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Harvesting Losses for a Cut-and-Chip Harvesting System Operating in Willow Short-Rotation Coppice

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Abstract: In any short-rotation coppice (SRC) operation, a certain percentage of harvestable material is unrecovered, which contributes to harvesting system losses. This material may be in the form of merchantable and non-merchantable components. These losses affect economics but also influence yield, nutrient cycling, and carbon sequestration. There are very few estimates for harvesting losses available in the literature, and they are limited by small sample sizes. The objective of this work was to provide a broad overview of harvesting losses in willow SRC over a wide range of standing biomass and harvesting conditions. The average total harvesting losses were between 3 and 4 Mg ha^{-1}, which is between 6 and 7 percent of the standing biomass. Losses can spike to nearly 40% on less than 3% of the area. Harvesting losses are significantly, but weakly, correlated with increased standing biomass. These results highlight the complexity and variability in harvesting losses as well as which aspects of harvesting systems might be targeted to reduce or partition material losses. These results have implications for designing machinery and economic modeling of these systems.

Keywords: short rotation coppice; willow biomass; harvesting losses; agricultural and forestry waste biomass

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1. Introduction

1.1. Willow Systems

There is a projected annual potential to sustainably produce over a billion megagrams of biomass for the United States for feedstocks sourced from agriculture, forestry, and dedicated bioenergy crops [1]. Meanwhile, the EU has an objective to source 20% of energy from sustainable sources such as biomass [2]. Latin America also has objectives to offset fossil fuel use [3]. One sector of dedicated energy crop systems in both regions is short-rotation coppice (SRC), which includes willow (*Salix* spp.) and poplar (*Populus* spp.) and could supply 20–25% of this biomass [4–6].

Short rotation coppice includes tree and shrub species that are often grown in an agricultural paradigm; high densities and much shorter rotations than typical forestry crops [7–9]. In the case of willow, they are commonly established by planting dormant cuttings of improved genetic cultivars in double rows at a density of about 13,500 plants ha^{-1} [10,11]. The spacing between double rows accommodates equipment for harvesting or other maintenance. After establishment, the crop is typically harvested on 3- or 4-year cycles, but ideally, harvesting takes place once the crop has achieved a standing biomass of between 30 and 100 Mg$_{wet}$ ha^{-1} [5]. Seven harvest cycles are typically expected to serve as the lifespan for a single planting.

Harvesting is a key part of SRC systems in terms of costs and greenhouse gas emissions [12,13]. The logistics associated with harvesting SRC traditionally represent anywhere from 45 to 60% of the total delivered cost of willow biomass and the cut-and-chip operation of the harvester alone represents about one-third of the delivered cost [12]. Although there have been improvements that reduce costs and improve overall system efficiency [5], the scale of deployment in terms of equipment and personnel to optimize the system has not yet been fielded [12,14,15].

The sources of uncertainty and variation associated with the different SRC harvesting system components and logistics need to be understood [16,17]. For instance, climate change has affected the timing of harvesting operations in New York due to unreliable ground conditions with the onset of winter [18]. This, in turn, affects machine performance, crop regrowth, and nutrient cycling [19]. This information is applied to our understanding of harvesting systems and feedstock supply chains on commercial scales [12,15,20,21]. This type of information is necessary for land managers to optimize decisions and for modelers to evaluate the logistics and costs of these systems.

Many types of specialized machinery have been developed for harvesting SRC [4,22–24]. The current state-of-the-art method employs forage harvesters that cut and chip stems in a single-pass process while filling support vehicles that move material to storage or transport. Generally, machine specifications include 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 material capacity of up to 100 Mg_{wet} h^{-1} [25–27]. One aspect of these systems that is not well understood is how much material is left in the field after harvesting operations.

1.2. Losses and Efficiency

In forestry, woody debris left behind after harvesting operations is commonly referred to as slash or harvesting residues [28]. In agriculture, crop materials lost to any factor are referred to as losses, which may be partitioned due to cause (e.g., weather, disease, harvesting, and storage) or type (merchantable, non-merchantable, drop, etc.) [29]. In this research, the term harvesting losses will be used and is defined as the SRC biomass that is not collected by the harvester and is left in the field following harvesting operations.

The effectiveness of machinery to perform a specific function is generally termed efficiency [29,30]. The rate at which a machine such as a forage harvester processes material is termed material capacity and is typically reported in Mg h^{-1}. The efficiency at which the harvesting machine captures material SRC biomass standing in the field may be termed material efficiency and is reported as a percent of standing biomass in the field. It is important to distinguish these terms as there are some inconsistencies in the manner they are used in the gray and refereed literature. General terms may not include the context of the type or cause, where such partitioning may be relevant.

Scant information is available for accurate estimates of harvesting losses in SRC like willow, and those estimates are somewhat disparate. However, quantifying losses is important because large-scale modeling of biomass supply needs to account for these losses to accurately project supply for large-scale facilities. Past studies use standing biomass yield, which does not account for harvesting losses [14,15].

Quantifying slash and forest floor material is commonly carried out on fixed-area plots and collecting all material within its bounds [31,32]. Berhognary (2013) collected materials following a willow harvest of two-year-old stems using one-meter-square plots [33]. They documented that the quantities of unrecovered biomass range from 1.1 to 3.2 Mg_{dry} ha^{-1}, and material efficiencies as minimal as a few percent to as poor as 68.7 percent on a 2-year-old stand with standing biomasses of only 8 Mg_{dry} ha^{-1}. Harvesting losses for a biobaler system were found to be between 1.28 and 3.61 Mg ha^{-1}, representing 5.7 to 20.1% with a mean of 11.3% measured with 3.2 m^2 main plots and subplots for smaller material [34]. However, large-scale harvesting can result in debris and soil disturbances in patterns that are not captured within a one-meter-square plot. Eisenbies et al. (2005) reported amounts of harvest slash in a forest operation that ranged from 5.6 to 9.1 Mg ha^{-1}, but more importantly, they illustrated the degree of spatial variability in the deposition of slash that can be encountered at scales around 20 m square following harvesting operations on forest plantations [35].

Eisenbies (2014) conducted a pilot study following a commercial willow biomass harvest on a 4-year-old stand with biomass ranging between 40 and 80 Mg ha^{-1}, and harvesting losses between approximately 1.5 and 2.0 Mg ha^{-1} [25]. That study used

2.29 m by 6.1 m plots straddling a conventional double row for SRC willow and scaled to capture larger patterns of residues. The categories of materials collected in these plots were (1) uncut stems that remained attached to a stool; (2) cut stems that were severed from the stool by the header but did not feed into the harvester and ended up left in the field; (3) dragged stem material that appeared to be stems collected and deposited in bundles after being caught in the header for some unknown distance; and (4) shakes—detached, unmerchantable, stem tips that were less than 2.5 mm in 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. Shakes were collected on a subplot measuring 2.29 by 0.31 m.

1.3. Objectives

While information and data on how cut-and-chip systems function in SRCs have improved in the past two decades, key results and relationships, and modeling of large-scale SRC production for biorefineries rely on projected production. Extrapolating results from yield trials in the field or yield maps that are based on yield trials to biorefinery scales lack good information about harvesting losses. Losses of 5–10% in the field for a facility that uses 500,000 Mg a year would require an additional 2500 to 5000 ha of willow to meet facility demand. Information in the refereed literature is somewhat disparate and based on relatively small sample sizes and perhaps undersized plots. The objective of this study is to quantify and characterize harvesting losses and material efficiency for a commercial cut-and-chip harvesting system operating in SRC willow systems in both single-cultivar and mixed-cultivar stands over a range of crop and field conditions.

2. Materials and Methods

2.1. Experimental Design

Harvesting losses were collected following willow harvests over a six-year period using methods developed from a 2012 pilot study [25] (Table 1). The objective was to collect and quantify material representative of a particular range of standing biomass or conditions (e.g., leaf-on or leaf-off condition). Data were utilized only from plots where georeferenced information associated with harvesting machine performance on a wagon-load basis was also collected and developed from the methodology described in Eisenbies (2014). From load data corresponding to each sampled plot, the following data were collected: standing biomass delivered (Mg_{wet} ha^{-1}), harvester material capacity (Mg_{wet} h^{-1}), and harvester field capacity (ha h^{-1}) [25]. Having these data allowed us to examine if these parameters influenced the losses that were measured. Stem ages for willow crops generally ranged from 3–5 years, with one site with some portions of the field where willow was older than 5 years (Table 1).

Table 1. Site locations, demographics, and sampling intensity for willow stands where plots for harvesting losses were established.

Site	Lat/Long	Date	Season	Rotation	Stem Age	Monitored Loads	Harvested Area	Total Sampling Plots
				N	y	N	ha	N
Lafayette, NY, USA	42°58′46.0″ N 76°06′43.3″ W	June 2016	Leaf-on	2 or more	5+	58	5.4	54
Cape Vincent, NY, USA	44°03′05.8″ N 76°16′55.6″ W	October 2016	Leaf-on	1	3	30	32	2
Solvay, NY, USA	43°03′57.6″ N 76°15′43.0″ W	January 2017	Leaf-off	1	4	16	0.6	13
Solvay, NY, USA	43°03′57.6″ N 76°15′43.0″ W	June 2017	Leaf-on	1	4	48	2.7	39
Jacobs, NY, USA	44°07′32.8″ N 76°18′59.7″ W	September/ October 2017	Leaf-on	1	4	199	38	46
Rockview, PA, USA	40°51′33.1″ N 77°47′47.1″ W	March 2019	Leaf-off	2	3	108	14.2	22
Solvay, NY, USA	43°03′57.6″ N 76°15′43.0″ W	January 2022	Leaf-off	2	3, 5	67	3.6	57
Total						526	95.5	233

2.2. Site Descriptions

Six commercial willow harvests conducted between 2016 and 2022 had standing biomass delivered and harvester material capacity and harvester field capacity data collected, making them candidate sites. Harvesting loss data were collected from a total of 233 plots (described below) (Table 1). Willow stands comprised an array of hybrid species, either in blocks of a single cultivar or in blocks where cultivars were mixed at the time of planting (Abrahamson, 2010). Plant spacing was 0.61 m intervals on 0.76 m wide double rows. Double rows were spaced at either 2.29 m or 2.59 m on-center, the latter to better accommodate newly developed harvesting and collection equipment with wider vehicle widths.

2.3. Harvesting Operations

Operations were conducted as a single-pass, cut-and-chip process using a New Holland FR-9080 or FR-9090 forage harvester (Turin, Italy) equipped with a New Holland 130FB coppice header using blades recommended for willow (710 or 760 mm diameter, 4 mm thick with 6 mm Stellite™ tips) [36]. Harvests were conducted in a wide array of weather conditions. The header was equipped with either a push bar for pushing stems forward or a custom hydraulic device that used screw augers to force standing material left and down and facilitate the feeding of tall stems. The material was cut, chipped, and blown into locally hired collection vehicles consisting of tractor-drawn dump wagons or carts; these vehicles carried loads anywhere from 6 to 12 Mg of fresh material. The length of cut selected by the operator was the largest setting ("33-mm") to maximize fuel economy and harvesting rate; this chip size was also preferred by end users of the material. Harvester performance and standing biomass were determined on a load basis using methods described by [18,25].

2.4. Collection of Harvesting Losses

Study plots were stratified across the range of standing biomass for a given harvest and randomly located along rows (Figure 1). Two lengths of sample plots were utilized over the course of this study: 3.05 m and 4.57 m. Plot width matched the nominal row width for the site (nominal widths of 2.29 m or 2.59 m). Shorter plots were adopted later in the study to increase spatial coverage and address specific research questions. Data from all plots were reported on an area basis. Losses were collected by hand. The categories for stem material were cut, uncut, and dead (Table 2). Two randomly located 0.31 m wide subplots within the main plot were used for small materials: shakes and wood chips (Figure 1). Where possible, cultivars were identified based on the geolocation of loads where only one cultivar was present. In cases where the cultivar was unknown or multiple cultivars filled the wagon, they were labeled as "mixed".

Dead stems were not encountered in large amounts until an effort was made to locate fields with higher amounts of standing biomass for leaf-off harvests (>60 Mg ha^{-1}). These stands were harvested in Solvay, NY, in January 2022. Once harvesting started and loss data were collected from some initial plots, it became apparent that a larger proportion of dead stem material was present in the loss plots than previously encountered. As a result, an additional category of dead stem material was added to the sampling protocol. Determination of dead stem material on the ground was qualitatively based on the integrity and apparent moisture of the bark and wood.

To sample a plot, the ends were established using a fixed-length chain and the sides were by the center of the wheel tracks (Figure 1). If the cut or broken end of a stem was within the plot boundary, the entire piece was collected whether other parts were in the plot or not. If the cut or broken end was not inside the plot, the entire piece was discarded whether other parts of it were inside the plot or not. Once the plot was established, it was initially screened so borderline "in" and "out" pieces could be sorted, placing them further in or out while avoiding trafficking the main plot. Next, the subplots for shakes and chips were randomly located and sampled before walking within the plot boundaries. Finally, large material was collected, categorized, reduced in size using sheers, and placed in paper bags. Materials were oven-dried at 65° C to a constant weight.

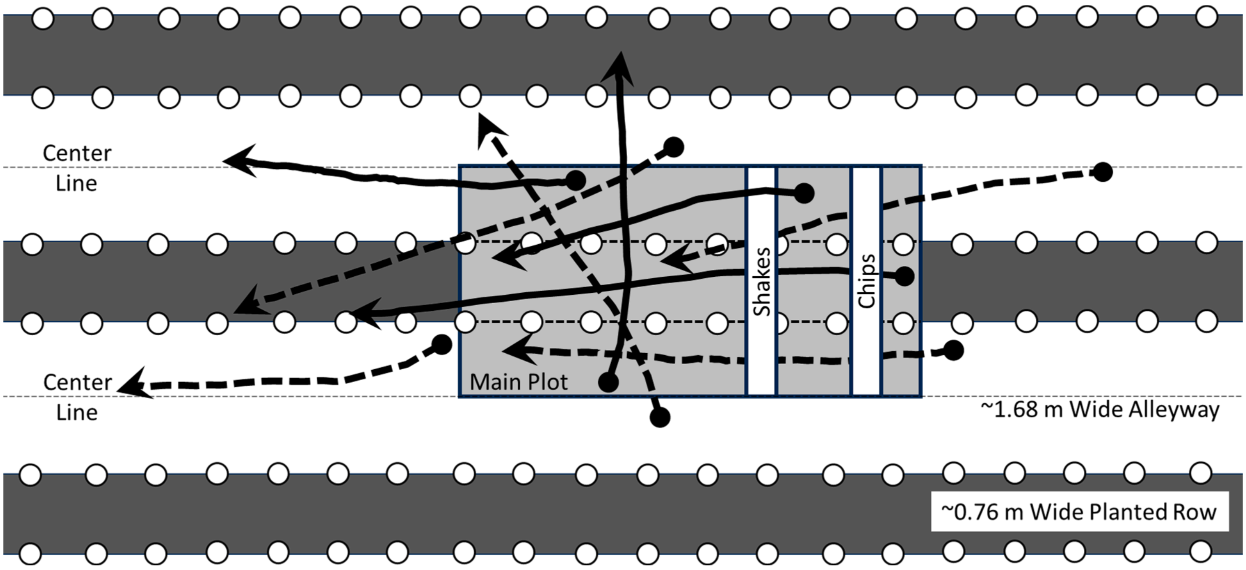

Figure 1. Diagram of variably sized, main sampling plot to measure harvest losses from single-pass cut-and-chip harvester. The width of the plot covers the space occupied by a single double row of willow (plants are indicated by open circles) and is either 2.29 or 2.59 m wide. Chip and shake subplots were randomly located within the main plot. Lines represent stems or stem pieces with the dot representing the cut end of the stem and the point representing the stem tip. Solid lines indicate stems that would be sampled; based on sampling protocol, the entire stem is sampled. Dashed lines indicate stems that would not be sampled; based on sampling protocol, the entire stem is discarded.

Ancillary studies were conducted to address some ad hoc and post hoc research questions that were raised over the course of the larger inventorying project. The same stand was harvested at Solvay, NY, in two different rotations, which provided opportunities to sample harvesting and compare interior and edge plots during leaf-on and leaf-off harvesting. Plots were installed to assess if losses were greater at the point where the harvester entered or exited a field in comparison to points when the harvester was moving along a row. Sampling was designed using plots that straddled the edge of the field where the harvester entered or exited (edge plots) and sampling was conducted away from the edges of the field (interior plots) in different cultivars so that harvesting losses at row entries, row exits, and interior plots could be compared for different seasons. Edge plots were placed so that half the length of the plot was in the willow stand and half was in the headland.

A field with high-standing biomass (>60 Mg ha^{-1}) was included in the harvested area at Solvay in 2022 to increase the number of samples with harvesting loss data from higher-biomass stands. This stand was five years old at the time of harvest, so older than the typical 3–4-year rotation for SRC willow. After harvesting, it was noted that the proportion of dead material on the ground following harvesting appeared higher than was typical. It became apparent that a high proportion of the dead material did not get processed by the harvester and was instead left on the site. Aside from creating a sub-category for this material, several post hoc plots were established in some remnant uncut areas to determine the proportion of live:dead wood in standing trees within the high-biomass stand. Diameter distributions for 3.05 m plots were used to calculate basal area, which is generally proportional to biomass without requiring height measurement [37,38].

Table 2. Definitions of the different components of harvested biomass collected in loss plots.

Component	Definition	Determination	Units
Cut	Willow stems with a diameter at the base >2.5 mm that were fully severed from stool but left on the ground	Hand collected, main plot	Mg_{dry} ha^{-1}
Uncut	Willow stems with a diameter at the base >2.5 mm that were not fully severed from stool	Hand collected, main plot	
Shakes	Non-merchantable (due to shape) willow stems <2.5 mm collected from random subplot	Hand collected, shake subplot	
Chips	Chipped woody material that was processed by a forage harvester, but found on the ground	Hand collected, chip subplot	
Dead	Dead willow stems lying on the ground	Hand collected, entire plot	
Total harvesting losses	Sum of cut, uncut, shakes, chips, and dead material	Calculated	
Merchantable harvesting losses	Sum of harvesting losses including cut + uncut + chips + dead —or—total harvesting losses − shakes	Calculated	
Stem harvesting losses	Sum of harvesting losses including cut + uncut + dead material	Calculated	
Standing biomass delivered	Dry weight of biomass in the collection vehicle over the area where the material was harvested on a load basis	Time–motion study methods [18,25]	
Adjusted standing biomass	Standing biomass delivered plus total harvesting losses, not including chips	Calculated [34]	
Percent merchantable losses	Merchantable harvesting losses/adjusted standing biomass	Calculated	%
Merchantable losses in place	Merchantable harvesting losses minus chips	Calculated	
Percent merchantable losses in place	Merchantable harvesting losses in place/adjusted standing biomass	Calculated	

2.5. Statistical Methods

Summary statistics for percentile groupings (based on total harvesting losses) were calculated using the UNIVARIATE and MEANS procedures (SAS 9.4). Analysis of variance was used to test simple comparisons of harvesting losses between seasons and percentile groupings using the GLIMMIX procedure. A factorial design was used to evaluate cultivars, entries, exits, and interior plots using the GLIMMIX procedure (SAS 9.4); however, the cultivar was eliminated as it essentially represented standing biomass and was determined to confuse the results.

Regressions were conducted using the REG and ROBUSTREG procedures (SAS 9.4). Several dependent variables were considered (total harvesting losses, merchantable harvesting losses, and merchantable harvesting losses in place) (Table 2) and their percentage of standing biomass was determined; a log transform was used to normalize the data. A minority of plots (8) had exceptionally high amounts of biomass due to wagon spillage, header jams, or other reasons; thus, the data used for this modeling were restricted to interior plots in the 5th to 95th percentiles. The full models (Equation (1)) followed the general form,

$$Y = \beta_0 + (\beta_1 \cdot SB) + \left(\beta_2 \cdot SB^2\right) + (\beta_3 \cdot L) + (\beta_4 \cdot L \cdot SB) + \left(\beta_5 \cdot L \cdot SB^3\right) + (\beta_6 \cdot HP) + \varepsilon \quad (1)$$

where:

SB = adjusted standing biomass Mg_{dry} ha^{-1} (Table 2)
L = season (leaf-on = 1, leaf-off = 0)

HP = harvester performance metric
ε = error

The harvester performance metrics material capacity (Mg h^{-1}) and field capacity (ha h^{-1}) were tried as covariates. Candidate models were selected using the REG procedure (SAS 9.4) applying the correlation coefficient, Mallows Cp [39], and backward selection as methods. However, due to the presence of outliers and influential observations, the ROBUSTREG procedure (SAS 9.4) was used to generate final model coefficients; this procedure down-weights outliers and leverage points in the dataset to lower their influence without eliminating "true" observations.

3. Results and Discussion

3.1. Total Harvesting Losses

Across all sites and seasons (leaf-on and leaf-off conditions), standing biomass ranged between 5 and 133 Mg ha^{-1} and harvesting losses ranged between <0.4 and 25.0 Mg ha^{-1} (Figure 2). The data were highly variable with substantial outliers. However, most harvesting losses were under 11 Mg ha^{-1}; 95% of the sampled area was below 10.8 Mg ha^{-1}; 90% was below 8.1 Mg ha^{-1}; and the median was 2.67 Mg ha^{-1}. A slight trend of increasing losses with increased standing biomass was discernable. Total harvesting losses include both merchantable (cut, uncut, chips, and dead) and non-merchantable (shakes) harvesting losses. As a proportion of standing biomass, merchantable harvesting losses ranged between 0.3 and 43.6 percent of standing biomass (Figure 3). Merchantable harvesting losses were <14.2% of standing biomass for 90% of the plots and <23.1% for 95% of the plots; the median was 6.8%.

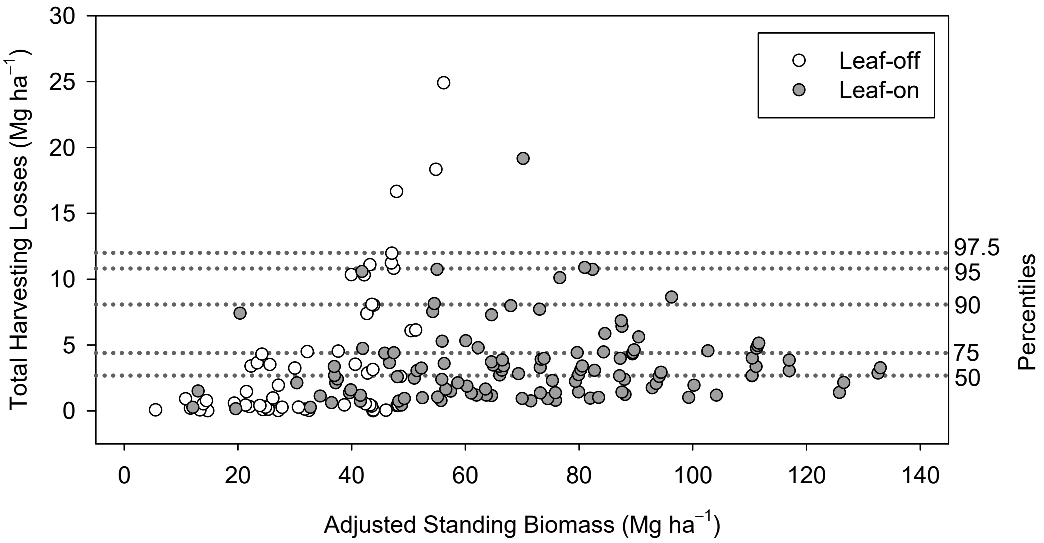

Figure 2. Total harvesting losses for leaf-on and leaf-off harvests from all categories of material (cut, uncut, chips, and shakes) across a range of adjusted standing biomass in willow fields at the time of harvest.

The values in this study are comparable to those found in a pilot study for this work. Eisenbies et al. (2014) reported harvesting losses between 1.5 and 2.1 Mg ha^{-1} in a leaf-off harvest, which represented six to eight percent on stands with standing biomass between 20 and 40 Mg ha^{-1} [25]. This research only included a small number of plots, and compared to plots in this study where the standing biomass values are in a similar range, the results are comparable to the median for other leaf-off harvests in this study. In addition, the harvests in the pilot study were conducted on extremely level and firm ground with an essentially brand-new harvester and header unit, thus essentially ideal conditions.

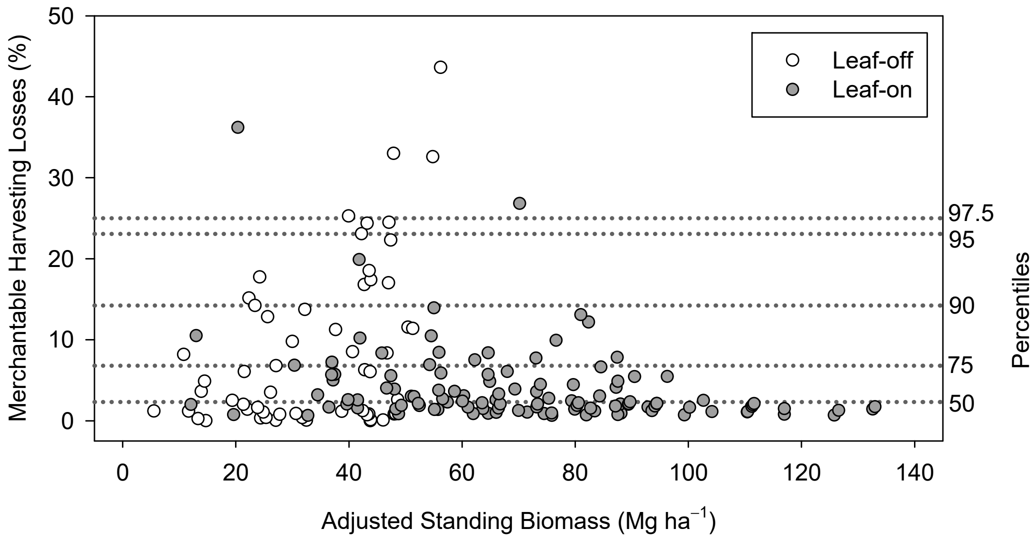

Figure 3. Percent of merchantable harvesting losses for leaf-on and leaf-off harvests across a range of adjusted standing biomass of willow crops.

There are few studies in the refereed literature that report harvesting losses in SRC willow with a cut-and-chip harvester. Berhongaray et al. (2013) reported drop losses including a similar New Holland harvester platform that was between 1.05 and 3.23 Mg ha^{-1}, and average percentage losses of 10.7 and 27.7% of the standing biomass [33]. The absolute value for harvesting losses is consistent with this study, but the reported percentage (>25%) for their forage harvester seems comparatively high given the distributions observed in this study. Their work was conducted on two-year-old stands. A possible explanation for the discrepancies could be that there is a baseline drop rate for forage harvesters, so in young low biomass stands the percentage of dropped material could be higher. This seems plausible given the overall pattern seen in Figure 2. In addition, the experimental replication used was only four 1 m^2 plots per harvest system. The amount of replication in Berhongaray et al. (2013) may have been inadequate, given the type of variability observed in this study with 233 plots over 5 m^2 each [33].

The only other data from short rotation willow were reported by Savoie (2013) for a biobaler system in leaf-on and leaf-off conditions [34]. They collected material from 19 plots that were 3.2 m^2 in size on several fields, but the crop size was not reported. The absolute range of total harvesting losses was from 0.74 to 5.17 Mg ha^{-1}, which is comparable to those observed in this study (Figure 2). However, the mean field losses from individual fields ranged from 5.7 to 20.1% with an average of 11.3%. This value seems slightly higher in terms of percentage than what is reported here for the cut-and-chip system (Figure 3).

3.2. Partitioning of Harvesting Losses

Leaf-on harvests had more observations (118 for leaf-on versus 57 for leaf-off) over a greater range of standing biomass (approximately 10 to 60 Mg_{dry} ha^{-1} for leaf-off and 10 to 130 Mg_{dry} ha^{-1} for leaf-on). Mean total harvesting losses across all the interior sampled plots (N = 175) was 3.55 Mg ha^{-1} (Table 3), which were on average 6.6 percent of standing biomass (Table 4). Overall, there were no significant differences in total harvesting losses between leaf-on and leaf-off seasons, but leaf-on harvests had significantly higher amounts of merchantable and stem drops compared to leaf-off material (Table 3). Those detected differences are due to the influence of dead stems observed on the final harvest in 2022. There were 12 total plots taken where dead material was collected, representing about 20 percent of the total observations for leaf-off material. Within those plots, dead material represented a mean of 36% of total harvesting losses and ranged between 13 and 78%. This suggests that in cases where significant amounts of standing dead material are present, that material may not be processed well by cut-and-chip systems and the amount of material left behind may be higher.

Table 3. Partitioning of standing biomass and harvesting losses for the entire study, season (leaf-on and leaf-off conditions), and percentile groups. Letters indicate significant differences within the column for combined season or combined percentile group rows only. Standard errors are found in the Supplementary Materials, Table S1.

Percentile Group	*N*	Adjusted Standing Biomass	Standing Biomass Delivered	Total Harvesting Losses	Merchantable Harvesting Losses	Stem Harvesting Losses	Cut	Uncut	Shakes	Chips	Dead
						Mg_{dry} ha^{-1}					
					Combined						
All	175	59.13	56.21	3.55	2.81	2.19	1.84	0.14	0.73	0.63	0.20
					Combined Season						
Leaf-off	57	34.11 b	30.62 b	3.81 a	3.59 a	3.28 a	2.56 a	0.09 a	0.22 b	0.32 a	0.63
Leaf-on	118	71.21 a	68.56 a	3.42 a	2.44 b	1.66 b	1.50 b	0.17 a	0.98 a	0.78 a	0.00
					Combined Percentile Groups						
$P_{0–5}$	8	28.36 B	28.33 B	0.03 D	0.03 D	0.02 E	0.02 D	0.00 B	0.01 C	0.01 C	0.00 D
P_5–P_{90}	150	60.91 A	58.70 A	2.71 C	2.00 C	1.5 D	1.32 C	0.14 B	0.71 B	0.50 C	0.04 D
P_{90}–P_{95}	9	59.60 A	51.50 AB	10.04 B	8.33 B	6.39 C	5.49 B	0.14 B	1.71 A	1.94 B	0.76 C
P_{95}–$P_{97.5}$	4	54.59 AB	43.42 AB	11.28 B	10.17 B	10.05 B	7.54 B	0.02 B	1.12 AB	0.12 C	2.50 B
$P_{97.5}$–P_{100}	4	57.29 AB	41.66 AB	19.76 A	19.26 A	15.14 A	11.15 A	0.66 A	0.50 BC	4.12 A	3.32 A
					Leaf-off Condition						
$P_{0–5}$	8	28.36	28.33	0.03	0.03	0.02	0.02	0.00	0.01	0.01	0.00
P_5–P_{90}	40	32.29	30.42	2.27	2.14	1.74	1.52	0.07	0.13	0.41	0.14
P_{90}–P_{95}	3	43.21	32.83	10.49	10.14	10.04	7.77	0.00	0.34	0.10	2.27
P_{95}–$P_{97.5}$	3	45.78	34.49	11.42	10.03	9.90	6.57	0.00	1.40	0.13	3.32
$P_{97.5}$–P_{100}	3	52.99	33.32	19.96	19.40	19.11	13.88	0.81	0.55	0.29	4.42
					Leaf-on Condition						
$P_{0–5}$	0										
P_5–P_{90}	110	71.32	68.99	2.87	1.94	1.41	1.25	0.16	0.92	0.53	0.00
P_{90}–P_{95}	6	67.79	60.84	9.82	7.43	4.56	4.36	0.21	2.39	2.86	0.00
P_{95}–$P_{97.5}$	1	81.00	70.21	10.87	10.60	10.52	10.43	0.09	0.27	0.08	0.00
$P_{97.5}$–P_{100}	1	70.19	66.67	19.15	18.80	3.21	2.98	0.22	0.32	15.62	0.00

Plots are separated into five percentile groupings (0–5, 0–90, 90–95, 95–97.5, and 97.5–100). Among the percentile groups, the 5–90th percentile represents the vast majority of all the harvests where data on losses were collected. The groups are comparable because they represent similar standing biomass, except for the 0–5% group that had lower standing biomass. There were no significant differences in adjusted standing biomass or standing biomass delivered from the 5–90% group and two groups in the 95–100% range. The average total harvesting losses for the reference group, representing 85 percent of the monitored harvesting area, was 2.71 Mg ha^{-1}, between one-third to one-sixth of the total harvesting losses observed in the upper three percentile groups.

The higher total harvesting losses for the upper three percentile groups are associated largely with 4 to 10 times increases in stem wood losses (Table 3). The harvester can be sensitive to large slugs of biomass moving through the header. Sometimes the sheer number of stems that are being felled at the same time cannot be fed smoothly or do not simultaneously fit through the throat of the header, which causes jams. To correct jams, the operator must stop the harvester and reverse the feed rolls, which can lead to stems being dropped on the ground. In other circumstances, cut stems get caught on the uncut stems of plants in front of the harvester, and due to stem form may rotate off into the space between the double rows and away from the header's control.

Table 4. Proportion of biomass as a percentage of higher-order partition for the entire study, and percentile groups. Season (leaf-on and leaf-off conditions) are not presented but can be calculated from Table 3. Standard errors are found in the Supplementary Materials, Table S2.

Group	Standing Biomass Delivered	Total Harvesting Losses	Merchantable Harvesting Losses	Stem Harvesting Losses	Cut	Uncut	Shakes	Chips	Dead
				Percent of Adjusted Standing Biomass					
All	94.6	6.6	5.5	4.3	3.6	0.3	1.1	1.3	0.4
				Percent of Adjusted Standing Biomass					
$P_{0–5}$	99.8	0.3	0.2	0.2	0.2	0.0	0.0	0.1	0.0
$P_5–P_{90}$	96.0	5.1	4.1	3.8	2.6	0.3	1.0	1.1	0.9
$P_{90}–P_{95}$	84.9	18.7	15.8	12.3	10.2	0.3	2.8	3.6	1.8
$P_{95}–P_{97.5}$	78.2	22.1	19.7	19.8	14.1	0.3	2.3	0.2	5.4
$P_{97.5}–P_{100}$	71.0	34.9	34.0	28.0	20.4	1.2	0.9	6.0	6.4
				Percent of Standing Biomass Delivered					
$P_{0–5}$		0.3	0.2	0.2	0.2	0.0	0.1	0.1	0.0
$P_5–P_{90}$		5.5	4.4	3.2	2.8	0.3	1.1	1.2	0.1
$P_{90}–P_{95}$		22.6	19.4	15.3	12.7	0.3	3.2	4.0	2.3
$P_{95}–P_{97.5}$		28.8	25.7	25.5	18.2	0.1	3.1	0.3	7.2
$P_{97.5}–P_{100}$		52.6	51.2	44.7	33.0	1.7	1.4	6.5	10.0
				Percent of Total Harvesting Losses					
$P_{0–5}$			92.4	85.2	85.2	0.0	7.6	7.2	0.0
$P_5–P_{90}$			77.6	62.2	55.7	5.9	22.4	15.4	0.6
$P_{90}–P_{95}$			82.2	62.2	53.6	1.4	17.8	19.9	7.2
$P_{95}–P_{97.5}$			90.1	89.1	67.2	0.2	9.9	1.2	21.7
$P_{97.5}–P_{100}$			97.3	75.7	54.0	3.6	2.7	22.0	18.1
				Percent of Merchantable Harvesting Losses					
$P_{0–5}$					92.8	0.0	na	7.2	0.0
$P_5–P_{90}$					69.8	8.6	na	21.0	0.6
$P_{90}–P_{95}$					63.4	1.9	na	27.2	7.5
$P_{95}–P_{97.5}$					73.7	0.2	na	1.1	24.9
$P_{97.5}–P_{100}$					55.5	3.7	na	22.0	18.8

The other contributors to total harvesting loss outliers include dead wood or chip piles. Dead wood was not observed in the willow crops harvested in this study until the final harvest. This stand included a 5-year-old section that had a higher percentage of standing dead stems than had been previously encountered on younger stands. This dead wood increased harvesting losses substantially, and all the plots of this kind that fell in the dead wood were in the 90% percentile or above. The stand's age and the fact that the location is a former industrial site with unique substrate, with high pH, low nutrient levels, and high salt content, may have contributed to greater stem mortality. The mean dead biomass loss measured in these plots was 2.97 Mg ha^{-1} (approximately 25% of the total harvesting losses on average) and was never collected on previous plots because it was negligible in quantity.

Chipped biomass was another source of increased biomass in outliers. There were four plots with mean chip losses of 4.12 Mg ha^{-1}, and one plot with 15 Mg ha^{-1} (Table 3). So, for a small number of plots, this value was large, but the mean across all plots was only 0.63 Mg ha^{-1}. This occurred when chips were either blown on the ground because a collection vehicle was unavailable, overspray when the collection vehicle was not positioned properly, or spillage when the collection vehicle was full. While not as substantial as stem wood losses, the quantities could still exceed the total mean harvesting losses for the 5–90 percentile group.

In a pilot study [25], shakes were prominent, contributing about 40% of the total losses. In the current study, the overall average was 20.6% of total harvesting losses. Shakes during leaf-on harvests were significantly greater (0.98 Mg ha^{-1} or 28.7% of total losses) than for leaf-off harvests (0.22 Mg ha^{-1} or 5.8% of total losses). Interestingly, the pilot study was a leaf-off harvest and does not follow the trend observed. The harvest for the pilot study was conducted in conditions below −10 Celsius degrees; none of the harvests that have occurred since have been that cold. It is the belief of the authors that the plants were brittle, and the tips of stems broke more easily as the plants were cut and fed through the header. The sampling methodology also took stems whole, any material not separated from main stems (especially unseparated shakes material) was not partitioned. Additionally, the frozen ground in the pilot study made collecting and distinguishing between harvesting losses and ground debris a far simpler task in that effort; shakes were in high contrast to the light snow and not frozen to the ground. In later leaf-off collections, the ground was often wet, unfrozen, and uncomfortable for exposed fingers. The discrepancy between the leaf-on and leaf-off differences in shakes (four times higher on leaf-on material) suggests the collection of material less than 2.5 mm in diameter is possibly affected by conditions. A future solution to this problem could be smaller, fixed area plots for shakes taking material below the 2.5 mm cutoff whether attached to a stem or not.

The interest in shakes was that they are non-commercial in that they tend to lower the quality of chips due to their dimensions and higher bark:wood ratio [25,40]. DeSouza (2020) found that hand-harvesting results in more complete removal of standing biomass compared to commercial harvesting, and harvesting losses contain approximately 20–35% of the total nutrient content while only representing 7 to 15% of the mass of the aboveground biomass [41]. In specific terms, N, P, and Mg were similar between merchantable and shake material, but K, Ca, and S were higher in shake losses. Thus, the loss of shakes is potentially beneficial to SRC both in terms of increasing biomass quality and maintaining site productivity.

3.3. Regression Modeling

Regression modeling yielded several candidate models that illustrate the significant relationship between standing biomass and season on total harvesting losses, merchantable harvesting losses, and merchantable harvesting losses in place as described in Table 3. Transition plots into and out of fields were not included (see ad hoc analysis results). However, r-squares ranged between 0.1 and 0.3, meaning these regressions may be suitable for demonstrating that there is a subtle relationship between standing biomass and harvesting losses when calculating means for entire harvests, but they are unsuitable for predicting losses at individual geographic points. The best-performing model was polynomial and it predicted the natural log of merchantable harvesting losses in place based on adjusted standing biomass ($p < 0.0001$; Equation (2); Figure 4), which had an r-square of 0.261 and a root mean square error of 0.905.

$$\mathrm{Ln}(M) = -1.5926 + (0.597 \cdot SB) - \left(0.0003 \cdot SB^2\right) + \varepsilon \quad (2)$$

where:

M = merchantable harvesting losses in place (Mg_{dry} ha^{-1}) (Table 2)

SB = adjusted standing biomass (Mg_{dry} ha^{-1})

ε = error

It is presumed that the primary reason the models did not perform particularly well is that the standing biomass is derived by weighing a whole load of harvested biomass (typically 5–10 Mg_{wet} that covers a field area of 0.05 to 0.1 ha), whereas the harvesting losses are determined at the plot scale of 10–15 m^2. In future work where plot-level prediction is desired, several factors are worth consideration in such a research effort: plot-level data including biomass, diameter distribution or basal area, standing dead stems, plant height, harvester speed, material capacity, topography, microtopography (e.g., rutting), temperature during harvesting, season, and antecedent precipitation. In addition, large plots should only focus on the cut and uncut size classes. Smaller materials could be used on traditional fixed-area plots decoupled from the main plots. Species or cultivars may also be a factor, but that would likely be colinear with standing biomass and diameters. To examine these differences would likely require a focused effort where standing biomass was carefully stratified within species.

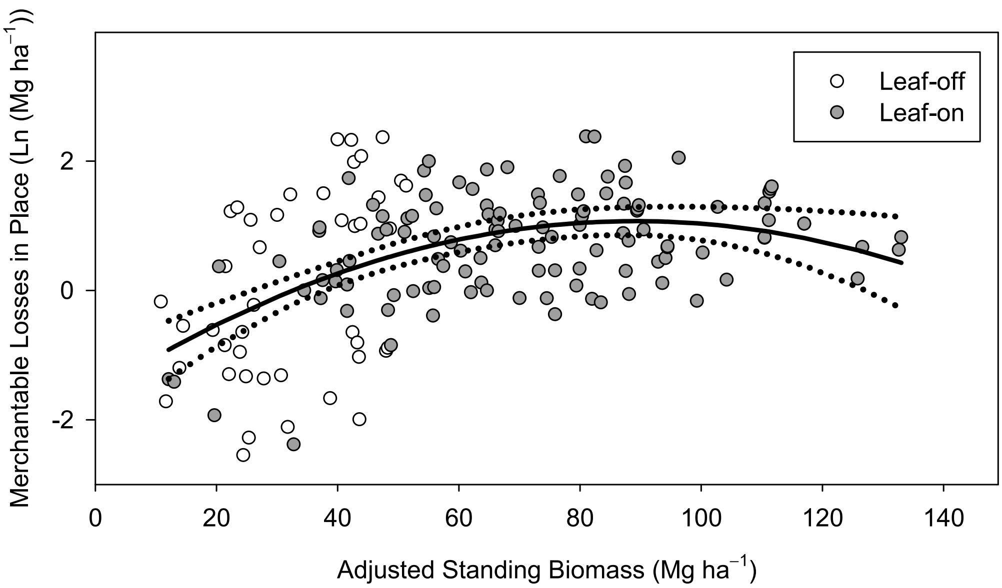

Figure 4. Relationship between the log of merchantable losses in place (Table 2) and adjusted standing biomass for interior plots. Solid line indicates the modeled mean, dotted lines indicate the 95% confidence limits for the mean.

3.4. Harvest Losses during Field Transitions

Over the course of this research, questions were raised by colleagues about potential differences in harvesting losses within the stand versus when the harvester entered and left a stand and about the amount of material that might be carried off the field and deposited in the headlands. Headlands can require vehicle maneuvers in tight quarters so that the header is not aligned with the crop, or the spout is not aligned with the collection vehicle, raising the potential for increased harvesting losses.

The question addressed was whether there were differences between entries and exits in terms of total harvesting losses by season, merchantable harvesting losses, and stem-only harvesting losses. For most of the metrics assessed, there was no difference between entry and exit plots. For total losses, there were no significant differences between entries versus exits (p = 0.7580), season (p = 0.3871), or their interaction (p = 1.0000). Similarly, there were no significant differences in merchantable losses: entries versus exits (p = 0.5982), season (p = 0.7399), or their interaction (p = 0.7427). However, with stem-only losses, harvester exits had 1.99 Mg ha^{-1} versus 1.15 Mg ha^{-1} for harvester entries (p = 0.0419) but did not vary by season (p = 0.6182) or their interaction (p = 0.1713). In addition, the cultivar was eliminated because it was ultimately correlated to standing biomass. Intuitively, this result captures the fact that the header is empty of material while entering stands and potentially full of stems when exiting stands, some of which may be dropped and not pulled into the harvester, especially if the forward motion of the harvester stops when it exits.

A follow-up question was about differences between interior plots and transition plots (entries and exits). Interior plots were found to have significantly higher total and merchantable losses than transitional plots, at values of 50 to 230 percent more (Table 5). However, with stem-only losses, there was only a detectable difference in leaf-off harvests. It seems apparent that the relationship with total harvesting losses between seasons and between positions was predominantly driven by non-merchantable losses (shakes) and chipped losses. The only detectable difference in stem-only losses was interior versus transition plots for leaf-off harvests (Table 5). This result was the reason for not including transitional plots in the regression modeling or partitioning results.

Table 5. Comparison of three types of harvesting losses in interior plots and transitional plots (entries and exits) for leaf-on and leaf-off harvests. Numbers in parentheses are the standard errors. Letters indicate significant differences within the column only.

Location	*N*	Total	Merchantable	Stem-Only
			Mg ha^{-1}	
Interior				
Leaf-off	26	4.12 (0.61) B	3.93 (0.60) A	2.30 (0.61) A
Leaf-on	15	7.03 (0.78) A	4.98 (0.69) A	1.62 (0.66) AB
Transitional				
Leaf-off	17	2.39 (0.33) C	2.29 (0.33) B	1.06 (0.27) B
Leaf-on	12	2.88 (0.44) BC	2.13 (0.31) B	1.41 (0.31) AB

3.5. Ratios of Live to Dead Stems

The question that was addressed based on conditions encountered in the field was related to the amount of dead wood present in the final harvest of this study. The dense, 5-year-old stand had standing, dead stems that were present in sizes and quantities that had not previously been encountered as a significant component of harvesting losses. Before the entire stand was cut, a post hoc survey was conducted to determine the ratio of live:dead cross-sectional area in the uncut stand vs. the ratio of biomass in the adjacent plots where harvesting losses had been collected. Stem cross-sectional area is proportional to standing biomass in willow stands without requiring height measurement [37,38]. Standing biomass had a live:dead ratio of 0.930, which was significantly greater (p = 0.0005) than the proportion of stem biomass collected from the ground, which was 0.742. Dead wood was usually broken up; the assumption was that it was likely more prone to shatter and break up during harvesting operations compared to live stems. It is presumed that dead stems are not flexible enough to clear both sets of feed rolls as live stems; thus, dead wood appears to have a higher propensity to be left behind.

3.6. Implications

Average harvesting losses in the range of 6 to 7 percent provide a good estimate of harvesting losses from cut-and-chip harvesting systems on large-scale SRC operations. While the results from this study show that there is quite a bit of variability in the data, these values do represent data collected across a wide range of crop, field, and harvesting conditions for SRC willow. As a result, they represent a useful addition to efforts to model the supply of willow biomass for large-scale biorefineries or other end users.

While losses found in this study may inspire efforts to improve harvesting equipment, there are trade-offs that need to be considered. For most of the plots with very high harvesting losses, it is possible to minimize these values. Changes in harvesting operations to reduce harvesting losses could address most of the high-percentage loss plots reported here. Attempts to reduce losses from the plots typical of the 90th percentile and lower may not be desirable as they may impact material capacity, material quality, and nutrient losses, creating a complicated cost–benefit problem that should be addressed. Certainly, efforts to improve harvester performance or situational awareness when handling slugs of stem material should be considered along with efforts to reduce spillage of chips, which represents material that has already been moved through the harvester. There is clearly a benefit in terms of nutrient retention from harvesting losses. Observations in the field during harvesting operations indicate that separation of lighter material (i.e., leaves and shakes) begins to occur as material exits the harvester spout and is delivered into collection vehicles. The addition of properly designed baffles in the spout may enhance this pattern and leave more of this fine, higher-nutrient-concentration material on the site. This material is also of lower quality for most biomass end uses so leaving it on site may also improve overall feedstock quality.

4. Conclusions

The primary purpose of this study was to conduct a broad investigation of harvesting losses on short-rotation willow crops. Overall total harvesting losses were between 3 and 4 Mg ha^{-1}, which is between 6 and 7 percent of standing biomass. On a small percentage of the area, harvesting losses can spike to nearly 40% of standing biomass due to slugs of stems that are dropped, spilled chips from the dump wagon, or standing dead wood that shatters. Of the total harvesting losses, approximately 15% consists of non-merchantable material.

There was a slight positive relationship detected between standing biomass and harvesting losses. However, additional work is required to determine the specific causes of harvesting losses. There are a variety of machine performance and environmental factors that could be driving losses.

These results have important implications for scaling up these systems where managers and modelers will need to consider results from yield trials and project the quantity of material being removed from the site for economic or logistics modeling. Machine designers may also consider the partitioning of harvesting losses into components that improve or degrade feedstock quality; some losses appear to be beneficial to the crop and to the feedstock.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17071541/s1, Table S1. Standard errors for values in Table 3. Table S2. Standard errors for values in Table 4.

Author Contributions: The conceptualization of this paper was carried out by M.H.E. and T.A.V. Methodology was designed and refined by M.H.E. and T.A.V. Field work was supervised by M.H.E. Statistical analysis, data curation, and visualization were conducted by M.H.E. Investigation and original draft preparation were conducted by M.H.E. Writing, review, and editing were conducted by M.H.E. and T.A.V. Supervision and project administration were conducted by T.A.V. Funding acquisition was conducted by T.A.V. and M.H.E. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available yet, but will be archived in a data commons in the future.

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