the rows and either 1.22 m or 0.61 m along the row. Along the row, poplars were planted alternating 0.3 m to the left and right of the center line (zig-zag) along the row to accommodate the drip irrigation line. For dedicated crops each row contained poplar being coppiced on two year rotations. In the interplanted treatment rows alternated between SRWC and sawtimber rows and spaced 3.05m apart. As a result the dedicated poplar was planted at two spacings, 6.1 m between SRWC rows and either 1.22 m or 0.61 m along the row. The sawtimber crop was planted between these SRWC rows at a spacing of 6.1 m and 3.05 m along the row. Sawtimber crops were established at the same time as the short-rotation rows, but intended to be harvested after 10-12 years of growth. For the purposes of this paper, the 0.61 m and 1.22m down-the-row spacings will be referred to as S6 and S12 respectively for simplicity. Tree diameter and heights were measured on three randomly located plots (3m x 9m) per treatment combination.

2. 2. Harvest Activities

Harvest activities were monitored between November 18-21 and December 10-11, 2014. Mean temperatures ranged between -8 and 1 ^{o}C in November and was between 11 and 13 ^{o}C in December. Ground conditions were good and sufficiently firm to operate. The harvester platform tested was a New Holland FR9080 harvester, equipped with a New Holland

130FB coppice header fitted with saw blades that were specifically selected for harvesting poplar as opposed to willow. Poplar blades are comparatively smaller diameter and have larger tips that are better suited for larger-diameter poplar stems. The harvests were managed by an experienced operator with hundreds of hours harvesting short term woody crops using this equipment, and supported by a locally sourced crew and collection vehicles. Various three-axle, 10 to 15 Mg capacity dump trucks were used to collect chips from the harvester. The length of cut selected by the operator was the largest setting ("33mm"), which satisfied end user chip size specifications. Priority was given to harvesting contiguous plantings of each cultivarover more efficient harvesting patterns. Ground speed varied across the field and was adjusted by the operatorto maximize production while limiting potential problems with material jams or equipment breakdowns. Headland efficiency was lowdue to the collection vehicle operators'lack of familiarity with SRWC and the need to cut the entire block of a single cultivar at a time; thus, results focus on in-field harvester performance excluding headland activities in order to assess the influence of cultivar, spacing and planting design. Collection system efficiency is not formally assessed, but chips were hauled 5.3 km where each load was weighed to the nearest 0.1 Mg and unloaded for short-term storage.

2. 3. Harvester Monitoring

Between November 18 and 21, 2014 machinery activities were tracked during the harvests using a combination of GPS data loggers recording positions every second and field observations. Harvester performance was monitored based on GPS techniques outlined by Eisenbies et al [34]. A GeoXM GPS unit (Trimble Navigation Ltd.) was used to monitor the harvester; equipped with an external antenna the unit is capable of sub-meter accuracy after differential corrections. Juno SB GPS or GeoXH units (Trimble Navigation Ltd.) were used to monitor the collection system vehicles; equipped with external antennas, they are capable of sub-meter to 3 m accuracy. Control points were defined any time conditions changed (e. g. the harvester enters or leaves the field at then end of the row, a collection vehicle is filled and separates from the harvester to depart for the landing, or a new collection vehicle arrives and engages with the harvester, delays, or any state as deemed necessary by the observer). The distance between two control points was identified as a leg. GPS data for the harvester and associated collection vehicle were separated into legs and combined into complete loads; loads being the experimental replication [34]. Delays/holds are defined as the period of time where the harvester's speed drops below 0.64 km h^{-1} (a speed where position changes became indistinguishable from GPS noise) twice within 5 seconds, for 5 seconds or more, and separated by at least 5 seconds from any other delay. The observational unit was individually weighed loads, each of which may be comprised of one or two rows. The average number of loads for each treatment combination was between six and seven.

Observers were positioned in the harvester cab and at the harvest landing and short term storage sites to record times for row entries, exits, collection vehicle exchanges, dump times, load weights and truck tares, and other harvest activities. Cultivars and treatment spacings were identified beforehand using unique colored flagging at the ends of each row. Field notes included flag colors, harvester entry and exit times, rendezvous time and serial number of collection vehicles, truck weights, and delivery times. UTC time to the nearest second was the variable key used to link data sets which was collected by observers using hand held GPS units. Operational data were supplemented using the manufacturer's onboard

IntelliView(tm) system that records engine load (%) and fuel consumption (L h^{-1}) each second as well as a variety of other parameters (e. g. time, GPS position, engine load, C_m). Between December 10 and 12, only field notes and data from the IntelliView system were collected; however, row lengths were fixed thus all metrics could still be determined with the exception of field delays and delay times.

Harvester speed (km h^{-1}), C_f (ha h^{-1}), fresh standing biomass (Mg ha^{-1}), and C_m of fresh biomass (Mg h^{-1}) [45–47] are calculated on a load basis based on the GPS methods described in Eisenbies et al [34]. For the interplanted sites, standing biomass and C_f were calculated using 3.05 m spacing (excluding the timber rows) in order to make the calculated performance parameters directly comparable to the dedicated rows. For standing biomass, harvest losses to the ground (drops) were not monitored; thus, load weights represent delivered biomass. Fresh weights, as opposed to oven-dry weights, are reported given that fresh weights drive harvesting and delivery costs. Moisture content was determined using ASABE method s [48].

2. 4. Statistical analysis

Individually weighed loads with in-field efficiencies greater than 80% were the experimental replicate; loads with efficiencies less than 80% are reported but not utilized in the statistical analyses since the nature and length of field delays were associated with equipment faults (e. g. tire punctures, header faults, metal detections) rather than treatments. The 80% cutoff is a means of defining the inference space rather than biased determinations of individual observations' "validity". Statistical comparisons of performance metrics associated each loadrelative to crop treatments were made in SAS 9.2 (SAS Institute) using the GLIMMIX procedure. Normality assumptions were tested using the UNIVARIATE procedure. Crop treatments comprised of a factorial design featuring four cultivars, two spacings (S6 and S12), and two planting designs (dedicated and interplanted). Significant differences were evaluated by pairwise comparisons of least squares means using the PDIFF option in the LSMEANS statement. Relationships between continuous performance factors (i.e. engine load, standing biomass, C_m, fuel consumption, and crop-specific fuel consumption (L Mg^{-1}) were made with multiple linear regression methods in the REG procedure in SAS 9.2. The full model consisted of standing biomass, engine load, and C_m and each of these terms squared. Candidate and final model selection was obtained using both backwards selection and the Mallow's Cp statistic [49].

3. Results and Discussion

3. 1. Biomass yields

Mean standing fresh biomass among the cultivars ranged between 42 and 64 Mg ha^{-1}, and mean moisture content was between 43 and 44%; as stated previously, a 3.05 m spacing was used for both the interplanted and dedicated treatments to make them comparable. Main model effects indicated that standing biomass from interplanted stands was approximately 10 Mg ha^{-1} greater than dedicated stands ($P<0.0001$), and the higher planting density (S6) resulted in about 5 Mg ha^{-1} greater biomass ($P=0.0026$) (Figure 1). Cultivars performed similarly in the dedicated plots, but OP367 had significantly higher productivity ($P=0.0091$) in the interplanted sites yielding about 5 to 10 Mg ha^{-1}more than other cultivars. Neither the two-way interaction of spacing and cultivar ($P=0.6021$), or the three-way interaction of cultivar, spacing, and planting design ($P=0.1377$) were significant. However, the interactions between planting design and cultivar ($P=0.0045$) and planting design and spacing ($P=0.0109$) were both significant.

Essentially, the statistically higher yields observed by cultivars occurred primarily in the interplanted plots (range 48.8 to 63.5 Mg ha^{-1}), with less separation between cultivars observed on dedicated sites (range 41.3 to 48.5 Mg ha^{-1}). Similarly, there was no real separation in production due to spacing on the dedicated plots (range 44.7 to 45.6 Mg ha^{-1}), but there were significant differences between the S6 and S12 spacing on the interplanted sites (range 51.4 to 60.3 Mg ha^{-1}) largely due to the higher productivity observed for OP367 (Figure 1). Mean heights on productivity plots ranged between 7.6 and 10.2 m, mean diameters ranged between 47 and 65 mm, and survival in treatment combinations was 94% or greater.

[INSERT FIGURE 1]

Developing silvicultural prescriptions for SRWC is an evolving process, but controlling growing conditions using spacing or other methods is a well established principle in the production of woody crops [17,18,50]. The higher production observed in the interplanted stands may be in part due to less overall competition due to the lower planting density in the sawtimber rows as compared to the dedicated plots. In subsequent harvests, the sawtimber rows would be expected to have a greater impact on interplanted rows and eventually the bioenergy rows phased out for the remainder of the sawtimber rotation.

3. 2. Harvester Performance

The mean in-field C_m for loads where in-field delays included less than 20% downtime (62 of 78 loads) was 63.6 Mg h^{-1} and the range for these observations was between 50 and 78 Mg h^{-1} (Table 1). A mean engine load of 65% and ranging between 32 and 110 %of rated power are indicative of the operator's effort to balance between productivity and avoiding mechanical issues.

[INSERT TABLE 1]

As standing biomass increases C_m begins to level off as larger harvested plants are more resistant to machine progress [32,34]. Thus, regarding crop treatment effects on C_m the primary influencers were spacing and planting design (Table 2 and 3) but the main effect of cultivar was not significant (P=0.3515). C_m was significantly higher on interplanted stands (66.9 Mg h^{-1}) compared to dedicated plots (59.7 Mg h^{-1}) (P<0.0001) (Table 3). Similarly C_m for S6 spacing (64.1 Mg h^{-1}) was higher than stands where a S12 spacing (60.8 Mg h^{-1}) was used (P=0.0265). Riding as an observer in the harvester during operations gave the impression that the S12 spacing was more jarring on the machine and the flow of material into the harvesterdid not feel as smooth and consistent down the row. In this wider spacing the machine would cut and process most of a stem before the next one was encountered resulting in stems feeding in slugs rather than an even stream, and there was audible variability in engine loading. Conversely, the harvester's progress on the S6 spacing was much smoother and predictable which is exhibited in wider instantaneous power distributions among randomly selected segments of the two spacings (Figure 2); effectively, the operator was able to more consistently apply power at a higher level and the machine ran more smoothly.

[INSERT FIGURE 2]

[INSERT TABLE 2]

[INSERT TABLE 3]

Work in poplar, willow, eucalyptus SRWC has suggested that the relationship between C_m and standing biomass is not linear [32,34,51]. Specifically, in stands with low standing biomass C_m is limited by the maximum harvester speed allowed by ground conditions. In the case of the stands in this study the maximum speed was slightly above 5.0 km h^{-1} which translates to just over 2.8 ha h^{-1}.

As standing biomass increases, the crop presents greater resistance to the harvester and C_m plateaus. In some cases, the transition between the linear and curvilinear portions of the C_m response defined by harvester speed has appeared to be abrupt [34], or even to increase asymptotically [32]. These harvests also suggested an asymptotic relationship, but the range of standing biomass was not sufficient to ascertain if there was a defined transition below 30 Mg ha^{-1} or where the maximum C_m was over 80 Mg ha^{-1} (Figure 3). The slope and level of the plateau is likely defined by a combination of factors including harvester power, site conditions, crop architecture, and operator behavior. Poplar stools often produce multiple stems but not as numerous as willow and tend to be taller and have larger diameters, although not as large as eucalyptus. This could explain the less abrupt transition to the plateau observed on other harvests and presents an interesting research question for future work.

[INSERT FIGURE 3]

Mean C_f was 1.3 ha h^{-1} on dedicated plantings compared to 1.2 ha h^{-1} on interplanted sites (P=0.0180) due to the differences in standing biomass. An interesting dichotomy on the interplanted sites was the higher growth and performance of the cultivars, perhaps attributed to the amount of overall competition between rows, coupled with the challenges with collecting biomass. Specifically, the collection vehicles had to follow behind the harvester on interplanted sites which kept operators out of visual contact and increased the difficulty for communications and coordinated movements between them.

The 9080 harvester consumed fuel at a mean rate of 83.7 L h^{-1} and had a mean crop-specific fuel consumption of 1.35 L Mg^{-1}; the mean engine load was 64.9% (Table 2). There were no effects on these variables observed for cultivar, spacing or planting design. Fuel use increases asymptotically with engine load consuming fuel at a rate of 114 L h^{-1} while operating at 100% engine load. Regression models for fuel use based on engine load was significant (adjusted R^2=0.9134; Table 4) and was asymptotically related to engine load (top panel; Figure 4). In the case of crop-specific fuel consumption mean fuel use per Mg chips produced was 1.34 L Mg^{-1}. Regression analysis (adjusted R^2=0.7256; Table 4) suggests that less fuel is consumed per unit of biomass as standing biomass increases (bottom panel; Figure 4). According to these results, each 10 Mg ha^{-1} increase in standing biomass improved fuel economy by 0.11 L Mg^{-1}. Thus, given the means and ranges of data observed, fuel economy improves about 3 to 5 % for each 10 Mg ha^{-1} increase depending on engine load. This study did not evaluate the effect of cut length on fuel consumption. Guerra et al. [32] reported a 20 to 30% reduction in C_m and an approximately 20% increase (weighted average) in crop-specific fuel consumption when chip size is reduced from 30 to 20 mm using a New Holland FR9060 harvester. Thus, chip size selection and harvester model selection may be several times more influential on overall fuel use.

[INSERT TABLE 4]

[INSERT FIGURE 4]

3. 3. Harvest timing and field delays

Timing and delay information are presented for the purpose of providing information on issues specific to this harvest and provide context. Approximately 20 hours of harvester operations were monitored on 15.0 ha of crops. Although not a specific focus of harvest monitoring, delays attributed to the harvesteraccounted for 19% of the in-field run time for all loads, but for the loads where efficiency was greater than 80% the mean efficiency was 95.6%. In recent willow and eucalyptus SRWC studies in-field delays were also less than 10% [32,34].

Specific causes of in-field delays in this study primarily included collection vehicle tire punctures, and operator reaction to machine feedback. The harvester and header were slightly overdue for scheduled maintenance. One lengthy stoppage was to troubleshoot the hydraulic system. Additionally, the field was located next to open grassland, which caused the unique problem of large clusters oftumbleweeds gathering in the rows and collecting in front of the header for 5-10 m or more; this limited operator visibility and required regular clearing for the 10-15 rows adjacent to the grassland.

3. 4. Implications

The implication of this study is that cultivar, spacing and planting design may influence standing biomass, which is the primary factor affecting C_m. However, such a conclusion is tempered by the need for more data and direct studies that focus on maintenance, breakdowns, and loading issues in regular commercial operations. It could be tempting to conclude based on the lower panel of Figure 4 that running the harvester at a lower engine load would incur a fuel savings; however, other factors such as C_m and labor costs would also have to be considered. Ultimately, the harvester operator must balance many variables so that the machine and operation proceed consistently and reliably, which stresses the importance of operator experience.

Generally speaking, the more biomass that is being harvested, and the more material passing through the machine will result in more efficient use of harvester fuel. Although we did not detect a relationship between C_m and fuel consumption (P=0.0896; R^2 = 0.03), Guerra et al [32] did show such a relationship. SRWC are also less fuel efficient to harvest than silage crops which require only 0.5 to 0.6 L Mg^{-1}, but wood is harder and there has been considerably more harvest-system development for silage crops. Our range of 1.2 to 1.5 L Mg^{-1} are comparable to the range of 1.3 to 2.2 L Mg^{-1} reported by the Guerra et al. [32] stocking and chip size study. However, woody biomass cut and chipped by forage harvesters can often be utilized by end users without additional processing (e. g. drying, densification, etc); crop-specific fuel consumption alone is not the only consideration.

Previous work has shown that costs decrease precipitously when operating in crops with increasing standing biomass [29]. One way to increase standing biomass is to extend the rotation length a year or two. However, there may also be a risk associated with delaying harvests since site variation may cause sections of the field to produce stems that exceed the header's design specifications and increase costs by increased downtime and repairs. Conversely, there may be unnecessary fuel costs associated with deploying harvesting machines that are over-sized for the standing crop [38]. Other options to improve economy at the time of harvest would be to increase chip size, but this may affect conversion efficacy or incur processing costs elsewhere in the supply chain [31,32].

Finally, it should be reiterated, the data utilized in this paper only reflect machine performance as it works in the field. The study does not consider the effect of headland activities where maneuvers and collection system configuration can have large effects on overall C_m, but are largely independent of silvicultural choices, site topography, or operator experience [29,52–54].

4. Conclusions

SRWC growers are faced with an array of management decisions throughout the crop cycle that have repercussions on subsequent activities. The planting patterns used during crop establishment will influence plant growth form and yields that will ultimately be reflected in machine performance, which dictates harvesting logistics. Research is needed to address these issues in order to collectively optimize the various parts of SRWC systems rather than just a single factor at a time.

This study evaluated the influence that four commercially-interesting planting designs and spacing combinations had on cultivar yield and harvester performance in a commercial-scaled short-rotation poplar stand. Overall, SRWC interplanted with sawtimber had a mean crop yield over 25% greater than the dedicated SRWC plots. C_m, or throughput, was over 10% higher on interplanted stands. However, interplanted sites present problems with collection system logistics. Narrower spacing along the row improved both crop yield per ha and C_m by about 5%, and was more desirable from an operator perspective.

Results were consistent with recent studies in other SRWC. The relationship between C_m and standing biomass is not linear and tends to plateau as standing biomass increases. Crop-specific fuel consumption may range between 1.2 and 2.2 L Mg^{-1}, which is almost twice that of other forage crops. However, SRWC biomass in cut-and-chip systems requires less or no preprocessing by end users. The benefits of planting design and spacing on fuel consumption were 4 to 6 times less impactful than chip size settings that have been tested in other trials. Although the effect on fuel consumption may be comparatively minor, given the cost of harvesting these silvicultural choices may still be impactful once SRWC systems are more widely deployed. The selection of equipment that properly sized for the crop being harvest will be a critical factor in managing and optimizing the costs for SRWC systems.

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Table 1.Harvester performance for poplar cultivars harvested using a single pass cut and chip harvester where field efficiency was greater than 80 percent.

Cultivar		BC78		BC79		OP367		PC4	
Number of Loads	n	17		12		18		17	
		mean (standard error)							
Effective Material Capacity (C_m)	Mg h^{-1}	68.3	(2.1)	61.1	(2.7)	61.6	(2.2)	62.7	(1.5)
Effective Field Capacity (C_f)	ha h^{-1}	1.86	(0.17)	1.74	(0.22)	1.44	(0.12)	1.6	(0.13)
Speed	km h^{-1}	4.5	(0.12)	4.2	(0.10)	3.8	(0.14)	4.2	(0.15)
Field Efficiency	96 (0.8)								
Engine Load	%	64	(4.6)	67	(2.8)	65	(3.7)	64	(4.2)
Fuel consumption	L h^{-1}	83	(4.4)	88	(2.6)	85	(4.1)	81	(4.6)
Crop-specific fuel consumption	L Mg^{-1}	1.22	(0.061)	1.46	(0.055)	1.40	(0.077)	1.30	(0.088)

Table 2.Harvester performance for poplar spacing treatments harvested using a single pass cut and chip harvester for loads where field efficiency was greater than 80 percent. Final column are combined low efficiency runs where field efficiency was less than 80%.

Planting Design		Dedicated				Interplanted				Low Efficiency	
Spacing		S6		S12		S6		S12		S6 & S12	
Number of Loads	n	25		10		14		13		16	
		mean (standard error)									
Biomass	Mg ha^{-1}	45.5	(1.01)	42.9	(2.10)	60.9	(2.19)	52.1	(1.99)	37.7	(3.21)
Effective Material Capacity (C_m)	Mg h^{-1}	60.4	(1.09)	58.1	(2.17)	70.7	(1.02)	62.9	(2.17)	32.8	(3.50)
Effective Field Capacity (C_f)	ha h^{-1}	1.29	(0.04)	1.35	(0.04)	1.17	(0.04)	1.22	(0.06)	0.82	(0.13)
Speed	km h^{-1}	4.2	(0.13)	4.4	(0.12)	3.8	(0.12)	4.0	(0.19)	2.7	(0.23)
Field Efficiency		96	(0.1)	94	(0.2)	96	(0.1)	94	(0.2)	53	(5.0)
Engine Load	%	64.9 (2.0)								53	(3.1)
Fuel consumption	L h^{-1}	83.7 (2.09)								70.6	(3.16)
Crop-specific fuel consumption	L Mg^{-1}	1.34(0.039)								2.66	(0.356)

Table 3.Linear model results for poplar spacing trials using a single pass cut and chip harvester for loads with less than 20% in field delays.

	Standing Biomass	Effective Material Capacity (C_m)	Effective Field Capacity (C_f)	Engine Load	Fuel consumption	Crop-specific fuel consumption
	Mg ha^{-1}	Mg h^{-1}	ha h^{-1}	%	Lh^{-1}	lMg^{-1}
Effect		Pr> F				
Interplant (int)	<0.0001	<0.0001	0.0180	0.3676	0.6315	0.2891
Spacing (spc)	0.0026	0.0265	0.1116	0.1544	0.2962	0.0580
Cultivar (cul)	0.0091	0.3515	0.0073	0.7699	0.6273	0.4279
spc*cul	0.6021	0.2455	0.8695	0.9811	0.9928	0.8167
int*spc	0.0109	0.0204	0.9549	0.2189	0.4764	0.6773
int*cul	0.0045	0.2913	0.4152	0.2796	0.3060	0.4728
int*spc*cul	0.1377	0.0409	0.0204	0.7597	0.6407	0.2490

Table 4.Model diagnosticsfor fuel consumption and crop-specific fuel consumption (fresh biomass) based on engine loading for regressions presented in Figure 4.

	Regression models			
Parameter	Fuel consumption (L h^{-1})		Crop-specific fuel consumption (L Mg^{-1})	
	Beta	Pr> |t|	Beta	Pr> |t|
Intercept	-11.80644		0.34621	
Engine Load	1.96523	<0.0001	-0.01158	<0.0001
Engine Load^2	-0.00707	0.0001	0.03241	0.0001
Standing Biomass			-0.0001207	0.0316

Figure Captions

Figure 1. Standing biomass for freshly harvested chips delivered to short term storage based on cultivar (top panel) and spacing (bottom panel) for two planting designs. Harvest losses on the ground (drops) were not monitored.

Figure 2. Sample distribution of engine power (second by second basis) in S6 and S12 spacing illustrating the smoother performance of the harvester in the narrower spacing.

Figure 3. Relationship between standing biomass and effective material capacity for delivered loads above and below 80% efficiency in a poplar stand.

Figure 4. Fuel consumption (L h^{-1}) and crop-specific fuel consumption (L Mg^{-1})for fresh biomass relative to engine loadfor poplar harvested using a single pass cut and chip harvester. For regression models, X_1 = Engine Load as a percent and X_2 = Standing fresh biomass in Mg ha^{-1}.

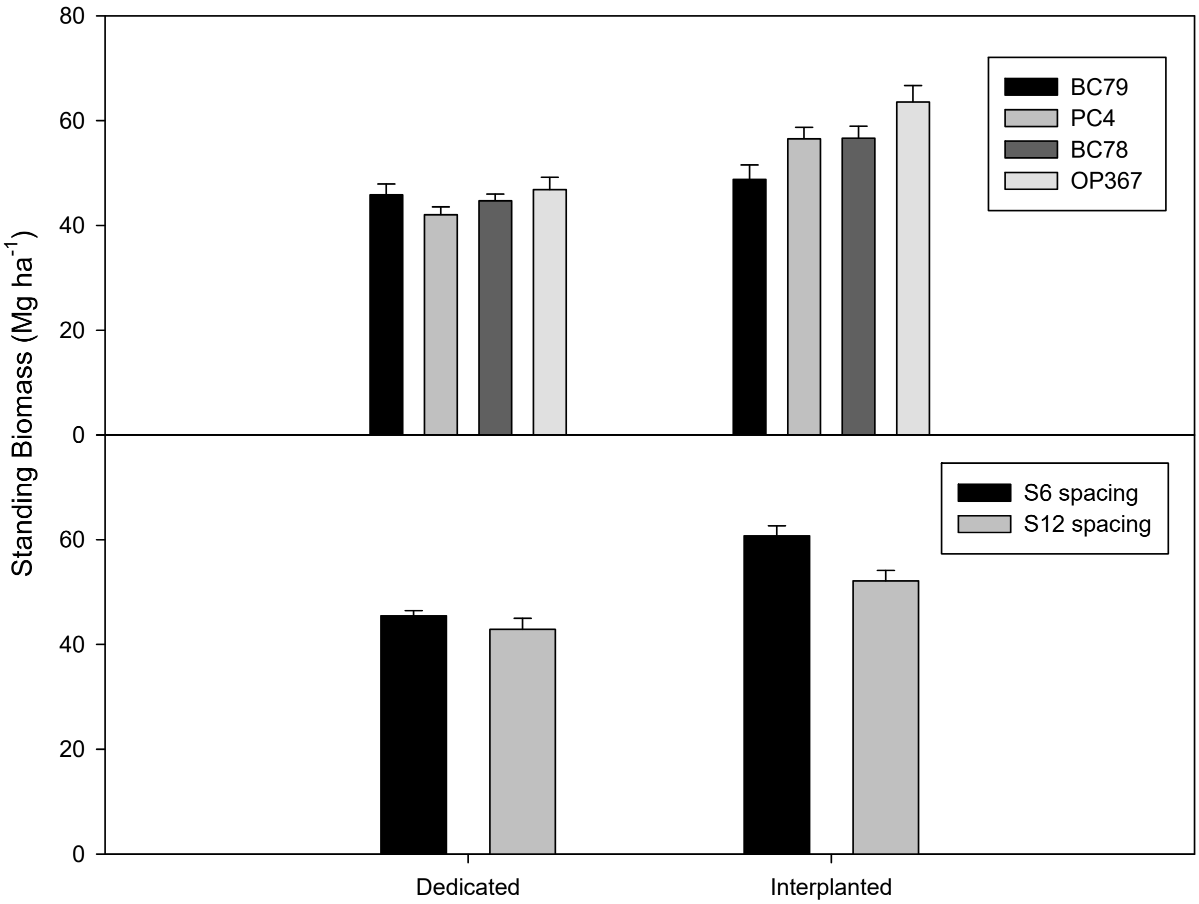

Figure 1. Standing biomass (mean ± standard error) for freshly harvested chips delivered to short term storage based on cultivar (top panel) and spacing (bottom panel) for two planting designs. Harvest losses on the ground (drops) were not monitored.

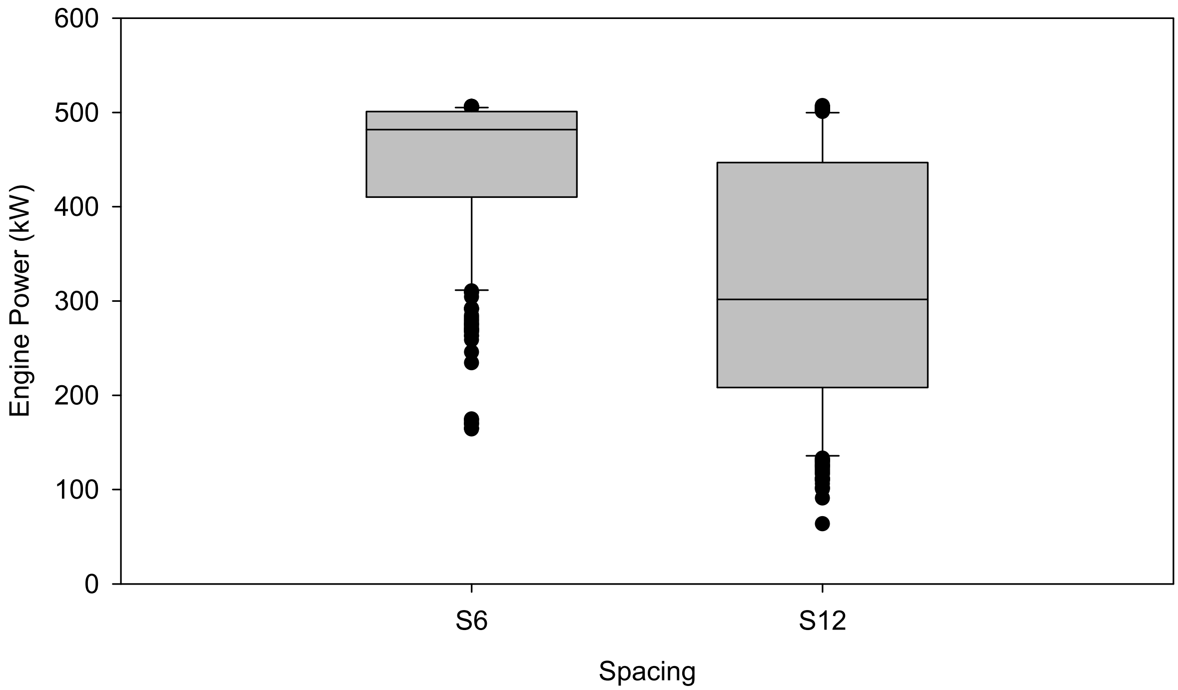

Figure 2. Sample distribution of engine power (second by second basis) in S6 (n=400) and S12 (n=400) spacing illustrating the smoother performance of the harvester in the narrower spacing.

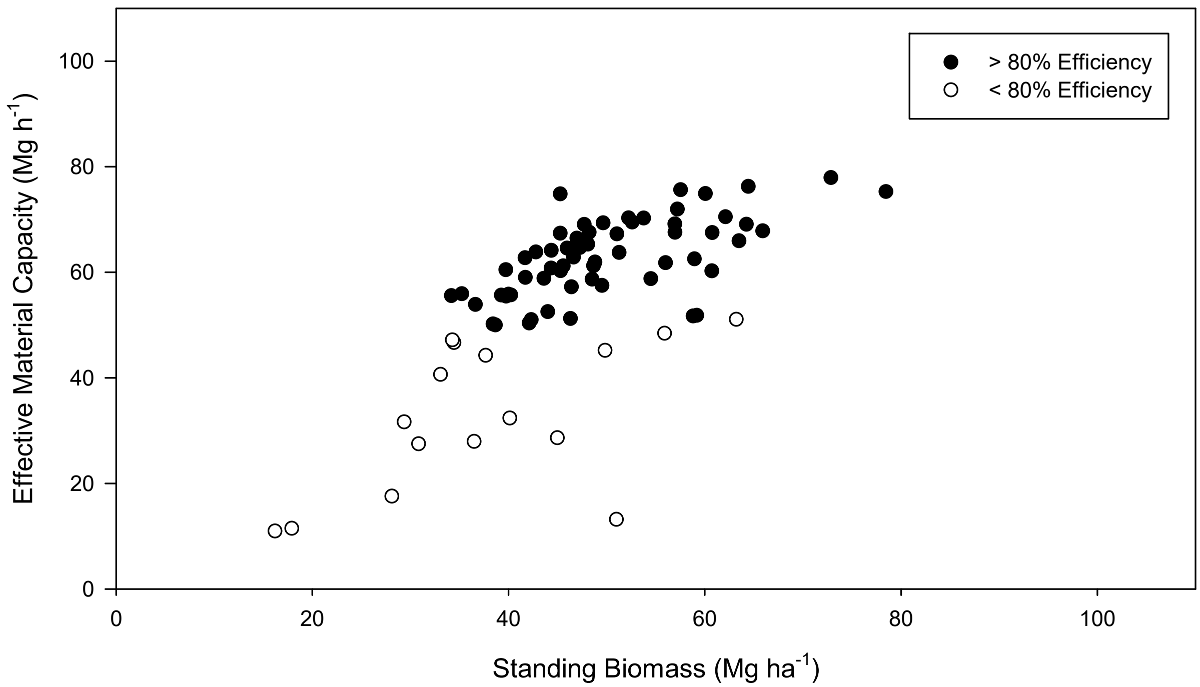

Figure 3. Relationship between standing biomass and effective material capacity for freshly harvested chip loads above and below 80% efficiency in a poplar stand. Harvest losses on the ground (drops) were not monitored.

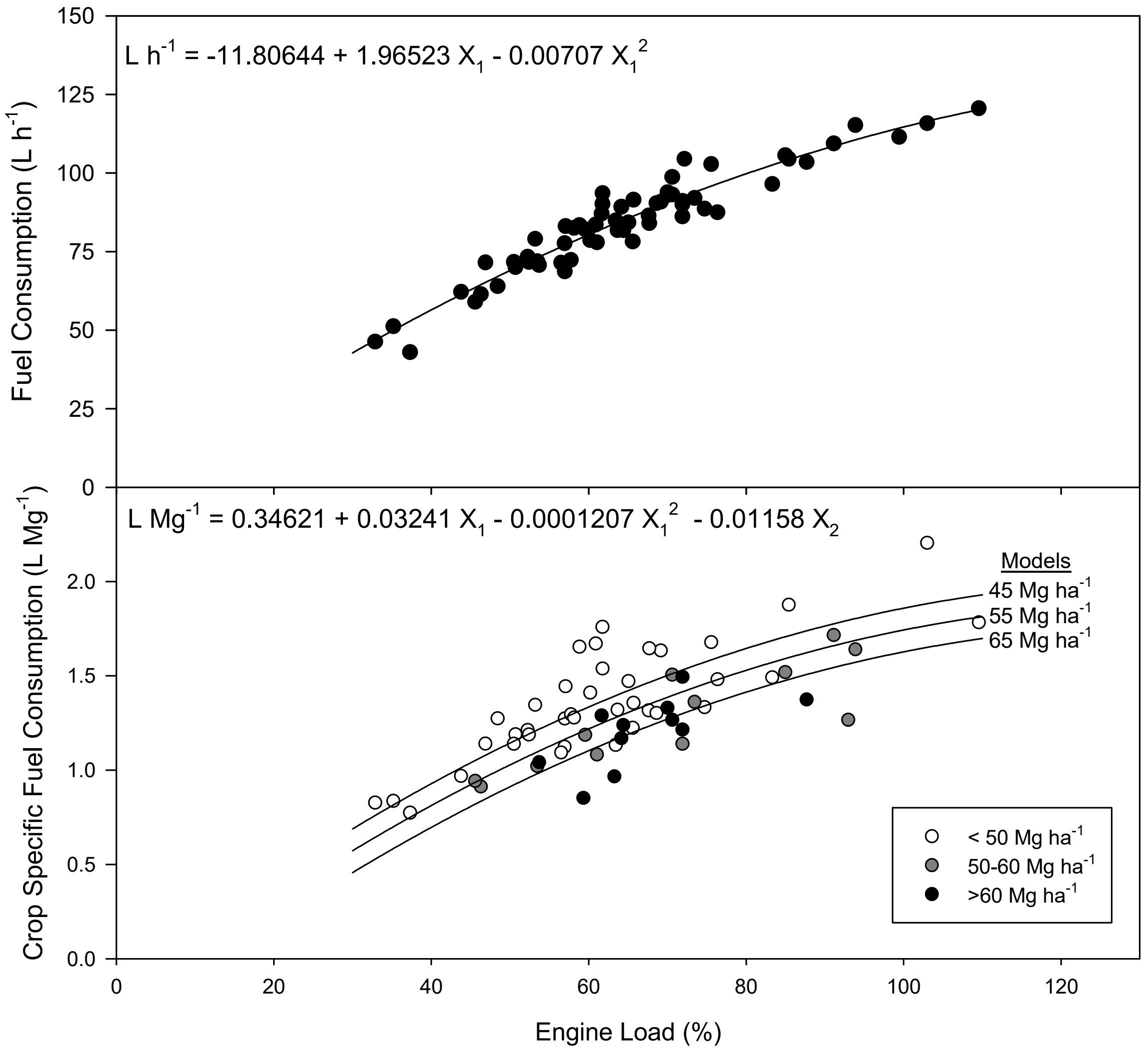

Figure 4. Fuel consumption (L h^{-1}) and crop-specific fuel consumption (L Mg^{-1})for fresh biomass relative to engine loadfor poplar harvested using a single pass cut and chip harvester. For regression models, X_1 = Engine Load as a percent and X_2 = Standing fresh biomass in Mg ha^{-1}.