**Cut-and-chip harvester material capacity and fuel performance on commercial-scale willow fields for varying ground and crop conditions**

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**Abstract**
Shrub willow (*Salix* spp.) is capable of producing commercially attractive amounts of biomass in short rotations, but harvesting costs and logistics remain a concern. There is a particular need for information about harvesting operations on larger, commercial short-rotation woody crop systems. Another recent issue on commercial fields in northern New York is commercial growers conducting harvests during the growing season rather than the recommended dormant season when fields may be too wet to harvest. This study evaluated and modeled the in-field performance of a cut-and-chip harvester for almost 700 wagonloads of chips operating in commercial willow fields in a wider array of crop and field conditions than have been previously reported. Analysis indicated that the time of harvest (leaf-on or leaf-off) and whether site conditions were wet or dry affected the harvester’s material capacity. Mean material capacity was greatest for leaf-off, dry conditions (71.8 Mg/hr) and lowest for leaf-on harvests, which were similar for wet (30.4 Mg/hr) and dry conditions (29.7 Mg/hr). Mean crop specific fuel consumption ranged between 1.3 and 3.3 L/Mg, but can get considerably higher for standing biomasses below 40 Mg/ha. Wet ground conditions and leaf-on harvests tend to decrease material capacity and increase fuel consumption as the harvester has to divert power to forward movement and material processing. Relationships for material capacity and fuel consumption based on standing biomass, time of harvest and ground conditions will be essential for evaluating and modeling the economic and environmental impacts of commercial-scale willow operations.

**KEYWORDS**
fuel consumption, harvesting logistics, leaf-on harvesting, material capacity, short-rotation woody crops, wet-weather harvesting, willow
1 | INTRODUCTION

1.1 | Background

Sources of biomass for energy or bioproducts include forests, short-rotation woody crops (SRWC), herbaceous perennial crops, and other various residue streams (El Bassam, 2010; U.S. Department of Energy, 2016). Projected demand will have to be met by multiple feedstocks; thus, a key challenge will be to create supply systems that deliver large quantities of consistent quality biomass efficiently and cost effectively (U.S. Department of Energy, 2016). Woody biomass in the form of dedicated crops, forest residues, or waste products (e.g., milling and/or construction) could contribute certain benefits such as their availability through much of the year, and generally consistent quality (Volk, Heavey, & Eisenbies, 2016). SRWC, such as shrub willow (Salix spp.) and hybrid poplar (Populus spp.), are being developed in North America and Europe for bioenergy (Mola-Yudego, 2010; Volk et al., 2016) and eucalyptus (Eucalyptus spp.) in other regions (Rockwood, Rudie, Ralph, Zhu, & Winandy, 2008; Sims, Hastings, Schlamadinger, Taylor, & Smith, 2006). SRWC had been scaled up in parts of the United States (Berguson et al., 2010; Owens, Karlen, & Lacey, 2016), and they have the potential to provide ecosystem and environmental benefits in addition to energy production (Rockwood et al., 2004; Volk et al., 2016; Zalesny et al., 2016).

Willow biomass crops are managed using a combination of techniques and knowledge drawn from both agriculture and forestry. Current willow systems use a coppice management system that allows multiple harvests from a single planting of improved shrub willow cultivars; current recommendations suggest every 3–4 years with the crop being replaced after 20–25 years (Abrahamson, Volk, & Smart, 2010). These also typically have higher planting densities and more intensive management than natural or more conventional plantation forest systems in North America. Shrub willow biomass crops may be grown in low or high quality sites, but marginal agricultural land is often chosen due to the limitation of growing other crops. One advantage is the ability to regenerate SRWC as coppice rather than replanting using new stock with each harvest (Dickmann, 2006). The reported range for above-ground yield for short-rotation willow ranges between 8 and 12 Mg ha⁻¹ year⁻¹ of oven dried biomass depending on site characteristics, soil properties, climate, and cultivar, but most yields range between 20 and 100 Mg/ha (Slight et al., 2016).

In spite of the attributed benefits to shrub willow biomass crop systems, their expansion and deployment has been constrained by higher production costs and lower market acceptance (Volk, Castellano, & Abrahamson, 2010). Harvesting is the largest single cost factor for willow biomass comprising about one-third of the final delivered cost; harvesting, handling, and transportation combined account for 45%–60% of its delivered cost (Buchholz & Volk, 2011). Since harvesting costs are so significant, understanding variation is essential for devising and evaluating the type of harvesting systems expected to supply large-scale end users (Griffiths et al., 2019; Kenney, Smith, Gresham, & Westover, 2013).

A number of specialized harvesters exist for SRWC, but systems are still being developed due to the limited scale of SRWC deployment, evolving technology, differing operational scales, management objectives, and need for continued improvement (Vanbeveren et al., 2017; Westover, Howe, & Carpenter, 2016). Currently, systems that cut-and-chip the material in a single operation appear to be the most economical (Ehlert & Pecenka, 2013; Savoie, Herbert, & Robert, 2013, 2014; Van der Meijden & Gigler, 1995) and generate material that is of consistent quality (Eisenbies, Volk, Posselius, Shi, & Patel, 2014). The potential to generate usable chipped material in the field during harvesting operations could complement other woody biomass supply chains because advanced uniform format feedstock systems project significant cost savings if preprocessing steps are performed as close to harvesting and collection steps as possible (Hess, Wright, Kenney, & Searcy, 2009).

Properly matching harvesting equipment to a production system will have a significant impact on the costs and efficiency of a production system (Berhongaray, El Kasmioui, & Ceulemans, 2013; Miao, Shastri, Grift, Hansen, & Ting, 2012). There is a need to understand the sources of uncertainty and variation associated with the different components of harvesting systems (Kenney et al., 2013; Sharma, Ingalls, Jones, & Khanchi, 2013; Stanturf et al., 2019), and applying this knowledge to adequately select, model, or improve these harvesting systems and feedstock supply chains, particularly at commercial scales (Caputo et al., 2014; Crawford et al., 2016; Johnson, Willis, Curtright, Samaras, & Skone, 2011). Modeling based on limited field operations showed that cost reductions can be achieved by consideration of factors such as crop yields, distance to short-term storage, and collection systems (Ebadian et al., 2018); however, the amount of variability that exists suggests opportunities for further improvement.

Eisenbies, Volk, Abrahamson, et al. (2014) hypothesized that the upper bounds of material capacities (C_m) for harvesters relative to standing biomass delivered (BM_D) in short-rotation crops such as willow may be ground, vegetation, or mechanically limited. When standing biomass is low (i.e., <30 or 40 Mg wet/ha), ground conditions permit a maximum speed; thus, material capacity (C_m in Mg/hr) increases linearly with BM_D. Once standing biomass reaches a high enough amount, the harvester’s ability to process material becomes the limiting factor; thus, C_m plateaus. It was additionally hypothesized that C_m and/or harvester efficiency (EFF_H) would fall off once standing biomass exceeded the
mechanical limits of the machine; and further, the pattern would be affected by ground and crop conditions, machine horsepower, operator experience, and other factors. Other related work on harvester performance in willow biomass crops has often been based on relatively small trials over short periods of time (Vanbeveren et al., 2017). The variation caused by different willow crop, field, weather and operational conditions has not been fully explored or captured. This type of information will be of particular interest to management decisions and necessary for modelers working to evaluate logistics and costs of these systems.

1.2 | Justification and objective

As willow and other SRWC systems are scaled up, growers will face situations requiring pragmatic choices about when and where to harvest that may conflict with timing that is biologically optimal. The general recommendation for willow is to harvest in late fall or early winter after leaf fall (Abrahamson et al., 2010; Dimitriou & Rutz, 2015). However, experience in some regions has shown that recommendation can result in only a narrow window of opportunity with unpredictable or inconsistent ground conditions. This is especially true when willow occupies lower quality land with somewhat poorly to very poorly drained soil. In addition, difficulties securing and mobilizing equipment on short notice have caused some commercial growers to start harvesting in the late summer or early fall after leaf fall (Abrahamson et al., 2010; Dimitriou & Rutz, 2015). These being SRWC, stool and stem density are not related to stocking and standing biomass as long as survival is adequate (≈>80%) because other trees fill in.

Should an expanded harvest window become the norm, harvests will be conducted during parts of the growing season and/or under a wider range of crop, ground and weather conditions than has been reflected in previous work. In addition, the size of the harvest window will influence equipment needs and deployments, and ultimately may have biological implications for crop health and regeneration. Although data are available from other trials, most are of a smaller scale and fail to capture the variability necessary for models that can assess the economic and environmental benefits and impacts of commercial-scale systems for biorefineries that may require hundreds or thousands of Mg of feedstock per day. The objective of this study was to conduct a broad evaluation of harvester performance in willow crops (e.g., material capacity, fuel use) at a commercial scale over multiple years and harvests that captures variation in crop and weather conditions.

2 | METHODS

2.1 | Study plan

The study plan for this work entailed collecting harvester performance data from commercial-scale harvests in varied conditions over a period of several years. The key variables of interest are material capacity and crop specific fuel consumption (FC_C; Eisenbies et al., 2017) for independent loads summarized down the row (excluding headlands and activities). For the purposes of this paper, the collection systems (i.e., tractors and wagons, silage trucks etc.) will not be evaluated because the machine types, operators, and were variable which make comparisons difficult. In addition, the number of collection vehicles available was sometimes below the optimum recommended number which may have affected system logistics (Ebadian et al., 2018). Loads were initially categorized using cluster analysis and harvester performance in these resultant groups was evaluated further by employing regression analysis using standing biomass, rainfall, and season as independent variables. Cofactors such as EFF_H were also included where applicable.

2.2 | Sites

Seven commercial-scale willow harvests monitored in New York between 2012 and 2019 representing a wide range of stand and seasonal conditions are included (Table 1). Four sites (‘Auburn’, ‘Groveland’, ‘Solvay’, and ‘Rockview’) consisted of homogeneous plantings of common, commercial willow cultivars (e.g., Canastota, Fish Creek, Millbrook, Oneida, Owego, Owesco, S365, Sherburne, SV1, SX61, SX64, SX67, and Tully Champion); the other sites were non-contiguous, mixed plantings using the same cultivars. For the Auburn and Groveland harvests, sites were planted with a recommended spacing of 0.61 m intervals in 0.76 m wide double rows which were spaced 2.29 m on center as per the recommendations made in Abrahamson et al. (2010); the between row spacing was increased to 2.59 m on center on other sites to better accommodate harvesting equipment. These being SRWC, stool and stem density are not related to stocking and standing biomass as long as survival is adequate (>80%) because other trees fill in.

Data are comprised of a compilation of 694 monitored loads, with 192 machine hours down the row. A load is comprised of the biomass cut by the harvester and blown into a collection vehicle (either truck or wagon) carried to short-term storage or to the end user. Over 4,300 Mg of willow biomass was collected from 110 ha on fields or field sections ranging from 4 to 39 ha. At the sites Auburn (2012), Groveland (2012), Buffalo (2016), Jacobs (2017), and Masons (2017) the primary objective was to manage the
| Site       | Harvest dates | Latitude Longitude  | NCRS soil survey series names (90% of area)                                                                 | Slope classes (%) | Water table (m) | Monitored loads | Monitored biomass (Mg) | Monitored area (ha) | Plantings       | Stem/root age at harvest (year) | Operator | Harvester |
|------------|---------------|---------------------|-------------------------------------------------------------------------------------------------------------|-------------------|-----------------|-----------------|----------------------|-------------------|-----------------|-------------------------------------|----------|----------|
| Auburn, NY | Nov/Dec 2012  | 42°55′11.4″N 76°40′14.7″W | Ovid silt loam (56%) Lakemont silty clay loam (26%) Odessa silt loam (12%) | 0–6              | 0.15 – 0.60     | 81              | 838                  | 19.8              | Cultivar blocks  | 4/5                                 | A        | FR9080   |
| Groveland, NY | Dec 2012 | 42°42′12.8″N 77°44′48.1″W | Conesus silt loam (66%) Appleton silt loam (25%) | 0–8              | 0.15 – 0.60     | 70              | 571                  | 8.7                | Cultivar blocks  | 5/6                                 | A        | FR9080   |
| Buffalo P., NY | Oct 2016 | 44°03′05.8″N 76°16′55.6″W | Kingsbury silty clay (34%) Wilpoint silty clay loam (30%) Chaumont silty clay (29%) | 0–8              | 0.15 – 0.45     | 30              | 188                  | 10.6              | Mixed plantings | 3/4                                 | B        | FR9080   |
| Solvay, NY  | Jan 2017 Jun 2017 | 43°03′57.6″N 76°15′43.0″W | Industrial byproducts of the solvay process and organic amendments (Qiu, 2017) | Poorly drained   | 0.15+            | 64              | 218                  | 3.7                | Cultivar blocks  | 3/4                                 | B        | FR9080   |
| Jacobs, NY  | Sep 2017 Oct 2017 | 44°07′32.8″N 76°18′59.7″W | Kingsbury silty clay (42%) Chaumont silty clay (16%) Covington silty clay (15%) Hudson silt loam (12%) Madalin silt loam (6%) | Moderately well to very poorly drained | 0–8              | 0.15 – 0.45     | 199                  | 1,207             | 27.7             | Mixed plantings | 3/4                                 | B and C  | FR9080 FR9090 |
| Masons, NY  | Oct 2017  | 44°06′44.3″N 76°16′11.0″W | Kingsbury silty clay (48%) Chaumont silty clay (30%) Wilpoint silty clay loam (12%) | Somewhat poorly drained | 0–8              | 0.15 – 0.45     | 142                  | 842               | 28.6             | Mixed plantings | 3/4                                 | B        | FR9080   |
| Rockview, PA | Mar 2019 | 40°51′33.1″N 77°47′47.1″W | Hagerstown silt loam (72%) Hublers silt loam (19%) | Well drained     | 0–8              | 2+              | 108                  | 41                | 10.6             | Cultivar blocks  | 3/7                                 | B        | FR9080   |
| **Total**  |              |                     |                                                              |                   |                 |                 |                      |                   |                 | 694                | 3,905              | 109.7               |
harvests in an operationally realistic way; specifically, rational decisions concerning the time of harvest, workday, personnel, harvesting patterns, type and deployment of support vehicles, weather-dependent decisions, etc. were left to the vested parties (i.e., landowners, growers, and operators) with minimal input from researchers. In the case of the Solvay (2017) and Rockview (2019) sites, the harvest planning accommodated some input from researchers in order to achieve parallel objectives (i.e., harvesting individual cultivars as independent loads, limiting loads to individual rows). An analysis of the 2012 Auburn and Groveland harvest systems is found in Eisenbies, Volk, Abrahamson, et al. (2014); this paper expands on components of that data set and other sites to evaluate questions raised in that initial study as well as report data on fuel usage. There were two principal harvester operators (A, 21.7% of loads; B, 75.3%) used for these harvests, both with hundreds of hours of experience and knowledge harvesting SRWC using this equipment and thousands of hours of forage equipment in general. A capable third operator (C, 3.0% of loads) collected a subset of loads at the Jacobs site in order to evaluate operator effects on the same days, in the same machine, field sections, and conditions.

2.3 Data collection

Operations were conducted as a single-pass, cut-and-chip process using a New Holland FR-9080 (94.8% of loads; approximately 250/75 engine/cutter hours for initial sites, 1,800/1,040 hr at the end of the project) or FR-9090 (5.2%; approximately 3,000/2,000 engine/cutter hours at the Jacobs site) forage harvester equipped with a New Holland 130FB copper header using blades recommended for willow (760 mm diameter, 4 mm thick with 6 mm Stellite™ tips). Material was cut, chipped and blown into locally hired collection vehicles that ranged between generic silage trucks, tractor-drawn dump wagons or carts, and self-propelled dump wagons; these vehicles carried loads anywhere from 3 to 12 Mg of fresh material. The length of cut selected by the operator was the largest setting (‘33-mm’) in order to maximize fuel economy and harvesting rate (Guerra, Oguri, & Spinelli, 2016); this chip size was also preferred by end users of the material. Harvest and collection equipment operations were subsequently monitored using Trimble GPS devices (GeoXM, Geo 7, Juno SB, and Juno 3B series), using the methodology described in Eisenbies et al. (2014, 2017). Both loaded and empty collection vehicles from 694 individual loads were weighed with portable scales (Cardinal Scale Manufacturing Company) or at registered truck scale installations, if available, to obtain the fresh weight of biomass. Biomass weight was coupled with GPS and on-board harvester CAN bus diagnostics data (e.g., position, speed, engine load, engine power, fuel use, header engagement, and biomass estimates) to calculate standing biomass amounts, in-row C_m and in-row fuel use (Table 2). The key variables for the reader to remember that will recur throughout the rest of the paper are BM_D, C_m, aerial fuel consumption (FCA), and FCC. All calculations in this paper are based on a fresh-weight basis as it is the most relevant to the movement of material (Eisenbies, Volk, Posselius, Foster, et al., 2014).

Per-second fuel consumption data from the harvester used to calculate other measures of fuel consumption (fuel consumption rate [FCR], FC_A, and FC_C) were only available from the CAN bus for 303 of 694 loads. However, the time in an active or delayed state was known for all 694 loads. For the 303 loads with full-information, the mean FCR when the harvester was actively cutting and chipping the crop (≥0.64 km/hr) and the mean FCR when the harvester was delayed (<0.64 km/hr) were determined. Thus, indexes of fuel consumption (FCR_i, FCAi, and FCCi) for all 694 loads were calculated as a weighted mean based on time to serve as a surrogate. The adequacy of these indexes is specifically tested in data analysis and reported as results.

Daily rainfall amounts were obtained from the nearest available NOAA weather station provided by the National Centers for Environmental Information, climate data online (Baker, Eisched, & Diaz, 1995). The amounts of precipitation that occurred for multi-day intervals (2 and 5 days) before each load was harvested were determined. Longer antecedent periods were initially considered (up to 30 days), but as a predictive factor, the 2 day rainfall period was chosen because 1 day

| Variable | Units | Source or determination |
|----------|-------|------------------------|
| Material capacity (C_m) | Mg/hr | Load weight fresh biomass (scale), time in crop (GPS) |
| Standing biomass delivered (BM_D) | Mg/ha | Load weight fresh biomass (scale), row length (GPS), row width (distance between row centers) |
| Fuel consumption rate (FC_R) | L/hr | Harvester CAN bus (liters fuel recorded per second), time in crop (GPS) |
| Areal fuel consumption (FC_A) | L/ha | FCA (calculated), time in crop (GPS), row length (GPS), row width (distance between row centers) |
| Crop specific fuel consumption (FC_C) | L/Mg | FCA/BM_D |
| Harvester efficiency (EFF_R) | proportion | Ratio of time working in crop/Total time in crop |

*aBecause each row is harvested discretely effective and theoretical field capacity are the same in these systems (ASABE, 2011).*
rainfall may occur after harvesting operations ended or cause them to cease; the 5 day reflects available long range forecasts.

Season was described using two methods. First, a simple leaf-on/leaf-off designation to indicate season based on tree dormancy. In an attempt to consider whether a continuous representation of season was more useful in the subsequent data analyses described below, a second method using a ‘Julian wave’ calculation that converts Julian dates using a sine function (Equation 1). For the Julian wave, harvests occurring near the summer solstice would approach a value of +1, and harvests approaching the winter solstice would be assigned a value of −1.

\[ JW = \sin \left( \frac{2\pi (264 - J)}{365} \right), \] (1)

where JW is the Julian wave value and J is the Julian date.

2.4 | Data analysis

Statistical analysis occurred in four stages: (a) establish the suitability of FCCi as a surrogate for FCC; (b) conduct a cluster analysis to identify unbiased groups as a basis for developing regression models; (c) conduct regression analysis to model key response variables; and (d) post hoc analyses.

2.4.1 | Evaluation of crop specific fuel consumption index

Establishing a crop specific fuel consumption index (FCCi) as an acceptable surrogate for FCC was accomplished using 303 loads where both FCC and FCCi values were available. A paired t test was used to evaluate whether the difference between FC and FCCi was significantly different than zero (alpha = 0.05) using the TTEST procedure in SAS 9.4. Additionally a zero intercept regression model was used to test whether the slope of FCC versus FCCi was significantly different than 1 (alpha = 0.05) using the REG procedure (SAS Institute, 2009).

2.4.2 | Cluster analysis

Data were initially sorted using a cluster analysis as an unbiased approach to create groups using the CLUSTER procedure in SAS (SAS 9.4). Variables for the clustering included FCCi, BMd, load area (ha), field speed (km/hr), Cm, EFFH, delay counts (number/ha), delay rate (h/ha), cumulative precipitation summed over 2, and 5 days, whether trees were leaf-on or leaf-off, and Julian wave. The ‘single’, ‘average’, ‘complete’ and ‘ward’ methods were assessed; the ward method with the ‘noeigen’, ‘nonorm’, ‘std’, and ‘nosquare’ options was ultimately selected because it yielded results with minimal chaining (SAS Institute, 2009).

As a preview to the results described below, but necessary to frame the regression methods, four categories were identified: leaf-on and leaf-off, combined with wet- and dry-weather. Although leaves were the primary indicator of dormancy, some willow cultivars do not easily shed leaves in fall; in those cases the determination was based on other physiological factors such as leaf color or persistence. While leaf senescence is a readily apparent observation to make, it is difficult to objectively differentiate between ‘wet’ and ‘dry’ weather categories since ground conditions can be affected for many days after a rainfall; rainfall amounts alone were not helpful and/or significant when used as a continuous variable in preliminary models; a logistic regression model for making this determination is described below.

2.4.3 | Regression modeling

Results from the cluster analysis suggested two main groupings based on dormancy (leaf-on and leaf-off), and two secondary groups based on rainfall (wet- and dry-weather); this result guided subsequent regression modeling. Multiple linear regression models were developed to evaluate the effect of leaf and rainfall on Cm and FC Ai at an alpha = 0.05 level (Montogomery, Peck, & Vining, 2001). The full models for each incorporated standing biomass as a continuous variable, and leaf-on/off and rainfall/no-rainfall as categorical values; the Cm model included EFFH (the proportion of time the harvester was actively cutting in the row to the total time in the row; Equations 2 and 3). Four to six candidate models were initially identified using the REG procedure using the correlation coefficient (R²) and the Mallows Cp Statistic as initial selection criteria (Mallows, 1973). Collinearity of main effects was accessed using the variance inflation factor statistic and a threshold of 5.0 (Montogomery et al., 2001).

\[
C_m = \beta_0 + (\beta_1 \cdot \text{Leaf}) + (\beta_2 \cdot \text{Rain}) + (\beta_3 \cdot \text{Leaf} \cdot \text{Rain}) + (\beta_4 \cdot \text{BM}) + (\beta_5 \cdot \text{BM} \cdot \text{Leaf}) + (\beta_6 \cdot \text{BM} \cdot \text{Rain}) + (\beta_7 \cdot \text{BM} \cdot \text{Leaf} \cdot \text{Rain}) + (\beta_8 \cdot \text{BM}^2) + (\beta_9 \cdot \text{BM}^2 \cdot \text{Leaf}) + (\beta_{10} \cdot \text{BM}^2 \cdot \text{Rain}) + (\beta_{11} \cdot \text{BM}^2 \cdot \text{Leaf} \cdot \text{Rain}) + (\beta_{12} \cdot \text{EFF}_H) + (\beta_{13} \cdot \text{EFF}_H \cdot \text{Leaf}) + (\beta_{14} \cdot \text{EFF}_H \cdot \text{Rain}) + (\beta_{15} \cdot \text{EFF}_H \cdot \text{Leaf} \cdot \text{Rain}) + (\beta_{16} \cdot \text{BM} \cdot \text{EFF}_H) + (\beta_{17} \cdot \text{BM}^2 \cdot \text{EFF}_H), \] (2)

\[
FC_{Ai} = \beta_0 + (\beta_1 \cdot \text{Leaf}) + (\beta_2 \cdot \text{Rain}) + (\beta_3 \cdot \text{Leaf} \cdot \text{Rain}) + (\beta_4 \cdot \text{BM}) + (\beta_5 \cdot \text{BM} \cdot \text{Leaf}) + (\beta_6 \cdot \text{BM} \cdot \text{Rain}) + (\beta_7 \cdot \text{BM} \cdot \text{Leaf} \cdot \text{Rain}) + (\beta_8 \cdot \text{BM}^2) + (\beta_9 \cdot \text{BM}^2 \cdot \text{Leaf}) + (\beta_{10} \cdot \text{BM}^2 \cdot \text{Rain}) + (\beta_{11} \cdot \text{BM}^2 \cdot \text{Leaf} \cdot \text{Rain}). \] (3)
where Leaf is the tree dormancy based on leaf fall (1, 0) and Rain is the categorical variable based on cluster analysis (1, 0).

Final model selection from the pool of candidates was conducted in the GLIMMIX procedure (SAS 9.4) using the lowest Akaike information criterion (AIC) and Bayesian information criterion scores as the final criteria to compare the models’ performance. Due to the size ($N = 694$) and variability inherent to this data set, many observations were flagged by outlier and leverage statistics. In addition, there were patterns in the residual plots, but they could not be satisfactorily corrected by the standard Box–Cox transformations (Box & Cox, 1964). Thus, final model coefficients were determined using a weighted least squares approach in the ROBUSTREG procedure and utilizing a least trimmed squares (LTS) estimation method (SAS 9.4; SAS Institute, 2009). $FC_{Ci}$ was finally estimated by dividing the predicted $FC_{Ai}$ result by $BM_{f}$ for that observation (Table 2); this transformation essentially projects a linear result onto a nonlinear surface, but avoids the complexity and assumptions that would be necessary to perform nonlinear modeling approaches (Equation 4).

$$FC_{Ci} = FC_{Ai} \left( \frac{1}{BM} \right) = \left( \frac{L}{ha} \right) \left( \frac{ha}{Mg} \right) = \frac{L}{Mg}, \quad (4)$$

where $L$ is the liters of diesel fuel used down the row (excludes fuel used in headlands).

2.4.4 | Post hoc analyses

Summary statistics for the cluster analysis groups were conducted using the MEANS procedure (SAS 9.4). In addition, mean engine load was modeled using multiple linear regression using biomass and its square as the only regressors (Equation 5). Engine load on the New Holland harvester is expressed as a percent of the recommended engine load. The harvester tolerates engine loads in excess of 100 percent for short periods of time. Engine load is related to fuel consumption (Eisenbies et al., 2017), and it provides additional insight about the use of $FC_{Ci}$ as a surrogate for $FC_{C}$.

$$Engine \ load = \beta_0 + (\beta_1 \cdot BM) + (\beta_2 \cdot BM^2). \quad (5)$$

Harvester efficiency modeled as a beta regression using the GLIMMIX procedure (SAS 9.4) and a logit link function (Equation 6). The relationship shows the general effect of standing biomass, dormancy, and rain on $EFF_{H}$. The purpose of this analysis was to examine the hypotheses stated in Eisenbies, Volk, Abrahamson, et al. (2014) that suggested that harvester performance might be affected by excessive biomass by increasing the incidents of delays as biomass increases.

$$EFF_{H} = \frac{1}{1 + e^{-(\beta_0 + (\beta_1 \cdot BM) + (\beta_2 \cdot Leaf) + (\beta_3 \cdot Rain))}}. \quad (6)$$

Membership in the wet- and dry-weather groups for this data set in this paper was determined by the cluster analysis. In order to generalize the rainfall conditions that would determine group membership for similar sites that typify willow fields, a logistic model was created based on dormancy, and 2 and 5 day rainfall totals (Equation 5). Logistic regression was conducted in the GLIMMIX procedure (SAS 9.4) using a logit link function. Model performance for logistic and beta regressions was accessed using the area under the receiver operating characteristic (ROC) curve (SAS Institute, 2009).

$$Rain \ Group \ Probability = \frac{1}{1 + e^{-(\beta_0 + (\beta_1 \cdot Leaf) + (\beta_2 \cdot pp2) + (\beta_3 \cdot pp5))}}, \quad (7)$$

where $pp2$ is the 2 day rainfall total in mm and $pp5$ is the 5 day rainfall total in mm.

3 | RESULTS AND DISCUSSION

3.1 | Adequacy of $FC_{Ci}$

The mean difference between $FC_{C}$ and $FC_{Ci}$ was 0.025 L/Mg ($s = 0.376$) based on the paired $t$ test for 303 loads and not significantly different from zero ($p = .2432$). The slope estimate from the zero intercept regression model was 0.991 ± 0.013 ($p < .0001; R^2 = .9865$) and not significantly different than 1. The zero intercept model intercepts the 1:1 line and the standard intercept model (slope = 0.85758; intercept = 0.45885) between $FC_{Ci}$ values of 3 and 3.5 L/Mg; this suggests that $FC_{Ci}$ begins to slightly overpredict $FC_{C}$ above that range. Eisenbies et al. (2017) showed that the $FC_{R}$ for this machine is approximately 115 L/hr at 100% engine load, and decreased to about 70 L/hr at engine loads around 50%. In the case of these data there is a significant but variable relationship between standing biomass and engine load ($R^2 = .25$); however, mean engine load is approximately 85% at biomass values of 20 Mg/ha and increases as biomass increases.

While these results may seem unremarkable, the relationships suggest that the $FC_{Ci}$ may slightly overestimate $FC_{C}$ at lower standing biomass (e.g., <20 Mg/ha). By extension, while the indexes of fuel consumption based on time (e.g., $FC_{Ri}$, $FC_{Ai}$, and $FC_{Ci}$) may not be adequate replacements for measured fuel consumption (e.g., $FC_{R}$, $FC_{Ai}$, and $FC_{Ci}$) for individual loads, they are entirely suitable as a long-run surrogate to evaluate fuel consumption in the context of the stated objectives for this paper.

3.2 | Cluster analysis

Results from the cluster analysis identified four main groups based on dormancy (leaf-on, leaf-off) and rainfall (wet, dry)
Overall, leaf-off harvests had higher speeds and $C_m$, utilized less fuel per Mg harvested, and fewer delays. Although there was no chaining, the next level of between-cluster sums of squares was based on less consistent in-group divisions tied to standing biomass, material capacity, and delays. Despite the large N for this data set, there were constraints on the number of coefficients that could be reliably introduced into regression models, particularly due to latent variables and inherent site factors. Thus, subsequent analyses were limited to rainfall and dormancy as they relate to standing biomass and EFFH, which previous work have shown to be important factors in the performance of this system (Eisenbies et al., 2017; Eisenbies, Volk, Posselius, Foster, et al., 2014).

3.3 Material capacity

Regression modeling yielded a model that predicts $C_m$ as function of standing biomass and EFFH, and includes the rainfall and dormancy factors or their interactions (Table 4). As described, this final model was ultimately chosen based on the lowest AIC score, but other candidate models bear little practical difference in terms of their implications. Coefficients for the four combinations of fixed effects based on dormancy and rain conditions for the final model are presented as simplified equation using standing biomass and EFFH as inputs (Equation 8; Table 5; Figure 2).

$$C_m = \beta_0 + (\beta_1 \cdot BM) + (\beta_2 \cdot BM^2) + (\beta_3 \cdot EFFH) + (\beta_4 \cdot BM \cdot EFFH) + (\beta_5 \cdot BM^2 \cdot EFFH). \quad (8)$$

The model broadly indicates that $C_m$ is highest (mean 71.8 Mg/hr; peaking near 80 Mg/hr) when there are no leaves on the willow and when there has been a limited amount of rainfall, which corresponds to ground conditions that are

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**Figure 1** A dendrogram showing the assignment of observations of monitored willow harvesting ($N = 694$) into leaf-on and leaf-off, as well as dry-weather and wet-weather groups from cluster analysis based on methods described in text.
favorable for operating equipment. When there is heavy enough rainfall during the dormant season, there is approximately a 40% reduction in $C_m$ (mean 42.4 Mg/hr). A 2 day rainfall amount in excess of 5 mm is sufficient to increase the risk that ground conditions will impair vehicles and impact the entire operation. During harvesting, the operator must manage the vehicle as it distributes engine power to forward motion, cutting and feeding trees into the header, and processing material through the chipper and blower. When ground conditions are poor, more power is needed for forward motion and less is available for processing material.

Willow crop management guides indicate that harvesting willow during the dormant season (after leaf fall) results in the most vigorous regrowth of the plants, increases the quality of the chips, and greater amounts of nutrients are retained as litter cover (Abrahamson et al., 2010; Dimitriou & Rutz, 2015). However, a large portion of the lower quality land in the northeast US that is available for willow or other energy crops are often poorly

| TABLE 4 | Regression results and significant model components identified for regression models developed to describe harvesting operations with a single-pass cut-and-chip system operating in willow biomass crops |
|----------|----------------------------------------------------------|
|          | Material capacity ($C_m$) | Aerial fuel consumption ($FC_{Ai}$) | Harvester efficiency ($EFF_H$) | Rain group |
| Full model | Equation 2 | Equation 3 | Equation 6 | Equation 7 |
| Final model | Equation 8 | Equation 9 | Equation 10 | Equation 11 |
| ROBUSTREG $R^2$ | .8512 | .7407 |
| Area under ROC curve | 0.1810 | 0.9897 |
| $p$-value (F-value) | $F$-value | $p$-value | $F$-value | $p$-value |
| Leaf | <.0001 | 15.6 | <.0001 |
| Rain | .0301 | 4.7 | <.0001 | 50.5 |
| Leaf*Rain | <.0001 | 232.1 | <.0001 | 54.8 |
| $BM_D$ | <.0001 | 33.6 | <.0001 | <.0001 |
| $BM_D$*Leaf | <.0001 | 83.2 | <.0001 | 32.7 |
| $BM_D$*Rain | .0036 | 8.56 | .0193 | 5.5 |
| $BM_D$*Leaf*Rain | | | |
| $BM_D^2$ | | |
| $BM_D^2$*Leaf | <.0001 | 28.2 | |
| $BM_D^2$*Rain | | |
| $BM_D^2$*Leaf*Rain | | |
| $EFF_H$ | | |
| $EFF_H$*Leaf | <.0001 | 33.78 | |
| $EFF_H$*Rain | .0125 | 6.28 | |
| $EFF_H$*Leaf*Rain | | |
| $BM_D$*EFF_H | <.0001 | 328.6 | |
| $BM_D^2$*EFF_H | <.0001 | 87.9 | |
| $pp^2$ | | <.0001 |
| $pp^5$ | | <.0001 |

ROC, receiver operating characteristic.

| TABLE 5 | Combined regression betas for use with Equation 8 to predict material capacity ($C_m$) of a single-pass cut-and-chip harvester operating in willow biomass crops in different seasons and under different precipitation conditions |
|----------|----------------------------------------------------------|
|          | $\beta_0$ | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $\beta_5$ |
| Leaf-off | | | | | | |
| Dry-weather | 21.2756 | 0 | 0 | 0 | 1.5548 | -0.0098 |
| Wet-weather | 35.8646 | -0.1690 | 0 | -31.0962 | 1.5548 | -0.0098 |
| Leaf-on | | | | | | |
| Dry-weather | 21.2756 | -0.7223 | 0.0051 | -14.4187 | 1.5548 | -0.0098 |
| Wet-weather | 51.7320 | -0.8913 | 0.0051 | -45.5149 | 1.5548 | -0.0098 |
drained (Stoof et al., 2015), and are difficult to access with harvesting equipment if the ground does not freeze in winter. As a result, landowners are intentionally harvesting willow in the late summer and early fall while willow still retains its foliage. Peak predicted Cm drop from approximately 80 to 40 Mg/hr when harvesting occurs with leaves on compared to leaf-off in good ground conditions; suggesting that leaf-on harvests are as or possibly more impactful on Cm as wet ground. In the case of wet ground, peak predicted Cm drops from approximately 55 to 30 Mg/hr between leaf-off and leaf-on harvests. A small group of loads can also be observed to deviate from the model line for the leaf-on, wet-weather. These observations were identified as leverage points during model development and given less weight by the weighted least squares procedures utilized used for the final model. The specific group of loads were related to a malfunctioning turbo unit on the harvester that affected performance. However, the observed separation only seemed to manifest on the leaf-on wet-weather loads, but not the leaf-on dry-weather loads. The flow of material into the throat of the harvester after it is cut is generally more variable and slower than for leaf-on material, which results in lower ground speeds so that flow of material is maintained and jams are minimized. Harvester operators describe leaf-on material as ‘heavy’, ‘sticky’, and ‘similar to that of alfalfa’, which can be felt in the machine as the blower draws more power from the engine. This is opposed to leaf-off materials which are ‘like corn silage’ and easier for the forage harvester to feed into the harvester, chip and blow into collection vehicles. Moisture content in the leaf-on material was 52.5%–57.1% compared to leaf-off material which was 44.4%–45% (Table 3).

Overall, harvests that have occurred since 2012 confirm the hypothesis made about Cm by Eisenbies, Volk, Abrahamson, et al. (2014); specifically, that Cm increases with standing biomass and plateaus, the plateau varies based on crop and weather conditions (Figure 2). What is less apparent is the distinct chine that was observed in the previous work. Studies that include willow, poplar, eucalyptus have also suggested that the transition from ground-limited to crop-limited Cm may not be as abrupt as was previously suggested (Eisenbies et al., 2017; Guerra et al., 2016; Vanbeveren et al., 2017). The data in this study cover a wider range of willow crops in terms of standing biomass, stem density, stem diameter and height and cultivars; the review by Vanbeveren et al. (2017) describes cut-and-chip harvesting for 26 willow studies with a median study area of 2 ha. In the case of this work data are obtained from a number of different locations where ground conditions vary and the operators of tractors and wagons to collect the chips had different amounts of experience working in willow crops. Most of the sites were harvested on fine-textured, frozen or unfrozen ground with somewhat or poorly drained soils (Table 1). All of these factors contributed to the scatter of the data and the less defined break in the Cm as standing biomass increases.

3.4 | Crop specific fuel consumption

Several significant candidate models were identified that predict FC_{AI} as function of standing biomass and include the rainfall and dormancy factors or their interactions with the final model being selected based on the lowest AIC score (Table 4). As with Cm, the candidate models bear little practical difference from each other in terms of their implications. The final model’s betas for the four combinations of fixed effects based on dormancy and rain conditions are presented in as simplified
equation using standing biomass as a continuous variables; as previously described, results for $FCA_i$ were scaled to an $FC_{Ci}$ basis using $BM_D$ (Equation 9; Table 6; Figure 3).

This study showed that mean crop specific fuel consumption ranged between 1.3 and 3.3 L/Mg (Table 3), but can be higher for individual loads if conditions are suboptimal or there is low biomass (Figure 3). Congruent with the results for $C_m$, the harvesters were most fuel efficient in stands that were harvested leaf-off in dry-weather with a mean $FC_C$ of 1.3 L/Mg (Table 3). Harvesting with leaves or in wet-weather increased mean fuel consumption and the patterns were higher especially for low harvested biomass load and were more variable (Figure 3). In all cases, mean $FC_{Ci}$ approaches a minimum that lies approximately between 1 and 2.5 L/Mg once standing biomass exceeds 40 Mg/ha.

Previous work in SRWC suggested that $FC_C$ ranges between 1.2 and 2.2 L/Mg, but in each of these cases the field conditions were consistent and quite good and the areas harvested relatively small (Eisenbies et al., 2017; Guerra et al., 2016). All observations for SRWC appear higher than those for common agricultural silage which may range between 0.45 and 1.2 L/Mg (Downs & Hansen, 1998; Ramos, Lanzas, Lyra, & Sandi, 2016; Wild & Walther, 2011). Fuel use for these machines is relative to engine load (Eisenbies et al., 2017; Guerra et al., 2016; Špokas & Steponavi, 2009). Harvester operators maximize engine load while balancing harvester speed, $C_m$, and other factors. Since engine load drops off less rapidly than $C_m$ in stands with low biomass (Figure 3), more fuel is expected to be required per Mg of material processed. Ultimately these results suggest that when conditions are optimal (leaf-off, dry-weather), harvesters will likely run more consistently and fuel consumption will better align with results from previous studies. When conditions are suboptimal (leaf-on and/or wet-weather), compounded by decreased standing biomass, harvester performance and fuel consumption may be impacted by several factors.

$$FC_{Ci} = FCA_i \left( \frac{1}{RM} \right) = \beta_0 + (\beta_1 \cdot BM) + (\beta_2 \cdot BM^2), \quad (9)$$

### Table 6
Combined regression betas for use with Equation 9 to predict areal fuel consumption ($FCA_i$) and crop specific fuel consumption ($FC_{Ci}$) for a single-pass cut-and-chip harvester operating in willow biomass crops

|       | $\beta_0$ | $\beta_1$ | $\beta_2$ |
|-------|-----------|-----------|-----------|
| Leaf-off |           |           |           |
| Dry-weather | 20.8959   | 0.8582    | 0         |
| Wet-weather | 59.1828   | 0.4842    | 0         |
| Leaf-on |           |           |           |
| Dry-weather | 64.1803   | 1.1559    | 0.0006    |
| Wet-weather | 67.2424   | 0.7819    | 0.0006    |

3.5 | Harvester efficiency

Harvester efficiency was a factor that affected material capacity as shown in previous sections. The area under the ROC curve for the beta regression model developed did not indicate a strong fit (ROC = 0.1810; SAS Institute, 2009), and as evidenced by the distribution of low-efficiency loads (Figure 4). However, overall the incidence of low-efficiency loads...
loads increases as biomass increases, and $\text{EFF}_H$ is negatively correlated to increasing $BMD$ (Equation 10; Figure 4). Willow dormancy and ground conditions were also significant components of the model, but there does not appear to be a great deal of practical significance between them with regards to the regressions due to the weak fit.

The proportion of loads with in-field $\text{EFF}_H$ values exceeding 0.8 were 0.99 for leaf-off, dry-weather, 0.93 for leaf-off, wet-weather, 0.86 for leaf-on, dry-weather, and 0.77 for leaf-on, wet-weather. Concurrently in-field delays were also longer on average for leaf-on and wet-weather harvests. Excluding excessive delays (>10 min), the mean in-field delay for leaf-off, dry- and wet-weather loads was 33 and 96 s respectively, while the delay for leaf-on, dry- and wet-weather loads was 75 and 107 s. Finally, the duration of excessive in-field delays was significantly greater for wet-weather harvests (29.8 min) compared to dry-weather harvests (15.4 min). Thus, the impact of leaf-on and wet-weather harvesting appears to increase the number and length of delays.

Reasons for work stoppages during in-field operations may include blockages of stems and plant material flowing into the header’s feed rolls, activation of the automatic metal detection system which protects the chipping blades, maintenance that requires immediate attention to prevent damage to the harvester, waiting for collection vehicles in the field, phone calls, etc. A more comprehensive examination of harvester delays, their cause and distribution, are being prepared in a separate study and are beyond the scope of this paper.

$$\text{EFF}_H = \frac{1}{1 + e^{-(2.8699 + (-0.01018 \cdot BMD) + (-0.2314 \cdot \text{Leaf}) + (-0.3286 \cdot \text{Rain})}}} \quad (10)$$

### 3.6 Rainfall group

Given that the $C_m$ and $FC_{C_l}$ models utilize a categorical variable for rainfall and ground conditions, a model is needed characterize these groups in order to extend these results to other data or incorporate them in simulation models. Probability of membership to each rainfall group was significantly influenced by a combination of 2 and 5 day rainfall amounts, and willow dormancy (Equation 11, Figure 5). All model components had $p < .0001$ and the area under the ROC curve was 0.98, suggesting a strong fit (Table 4; SAS Institute, 2009); thus this model is very efficient in discriminating between wet and dry conditions in these data.

For leaf-off harvests, as long as these sites were free of precipitation for at least 5 days prior to operations the probability is greater than 0.5 that they will fall into the dry-weather category. Additionally, if conditions had been dry for at 3–5 days prior to operations, these sites were more tolerant to precipitation of approximately 5 mm within the previous 2 days. Based on these observations, rainfalls exceeding approximately 10 mm at any time within the past 5 days were likely sufficient to tip the probability toward a wet-weather classification.

Leaf-on harvests were more tolerant of rainfall due to evapotranspiration. If cumulative precipitation did not exceed approximately 25 mm over 5 days, the probability of being classified as a wet-weather harvest does not exceed 0.5 (Figure 5). Transpiration rates for willow are considerably higher than other woody species, and can often exceed 3–10 mm per day during wet periods in the growing season depending also on site and management variables (Frédette, Labrecque, Comeau, & Brisson, 2019; Mirck & Volk, 2009). It may be argued that time periods exceeding
5 days or increased resolution could be useful for classifying loads based on wetness, but in terms of predicting when harvest windows might open for active harvests, forecasts beyond 5 days may not be considered actionable by operators. This is a complicated question with many decision factors that are beyond the scope of the data collected. However, a considerable amount of variability likely exists among appropriate sites with regard to the degree antecedent moisture conditions affecting harvesting operations because of factors such as soil types, drainage, slope, aspect, previous land use compaction etc.

Rain Group Probability

\[
\text{Rain Group Probability} = \frac{1}{1 + e^{-(-2.9596 + (-13.2492 \text{ Leaf}) + (0.4279 \times \text{pp}^2) + (0.4968 \times \text{pp}^5)}}}. \tag{11}
\]

3.7 | Uncertainty and sources of variation

The objective of this work was to examine data from willow harvests across a range of crop conditions and sites in order to draw insights about factors that impact harvesting operations. It is understood that there are or may be latent factors associated with the loads in this study that could explain additional variation: multiple sites, multiple operators, two machines, different collection systems and those operators, differing crop layouts, and other attributes. Unfortunately, the dynamics of commercial-scale harvests are such that these effects are difficult to control and it was our intention to collect data from harvests where operators were making the key decisions about how to proceed with minimal interference. A brief discussion of potential factors is necessary and helpful in guiding future research and analyses.

An obvious concern with these results are the possible performance differences among operators. There is no way to compare the two most experienced operators (A and B) because they worked on different sites and in harvesting seasons. They were both considerably experienced harvesting willow, each with hundreds of hours cutting this crop, but each had different operating styles. There are almost no observations where the crop, ground, weather and soil conditions were known to be similar enough to make a defendable comparison. They were both capable of achieving \(C_m\) above 60 Mg/hr, but operator A had the benefit of running almost exclusively in excellent ground conditions. Additionally, operator B had maintenance and repair duties that may have influenced his tendency not to push the equipment’s limits. A limited number of observations \((N = 34)\) were available for operators B and C on the same site, on the same days, in the same sub fields, using the same machine; C being the less-experienced operator. Operator B harvested 15 loads with a mean \(C_m\) of 40.4 Mg/hr, and operator C harvested 19 loads with a mean \(C_m\) of 33.4 Mg/hr \((p < .0001)\); BMd was not a significant covariate \((p = .4441)\) because these loads were collected on stands with a mean standing biomass of 55.8 Mg/ha \((SD = 13.5)\), which is in the range where \(C_m\) tends to plateau. Thus, a decrease in \(C_m\) associated with a less-experienced operator appears to have been around 15% based on these limited observations.

A loss of boost pressure between one of the turbos and intercooler on the FR9080 harvester was discovered after 18 September 2019, but before the last two harvesting days in October, resulting in diminished horsepower. This issue certainly affected the harvests at the higher-biomass Jacobs site \((x = 49.8\text{ Mg/ha})\) and lower-biomass Masons site \((x = 31.8\text{ Mg/ha})\), but it is unknown precisely how long before the discovery that the engine was impaired and whether it had affected earlier willow harvests. However, it also true that the impairment only caused a noticeable group of observations above the modeled mean in wet-weather observations and was not evident in the dry-weather observations at the same harvest location (Figure 2). This suggests that the combination of issues (e.g., wet ground and low horsepower) magnifies impacts. The effect of the broken turbo was 3.5 Mg/hr overall \((p < .0001)\) with standing biomass as a significant covariate. However, standing biomass was considerably more influential than the turbo status \((F\text{-value} \ 101.3 \text{ versus} \ 21.1)\).
The final concern was the possible difference between the loads generated by the FR9080 and the small number of loads produced by the FR9090. A comparison of these two machines occurred on a limited number of loads on the same days with the same operator (B) in the same field sections on the Jacobs site. There was no significant difference in $C_m$ (34.2 Mg/hr) between the harvester models ($p = .1379$) when standing biomass was used as a covariate ($p < .0001$).

### 4 | CONCLUSIONS

The objective of this study was to conduct an evaluation of a large data set of harvester performance in willow biomass crops (e.g., material capacity, fuel use) at a commercial scale over multiple years and harvests capturing varied crop and weather conditions. Factors including standing biomass, presence or absence of leaves, recent rainfall as an indicator of ground conditions, and $\text{EFF}_H$ all impact material capacity and fuel consumption. The extent of this data set also captures the variability that occurs with different operators and equipment. The equations developed for material capacity and fuel consumption are an important improvement in understanding the dynamics associated with harvesting willow biomass crops and will be useful in assessments of economic and environmental impacts of these systems.

Overall, these results show that harvests in stands greater than 30 or 40 Mg/ha with leaf-off material on ideal ground result in the highest $C_m$ (>60 Mg/hr) and best fuel efficiency for the harvester (1.3 L/Mg). Harvesting in low-biomass stands and when conditions are not optimal (e.g., foliage present or during wet field conditions) resulted in degraded material capacity and fuel consumption. Wet ground and harvesting during the growing season when leaves are still on the willow both tend to reduce material capacity by approximately 30%–50% and/or increase variability. Fuel use increases exponentially in low-biomass stands, in this case stands below 30 Mg/ha. The simple explanation is that the fixed amount of power available to the harvester must be allocated to forward motion while cutting and processing material; rainfall and leaf-on material appear to decrease the amount of power available to for chipping and blowing the material into collection vehicles. This study also suggests that the harvest system studied may become more limited where standing biomass exceeds the range observed as evidenced by the trend where $\text{EFF}_H$ decreases with increased standing biomass. There remain many unknowns for how this system functions in stands with biomass greater than 80–100 Mg/ha.

This study confirms previous work that contended that harvester performance is tied to standing biomass, ground conditions, operator effects, and machine effects to a limited extent. However, it also seems to contradict previous conclusions in willow that the transition between ground-limited and crop-limited harvester performance was more abrupt. It also provides better context with observations for harvester performance from a wide array of small-scale studies from around the world.

In the past, recommendations were to harvest these sites after leaf fall on dry or frozen ground conditions. In recent years, winter conditions in the northeast United States have changed and the ground often does not freeze. As a result, commercial growers cannot rely on a long, dormant harvesting window in which to conduct their work. In practice, commercial growers have chosen to expand the windows when they harvest to include late summer and fall when leaves are still on the trees to take advantage of better ground conditions. These results are of crucial importance to scaling up these systems where managers and modelers will need to consider a wider array of weather and crop conditions in harvest planning. There will be trade-offs coming out of the necessity of operating in non-ideal conditions. As these harvesting systems remain in development, improvements to current equipment or methods are still needed. Systems or approaches that are more tolerant of non-ideal ground conditions and leaf-on material would be beneficial from a logistical and biological perspective.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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