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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 h^{-1}) and lowest for leaf-on harvests, which were similar for wet (30.4 Mg h^{-1}) and dry conditions (29.7 Mg h^{-1}). Mean crop specific fuel consumption ranged between 1.3 and 3.3 L Mg^{-1}, but can get considerably higher for standing biomasses below 40 Mg ha^{-1}. 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: Short Rotation Woody Crops; Willow; Harvesting Logistics; Material Capacity; Fuel Consumption; Wet weather harvesting; Leaf-on harvesting

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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 et al., 2016). Short rotation woody crops (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, Heavey, & Eisenbies, 2016) and eucalyptus (*Eucalyptus* spp) in other regions (D. 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 (D. L. 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 low or high quality sites, but marginal agricultural land is often chosen due to the limitations 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} $yr^{-1}$of oven dried biomass depending on site characteristics, soil properties, climate, and cultivar, but most yields range between 20 and 100 Mg ha^{-1} (Sleight et al., 2016).

In spite of the attributed benefits to shrub willow biomass crops 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 accounts 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 (M. H. 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 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^{-1}), ground conditions permit a maximum speed; thus, material capacity (C_m in Mg h^{-1}) 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 have 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 (M. H. Eisenbies, Volk, Therasme, & Hallen, 2019; Therasme, Eisenbies, & Volk, 2019). In other words, they are placing more importance on ground conditions and being able to complete harvests than on concerns about potential impacts of harvesting during the growing season. The economic and biological outcome of these choices remains an open question that requires additional fundamental data to evaluate their potential (Griffiths et al., 2019).

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 is available from other trials, most are of a smaller scale and fail to capture the variability necessary to for models that can assess the economic and environmental benefits and impacts of commercial scale systems for biorefineries that may requires hundreds or thousands of Mg of feedstock per day. The objective of this study is 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 (M. H. Eisenbies et al., 2017) for independent loads summarized down the row (excluding headland turns 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 harvester efficiency 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 was 0.61-m intervals in 0.76-m wide double rows which were spaced 2.29-m on center 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 short rotation woody crops, 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 is 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 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. land-owners, 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 are found in Eisenbies 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 in 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 hours 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 coppice 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 (2017; 2014). Both loaded and empty collection vehicles from 694 individual loads were weighed with portable scales (Cardinal Scale Manufacturing Company, Webb City, MO) 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 material capacities, 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 standing biomass delivered (BM_D), material capacity (C_m), aerial fuel consumption (FC_A), and crop specific fuel consumption (FC_C). All calculations in this paper are based on a fresh-weight basis as it is the most relevant to the movement of material (M. H. 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 (FC_R), aerial fuel consumption (FC_A), and crop specific fuel consumption (FC_C)) were only available from the CAN bus for 303 of 694 loads. However, the time in an active or delayed state were known for all 694 loads. For the 303 loads with full-information, the mean FC_R when the harvester was actively cutting and chipping the crop (≥ 0.64 km h^{-1}) and the mean FC_R when the harvester was delayed (<0.64 km h^{-1}) were determined. Thus, indexes of fuel consumption (FC_{Ri}, FC_{Ai}, and FC_{Ci}) 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 (CB Baker, Eischeid, & 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 two-day rainfall period was chosen because one-day rainfall may occur after harvesting operations ended or cause them to cease; the five-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.

Equation 1:

$$\mathrm{JW} = \sin\left(\frac{2\pi(264 - J)}{365}\right)$$

Where: JW = Julian Wave value

J = Julian Date

2.4. Data analysis

Statistical analysis occurred in four stages: (1) establish the suitability of FC_{Ci} as a surrogate for FC_C; (2) conduct a cluster analysis to identify unbiased groups as a basis for developing regression models; (3) conduct regression analysis to model key response variables; and (4) post hoc analyses.

2.4.1. Evaluation of Crop Specific Fuel Consumption Index (FC_{Ci})

Establishing a crop specific fuel consumption index (FC_{Ci}) as an acceptable surrogate for FC_C was accomplished using 303 loads where both FC_C and FC_{Ci} values were available. A paired t-test was used to evaluate whether the difference between FC_C and FC_{Ci} 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 FC_C vs FC_{Ci} was significantly different than 1 (alpha=0.05) using the REG procedure (SAS 9.4).

2.4.2. Cluster Analysis

Data was 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 FC_{Ci}, BM_D, load area (ha), field speed (km h^{-1}), C_m, EFF_H, delay counts (number ha^{-1}), delay rate (h ha^{-1}), cumulative precipitation summed over 2, and 5 days, whether trees were leaf-on or -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 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 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 C_m 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 C_m model included harvester efficiency (EFF_H; 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 (R^2) and the Mallows Cp Statistic as initial selection criteria (Mallows, 1973). Colinearity of main effects was accessed using the Variance Inflation Factor statistic and a threshold of 5.0 (Montogomery, Peck, & Vining, 2001).

Equation 2:

$$\begin{aligned} C_m = \beta_0 &+ (\beta_1 \cdot Leaf) + (\beta_2 \cdot Rain) + (\beta_3 \cdot Leaf \cdot Rain) + (\beta_4 \cdot BM) + (\beta_5 \cdot BM \cdot Leaf) \\ &+ (\beta_6 \cdot BM \cdot Rain) + (\beta_7 \cdot BM \cdot Leaf \cdot Rain) + (\beta_8 \cdot BM^2) + (\beta_9 \cdot BM^2 \cdot Leaf) \\ &+ (\beta_{10} \cdot BM^2 \cdot Rain) + (\beta_{11} \cdot BM^2 \cdot Leaf \cdot Rain) + (\beta_{12} \cdot EFF_H) \\ &+ (\beta_{13} \cdot EFF_H \cdot Leaf) + (\beta_{14} \cdot EFF_H \cdot Rain) + (\beta_{15} \cdot EFF_H \cdot Leaf \cdot Rain) \\ &+ (\beta_{16} \cdot BM \cdot EFF_H) + (\beta_{17} \cdot BM^2 \cdot EFF_H) \end{aligned}$$

Equation 3:

$$\begin{aligned} FC_{Ai} = \beta_0 &+ (\beta_1 \cdot Leaf) + (\beta_2 \cdot Rain) + (\beta_3 \cdot Leaf \cdot Rain) + (\beta_4 \cdot BM) + (\beta_5 \cdot BM \cdot Leaf) \\ &+ (\beta_6 \cdot BM \cdot Rain) + (\beta_7 \cdot BM \cdot Leaf \cdot Rain) + (\beta_8 \cdot BM^2) + (\beta_9 \cdot BM^2 \cdot Leaf) \\ &+ (\beta_{10} \cdot BM^2 \cdot Rain) + (\beta_{11} \cdot BM^2 \cdot Leaf \cdot Rain) \end{aligned}$$

Where

Leaf = Tree dormancy based on leaf fall (1,0)

Rain = 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 AIC and BIC 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_D 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).

Equation 4:

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

Where:

L = 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 (M. H. Eisenbies et al., 2017), and it provides additional insight about the use of FC_{Ci} as a surrogate for FC_C.

Equation 5:

$$Engine\ Load = \beta_0 + (\beta_1 \cdot BM) + (\ \beta_2 \cdot BM^2)$$

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 harvester efficiency. The purpose of this analysis is to examine the hypotheses stated in Eisenbies et al. (2014) that suggested that harvester performance might be affected by excessive biomass by increasing the incidents of delays as biomass increases.

Equation 6:

$$EFF_H = \frac{1}{1 + e^{-(\beta_0 + (\beta_1 \cdot BM) + (\ \beta_2 \cdot Leaf) + (\beta_3 \cdot Rain))}}$$

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 were accessed using the area under the ROC curve (SAS Institute, 2009).

Equation 7:

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

Where:

pp2 = 2-day rainfall total in mm

pp5 = 5-day rainfall total in mm

3. Results and Discussion

3.1. Adequacy of Crop Specific Fuel Consumption Index (FC_{Ci})

The mean difference between FC_C and FC_{Ci} was 0.025 L Mg^{-1} (s=0.376) based on the paired t-test for 303 loads and not significantly different from zero (P=0.2432). The slope estimate from the zero intercept regression model was 0.991±0.013 (P<0.0001; R^2=0.9865) 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^{-1}; this suggests that FC_{Ci} begins to slightly over predict FC_C above that range. Eisenbies et al. (2017) showed that FC_R for this machine is approximately 115 L h^{-1} at 100% engine load, and decreased to about 70 L h^{-1} 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=0.25); however, mean engine load is approximately 85% at biomass values of 20 Mg ha^{-1} and increases as biomass increases.

While these results may seem unremarkable, the relationships suggest that the FC_{Ci} may slightly over-estimate FC_C at lower standing biomass (e.g. < 20 Mg ha^{-1}). 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_A, and FC_C) 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) and (Figure 1, Table 3). Overall, leaf-off harvests had higher speeds and material capacities, 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 harvester efficiency, which previous work have shown to be important factors in the performance of this system (M. H. Eisenbies et al., 2017; M. H. Eisenbies, Volk, Posselius, Foster, et al., 2014).

3.3. Material Capacity (C_m)

Regression modeling yielded a model that predicts C_m as function of standing biomass and harvester efficiency, 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. The final model's betas for the four combinations of fixed effects based on dormancy and rain conditions are presented as simplified equation using standing biomass and harvester efficiency as inputs (Equation 8; Table 5; Figure 2).

Equation 8:

$$C_m = \beta_0 + (\beta_1 \cdot BM) + (\beta_2 \cdot BM^2) + (\beta_3 \cdot EFF_H) + (\beta_4 \cdot BM \cdot EFF_H) + (\beta_5 \cdot BM^2 \cdot EFF_H)$$

The model broadly indicates that C_m is highest (mean 71.8 Mg h^{-1}; peaking near 80 Mg h^{-1}) 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 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 h^{-1}). 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 drained (Stoof et al., 2015), which are difficult to access in the winter if the ground does not freeze. As a result, landowners are intentionally harvesting willow in the late summer and early fall while willow still retains it foliage.

Peak predicted material capacities (C_m) drop from approximately 80 to 40 Mg h^{-1} 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 C_m as wet ground. In the case of wet ground, peak predicted C_m drops from approximately 55 Mg h^{-1} to 30 Mg h^{-1} 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 to 57.1% compared to leaf-off material which was 44.4 to 45% (Table 3).

Overall, harvests that have occurred since 2012 confirm the hypothesis made about C_m by Eisenbies et al. (2014); specifically, that C_m 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 C_m may not be as abrupt as was previously suggested (M. H. Eisenbies et al., 2017; Guerra et al., 2016; Vanbeveren et al., 2017). The data in this study covers 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 is 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 C_m as standing biomass increases.

3.4. Crop Specific Fuel Consumption (FC_C)

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 C_m, 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 FC_{Ai} 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^{-1} (Table 3), but can be higher for individual loads if conditions are sub-optimal 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^{-1} (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^{-1} once standing biomass exceeds 40 Mg ha^{-1}.

Previous work in SRWC suggested that FC_C ranges between 1.2 and 2.2 L Mg^{-1} , but in each of these cases the field conditions were consistent and quite good and the areas harvested relatively small (M. H. 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^{-1} (Downs & Hansen, 1998; Ramos, Lanças, Lyra, & Sandi, 2016; Wild & Walther, 2011). Fuel use for these machines is relative to engine load (M. H. 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 that fuel consumption aligns with other studies. When conditions are sub-optimal (leaf-on and/or wet-weather), compounded by decreased standing biomass, harvester performance and fuel consumption may be impacted by several factors.

Equation 9:

$$FC_{Ci} = FC_{Ai}\left(\frac{1}{BM}\right) = \frac{\beta_0 + (\beta_1 \cdot BM) + (\beta_8 \cdot BM^2)}{BM}$$

3.5. Harvester Efficiency (EFF_H)

Harvester efficiency (EFF_H) 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 increases as biomass increases, and EFF_H is negatively correlated to increasing BM_D (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 EFF_H values exceeding 0.8 were 0.99 and 0.93 for Leaf-off, dry- and wet-weather respectively, and 0.86 and 0.77 for leaf-on, dry-weather and wet-weather. Concurrently in-field delays were also longer on average for leaf-on and wet-weather harvests. Excluding excessive delays (> 10 minutes), the mean in-field delay for leaf-off, dry- and wet-weather loads was 33 and 96 seconds respectively, while the delays for leaf-on, dry- and wet-weather loads 75 and 107 seconds. Finally, the duration of excessive in-field delays was significantly greater for wet-weather harvests (29.8 minutes) compared to dry-weather harvests (15.4 minutes). 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 requiring immediate attention to prevent damage to the harvester, waiting for collection vehicles in the field, phone calls, etc. A more comprehensive examination of the distribution and circumstances of harvester delays are being prepared in a separate study and are beyond the scope of this paper.

Equation 10:

$$EFF_H = \frac{1}{1 + e^{-(2.8699+(-0.01018 \cdot BM)+(-0.2314 \cdot Leaf)+(-0.3286 \cdot Rain))}}$$

3.6. Rainfall Group

Given that the C_m and FC_{Ci} 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-day and 5-day rainfalls amounts, and willow dormancy (Equation 11, Figure 5). All model components had P-values less than 0.0001 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 discriminating between wet- and dry- conditions in this 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 to 5 days prior to operations, these sites were more tolerant to precipitation of approximately 5 mm within the previous two days. Based on these observations, rainfalls exceeding approximately 10 mm at any time within the past 5 days are 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 to 10 mm per day during wet periods in the within 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 harvests windows might open for an active harvests, forecasts beyond five 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 regards to the degree antecedent moisture conditions affect harvesting operations because of factors such as soil types, drainage, slope, aspect, previous land use compaction etc.

Equation 11:

$$Rain\ Group\ Probability = \frac{1}{1 + e^{-\left(-2.9596 + (-13.2492 \cdot Leaf) + (0.4279 \cdot pp2) + (0.4968 \cdot pp5)\right)}}$$

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 where 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 are differences between 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 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 material capacities above 60 Mg h^{-1}, 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 h^{-1}, and operator C harvested 19 loads with a mean C_m of 33.4 Mg h^{-1} ($P<0.0001$); BM_D was not a significant covariate ($P=0.4441$) because these loads were collected on stands with a mean standing biomass of 55.8 Mg ha^{-1} (stddev=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 Sep 18, 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 ($\bar{x}$ = 49.8 Mg ha^{-1}) and lower-biomass Masons site ($\bar{x}$ = 31.8 Mg ha^{-1}), 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) magnify impacts. The effect of the broken turbo was 3.5 Mg h^{-1} overall ($P<0.0001$) with standing biomass as a significant covariate. However, standing biomass was considerably more influential than the turbo status (F value 101.3 vs 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 h^{-1}) between the harvester models ($P=0.1379$) when standing biomass was used as a covariate ($P<0.0001$).

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 harvester efficiency 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^{-1} with leaf-off material on ideal ground result in the highest material capacities (> 60 Mg hr^{-1}) and best fuel efficiency for the harvester (1.3 L Mg^{-1}). Harvesting in low-biomass stands and when conditions are not optimal (e.g. foliage present or during wet field conditions) material capacity and fuel consumption were observed to degrade. Wet ground and harvesting during the growing season when leaves are still on the willow both tend to reduce material capacity by approximately 30 to 50% and/or increase variability. Fuel use increases exponentially in low biomass stands, in this cases stands below 30 Mg ha^{-1}. 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 harvester efficiency decreases with increased standing biomass. There remain many unknowns for how this system functions in stands with biomass greater than 80 to 100 Mg ha^{-1}).

This study confirms previous work that contended that harvester performance is tied to standing biomass, ground conditions, operator effects, and to a limited extent machine effects. 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 US 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 tradeoffs 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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Table 1: Site names and locations of harvests of willow biomass crops with dates, monitored number of loads and areas, and collected biomass, cultivars, ages, operator ID's and harvester used.

Site	Harvest Dates	Lat/Long	Information on Predominant Soils				Monitored Loads	Monitored Biomass (Mg)	Monitored Area (ha)	Plantings	Stem/Root Age at Harvest (y)	Operator	Harvester
			NCRS Soil Survey Series Names (90% of area)	Drainage Classes	Slope Classes (%)	Water Table (m)							
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%)	Somewhat to very poorly drained	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%)	Well to poorly drained	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%)	Somewhat to very poorly drained	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	0-2	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	1207	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	3905	109.7				

Table 2: Primary machine variables and how they are measured or determined. All values reflect performance in-crop, down the row, including any delays in the row but excluding any activity in headlands.

Variable		**Units**	**Source or Determination**
Material Capacity	C_m	Mg h^{-1}	Load weight fresh biomass (scale), time in crop (GPS)
Standing Biomass Delivered	BM_D	Mg ha^{-1}	Load weight fresh biomass (scale), row length (GPS), row width (distance between row centers)*
Fuel Consumption Rate	FC_R	L h^{-1}	Harvester CAN bus (liters fuel recorded per second), time in crop (GPS)
Areal Fuel Consumption	FC_A	L ha^{-1}	FC_L (calculated), time in crop (GPS), row length (GPS), row width (distance between row centers)*
Crop Specific Fuel Consumption	FC_C	L Mg^{-1}	FC_A / BM_D
Harvester Efficiency	EFF_H	proportion	Ratio of Time working in crop:Total time in crop

* because each row is harvested discretely effective and theoretical field capacity are the same in these systems (ASABE, 2011)

Table 3. Mean values (stddev in parentheses) of key parameters based on the cluster analysis of 694 loads of harvested willow biomass crops during the growing season and dormancy under wet and dry weather conditions.

Category	N	Material Capacity (C_m)	Standing Biomass Delivered (BM_D)	Harvested Willow Moisture Content	Effective Field Capacity (C_a)	Speed	Crop Specific Fuel Consumption Index (FC_{Ci})	Harvester Efficiency (EFF_H)*	Delay Count	Delays Rate	Cumulative Rainfall		Julian Wave**
		Mg h^{-1}	Mg ha^{-1}	%	ha h^{-1}	km h^{-1}	L Mg^{-1}	%	count ha^{-1}	h ha^{-1}	2-day mm	5-day mm	
Leaf Off													
Dry Weather	141	71.8 (12.1)	55.0 (16.6)	44.4 (0.02)	1.37 (0.29)	6.0 (1.3)	1.31 (0.27)	0.98 (0.04)	3.2	0.32	0.4	1.9	-0.94 (0.06)
Wet Weather	136	42.4 (14.7)	44.1 (12.7)	45.0 (0.02)	0.96 (0.30)	4.2 (1.3)	2.41 (1.08)	0.95 (0.10)	10.0	0.93	4.5	9.0	-0.46 (0.24)
Leaf On													
Dry Weather	310	29.7 (10.1)	42.4 (20.0)	57.1 (1.40)	0.68 (0.26)	3.0 (1.0)	3.26 (1.19)	0.92 (0.14)	15.1	0.75	1.7	6.8	0.08 (0.41)
Wet Weather	107	30.4 (12.5)	47.2 (18.9)	52.5 (0.02)	0.62 (0.27)	2.7 (1.0)	3.26 (1.48)	0.88 (0.15)	30.9	0.92	19.5	36.1	0.01 (0.26)

* Excluding headland turns

** Julian wave expresses the winter solstice (-1), summer solstice (+1) and equinoxes (0) as a sine function

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	0.8512		0.7407			
Area Under ROC Curve					0.1810	0.9897
	P-value (F-value)	F-Value	P-value	F-Value	P-value	P-value
Leaf			<0.0001	15.6	0.0226	
Rain	0.0301	4.7	<0.0001	50.5	0.0004	
Leaf*Rain	<0.0001	232.1	<0.0001	54.8		
BM_D			<0.0001	33.6	<0.0001	<0.0001
BM_D*Leaf	<0.0001	83.2	<0.0001	32.7		
BM_D*Rain	0.0036	8.56	0.0193	5.5		
BM_D*Leaf*Rain						
BM_D^2						
BM_D^2*Leaf	<0.0001	28.2				
BM_D^2*Rain						
BM_D^2*Leaf*Rain						
EFF_H						
EFF_H*Leaf	<0.0001	33.78				
EFF_H*Rain	0.0125	6.28				
EFF_H*Leaf*Rain						
BM_D*EFF_H	<0.0001	328.6				
BM_D^2*EFF_H	<0.0001	87.9				
pp2						<0.0001
pp5						<0.0001

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 season and under different precipitation conditions.

		β_0	β_1	β_2	β_3	β_4	β_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

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

		β_0	β_1	β_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

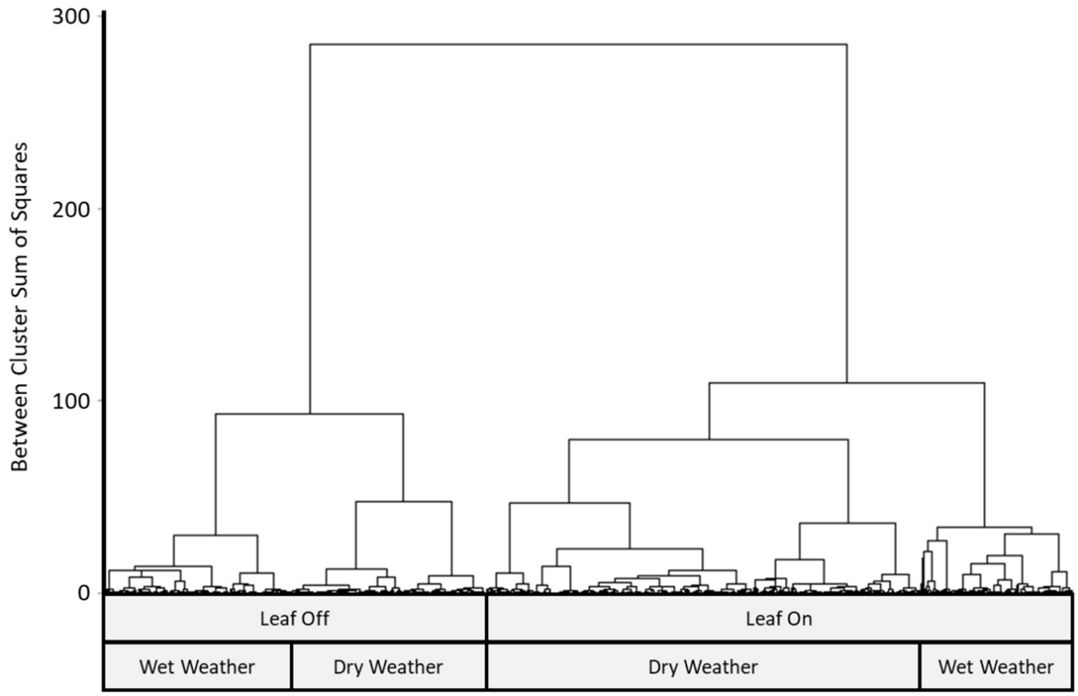
Figure 1: A dendrogram showing the assignment of observations of monitored willow harvesting (N=694) into leaf-on and leaf-off, as well as dry-weather and wet-weather groups from cluster analysis based on methods described in text.

Figure 2. Change in the material capacity (C_m) of a single pass cut and chip harvester in willow biomass crops as standing biomass delivered (BM_D) varies when the plants have leaves on or not and with wetter or drier conditions based on the incidence of recent rainfall.

Figure 3. Change in the crop specific fuel consumption index (FC_{Ci}) of single pass cut and chip harvester in willow crops as standing biomass delivered (BM_D) varies when the plants have leaves on or not and for the wet and dry categories for ground conditions.

Figure 4: Change in harvester efficiency (EFF_H) of single pass cut and chip harvester in willow crops as standing biomass delivered (BM_D) varies when the plants have leaves on or not and with the incidence of recent rainfall.

Figure 5: Probability that a load is classified as wet-weather based on 2-day (x-axis) and 5-day (curves) cumulative rainfall totals for leaf-on and leaf-off harvests.



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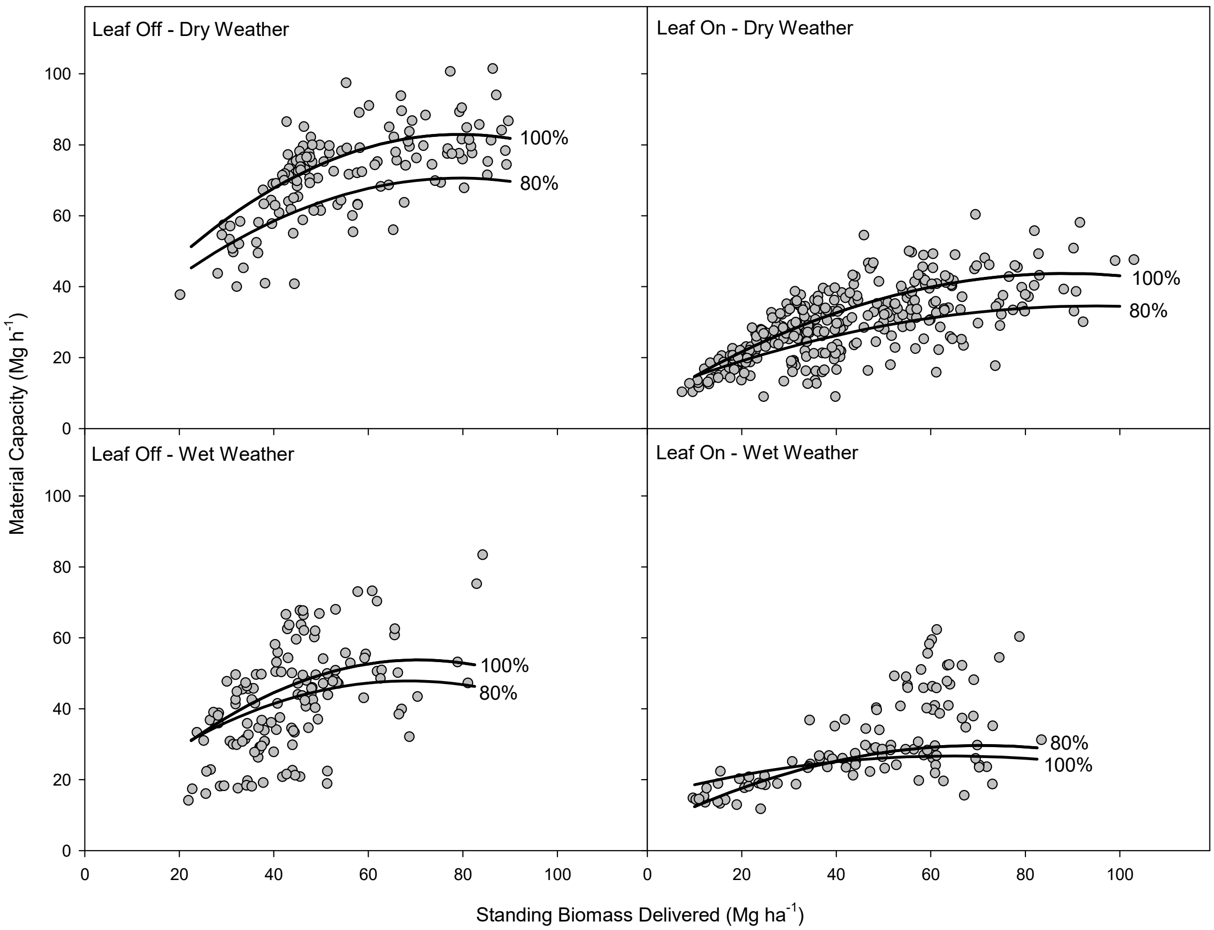

Figure 2. Change in the material capacity (C_m) of a single pass cut and chip harvester in willow biomass crops as standing biomass delivered (BM_D) varies when the plants have leaves on or not and with wetter or drier conditions based on the incidence of recent rainfall.

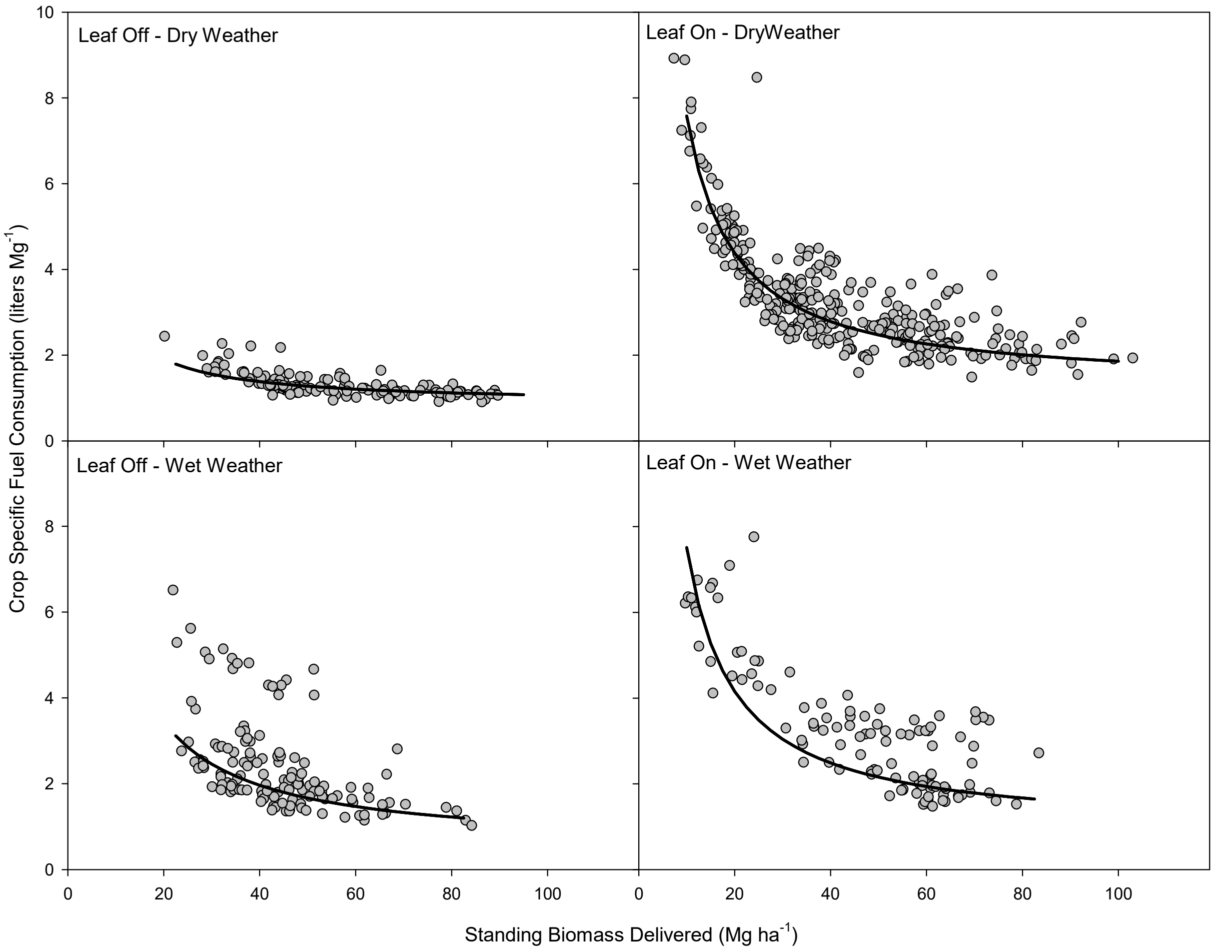

Figure 3. Change in the crop specific fuel consumption index (FC_{Ci}) of single pass cut and chip harvester in willow crops as standing biomass delivered (BM_D) varies when the plants have leaves on or not and for the wet and dry categories for ground conditions.

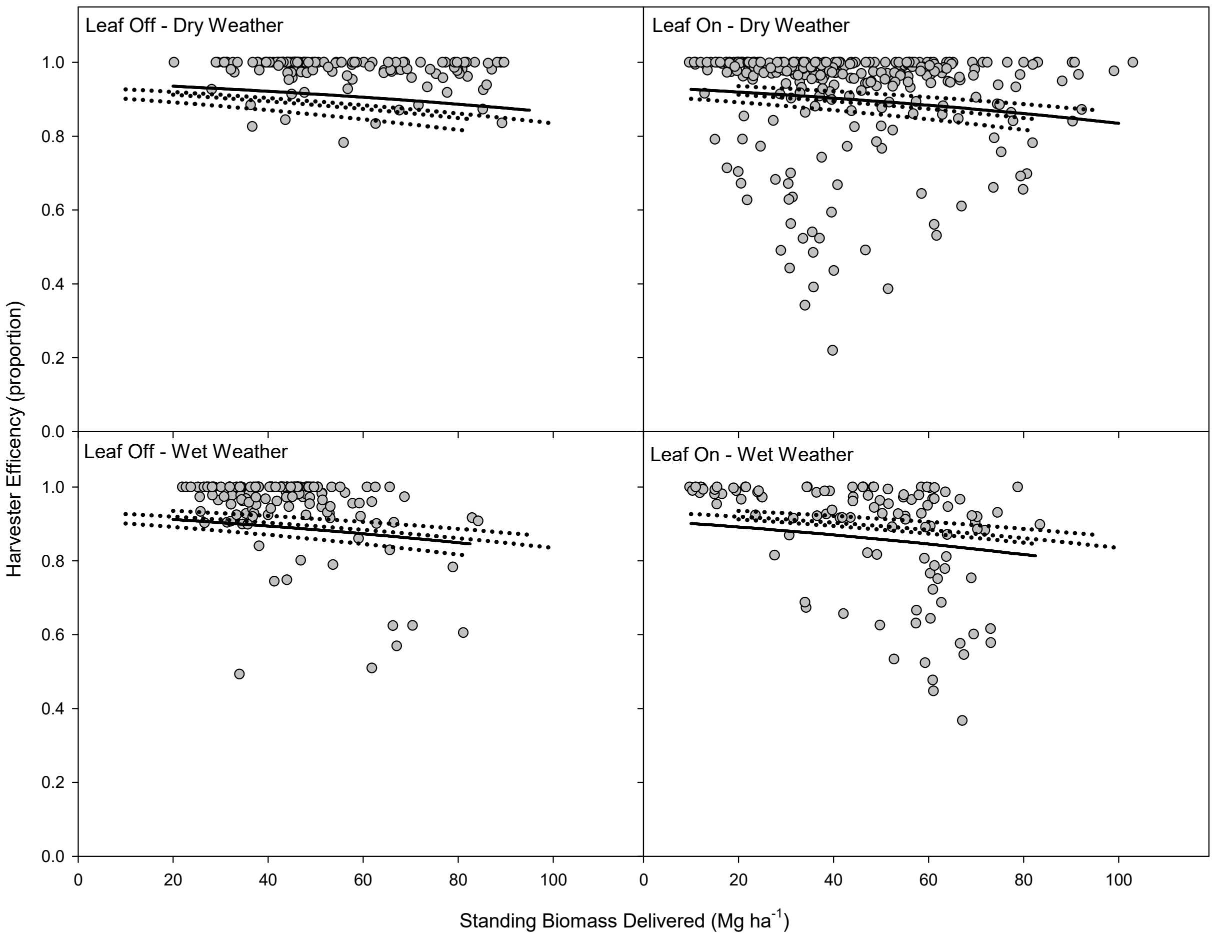

Figure 4: Change in harvester efficiency (EFF_H) of single pass cut and chip harvester in willow crops as standing biomass delivered (BM_D) varies when the plants have leaves on or not and with the incidence of recent rainfall.

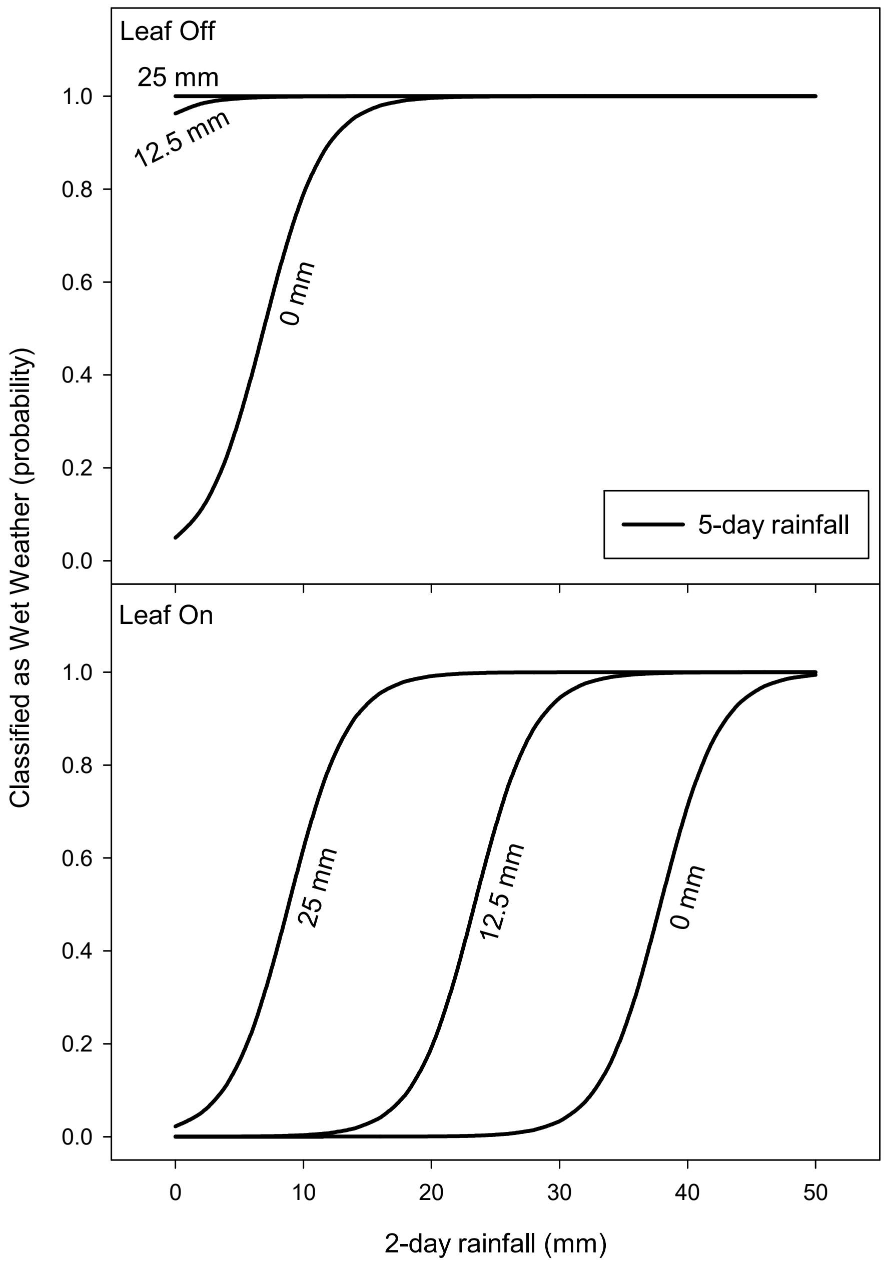

Figure 5: Probability that a load is classified as wet-weather based on 2-day (x-axis) and 5-day (curves) cumulative rainfall totals for leaf-on and leaf-off harvests.

SUPPLEMENTAL MATERIAL

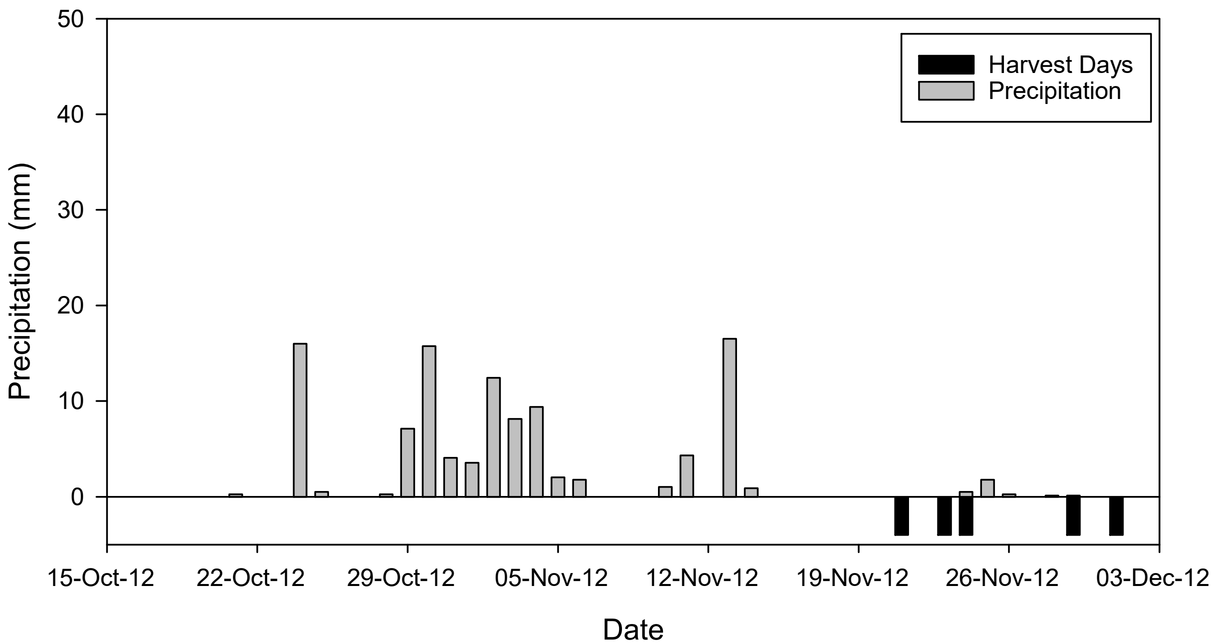

Figure A1: Antecedent precipitation 30 days prior to harvests at the Auburn site in New York State.

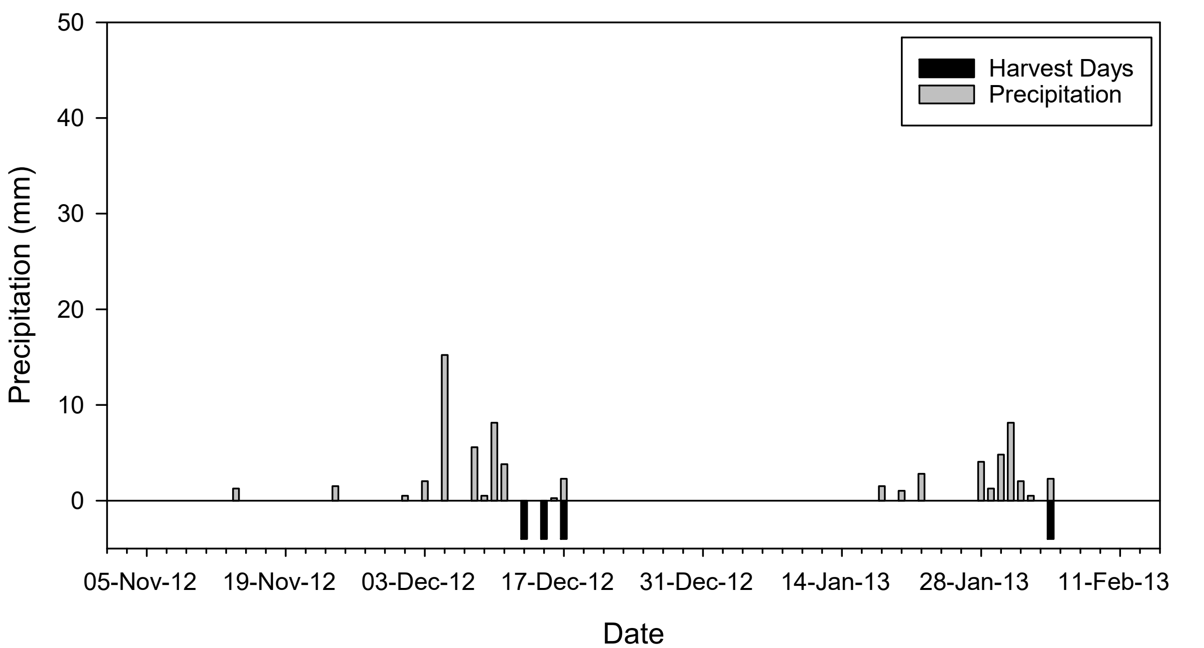

Figure A2: Antecedent precipitation 30 days prior to harvests at the Groveland site in New York State.

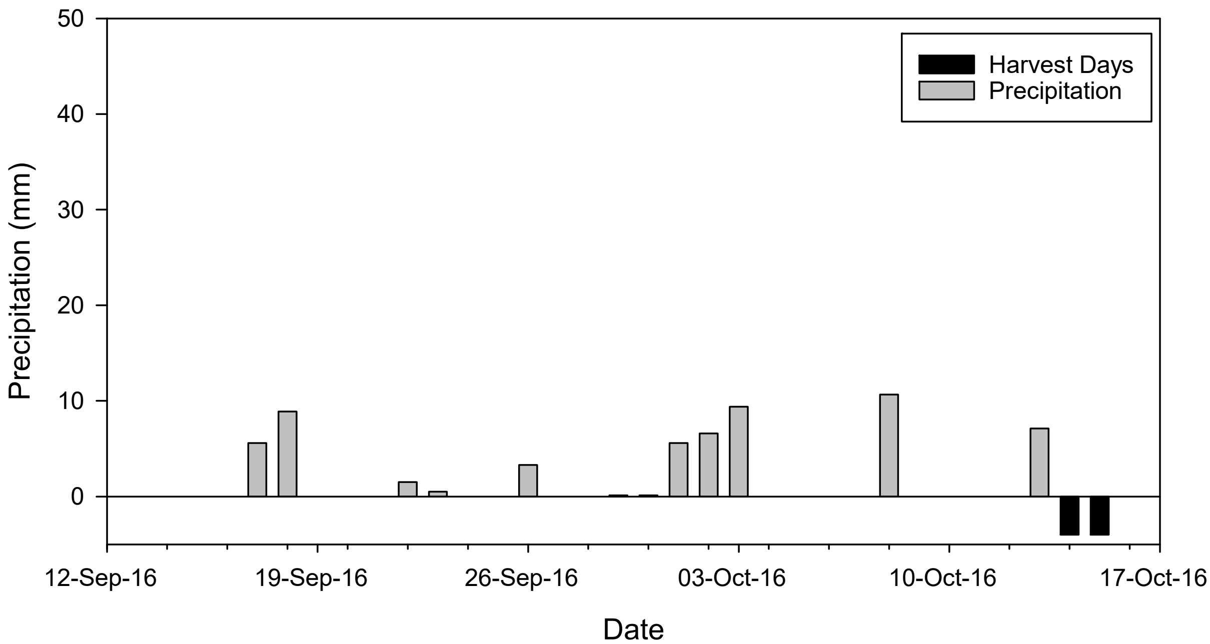

Figure A3: Antecedent precipitation 30 days prior to harvests at the Buffalo site in New York State.

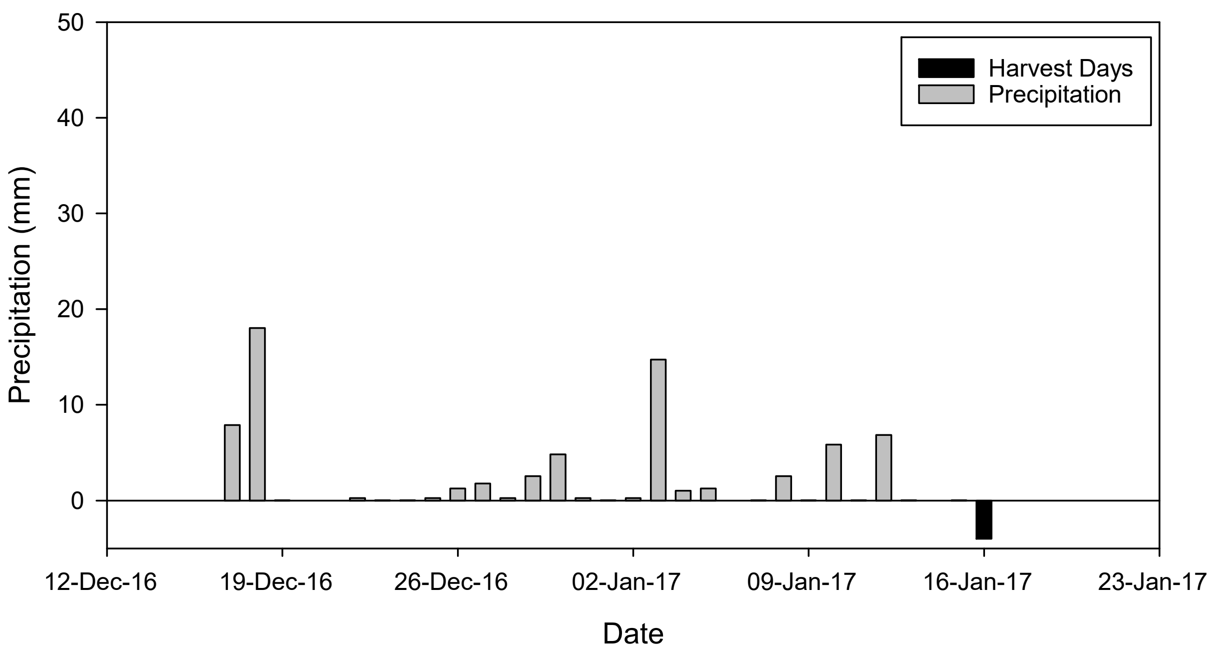

Figure A4: Antecedent precipitation 30 days prior to the winter harvest at the Solvay site in New York State.

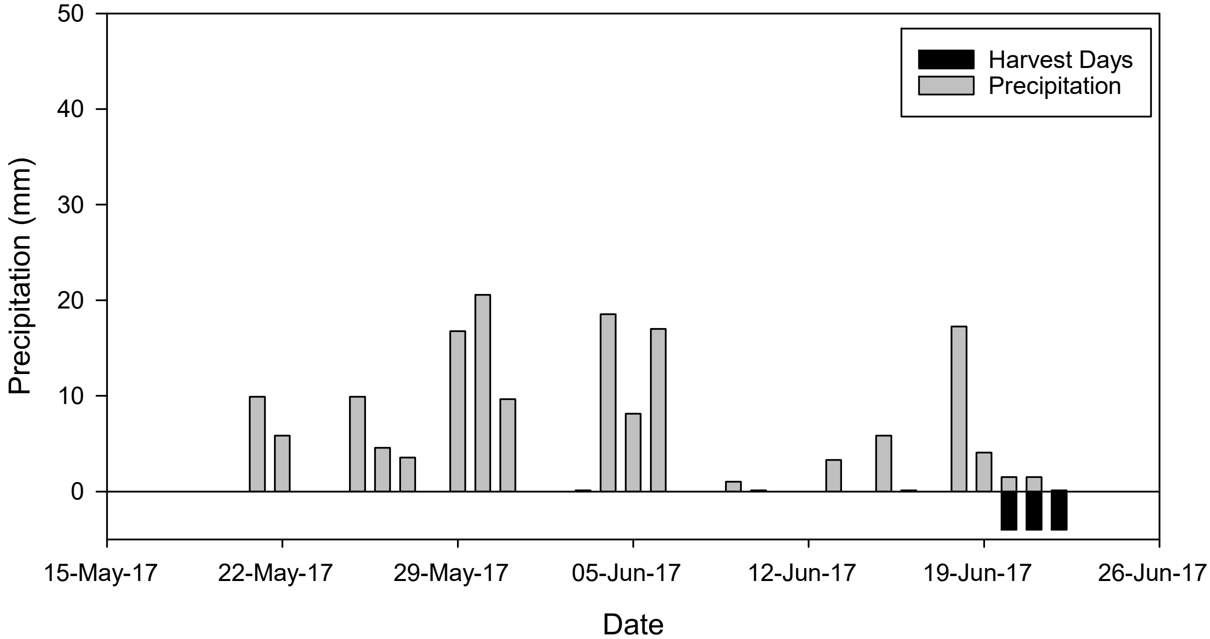

Figure A5: Antecedent precipitation 30 days prior to the summer harvest at the Solvay site in New York State.

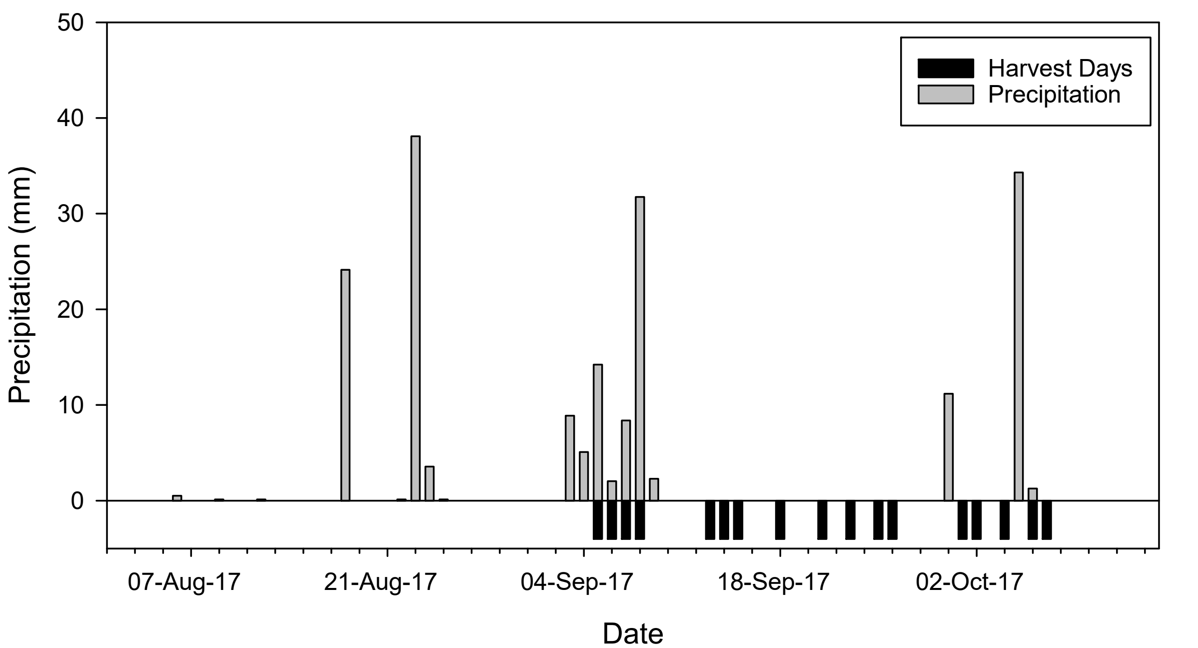

Figure A6: Antecedent precipitation 30 days prior to the harvests at the Jacobs and Masons sites in New York State.

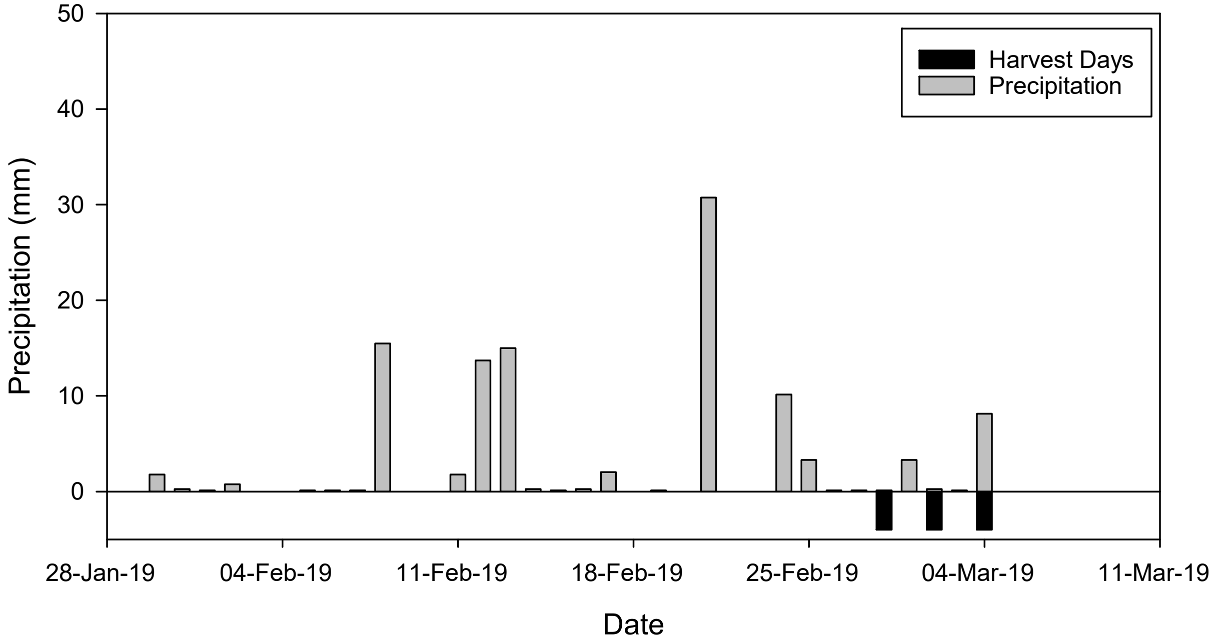

Figure A7: Antecedent precipitation 30 days prior to the harvests at the Rockview site in Pennsylvania.