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Evaluation of a single-pass, cut and chip harvest system on commercial-scale, short-rotation shrub willow biomass crops

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Abstract

Harvesting is the single largest cost in the production of short rotation woody crops (SRWC) like shrub willow and previous systems tested in North America have not been effective for the size of material grown. The objective of this study was to evaluate the performance of a single-pass, cut and chip harvester in conjunction with two locally-sourced chip collection systems on 54 ha of coppiced willow harvests in New York State. Harvesting and collection equipment was tracked for 153 loads over 10 days of harvesting using GPS dataloggers. Effective material capacities (C_m) increased linearly with standing biomass up to 40 to 45 Mg_{wet} ha^{-1} because ground speed was limited by ground conditions. This relationship changed dramatically with standing biomass in the 40 – 90 Mg_{wet} ha^{-1} range, where C_m plateaued between 70 and 90 Mg_{wet} hr^{-1} and was limited by crop conditions and harvester capacity. The relationship between standing biomass and the harvester's C_m will probably change under different crop and ground conditions. The size of the harvester and the experience of the operator are other factors. This nonlinear relationship will impact cost and optimization modeling SRWC systems. Improperly sized headland and long haul distances impeded the performance of locally sourced collection systems resulting in a 33% decrease in C_m from the field to the headlands, and 66% from the field to short-term storage as biomass moves through the system.

Keywords: Short rotation woody crops, coppice systems, harvest logistics, effective material capacity, effective field capacity, efficiency

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Introduction

Biomass for bioproducts and bioenergy can be sourced from forests, agricultural crops, various residue streams, and dedicated woody or herbaceous crops [1, 2]. Woody biomass of all types is available year-round from multiple sources including natural forests, short rotation woody crops (SRWC) and other residue streams, so end users are not dependent on a single source of material. This ensures a consistent feedstock supply, reduces the risk of dramatic price fluctuations, and eliminates the needs for complicated and expensive long-term storage of material [3]. Woody biomass has the potential to be an important source of biomass in the northeastern US where forests occupy 67% of the land area [4], agricultural production has been in a 20-year decline, and crop residues are limited because of the dominance of dairy in the agricultural sector, which results in the majority of corn crops being harvested for silage. As perennial cropping systems, both forests and SRWC, like willow (*Salix spp*.) produce environmental benefits beyond a renewable source of biomass and may be less prone to yield fluctuations caused by abnormal weather patterns, or pest and disease outbreaks than annual crops [5, 6].

Shrub willow biomass crops may be grown on marginal agricultural land using a coppice management system that allows multiple harvests, usually every three or four years, from a single planting of improved shrub willow cultivars [7]. 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 [3].

Despite the benefits associated with shrub willow biomass crops systems, their expansion and deployment has been constrained by higher production costs and lower market acceptance associated with perceptions of chip quality and wood characteristics [8]. For willow biomass, crops harvesting is the largest single cost factor at one third of the final delivered cost; harvesting, handling, and transportation combined accounts for 45-60% of its delivered cost [9]. Improving harvester efficiency by 25% could reduce the delivered cost of SRWC by approximately \$0.47/GJ (\$7.50 $\mathrm{Mg}_{\mathrm{dry}}$). Harvesting is also the second largest input of primary fossil energy in the system, after commercial N fertilizer, and accounts for about one third of the energy input [5, 10].

Several types of specialized harvesting machinery exist for SRWC, but due to the limited scale of SRWC deployment, evolving technology, differing operational scales, and management objectives, there is no dominant system. However, systems that cut and chip the material in a single operation generally appear to be the most economical [11–14]. Properly matching harvesting equipment to a production system will have a significant impact on the costs and efficiency of a production system [15, 16]. Thus, there is a significant need to understand the sources of uncertainty and variation associated with the different components of bioenergy production systems [17, 18]. A fuller understanding of the sources and degree of uncertainty with regards to the harvesting and feedstock supply chain is required in order to adequately select, model, or improve these systems [5, 19].

Since 2003, several types of single-pass, cut and chip systems have been evaluated in New York State for willow coppice systems using existing or modified platforms from throughout the world. Technical hurdles encountered included durability of equipment in SRWC, chips lacking a consistent size (< 45 mm) and quality, and irregular feeding of stems from the cutter to the chipper [8]. The inconsistent quality of the feedstock in particular has been a major issue with regards to end-user acceptance. In 2008, Case New Holland (CNH) began development of a prototype short rotation coppice header (130FB) for their FR9000 series of forage harvesters in an effort to address these challenges. Machine specifications included the ability to harvest double rows of stools containing stems up to 120 mm in diameter, and the ability to produce 10 to 45-mm long chips at a field capacity up to 2 ha hr^{-1}.

Objectives

The objective of this study is to evaluate the performance of a single-pass, cut and chip harvesting platform and associated collection system based on a New Holland FR9080 forage harvester fitted with a second-generation New Holland 130FB short rotation coppice header on two commercial scale willow biomass crops. Specifically, performance metrics include effective material capacity (C_m) and effective field capacity (C_a) as defined by the ASABE [20], headland turn times, down-time, and efficiency losses throughout all phases of the harvesting system between cutting of stems and delivery of chipped material to short-term storage.

Materials and Methods

Site descriptions

Two sites were selected for harvest in the 2012-2013 harvest season: (1) two fields of coppiced, first rotation, 4-yr-old aboveground (five year old belowground), willow crop totaling about 40 ha located near Auburn, NY (42°55’22”N, 76°40’21”W) with standing biomass ranging between 20 and 65 Mg_{wet} ha^{-1} and (2) two uncoppiced, first rotation,5-yr-old willow plantations totaling 14 ha located near Groveland, NY (42°42’09”N, 77°44’49”W) with standing biomass ranging between 30 and 95 Mg_{wet} ha^{-1}. Both sites consisted of homogeneous plantings of multiple willow cultivars (Canastota, Fish Creek, Millbrook, Oneida, Owego, Owesco, S365, Sherburne, SV1, SX61, SX64, SX67, and Tully Champion) at 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. [7]. These cultivars represent a wide range of productivities, heights, diameters, stem forms (bowed to straight), and stem densities [21].

The soils at the Auburn site were formed on lake and glacial till plains and are comprised of silt loams and silty clay loams; seasonal water tables are within 0.15 m to 0.60 m of the surface and soils are very- to somewhat-poorly-drained (U.S. Department of Agriculture, Natural Resource Conservation Service, Web Soil Survey). When dry, the clay content of the subsoil makes them sufficiently strong to support heavy equipment, but since they reside in geomorphic depressions there is the potential for standing water in winter, which can become limiting to machine mobility even with very little precipitation; a system of drainage ditches in and around the fields was present to facilitate soil drying. The soils at the Groveland harvest were formed in glacial till and comprised of silty loams; seasonal water tables are within 0.15 to 0.60 m of the surface and the soils are somewhat poorly-drained to well-drained (U.S. Department of Agriculture, Natural Resource Conservation Service, Web Soil Survey). Historically, only the western periphery of the western field generally becomes wet enough to limit farm operations in December according to the landowner.

These plantations were originally installed and maintained by commercial entities outside of the harvester development project; thus, there was no specific experimental design regarding cultivar selection, areas planted, arrangement of fields, or silvicultural practices used. These sites had the advantage of being commercial scale; however, they also presented significant challenges with regards to headland and row-spacing specifications, landings, collection system logistics, and in-field slopes in some areas. Ultimately, both harvest locations served as opportunities to evaluate an array of logistical constraints on C_m and chip quality over a wide range of standing biomass in an operationally realistic setting. Due to moderate drought conditions in 2011 and 2012, coupled with poor drainage and poor weed control during establishment, cumulative growth at Auburn was probably more typical for a 3-yr-old stand [21].

Order of harvest

Harvest dates at Auburn, NY followed leaf senescence and occurred on November 21, 23, 24, 29, 30, and Dec 1, 2012. Harvest dates at Groveland occurred on Dec 13, 15, and 17, 2012 and Feb 4, 2013. The harvester platform tested was a New Holland FR9080 harvester, equipped with a New Holland 130FB coppice header. The harvests were managed by an experienced operator with thousands of hours of experience in the manufacturer's forage harvesters and hundreds of hours harvesting short term woody crops, and supported by a locally sourced crew and collection vehicles. Harvesting patterns on the Auburn and Groveland harvests were executed at the discretion of the harvester operator in consultation with researchers to expedite the removal of material. Generally, there was no external direction given to the operator to harvest cultivar groups in a specific order and disrupt what was considered by the harvester and collection system operators to be the optimal harvesting patterns. The operational objective was to simulate a commercial harvest, specifically maximize C_m and optimize machine time. Emphasis was placed on the efficient removal of material over research goals that may have included harvesting particular cultivars. There were a few exceptions (about 25 out of the total 375 rows harvested at Auburn) to this pattern where the operator was asked to harvest large blocks of a specific cultivar so data could be collected. Due to good weather and ground conditions, the operator was able to keep harvester engine-loading at or near 100%, according to the machine's data screens, for the majority of cutting operations.

The length of the majority of rows at Auburn and Groveland were between 150 and 500 meters, excluding a small percentage (<5%) of end rows. Headlands at both sites were often less than 8 m wide, which was below the recommended widths, and presented dynamic and challenging operating conditions. Headlands were a particularly difficult problem at the Groveland site where boundaries on the back edge of the field were within 4 m of the willow crop on the rear portion of the field and lined with large trees and a fence line. Auburn headlands had slightly more room and were bounded by obstacles such as drainage ditches or hedgerows, which offered a slightly less challenging, but less than optimal situation overall.

Two locally-sourced collection systems were tested during the harvests, consisting of five vehicle types (Table 1). The collection system at Auburn consisted exclusively of silage trucks equipped with high floatation rear tires for the first three days thanks to reasonable field conditions and adequate headland space in the most accessible parts of the field. Chips were transported approximately 7 km where they were weighed, samples were collected, and the biomass was placed into short-term storage on a hard surface pad. Maximum capacities of the collection vehicles ranged between 5 and 12 Mg. After numerous front tire puncture incidents the third day, a mixture of silage, and dump wagons was employed. Dump wagons at Auburn required the additional step of transferring chips to a waiting silage truck, which carried chips to short term storage. The collection system at Groveland consisted exclusively of dump wagons that transferred chips into waiting trucks, which transported loads 1 km to a location where they were weighed and put into short term storage on an unpaved pad.

Time motion methods

Machinery activities were tracked during the harvests using a combination of GPS data loggers recording positions every second and field observations. A GeoXM GPS unit (Trimble Navigation Ltd.) was used to monitor the harvester; equipped with an external antenna the unit is capable of sub-meter accuracy after differential corrections. Juno SB GPS units (Trimble Navigation Ltd.) were used to monitor the collection system vehicles; equipped with external antennas, they are capable of 1-3 m accuracy. Observers were positioned in the harvester cab and at the harvest landing and short term storage sites to record row entries, exits, collection vehicle exchanges, dump times, load weights and truck tares, and other harvest activities. Cultivars were codified beforehand using unique colored flagging at the ends of each row. Coordinated Universal Time (UTC) stamps and vehicle identification numbers were used as the key variables to link databases and field observations. Samples (2-4 kg) were obtained from each truckload and weighed to the nearest 0.1 g at the edge of the field on a scale (Mettler-Toledo PG 5002-S) [22]. The samples were returned to the lab and dried at 60°C until they reached a constant weight. Moisture content was determined gravimetrically [23].

Harvester activities were subdivided into legs (Figure 1); a leg being defined as a group of consecutive GPS positions with shared attributes, and a new leg begins any time conditions change (e.g. the harvester enters or leaves the field, a collection vehicle is filled and separates from the harvester to depart for the landing, or a new collection vehicle arrives and engages with the harvester). For example, leg_j might consist of a group of points from where tractor "T_n" engages the harvester mid-field to the edge of the field where the harvester enters the headland for a turn; by exiting the field leg_{j+1} is initiated. Legs are consecutively numbered and uniquely identified by the time stamp and location of their control point (i.e. the first point in the segment). Delays/holds are defined as the period of time where the harvester's speed drops below 0.64 kph (a speed where position changes became indistinguishable from GPS noise) twice within 5 seconds, for 5 seconds or more, and separated by at least 5 seconds from any other delay/hold; delay events within 5-seconds of each other were consolidated into a single event.

Control points for independent loads were also identified. Delivered loads to short-term storage serve as the replication for the production aspects of the analyses. Median harvested areas were approximately 0.3 and 0.2 ha load^{-1} at Auburn and Groveland respectively. In cases where chips are loaded directly into trucks, loads were usually comprised of contiguous legs. For example in Figure 1, load$_k$ consists of leg$_j$ and leg$_{j+2}$ for calculations of in field harvesting rates and delays. For calculations that include headlands and headland delays load$_k$ includes leg$_j$, leg$_{j+1}$ and leg$_{j+2}$. However, when trucks held more than a single wagon load or there was disorder in the collection system logistics, loads may or may not be comprised of consecutive legs. Multiple delivered loads that share chips from the same collection vehicle (i.e. when a wagon unloads part of its load into two trucks) were aggregated into a single independent load.

Collection vehicle work is divided into cycles (Figure 1). A cycle starts when the vehicle begins to receive chips, and ends after it unloads and returns to the harvester queue for its next load. For the purposes of this study the focus was on the cycle time for individual loads. In cases where multiple collection vehicles were used to generate a single load, the cycle times were aggregated. In cases where the collection vehicle did not deliver the material to short-term storage, the time the delivery truck took to make the trip to short term storage and back was added to the cycle time for that load based on field notes.

Harvester speed (kph), C_a (ha hr^{-1}), standing biomass yield (Mg$_{wet}$ ha^{-1}), and C_m (Mg$_{wet}$ hr^{-1}) [24, 25] are calculated by accounting the time and distances between control points based, weights of loads, and row spacing based on their associated load number. For example, if load$_j$ generated 12 Mg$_{wet}$, and the harvester spent 10 minutes in the planted area (leg$_j$ + leg$_{J+2}$) actively harvesting, C_m would be 72 Mg$_{wet}$ hr^{-1} (Figure 1); incorporating GPS legs representing 30 seconds of field delays would decrease C_m to 69 Mg$_{wet}$ hr^{-1}; incorporating a GPS leg for a 60 second turn in the headland (leg$_{j+1}$) decreases C_m to 63 Mg$_{wet}$ hr^{-1}. If the C_m for two collection vehicles delivering chips to short term storage at individual C_m's of 15 Mg$_{wet}$ hr^{-1} during load$_k$ the system C_m would be calculated as 30 Mg$_{wet}$ hr^{-1}. Wet weights, as opposed to oven-dry weights, are reported given that wet weights drive harvesting and delivery costs. Delay legs or headland legs, can be included or excluded from the calculations to evaluate system productivity for involved vehicles at a field-speed maximum, or at intermediate phases until delivery to short term storage. Efficiency is calculated by dividing C_m at any stage by the harvester's maximum C_m at field-speed [25].

In the context of evaluating the harvester platform's performance, turn times were not included in the calculations of C_a or C_m because they are confounded by the other machines working in the system, particularly on these sites where the headlands were less than half the recommended width. Also, loads are separated by harvester efficiencies greater and less than 90% (C_m in field, with field delays included : C_m at field speed) to delineate "high-efficiency" loads as a further means to isolate harvesting patterns. The collection system performance is linked to harvester performance by calculating a system C_m. The cycle C_m of an individual tractor is defined as load biomass divided by the cycle time (i.e. the time from the beginning of one load, until the beginning of the next load). Many collection vehicles are operating in series; therefore, the system C_m is calculated as the sum of cycle C_m's for all collection vehicles in the system at the inception of each new harvester load (Figure 1). Since harvester C_m is variable, system C_m may be greater than harvester C_m for an individual load, but over the course of a day mean system C_m must be less than the mean harvester C_m.

Harvester drop losses

A certain amount of residual woody biomass is not collected by the harvester and remains on site after harvesting. Visually, these loses can appear significant, particularly near the edge of the field where "goosenecking" of the willow plants is more pronounced and the harvester operator is still adjusting for ground conditions and vehicle positioning. This problem at the ends of the rows is further exacerbated by narrow headlands. Drop losses were collected at the Auburn site on 24 measurement plots (2.29 x 6.10 m) distributed spatially randomly on over 6 hectares (70 harvested rows) of 2 cultivars (Fish Creek and SV1); thus, statistical inference is limited to Auburn and these two cultivars. Plots were centered on double rows in two cultivars and at least 20 m from the edge of the field. Fish Creek is characterized by long and straight stems with smaller diameters; SV1 has larger diameter, bowed stems. An entire stem was collected if the cut end was within the boundaries of the plot, regardless of the position of the rest of the piece; stems that fell inside the plot, but the cut end was outside, were discarded. The previous components of the forest floor (i.e. leaves and decomposed material) and the chipped wood spilled from collection vehicles or from the spout were not collected. Materials were placed in four categories of merchantable and unmerchantable drops: (1) uncut- stems that remained attached to a stool; (2) cut -stems that were cut by the header, but did not feed into the harvester; (3) drag - clusters of cut stems (oriented the same direction with cut ends in almost the same location) that were deposited by the header after being collected and dragged some unknown distance; and (4) shakes- detached, unmerchantable, stem tips that were less than 2.5-mm diameter (borderline pieces were confirmed using a size gauge with a 2.5-mm slot) and usually less than 10-cm long that were probably dislodged during the violent shaking as stems entered the header. Due to their small size, shakes were collected from a random 2.29 x 0.31 m section of the main plot. Samples were dried at 60°C until they reached a constant weight.

Statistical analyses

Statistical comparisons were made in SAS 9.2 (SAS Institute) using the MIXED procedure for normally distributed data; data is normal unless otherwise noted. A repeated measures design was used to evaluate the C_m for each load at discrete stages in the harvesting system using autoregressive heterogeneous (ARH(1)) covariance structure (AR(1), CS, CSH, UN, and UNH were also considered)[26]. The GENMOD procedure was utilized to evaluate non-normal data (e.g. stem densities, turn times, delays, delay densities) using a gamma distribution [27, 28]. Drop loss categories were compared using simple contrasts in the MIXED procedure in SAS. The best model or distribution in the MIXED or GENMOD procedures was selected based on the lowest fit statistics (i.e. -2 res log likelihood, AIC, AICC, BIC). The REG procedure was used to evaluate change in harvester speed and C_m relative to standing biomass using a simple linear regression model [29].

Results and Discussion

Harvest Site Comparisons

There was significantly more standing biomass at the Groveland harvest site (70.0 Mg_{wet} ha^{-1}, 13.3 standard deviation) compared to Auburn (43.4 Mg_{wet} ha^{-1}, 7.1 standard deviation) ($P<0.0001$). At Auburn only 46% of the loads were harvested in standing biomass greater than 45 Mg_{wet} ha^{-1}, as opposed to 94% of the loads at Groveland. The mean moisture content for willow chips immediately post harvest was 44.4 % (standard deviation 2.17%); less than 1% of samples were above 50% moisture content. The willow was taller at Groveland (6.5 m) than at Auburn (4.9 m) ($P<0.0001$), but the overall range was 4.7 to 8.2 m and 3.3 to 7.8 m respectively. Mean stem density at Auburn was 145,000 stems ha^{-1}, which was greater than Groveland with 80,600 stems ha^{-1} ($P<0.0001$); the plants at Groveland were never coppiced. There was a significant difference in the overall diameter distributions for each site ($P<0.0001$); the mean stem diameter at Auburn was 16.4 (at 30 cm above ground), with all stems under 45-50 mm, and the mean diameter at Groveland was 20.6 mm, with 94.6 percent below 45-50 mm.

Harvester performance

Harvester speed or C_a are often reported as key performance parameters when describing harvester performance in coppice systems [9, 12, 30]. The assumption is that increased C_m is coupled to increased speed by default. There was no significant correlation between speed or C_a, and C_m ($P=0.7803$) for harvested loads over a wide range of standing biomass (Figure 2). For every 10 Mg_{wet} ha^{-1} increase in standing biomass between 35 and 90 Mg_{wet} ha^{-1}, in-field C_a decreased by 0.15 ha hr^{-1} (approximately 0.65 kph) for both combined loads and high-efficiency loads. It is unlikely that large material capacities can be realized from stands with low standing biomass because field speeds over 8-10 kph (1.8-2.3 ha hr^{-1} at the observed 2.29-m row spacing) become unrealistic for the majority of SRWC settings. Even if higher speeds are attained, the speed required to generate loads at an equivalent C_m increases exponentially as standing biomass decreases such that C_m becomes insensitive to incremental changes in speed from a practical standpoint (isolines, Figure 2).

C_m is the integrating variable that defines harvester or system performance. The operator kept engine loads at or near 100 percent, so it is assumed that the limits of the operator and harvesting platform were being achieved; a dichotomous pattern was observed (Figure 3). C_m initially increased within a concentrated band between 1.5 and 2.0 ha hr^{-1} for observed loads where standing biomass was between 0 and 40-45 Mg_{wet} ha^{-1}, with a distinct linear boundary along the 2-ha hr^{-1} C_a isoline, and a diffuse boundary below 1.5 ha hr^{-1}. This pattern is due to the limits of ground conditions on harvester speed and may be related to several factors: (1) Lack of traction may prevent higher speeds from being attained or a reduction in power available to the header and chipper; (2) Rough ground can damage the harvester or collection vehicles over a certain speed, and are physically demanding for operators; (3) Speeds greater than 10 kph (2.3 ha hr-1 at the observed 2.29-m row spacing) increase the risk of lifting and damage to stools as the harvester begins to move forward faster than the saw blades can cut through the stool.

C_m plateaued at an apparent inflection when the harvester begins to encounter standing biomass that exceeded 40-45 Mg_{wet} ha^{-1} (Figure 3). As noted previously, crop biomass above 40-45 Mg_{wet} ha^{-1} begins to limit harvester speed. The plateau in C_m attains a fairly level to slightly positively sloped plateau with the majority of loads falling between 70 and 90 Mg_{wet} hr^{-1}, and below the 120 Mg_{wet} hr^{-1} maximum reported by Savoie et al. [14]. The plateau slopes by an approximate 2.5-Mg hr^{-1} gain per 10Mg ha^{-1} increase in standing biomass; however, the statistical significance associated with the slope depends on the subjective cutoffs of standing biomass (e.g. 40, 45, or 50 Mg ha^{-1}) and load efficiency (e.g. 0.85, 0.9, or 1). The assumptions drawn from this kind of data will have repercussions in cost modeling SRWC systems and uncertainty analysis [5, 19].

In earlier project phases and before commercialization, the average in-field C_m of this harvester was 15 Mg hr^{-1} and has been improved steadily over the past few years [31, 32]. This harvester platform is based on a series of high-power forage harvesters (316-614 kJ sec^{-1}) [13]. Schweier and Becker [30] reported on the performance of an

FR9060 equipped with a commercial version of a 130FB coppice header on seven fields ranging from 0.31 to 4.94 ha and totaling 14 ha in Germany. In-field performance was not reported, but based on productive machine hours, cut times, turn times, and moisture contents as reported we interpolate an average in-field range of C_m between 34 and 61 Mg_{wet} hr^{-1}. The German study stool density (12,700 stools ha^{-1}) was lower than the Auburn and Groveland fields (14,350 stools ha^{-1}); larger stem sizes may have presented more resistance to the harvester. Berhongaray et al. [16] report productivity values for a more powerful New Holland FR9090 forage harvester in Belgium, but deployed it in a 7-ha, 2-yr-old poplar stand with a lower planting density (8,000 stools ha^{-1}) and approximately 15 Mg_{wet} ha^{-1} of standing biomass. The results from their study suggest that this type of system may not be suitable in SRWC with low standing biomass. The Auburn and Groveland trials that cut off point was around 40 – 45 Mg_{wet} ha^{-1}. While smaller machinery may be more suitable in field with low biomass, chipped material must meet end-user quality standards [17], which has been a challenge with previous harvester trials [8]. Harvesting systems based on forage harvesters in general, produce a consistently high-quality feedstock [12] and recently there has been work to develop a pull type forage harvester for SRWC that may be suitable in these crops [14].

It is not expected that the dichotomous performance pattern shown in Figure 3 is static for this harvester platform, but several general inferences can be drawn. The bounds of the pattern for any harvester platform working efficiently at its limits may shift given different site conditions, equipment capability, and personnel experience (Figure 4). While standing biomass is relatively low (less than 40 – 45 Mg_{wet} ha^{-1} in this study) harvester speed is limited by ground conditions and C_m is linearly related to standing biomass. Given different harvesting platforms, this portion of the pattern will probably rotate around the origin as ground conditions improve or degrade (Figure 4a). Once standing biomass reaches a level where it begins to limit speed, C_m reaches a level or gently sloped plateau (Figure 4b). C_a and the width of the plateau will depend on the power or capabilities of the harvester platform, the experience level of the operator and/or stand conditions. Beyond the range of standing biomass tested in this study, a third sub-pattern is anticipated where C_m declines due to the harvesting platform's mechanical limits. Willow coppice systems are currently capable of producing 8 to 14 Mg_{dry} ha^{-1} yr^{-1} [33]. A collection of the best five willow cultivars tested across a range of sites have production potentials between 8.7 and 15.6 Mg_{dry} ha^{-1} yr^{-1} with an average of 11.2 Mg_{dry} ha^{-1} yr^{-1} [33] or 58 – 104 Mg_{wet} ha^{-1} (average 75 Mg_{wet} ha^{-1}) after three years. Therefore it is unlikely that stands grown for the recommended 3 to 4 years would exceed the capabilities of platforms similar to the one tested in most circumstances [7].

The three sub-patterns that occur across the range of standing biomass can be joined to form overall patterns that could be modeled a variety of ways to determine the best harvesting platform for the range of expected crops, needs, or conditions (Figure 4c). Each of the sub-patterns may have discrete or diffuse boundaries to further complicate decisions. In systems where standing biomass is low and the speed of the harvest platform is never limited by vegetation, speed will be proportional to C_m. In situations similar to the Auburn and Groveland harvest, a dichotomous pattern would be observed. If a given harvest platform has mechanical limits above a certain level of standing biomass present in a field then a trichotomous relationship may be observed. Although the shape of this pattern is unknown, the expectation is that a decline in C_m would be observed. Ultimately the overall pattern, or range of patterns, will have considerable influence on the logistics and economics of a particular harvesting system in a given SRWC that has a specific set of field and crop characteristics. Simply projecting logistics or economics based solely on increases in speed may not accurately reflect the reality of how these harvesting systems will function at large scales.

Harvest System Performance

System performance is anchored by the harvester platform, and cannot exceed the harvester's C_m. The harvester represents the most significant capital cost and has the highest fuel consumption so it is considered a cost imperative to keep it working as much as possible and at as high a C_m as possible [17]. As chips are conveyed through the harvest system, each added component or stage of the operation impacts system efficiency. There is no recovery from an introduced inefficiency, and the effect will carry down the entire material stream. Ideally, a harvester should be supported by a collection system with a capacity to move chips at or slightly above the rate they are produced. One goal of this study has been to utilize locally-sourced collection equipment to receive chips from the harvester; a reduction in costs is expected by minimizing the number of pieces of specialized equipment required to harvest SRWC. However, due to the wide array of factors affecting harvest operations (e.g. site factors, field layout, vehicles, crew experience, etc.) [18, 34] developing an efficient harvest is a complex logistical problem and plans can easily devolve.

Harvesting at the Groveland site resulted in a significantly higher C_m at all phases ($P<0.0001$) because standing biomass was greater in Groveland than the Auburn location. At both sites, C_m decreased significantly at each step in the system with the exception of the sources of in-field delays ($P<0.0001$) (Table 2). There was no significant difference in the loss of efficiency between the headland and short term storage, 35 and 41 percent

(P=0.3715), or the overall loss of efficiency from field speed, 62 and 66 percent (P=0.2041) (Table 3) between Auburn and Groveland respectively. Standing biomass was a significant covariate (P=0.0279), implying that higher harvester material capacities place a greater performance demand on the collection system. A greater distance to the landing or short term storage also places a higher demand on the collection system. Because of the longer haul distance (7 km) to short term storage at Auburn, it would have been better served by more trucks. Unfortunately, trucks are also less tolerant of irregular or wet ground conditions and are more susceptible to tire damage especially when headlands are limited. The collection systems assembled for the Auburn and Groveland harvests utilized different collection systems that were considered the best available options based on previous experience over the course of this three-year project and in consultation with landowners at these locations. While the components of the systems and its layout were quite different, the overall efficiency of delivery of material to short term storage was similar.

There are very few studies available that have monitored the components of entire harvesting systems in SRWC. Schweier and Becker [30] report C_m's between 14.6 and 27.6 Mg_{dry} hr^{-1} which includes turn times; accounting for their reported moisture content of 55% this translates to 26.6 and 50.1 Mg_{wet} hr^{-1}. This is comparable to our reported values of 53.9 and 56.2 Mg_{wet} hr^{-1} (Table 2) for Auburn and Groveland respectively. Interpolating from Schweier and Becker's [30] reported data, their average losses due to the physical turns ranged between 16 and 39% and total losses in headlands between 19 and 63%. Their values compare similarly to our losses due to the physical turn between 16 and 24%, and 36 to 37% for Auburn and Groveland respectively. Observing the operator work, there is an art to spontaneously devising an optimal harvesting pattern that works for the harvester and makes best use of the collection vehicles. There are a myriad of patterns to choose from that minimize operator effort on turns, make best use of field conditions, and ease transitions for collection vehicles [24]. This is an important area where improvements in the system can be made in the future.

Field Delays

The harvester was very efficient during these harvests; 90% of loads at Auburn and 83% of loads at Groveland were greater than 90% efficient down the row. Delays in the field usually occurred due to minor problems such as jammed stems or adjusting speeds for collection vehicle exchanges. Longer delays are due to breakdowns or extended waits for collection vehicles. Overall, extended delays (> 5 minutes) comprised only 13 percent of the total number of delays that occurred at Auburn and 6 percent of the delays at Groveland; however, they accounted for 56 and 75 percent of the total amount of delay time in the headlands respectively. There was no significant difference in the length of extended delays between harvest locations (P=0.5117 - gamma distribution), or in the distributions of the delays less than 5 minutes (P=0.7055 - gamma distribution). The resulting loss in efficiency due to headland delays was 21 and 11 percent at Auburn and Groveland respectively, but the cumulative effect of headland turns and delays was approximately 33 percent for both sites. Auburn had a more significant loss of efficiency associated with headland delays (P = 0.0012) principally due to extended idle time while collection vehicles returned from the 7-km haul distance, compared to the 1-km distance at Groveland. There were also problems at Auburn with sidewall damage to truck tires and flat tires as they attempted tight turns to enter and exit the headlands that contributed further to this problem.

Headland Turns and Delays

Recommended headland widths for short rotation willow are over 8 meters in order to provide sufficient room for the harvester and collection vehicles to turn [7, 35, 36]. Due to lack of experience with SRWC, many landowners are used to planting traditional agricultural crops right up to the field edge. This was a particularly difficult problem at the Groveland site where headlands on the back edge of the field were often less than 4 meters and bounded by large trees and a fence line; Auburn headlands had more room and were bounded by drainage ditches, which offered a slightly less challenging situation. As a result, both sites had considerable drops in efficiency caused by the physical turning of the machinery at the ends of the rows (not including delays/holds) (Tables 2-3). There were significant differences in the frequency of headland delays between the two harvest sites ($P < 0.0001$ - gamma distribution), the primary difference being the frequency of delays lasting longer than 5 minutes; likely being due to the long wait times due to the distance to short term storage. Over 90 percent of headland delays were less than 60 seconds. The distributions of headland turn times (delays excluded) were not significantly different at the two harvests using traverse distance as a covariate (P=0.2565 - gamma distribution). Mean (median) turn times (delays excluded) were 106 (54) seconds at Groveland compared to 81 (39) seconds at Auburn. Overall, 81 percent of turn times (delays excluded) were less than 90 seconds, and only 5.5 percent were greater than 5 minutes.

Logistic Implications

This study was not positioned to resolve the logistic issues faced in the Auburn and Groveland scenarios. Determining the optimal number and type of collection vehicles or harvesting patterns for a given sized field and distance to short term storage is the domain of logistic models such as the Integrated Biomass Supply and Logistics Model (IBSAL) developed at Oak Ridge National Lab [34], or the Biomass Logistics Model (BLM) developed by the Idaho National Lab [37]. However, several lessons are clear from the data that was collected from these harvests: (1) the C_m of the harvester used in this study is consistent over a wide range of standing biomass expected for willow stands in a 3-4 year growing cycle, which should simplify the logistic challenges faced when planning harvesting operations; (2) if short-term storage site is to be employed, it should be located as close as possible to the harvest site; and (3) the design of the field at the time of planting needs to take into consideration the needs of harvesting operations, particularly as it related to headlands.

Drop Losses

There were significant cultivar ($P = 0.0245$), drop category ($P < 0.0001$), and cultivar by drop category interactions ($P = 0.0054$) for drop losses for the Fish Creek and SV1 cultivars at Auburn (Table 4). Mean standing biomass was 25.5 and 19 Mg_{dry} ha^{-1} and drop losses were 2.1 Mg_{dry} ha^{-1} for Fish Creek and 1.5 Mg_{dry} ha^{-1} for SV1 . The rate of drops calculated against the overall standing biomass indicates overall drop losses are around 8%. Six loads were closely tracked from the field to delivery and drop losses for those loads were closer to 6%. Unmerchantable shakes account for an average of 44% (standard error 2.6%) of the total amount of biomass left by the harvester, and ranged between 15 and 88% at individual plots.

Fish Creek plots had a higher amount of total drops and merchantable drops (Table 4). The harvester operator has frequently stated a preference for working in Fish Creek stands in the past due to the ease of operations associated with the straight stems; however, Fish Creek stands had almost three times the biomass of cut stems that were not fed into the harvester compared to SV1. A possible explanation is that the straightness of Fish Creek stems prevents them from becoming intertwined with other stems as they are gathered by the header and conveyed to the throat of the harvester. However, cultivars with a great deal of stool spreading and "goosenecking" require a great deal more concentration on the part of the harvester operator and so over time and large areas may impact the efficiency of the operation. Although the inference space of this analysis is limited to these two clones at one site, the issue with stem entanglement may be important to examine in more detail in the future.

There are very few studies that report losses from SRWC harvesting operations and the limited data has been collected differently. Berhongaray et al. [16] reported drop losses for a New Holland harvester platform between 1.05 and 3.23 Mg_{dry} ha^{-1}, which comprised between 10.7 and 27.7% of the standing biomass and varied depending on former land use, which may be indicative of site topography. Although their range is comparable to our value of 1.8 $\mathrm{Mg_{dry}\ ha^{-1}}$, as a percentage of standing biomass our drop losses were considerably lower. A possible explanation could be that there is a relatively consistent rate of dropped material associated the harvesting platform; therefore on a percent basis, stands with lower biomass will have a larger proportion of losses. Based on our results, the distribution of dropped material is highly variable at a plot level and requires a high sampling rate. The experimental replication used by Berhongaray et al. [16] was four 1-$\mathrm{m^2}$ plots per harvest system, which also may have been inadequate, based on the variability observed in the 24 14-$\mathrm{m^2}$ sample plots used for this study.

Conclusions

Two harvests were conducted in willow biomass crops between November 2012 and February 2013 in New York State; 153 loads were tracked using GPS data loggers. Ground conditions were very good, and the forage harvester was kept at or near 100% for the majority of cutting time. There was a dichotomous relationship between C_m and standing biomass on loads collected with greater than 90% efficiency. C_m increased linearly with speed in rows with less than 40 - 45 $\mathrm{Mg_{wet}\ ha^{-1}}$ of standing biomass, at which point C_m plateaued between 70 and 90 $\mathrm{Mg_{wet}\ hr^{-1}}$ up to 90 $\mathrm{Mg_{wet}\ ha^{-1}}$ of standing biomass. Between 1.5 and 2.1 $\mathrm{Mg_{dry}\ ha^{-1}}$ of material was cut, but not collected, approximately half of this was non-merchantable meristematic material.

Harvester performance is not static and depends on factors such as machine capability, operator experience, ground conditions, field layout, and crop conditions. In stands with low standing biomass, C_m may be entirely related to the maximum allowable groundspeed without damaging machines or the crop. In stands with high standing biomass within the mechanical limits of the harvester platform, C_m of the harvester may be related to machine capability, crop characteristics, and operator experience. Ultimately, performance patterns are an important consideration when pairing a specific harvester platform to a given SRWC system and projecting economics and logistics.

The performance of two locally sourced collection systems was adequate in the field; there was a 5% loss of efficiency largely due to short pauses to allow collection vehicles to pass through the header or vehicle exchanges. However, there was an overall two thirds loss of C_m between the harvester and delivery to short term storage. There was a 16-24% drop in $C_m$due to the physical turn, another 11-21% drop due to wait times in the headlands, and an additional 35 to 41% drop as chips were delivered to short term storage. The negative impact of improperly sized headlands is clear. Both of these harvests would have been better served by additional collection vehicles and at the Auburn site a shorter distance to short term chip storage would have improved system efficiency. Optimizing the number and size of collection vehicles for a given set of harvest parameters is a challenging logistical problem. When employing a locally sourced collection system, it is clear there is a potential learning curve associated with issues specific to SRWC. Improvements to collection systems should be a key research focus for harvest platforms of this type.

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Table 1 Listing of primary collection vehicles utilized at the Auburn and Groveland NY harvests between Nov 2012 and February 2013, with approximate payloads carried in field.

Vehicle Type	Example	Approximate Willow Chip Capacity (Mg_{wet})	Auburn Collection System	Groveland Collection System
3-axle silage truck	Mack DM690S Mack CH613	10-14	Yes	No
High Dump Sugarcane Wagon	Broussard 4408	10-12	Yes	Yes
Self Propelled Dump Wagons	Oxbo Pixall Big Jack (harvesting head removed)	7	Limited Use	Yes
2-wheel Dump Cart	Richardton 960	5-6	No	Yes

Table 2 Decrease in effective material capacity (C_m) (Mg_{wet} hr^{-1}) for loads as they move through key phases of harvesting and delivery of chips to short term storage, progressing from the idealized harvester operating at field speed* to delivery to short term storage. Columns 1-5 are derived from harvester data, and columns 6-7 are derived from collection system data. Letters indicate significant decreases C_m within site (row) only at the alpha = 0.05 level. Standard deviations are reported in parentheses

Harvest Site	**Number of Loads**	**Standing Biomass Delivered**	**------------------------- Field Components -------------------- **			**--- Headland Components---**		**--- Transport Components - --**	
			(1) Field Speed* Undelayed Harvesting	(2) Column (1) with Harvester Induced Delays Included	(3) Column (2) with Tractor Induced Delays Included	(4) Column (3) with Headland Turns Included	(5) Column (4) with Headland Delays Included	(6) Collection System C_m to Landing	(7) Collection System C_m to Short Term Storage
		Mg_{wet} ha^{-1}	**-- Decreasing C_m (Mg_{wet} hr^{-1}) --**						
Auburn	82	43.4	70.2 A	67.9 B	67.0 B	56.2C	44.8 D		26.4 E
			(11.4)	(12.2)	(12.7)	(12.6)	(17.8)		(15.9)
Groveland	71	70.0	76.6 a	71.9 b	71.7 b	53.9 c	48.2 d	39.9 e	25.3 f
			(12.3)	(15.7)	(15.8)	(14.8)	(16.2)	(20.7)	(11.3)

*field speed defined as “machine travel in the field during an uninterrupted period of functional activity“ [25]

Table 3 Mean percent decrease in effective material capacity (C_m) (Mg_{wet} hr^{-1}) through key phases in the harvesting and logistics systems as individual loads are harvested and transported to short term storage. Phases in the harvesting systems are based n the columns in Table 2. Letters indicate significant differences in columns only at the alpha = 0.05 level.

Harvest Site	**Phases of Harvest and Transport**				
	Decrease due to in-field delays	Decrease due to harvester turns	Decrease due to headland delays	Decrease due to transport to short term storage	Overall Decrease
	-------------------- mean percent decrease in C_m --------------------				
Auburn (82 loads)	4.7 a	16 b	21 a	35 a	62 a
Groveland (71 loads)	6.7 a	24 a	11 b	41 a	66 a
	-------------------- reference columns in Table 2 --------------------				
Harvesting system components from Table 2	Column (1) to (3)	Column (3) to (4)	Column (4) to (5)	Column (5) to (7)	Column (1) to (7)

Table 4 Mean drop losses for twenty, 14 m^2 plots (mean ± SE) after harvesting willow. (1) Uncut stems remained attached to a stool; (2) cut stems were cut by the header, but did not feed into the harvester; (3) drags were clusters of cut stems (oriented the direction of travel with cut ends in almost the same location); (4) shakes include detached, unmerchantable, stem tips that were less than 2.5 mm in diameter. Letters indicate significant differences at the alpha = 0.05 level.

Type	**Drop Losses**	
	Fish Creek	SV1
	Mg_{dry} ha^{-1} (standard deviation)	
Merchantable		
Uncut	0.09 B (0.05)	0.20 B (0.11)
Cut	0.84 A (0.15)	0.28 B (0.04)
Drags	0.34 B (0.07)	0.32 B (0.11)
Total Merchantable	1.27	0.80
Unmerchantable		
Shakes	0.80 A (0.06)	0.65 A (0.08)

Figure Captions

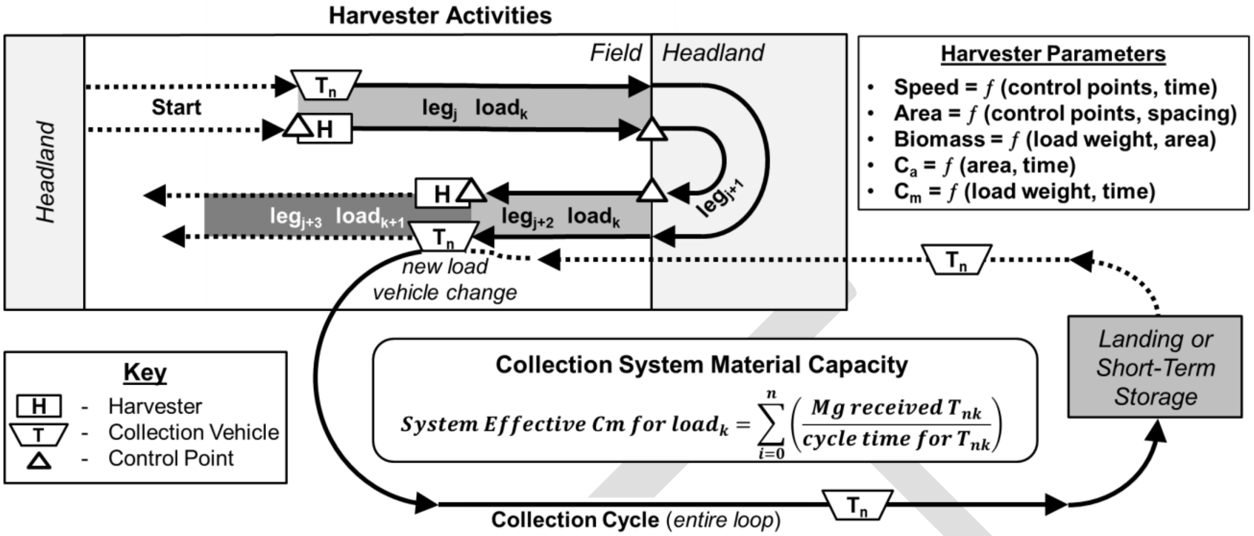

Figure 1 Cycle diagram illustrating how GPS data collected from several vehicles in the harvesting system were processed and summarized. GPS points are combined into unique legs identified by the UTC time stamp of their control point (e.g. entering or exiting the field for the harvester, engaging or disengaging the harvester for collection vehicles). Legs are combined for individual loads. Events such as vehicle turns can be included or excluded to evaluate the effect of those events on machine productivity. The timing and number of delays and holds for the harvester are calculated within the leg where they occur.

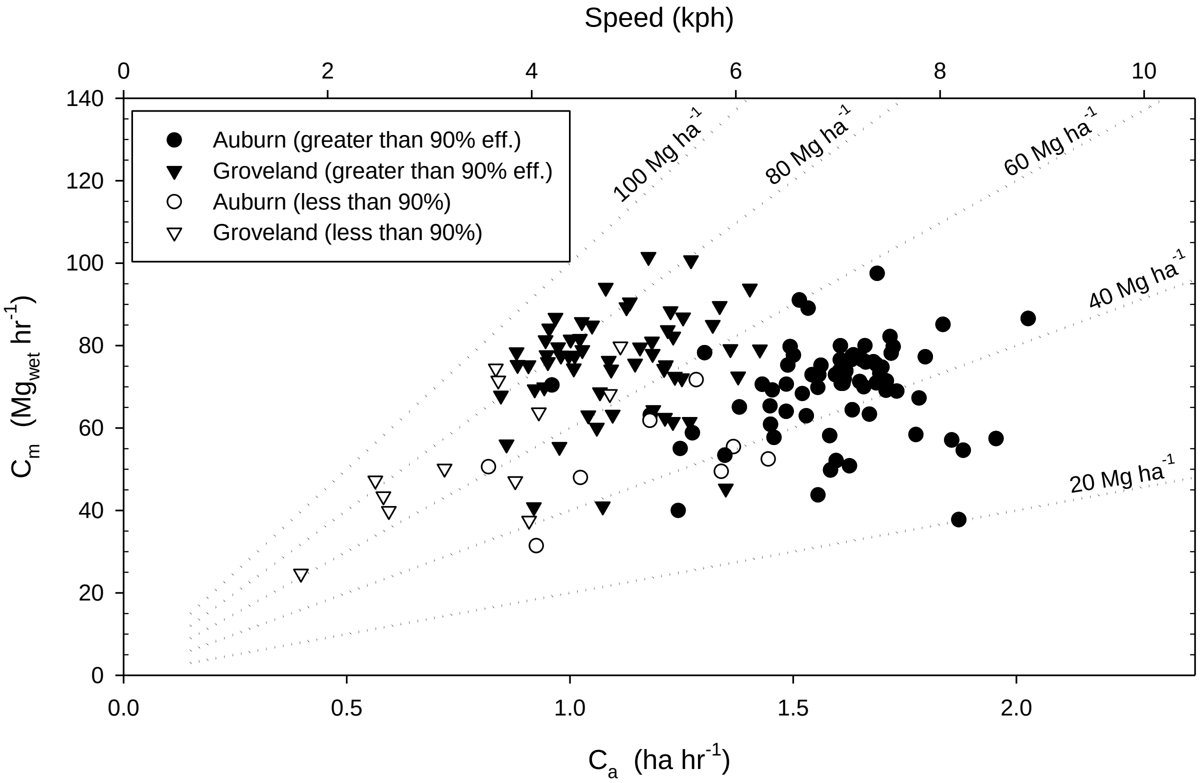

Figure 2 Effective material capacity (C_m) of the harvester in the field, but excluding time in the headlands, plotted against effective field capacity (C_a) and speed for 153 loads collected over 10 days at Auburn and Groveland, NY. Isolines indicate the standing biomass required for a given C_a on the X-axis to achieve a given C_m on the Y-axis.

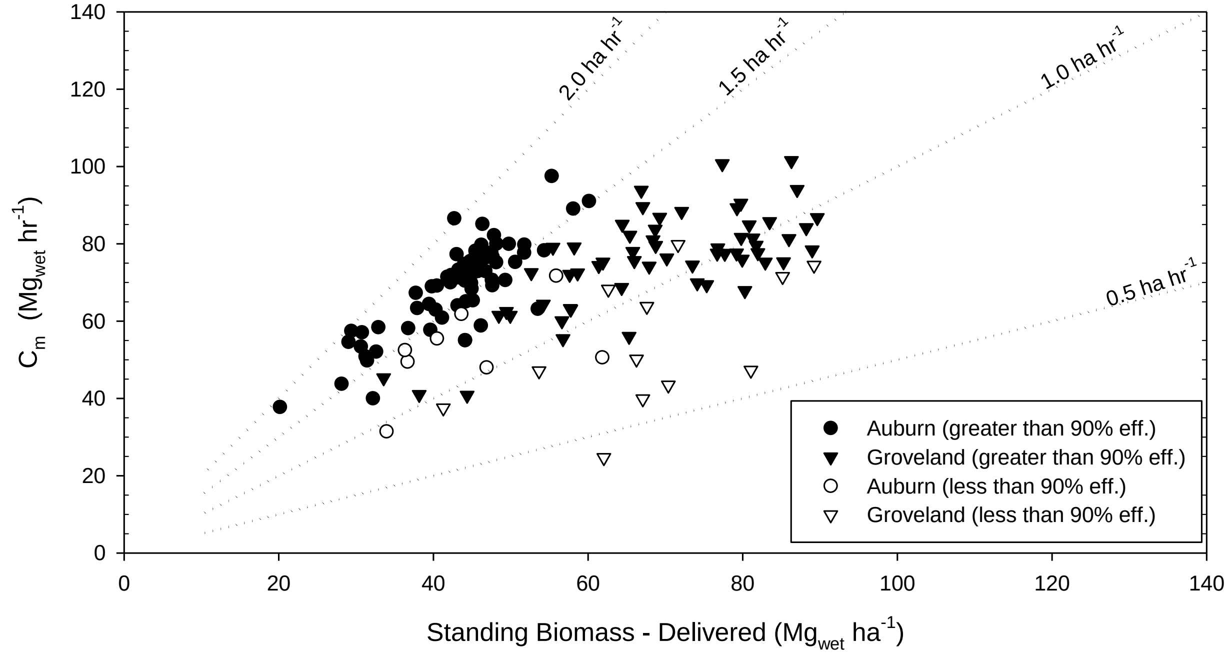

Figure 3 Effective material capacity (C_m) of the harvester in the field, but excluding time in the headland plotted against standing biomass for 153 loads collected over 10 days at Auburn and Groveland, NY. There is a linear increase in C_m as standing biomass increases to between 40 and 45 Mg_{wet} ha^{-1}. Above 45 Mg_{wet} ha^{-1} effective field capacity (C_a) is fairly stable or has a slight positive trend for loads with greater than 90% efficiency. Isolines indicate the C_a required for a given standing biomass on the X-axis to achieve a given C_m on the Y-axis.

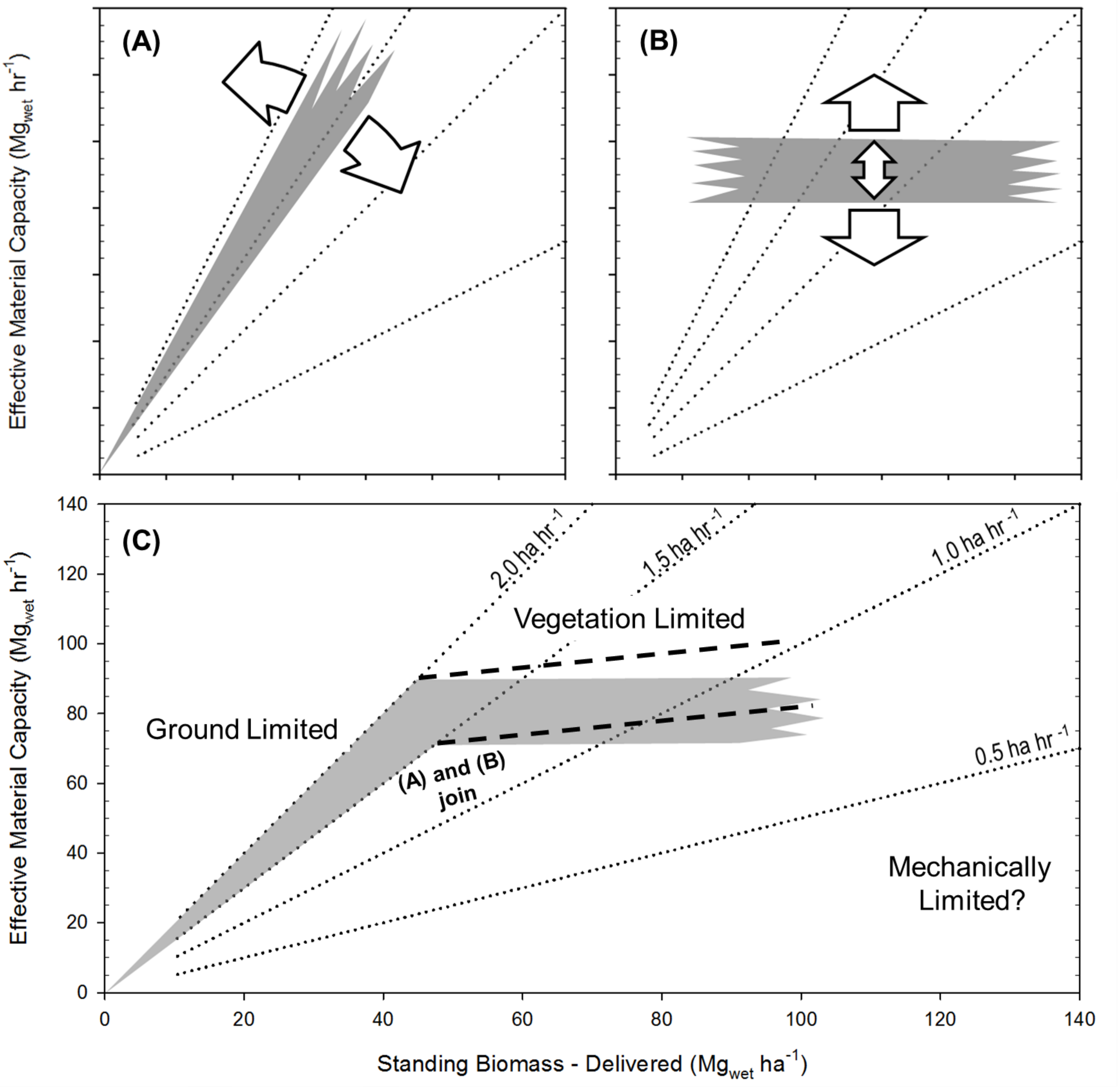

Figure 4 The potential variation in the relationship between effective material capacity (C_m)and standing biomass driven by different harvest factors. With low standing biomass ground speed limits C_m but the pattern will rotate around the origin (A). At higher standing biomass, C_m will be limited by the crop in the field but the location of the plateau and its slope will vary (B). The combined pattern will vary based on site, machine, operator, and crop variables (C). The grey band indicates the majority of data points observed at the Auburn and Groveland harvests. The dotted band represents a potential 2.5 Mg hr^{-1} increase in C_m per 10 Mg hr^{-1} per 10 Mg ha^{-1} increase in standing biomass.