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Switchgrass Harvest Progression in the North-Central USA

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Abstract In the North-Central USA, switchgrass to be used as a biomass feedstock typically will be harvested in the autumn. The accumulated area harvested over the harvest season (defined here as the harvest progression) will influence the size of the machinery fleet and seasonal labor required to complete the majority of the harvest before the first lasting snow. A harvest progression model was developed that uses drying rate, mower and baler productivity, and weather conditions as major inputs. Ten years of weather data (2005–2014) from Wisconsin, Iowa, and Nebraska (WI, IA, NE) were used. Harvest progression was modeled for four harvest systems involving conventional and intensive conditioning both swathed and tedded (CC, IC, CCT, and ICT, respectively) and two dates at which harvest began (1 September and after a killing frost). To reduce risk of exposing crop to prolonged periods of inclement weather, mowers were idled when more than 80 ha were cut but not yet baled. For all sites, the harvest start date and the mower idled constraint had greater impact on harvest progression than the type of harvest system. Harvest progression was greatest when mowing started on 1 September and continued whenever weather permitted (i.e., no mower idled constraint). Compared to the harvest system used today (CC), using the IC system resulted in more area harvested with less crop exposed to rain after cutting and considerably less area left to be baled in the spring. Starting harvest on 1 September, using intensive conditioning, and not idling the mowers might be considered the system that best balances the desire for rapid harvest progression, small equipment fleet size, low-capital expenditures, and maximum labor utilization.

Keywords Baling · Conditioning · Drying · Harvest · Switchgrass

Introduction

The Renewable Fuels Standard (RFS) that originated with the US Energy Policy Act of 2005 and was expanded with the Energy Independence and Security Act (EISA) of 2007 has a long-term goal of reaching 36 billion gallons of renewable fuel by 2022 [1]. Although starch-based feedstocks currently dominate renewable fuel production, the ambitious EISA goals will only likely be met through the addition of fuel derived from lignocellulosic sources including crop residues, perennial grasses, and double-cropped annuals. Switchgrass (*Panicum virgatum*) is considered an important perennial grass feedstock because it does not have annual establishment requirement, it can be grown on marginal land, is relatively drought tolerant, and produces large quantities of biomass [2].

Switchgrass typically is harvested and packaged with conventional hay-harvesting equipment. In the Southern USA, switchgrass can be harvested in the autumn after senescence and then throughout the winter and early-spring months as weather permits [3]. Delaying harvest beyond December resulted in an average 5.4% decline in harvested biomass per month in Oklahoma [4]. In northern climates, early-spring harvest can occur after the snow thaws, producing feedstocks with low ash and moisture [5]. Spring harvests also extend the harvest season, dilute equipment fixed costs over more area and hours, and expands the feedstock temporal availability, reducing the needs for extensive storage. However, over-

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winter yield reductions of up to 40% have been reported [5] and spring harvest can be delayed or even prevented due to late snowfalls, severe crop lodging, and muddy conditions [6, 7]. Delayed harvest could also encroach upon nesting season and increase nest disturbance of important or endangered avian species [8]. To limit risks associated with spring harvest in northern climates, it is anticipated that most large-scale end users will harvest in the autumn.

Timely harvest, aggregation, and placement into storage are required for perennial grasses to be competitive with other biomass crops. The progression of switchgrass harvest through the autumn depends on harvest start date, crop drying rate and weather conditions, and machine productivity. Harvesting perennial grasses after senescence or a killing frost removes fewer crop nutrients from the soil and increases stand life [9]. Stand loss can occur in switchgrass if there are fewer than 6 weeks between when harvest ends and the first killing frost [10]. However, delaying harvest until after a killing frost will cause equipment and labor conflicts with row-crop harvest and the window between a killing frost and a lasting snow (i.e., snow cover that lasts till spring) can be short in northern climates. Short harvest seasons require large equipment fleets to insure harvest before the first lasting snow. Switchgrass standing moisture in the early autumn is typically greater than 65% wet basis (w.b.) moisture [11, 12]. The crop would ideally be field dried to less than 22% (w.b.) moisture to insure conservation during storage and economical transport to end use. Field drying rate of perennial grasses has been found to be proportional to solar intensity, vapor pressure deficit, and wind speed and inversely proportional to soil moisture and swath density [13–15].

Hay producers are often highly capitalized with equipment to insure timely harvest of high-quality hay crops intended for livestock feed. The market value of these crops is greater than grasses to be used as biomass feedstocks, so this high level of capitalization may be justified. Delivery of cost-competitive grass feedstocks to large biorefineries will require optimizing the size of the harvest equipment fleet. The size of the harvest fleet required and resulting capital expenditures can be estimated by modeling the progression of grass harvest through the autumn. A harvest progression model can also be used to estimate seasonal labor requirements and labor utilization. Harvest progression is primarily dependent upon mower and baler productivity, crop drying rate, weather conditions, and field proximity.

The objectives of this work were to (a) develop a model of switchgrass harvest progression based on weather data and a model of switchgrass drying rate; (b) to execute the model using weather data from three different locations across the Northern USA; (c) to investigate the influence of grass conditioning system, swath density, and harvest start date on harvest progression; and (d) to estimate the effect these variables have on several economic factors.

Model Approach

Switchgrass harvest was assumed to involve mowing with a self-propelled windrower (SPW), field drying to less than 22% (w.b.) moisture, and then baling with a large square baler (LSB). To form a harvest team with compatible field productivity, one SPW was coupled with two LSB. The SPW was equipped with an integral tedder so, if desired, wide-swath drying could be accomplished without an additional field operation [16, 17]. To determine which days mowing or baling could take place, an hourly time-step model was developed that used historical weather data from three locations (see below). Weather, tractive conditions, and switchgrass moisture constraints were applied to determine if a day was considered a working day (i.e., mowing and/or baling permitted) or a non-work day (Fig. 1).

Rather than set an arbitrary daily work duration, environmental conditions were used to determine the beginning and end time for either cutting or baling. These operations were only allowed when solar radiation was greater than 100 W m^{-2} and relative humidity was less than 70%. Other important model assumptions and constraints are summarized in Table 1.

Mowing could commence only if there was less than 3-mm precipitation that day, the soil could support traction, and there was no excess crop already cut but not yet baled (Fig. 1). The latter condition was applied because baling had stricter constraints than mowing, and it was desired not to expose more than 80 ha of cut crop to a prolonged period of inclement weather. However, the extent of switchgrass losses due to prolonged time between cutting and baling are unknown, so the analysis was also done without this "mower idled" constraint. An intermediate operation of raking was required anytime switchgrass was dried in a wide swath (to narrow the swath to LSB pickup width), if any treatment had not been baled in 7 days, or if any treatment experienced precipitation greater than 5 mm after cutting but before baling. Baling could begin when constraints shown in Fig. 1 were met.

Tractable conditions occurred when the soil moisture content allowed travel by the SPW or tractor and LSB without causing significant soil damage [18, 19]. Mowing or baling of perennial sod crops like switchgrass are "surface" operations (i.e., non-tillage) so fields are considered tractable even when top-layer soil moisture is greater than the field capacity [20].

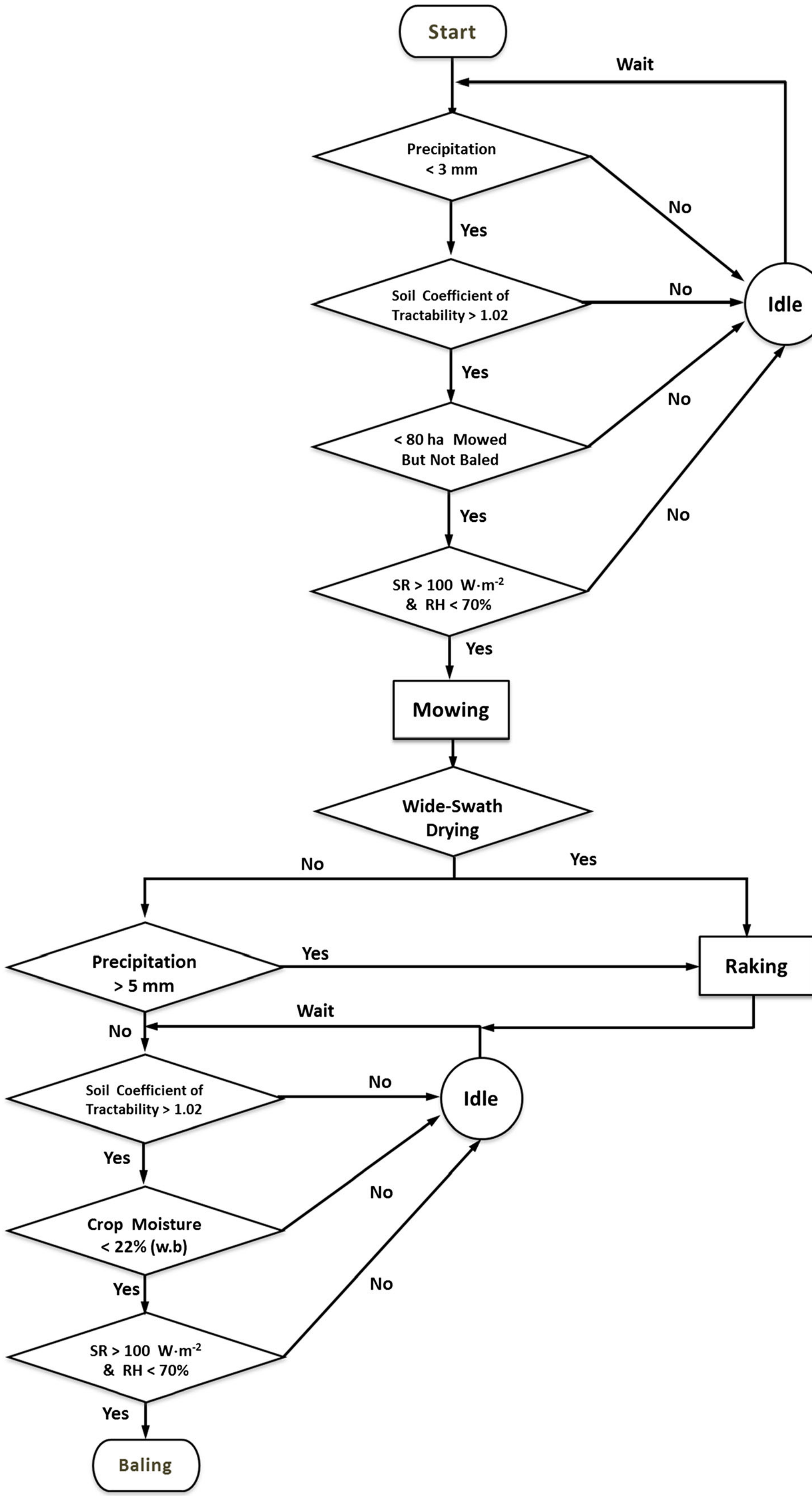

Fig. 1 Flowchart of decision conditions, constraints, and process order for harvest progression model

The model used the procedures and governing equations suggested by Rotz and Harrigan [20] and Hwang and Epplin [21] to determine if soil conditions allowed safe field traffic.

After the crop was cut, the model used weather data to estimate switchgrass moisture content. Weather data used included precipitation, relative humidity, solar radiation, vapor pressure deficit, and wind speed. A "parcel" was defined as the area of crop mowed per hour, and drying rate constants (Eq. 1 from [17]) and the thin-layer exponential grass drying model (Eq. 2 from [22]) were used to track the crop moisture of each parcel (see Nomenclature):

$$k = \frac{0.67(\mathrm{SI}) + 237.7(\mathrm{VPD}) + 205.4(\mathrm{CD}) + 449.6(\mathrm{RK})}{4.01(\mathrm{SD})} \tag{1}$$

$$M_t = M_{t-1}e^{-k(t)} \tag{2}$$

The time required to reach acceptable harvest moisture was affected not only by drying but also by rewetting from dew or rain. Models for dew and rain absorption suggested by Rotz [23] were used here. Switchgrass was assumed to absorb dew as a function of the moisture ratio, swath density, and time:

$$M_t = M_e + (M_{t-1} - M_e)e^{\frac{-(t)(WR)}{(SD)}} \tag{3}$$

Equilibrium moisture was modeled as an exponential function of relative humidity and wind speed [23].

$$M_e = e^{-2.5(1-RH)}\left(0.4 + 3.6e^{-0.2(WS)}\right) \tag{4}$$

Rewetting from rainfall was assumed to be proportional to the amount of rainfall [23]:

$$M_t = 4.0 + (M_{t-1} - 4.0)e^{\frac{-(WR)(P)}{(SD)}} \tag{5}$$

As switchgrass begins to senesce in the early autumn, its standing moisture begins to decline with time. An estimate of standing crop moisture was required to predict the time to 22% (w.b.) moisture. Published data from several sources was used to develop a relationship between date and standing moisture for switchgrass grown in the Northern USA [12, 17, 24, 25]. The relationship was modeled as a second-order polynomial which resulted in an R^2 = 0.85 (Fig. 2):

$$\mathrm{M}_0 = -0.0000359 \cdot \mathrm{JD}^2 + 0.0154939\,\mathrm{JD} - 0.9875 \tag{6}$$

These equations along with the constraints and decision points were developed into a comprehensive model that was

Table 1 Assumptions and constraints used to predict switchgrass harvest progression

Parameter	Assumption or constraint
Mower area productivity (AP_{SPW})—conventional conditioning	5.0 ha h^{-1}
Mower area productivity (AP_{SPW})—intensive conditioning	4.6 ha h^{-1}
Baler area productivity (AP_{LSB})	3.0 ha h^{-1}
Number of balers per mower	2
Maximum mower lead ahead of balers	No more than 80 ha cut but not yet baled[a]
Swath density for CC and IC harvest systems (i.e., not tedded)	1800 (g DM) m^{-2} equivalent to swath 50% of cut width [17]
Swath density for CCT and ICT harvest systems (i.e., tedded)	1125 (g DM) m^{-2} equivalent to swath 80% of cut width [17]
Daily start and end time limitations	Relative humidity (RH) <70% and solar insolation >100 W × m^{-2}
Date of killing frost	Day when temperature <−1 °C for 2 h
Maximum allowable baling moisture	22% (wet basis)
Workable day for either mowing or baling	<3 mm precipitation
Raking requirement	Any parcel that has not been baled within 7 days of cutting or last raking event, any parcel that experienced >5 mm rain after cutting, and all wide-swath treatments
Biorefinery annual dry mass requirement	300,000 Mg DM
Switchgrass dry basis yield	9.0 (Mg DM) ha^{-1}
Dry matter loss due to autumn rains	5%
Dry matter loss due to overwintering swaths	10%

[a] This constraint was removed under some scenarios considered

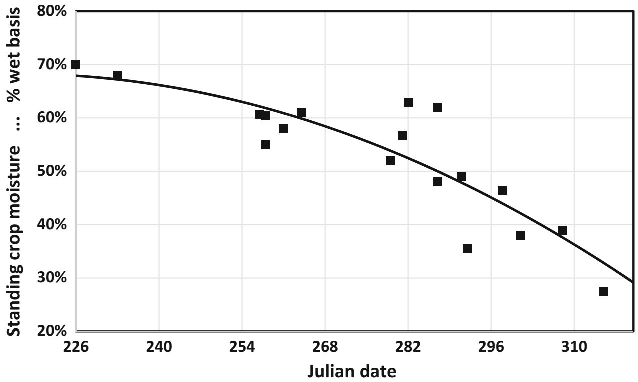

Fig. 2 Standing crop moisture versus date for switchgrass grown in the Northern USA based on data from [12, 17, 24, 25]

programmed using MATLAB (Mathworks Inc., Natick, MA). The model outputs included total area harvested by date, number of workable days for mowing or baling, non-workable days due to rain or traction limitations, fraction of total area exposed to rain, total hours mowing or baling, and area required to be raked due to rain or delayed harvest. The harvest season was assumed to end when there was a lasting snow—i.e., when snow would be expected to be present until the following spring.

Weather Data

Three locations were considered: Arlington, WI; Ames, IA; and York, NE. These sites were chosen as diverse but representative locations where switchgrass might be grown across the North Central USA [26]. The hourly data included average temperature (°C), relative humidity (%), wind speed (m s^{-1}), solar radiation (W m^{-2}), and precipitation (mm). Daily values for evapotranspiration were also used. Climate data from 1 September to 31 December for each year from 2005 to 2014 was used. The Arlington, WI, data were obtained from UW Extension Ag Weather (http://agwx.soils.wisc.edu/uwex_agwx/awon); the Ames, IA, data from Iowa State Mesonet (https://mesonet.agron.iastate.edu/); and the York, NE, data High Plains Region Climate Center's Automated Weather Data Network (http://www.hprcc.unl.edu/).

Scenarios Considered

The effects on autumn harvest progression of two techniques to enhance the drying rate of switchgrass were investigated: intensive conditioning and wide-swath drying (i.e., tedded). Intensive conditioning involved modifying the conditioning rolls to crush the stem along its full length. These rolls also had a differential speed to apply abrasive shear forces to disrupt the waxy epidermis of the stem [17]. Wide-swath drying involved a post-conditioning tedding operation that distributed the crop across about 80% of the cut width. Therefore, four harvest systems were considered: conventionally or intensively conditioned and dried in either narrow swaths or tedded to wide swaths (CC, CCT, IC, or ICT, respectively [17]) (Table 1). In the drying rate model (Eq. 1), these harvest systems would differ by conditioning level (CD) and swath density (SD) (Table 1) [17]. The mower productivity assumed in Table 1 reflects the expected mower speed given the assumed yield of 9 Mg DM ha^{-1}. It was assumed that intensive conditioning would reduce mower productivity by 8% due to greater power requirements of this conditioning system (Table 1).

The harvest season duration impacts many aspects of the feedstock logistics system and harvest costs, so several harvest durations and scenarios were considered. Mitchell et al. [2] recommended that harvesting does not begin until after a killing frost to ensure stand productivity and persistence. But killing frosts are occurring later in the autumn [27], so if inclement winter weather occurs soon after the killing frost, the harvest season may be very short. Starting harvest before a killing frost would provide a longer harvest season which reduces risks and increases equipment and labor utilization, but might decrease stand life. To determine the impact of the start of harvest, two dates were considered: 1 September and after a killing frost (see Table 1).

It was assumed that perennial grasses will not be a widely available commodity that can be purchased on open markets should feedstock availability be limited. Therefore, to insure feedstock availability to a large capital-intensive biorefinery, it was assumed that harvest would take place primarily in the autumn and that only limited overwintering would occur. Samson et al. [28] suggested that overwintering DM losses would be less with switchgrass cut and swathed in the autumn and overwintered compared to delaying mowing until the spring, so it was assumed that sufficient equipment and labor availability would be provided to complete all mowing in the autumn.

Statistical Analysis

Model output data such as area cut, baled or exposed to rain, were analyzed using the Fit Model platform in JMP Pro version 11 (SAS Institute Inc., Cary, NC). Significant differences between harvest systems, site, or start of harvest were determined using factorial analysis of variance with each of the 10 years representing a replicate output of the model. Statistical differences of averages were determined using

Table 2 Duration of autumn harvest season, working time per day, and days during season without rain based on 10-year averages

Start date	Site	10-year average[b] Harvest season duration[c] (days)	Work time per day[d] (h)	Fraction of days in season without rain (percent of total days)
1 September				
	WI and IA	86 b	8.8 a	62 b
	NE	100 a	8.7 a	83 a
After killing frost[a]				
	WI and IA	42 a	7.7 a	69 b
	NE	53 a	7.9 a	94 a

[a] Ten-year average Julian start date 288 or 291 for WI-IA and NE, respectively

[b] Means within a column with different markers (a–b) differ using Tukey's test at $P < 0.05$

[c] Number of days between start date and the first lasting snow

[d] Time per day available for mowing or baling based on constraints shown in Fig. 1

Tukey's test at $P < 0.05$. The model results from WI and IA were rarely different, so these results were pooled during statistical analysis.

Results

The NE site had significantly longer harvest duration due to later first lasting snow and had a greater fraction of the season without rain due to its more arid climate and fewer rain events (Table 2). The harvest duration was essentially halved and the work time per day reduced by 10% at all sites by waiting until after frost to start harvest. The 10-year average Julian start date after a killing frost was 288 or 291 (15 and 18 October) for WI-IA and NE, respectively. The time available per day to work as constrained by weather and daylight conditions (Fig. 1 and Table 1) was not significantly different between sites. Soil conditions prevented safe field traffic in only 2.5% of the days in this study (data not presented).

The NE site had weather conditions more favorable for drying (i.e., greater solar insolation and temperature, lower relative humidity) than the IA or WI sites, so the predicted drying rate constants were greater for the NE site (Fig. 3). The predicted drying rate constants for the CC harvest system were consistently less than the other three systems. The predicted drying rate of the CCT and IC harvest systems were similar, especially late in the season when drying conditions were less favorable. Because there were many factors which dictated when the crop could be baled (Fig. 1), greater drying rate did not always result in statistically significant shorter time between cutting and baling (i.e., time on ground or TOG) (Table 3). Generally, the CC system had the greatest TOG and the ICT system the shortest. Across both start dates, the ICT harvest system reduced TOG by 60% compared to the CC system. The NE site had numerically shorter TOG than WI-IA, although these differences were not always significant. However, differences in TOG between sites were less when only parcels not exposed to rain were considered. Since weather data was only available from specific sites, it was not possible to determine the spatial effects of rainfall. At

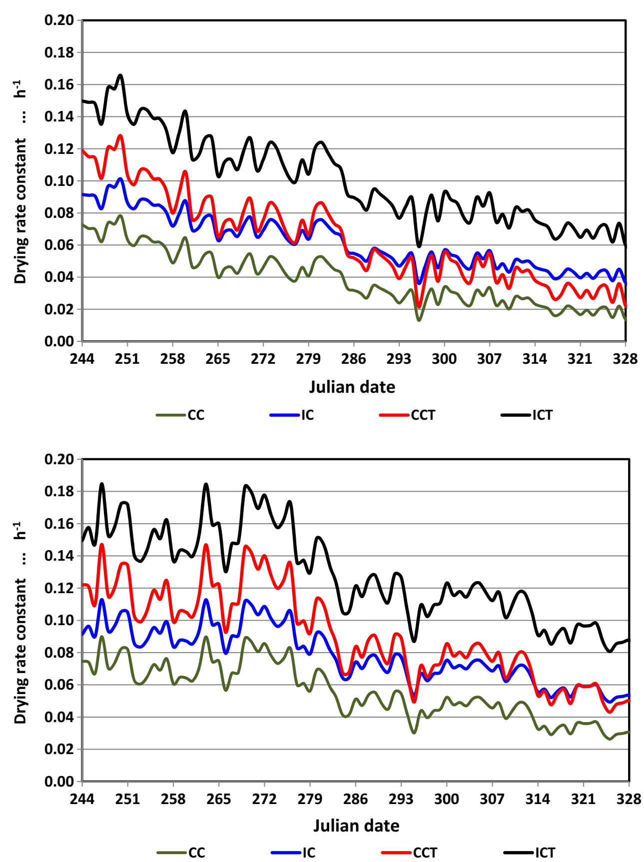

Fig. 3 Average daily predicted drying rate constants for daylight hours for four conditioning or swath-width harvest systems based on 10-year weather data for WI (*top*) and NE (*bottom*)

the WI-IA sites, rain events increased the average TOG by 27 and 42% for ICT and CC harvest systems, respectively. Rain increased TOG only 2 and 12% for these same harvest systems at the more arid NE site where fewer rain events occurred annually. When mowers were not constrained to stop when more than 80 ha was cut but not baled, more area was exposed to rain and the TOG increased, especially for the slower drying CC system. The TOG increased by 36 and 81% at the WI-IA sites and 12 and 108% at the NE site for ICT and CC harvest systems, respectively, when the mower idled constraint was removed. As the autumn harvest season progressed, ambient drying conditions ebbed and the average daily drying rate constants for the daylight hours decreased for all harvest systems (Fig. 3). The slower drying rates were partially offset by the drying of the standing crop before it was harvested, so TOG did not appreciably increase as the autumn progressed despite declining drying conditions. The TOG was longer in October than in September or November at the WI-IA site, but not the NE site.

The CC harvest system is the most common system in use today so it was considered the baseline for comparison in the following discussions [17, 28–30]. When harvest started on 1 September and all the constraints shown in Fig. 1 were applied, the faster drying IC and ICT systems had significantly fewer days with the mower idled, so these systems had greater area mowed and baled (Table 4). The number of days the mower was idled due to excess crop cut but not baled was the main factor that drove differences in area harvested between harvest systems. In the humid climates of WI and IA, the faster drying IC or ICT systems had a smaller fraction of the cut swaths subjected to rain and less crop left to bale in the spring. In the arid NE climate where fewer rain events occurred, the harvest system had no impact on fraction of crop subjected to rain. When the mowers were constrained to stop when more than 80 ha was cut and not baled, the fraction of crop left to bale in the spring was less than 5% of total. The IC and ICT systems improved machine utilization as measured by fraction of the total harvest season duration when mowing or baling could take place. Adding a tedding operation to either the CC or IC harvest systems numerically improved the area harvested, but these differences were not significant.

Table 3 Time (hours) between cutting and baling (i.e., time on the ground (TOG)) for two different mowing constraints

	Harvest	By site				By month			
	System[d]	WI and IA[e]	NE[e]	Average[f]	Site	September[e]	October[e]	November[e]	Average[f]
Mowers idled[a]									
All area[b]	CC	107 a	66 bc	86 x	WI and IA	67 b	88 a	68 b	74 y
	CCT	80 b	44 cd	62 y	NE	46 cd	54 bc	27 d	42 z
	IC	62 bc	39 cd	51 yz					
	ICT	47 cd	27 d	37 z					
Area not exposed to rain[c]	CC	64 a	56 ab	60 x	WI and IA	48 ab	56 a	49 ab	51 y
	CCT	57 ab	39 bcd	48 xy	NE	40 bc	47 abc	35 c	41 z
	IC	47 bc	37 cd	42 y					
	ICT	36 cd	26 d	31 z					
Mowers not idled[a]									
All area[b]	CC	198 a	132 b	165 x	WI and IA	103 b	178 a	92 bc	124 y
	CCT	137 b	91 bcd	114 y	NE	54 c	89 bc	83 bc	75 z
	IC	95 bc	49 cd	72 z					
	ICT	66 cd	30 d	48 z					
Area not exposed to rain[c]	CC	111 a	121 a	116 y	WI and IA	58 b	100 a	78 ab	79 z
	CCT	91 ab	84 abc	87 y	NE	47 b	78 ab	86 ab	70 z
	IC	66 bc	47 c	57 z					
	ICT	47 c	29 c	38 z					

[a] Mowers idled if more than 80 ha were cut but not yet baled, or mowing continued as long as other constraints were met (see Fig. 1)

[b] Averaged across all parcels mowed regardless of whether parcels had been exposed to rain or not

[c] Averaged across only those parcels not exposed to rain

[d] Conventionally or intensively conditioned and dried in either narrow swaths or tedded to wide swaths (CC, CCT, IC, or ICT, respectively)

[e] Data analyzed by full-factorial ANOVA. Means within rows and columns with different markers (a–d) differ using Tukey's test at $P < 0.05$

[f] Averaged across harvest system or site. Means within a column with different markers (x–z) differ using Tukey's test at $P < 0.05$

Table 4 Area mowed and baled per harvest team and fraction of available days when mowing or baling could take place when harvest starts on 1 September

Mowing Constraint		Area				Fraction (%) of total available days		
Site	Harvest system[c]	Mowed (ha)	Baled in fall (ha)	Baled in spring[d] (ha)	Exposed to rain after cutting (percent of total)	Mowing	Baling	Mower idled[d]
Mowers idled[a]								
WI and IA[b]	CC	1164 b	1090 b	74 a	49 a	28 b	39 b	33 a
	CCT	1386 b	1307 b	79 a	35 b	34 b	45 b	28 a
	IC	1816 a	1767 a	49 b	34 b	49 a	58 a	13 b
	ICT	1999 a	1955 a	44 b	25 b	54 a	62 a	8 b
NE[b]	CC	2489 b	2476 b	13 a	7 a	56 c	73 b	27 a
	CCT	3007 ab	2989 ab	18 a	5 a	68 b	79 ab	15 b
	IC	3034 ab	2987 ab	47 b	6 a	75 ab	81 ab	8 c
	ICT	3301 a	3257 a	44 b	5 a	81 a	84 a	2 d
Mowers not idled[a]								
WI and IA[b]	CC	2506 a	1902 a	604 a	43 a	62 a	50 b	
	CCT	2506 a	2031 a	475 a	29 b	63 a	56 ab	
	IC	2306 a	2183 a	123 b	34 ab	64 a	61 a	
	ICT	2306 a	2217 a	89 b	25 b	65 a	64 a	
NE[b]	CC	3718 a	3531 a	187 a	8 a	83 a	78 a	
	CCT	3718 a	3601 a	117 a	6 a	84 a	82 a	
	IC	3421 a	3365 a	56 b	6 a	85 a	82 a	
	ICT	3421 a	3370 a	51 b	5 a	86 a	84 a	

[a] Mowers idled if more than 80 ha were cut but not yet baled, or mowing continues as long as other constraints were met (see Fig. 1)

[b] Means within a column with different markers (a–d) differ using Tukey's test at $P < 0.05$

[c] Conventionally or intensively conditioned and dried in either narrow swaths or tedded to wide swaths (CC, CCT, IC, or ICT, respectively)

[d] Crop mowed in the autumn but not baled until the spring because it was not dry enough to bale before lasting snow

[e] Number of days the mower was idled because more than 80 ha was cut but not yet baled (see Fig. 1)

Eliminating the idled mower constraint considerably increased the area mowed and baled for the 1 September start date (Table 4), especially for the slower drying CC and CCT harvest systems. With this constraint removed, area mowed increased by 37 and 98% in NE and WI-IA, respectively, for these two harvest systems. For these two harvest systems, the area left to bale in the spring was now 22% of the total in WI-IA. In NE, overwintering was still low at less than 5% of the total. For each harvest system and site, the fraction of crop area rained on after cutting did not change much with the removal of this constraint. However, because the overall mowed area was greater, the total area exposed to rain after cutting increased by 40% across all sites and harvest systems.

Delaying the start of harvest until after killing frost and using all of the constraints shown in Fig. 1 curtailed the ability to harvest grasses before the first lasting snow (Table 5). Starting harvest after the killing frost reduced area mowed and baled in the autumn to between 40 and 60% of that when harvest started on 1 September. The fraction of cut crop exposed to rain increased, especially for the slower drying CC and CCT harvest system in WI-IA. There were only small differences in machine utilization between the two harvest start dates.

Eliminating the idled mower constraint considerably increased the area mowed and baled when harvesting started after a frost (Table 5), especially for the slower drying CC and CCT harvest systems. Area mowed increased by 27 and 131% in NE and WI-IA, respectively, for these two harvest systems. The type of harvest system had no significant effect on area mowed or baled when the idled mower constraint was removed. For these two harvest systems, the area left to bale in the spring was now 30% of the total in WI-IA but still less than 5% in NE.

The NE site had significantly ($P < 0.004$) greater area mowed and baled, less area overwintered, less crop rained on after cutting, fewer days with the mower idled, and greater machine utilization than the WI-IA sites across both harvest start dates. When the idled mower constraint was removed, there were no significant differences between harvest systems for most of the performance parameters considered.

Table 5 Area mowed and baled per harvest team and fraction of available days when mowing or baling could take place when harvest starts after frost

Mowing Constraint /Site	Harvest system[c]	Area				Fraction (%) of total available days		
		Mowed (ha)	Baled in fall (ha)	Baled in spring[d] (ha)	Exposed to rain after cutting (percent of total)	Mowing	Baling	Mower idled[e]
Mowers idled[a]								
WI and IA[b]	CC	484 c	410 b	74 a	38 a	29 b	33 b	40 a
	CCT	567 bc	498 b	69 ab	30 ab	34 b	39 b	35 a
	IC	865 ab	819 a	46 bc	27 ab	54 a	56 a	15 b
	ICT	960 a	920 a	40 c	17 b	60 a	63 a	9 b
NE[b]	CC	1467 a	1448 a	19 a	6 a	69 c	80 b	25 a
	CCT	1681 a	1650 a	31 a	5 a	79 b	86 ab	15 b
	IC	1731 a	1701 a	30 a	5 a	89 a	90 a	5 c
	ICT	1787 a	1763 a	24 a	4 a	92 a	93 a	2 c
Mowers not idled[a]								
WI and IA[b]	CC	1206 a	812 a	394 a	38 a	69 a	49 b	
	CCT	1206 a	878 a	329 a	24 ab	69 a	54 ab	
	IC	1110 a	1004 a	106 b	27 ab	69 a	61 ab	
	ICT	1110 a	1042 a	68 b	16 b	69 a	66 a	
NE[b]	CC	1996 a	1878 a	118 a	6 a	94 a	84 b	
	CCT	1996 a	1921 a	74 a	5 a	94 a	88 ab	
	IC	1836 a	1806 a	30 a	5 a	94 a	90 ab	
	ICT	1836 a	1811 a	25 a	4 a	94 a	93 a	

[a] Mowers idled if more than 80 ha were cut but not yet baled, or mowing continues as long as other constraints met (see Fig. 1)

[b] Means within a column with different markers (a–c) differ using Tukey's test at $P < 0.05$

[c] Conventionally or intensively conditioned and dried in either narrow swaths or tedded to wide swaths (CC, CCT, IC, or ICT, respectively)

[d] Crop mowed in the autumn but not baled until the spring because it was not dry enough to bale before lasting snow

[e] Number of days the mower was idled because more than 80 ha was cut but not yet baled (see Fig. 1)

Discussion and Economic Implications

The rate of harvest progression over the autumn harvest season affects the economics of switchgrass harvest [21]. Since the equipment cost and productivity differences were small between the four harvest systems studied, differences in the harvest cost per unit mass would also be small. However, the rate of harvest progression will impact the number machines needed to complete harvest, the annual capital expenditures (CAPEXs) for these machines, the total labor required, and the efficiency at which that labor was utilized [21, 31–33]. In this analysis, it was assumed that a large biorefinery would use switchgrass exclusively as its feedstock. In our analysis, we assumed that commercial enterprises would equip, staff, and manage the entire harvest. If this option was available, producers indicated that this method was preferred over farmer harvested switchgrass [34]. Utilizing commercial third-party custom harvesters to harvest cellulosic biomass was suggested as the most feasible means to manage CAPEX, maintain biomass quality, and produce the lowest cost feedstock [35].

The annual mass of crop harvested per harvest team was a function of yield and area baled:

$$MS_{annual} = Y_{fall}\cdot\left(AB_{autumn}\cdot(1-(A_{rain}\cdot 0.05)) + 0.9AB_{spring}\right) \quad (7)$$

The annual mass harvested per harvest team was reduced in the above equation by assuming that area cut in the autumn and receiving rain after cutting suffered a 5% DM loss and cut crop that remained in swaths overwinter would suffer a 10% DM loss [7]. To form a harvest team with compatible field productivity, one SPW was coupled with two LSB so the size of the

Table 6 Economic implications of starting switchgrass harvest on two different dates

		Start harvest on 1 September			Start harvest after frost		
Mowing constraint/ Site	Harvest system[c]	Number of machines[d,e] needed	Annual CAPEX[f] (mil $)	Total labor use efficiency[g] (percent of total)	Number of machines[d,e] needed	Annual CAPEX[f] (mil $)	Total labor use efficiency[g] (percent of total)
Mowers idled[a]							
WI and IA	CC	97	3.06	29	236	4.76	26
	CCT	81	2.84	35	199	4.41	30
	IC	62	2.56	48	130	3.57	48
	ICT	56	2.54	53	115	3.42	54
NE	CC	44	2.28	58	75	2.72	64
	CCT	36	2.17	70	65	2.55	74
	IC	36	2.20	73	63	2.61	78
	ICT	33	2.20	79	61	2.55	81
Mowers not idled[a]							
WI and IA[b]	CC-CCT	46	2.30	63	95	3.03	64
	IC-ICT	49	2.44	61	101	3.19	62
NE[b]	CC-CCT	30	2.08	86	55	2.42	87
	IC-ICT	32	2.13	82	59	2.57	83

[a] Mowers idled if more than 80 ha were cut but not yet baled, or mowing continues as long as other constraints were met (see Fig. 1)

[b] There were no significant differences in area harvested between the CC and CCT or IC and ICT harvest systems, so economic parameters were averaged across these two harvest systems

[c] Conventionally or intensively conditioned and dried in either narrow swaths or tedded to wide swaths (CC, CCT, IC, or ICT, respectively)

[d] Total number of self-propelled windrowers (SPWs) and large-square balers (LSBs) required. Each SPW was teamed with two LSB

[e] Each LSB would require 150-kW tractor which was not included in the machine count or the CAPEX calculation because it was assumed that the tractors would be leased or rented

[f] Capital recovery of SPW and LSB based on procedures in Turnhollow et al. [36]

[g] Fraction of time spent working over the harvest period assuming 7 days per week and 10 h per day (see Eq. 9)

machine fleet required over the autumn season was a function of the total biorefinery requirements and the annual mass harvested by each harvest team:

$$N_{fleet} = 3 \cdot \left[\frac{MS_{total}}{MS_{annual}} \right] \tag{8}$$

The CAPEX of the total harvest fleet of SPW and LSB was estimated using the procedures suggested by Turnhollow et al. [36]. It was assumed that the harvest enterprises would purchase the SPW and the LSB, but lease the tractors, so tractor costs were not included in the CAPEX analysis. Annual CAPEX was not directly proportional to the number of machines because of differences in annual usage and subsequent machine life.

The number of people required to operate this equipment was assumed to equal the number of machines. Since harvest is so timely, it was assumed that labor would be available 7 days a week and 10 h per day. The labor use efficiency was calculated as the ratio of the time actually spent working over the total available time during the harvest season:

$$EF_{labor} = \frac{1.33 \cdot \left(\frac{A_{\mathrm{SPW}}}{AP_{\mathrm{SPW}}} + 2 \cdot \frac{A_{\mathrm{LSB}}}{AP_{\mathrm{LSB}}} \right)}{\left(3 \cdot D \cdot \frac{10\ \mathrm{h}}{\mathrm{day}} \right)} \tag{9}$$

The 1.33 term in the equation above was based on the assumption that for every hour spent mowing or baling, the operator would spend 5 and 15 min on transport and maintenance, respectively. Unless other tasks can be assigned to maintain an expected income, it may be difficult to attract sufficient labor when a harvest system has low labor use efficiency [37].

When the mower idled constraint was applied, the faster drying IC and ICT harvest systems reduced the number of machines, labor, and capital required, and improved the efficiency of labor utilization (Table 6). Removing the mower idled constraint had a similar effect on these parameters, especially for the CC and CCT harvest systems. The economic advantages of faster drying harvest systems were lost when the mowers were not idled. At the WI-IA sites, the slower drying CC and CCT systems had more crop exposed to rain after cutting (Tables 4 and 5). Losses due to rain were originally set at 5% of DM. Assuming losses increased to 10% had a small impact (<3%; data not presented) on the number of machines, CAPEX and labor efficiency in WI-IA where rainfall was more likely and had essentially no impact on these economic factors in NE where the fraction of crop rained on was less than 10% of total area cut.

Delaying harvest until after a killing frost considerably increased the number of machines, labor, and capital required, especially for the WI-IA sites. Seasonal harvest of grain or silage crops is characterized by a shortage of workers [37]. It is anticipated that attracting enough qualified labor to staff so many switchgrass harvesting machines over a short 6-week harvest season would challenge this harvest approach. Meeting short seasonal labor needs could be met by employing third-party custom forage harvesters that can redirect labor to other tasks after switchgrass harvest, supplementing custom harvesters with local producers, hiring transnational harvesting employees [37], or eventually deploying autonomous cutting machines [38]. The current three largest cellulosic biorefineries primarily use third-party custom harvesters although some farmer harvested biomass is accepted [39]. No matter which harvest model is used, recruiting qualified seasonal labor can be expected to remain difficult [37]. So, perhaps the most important impact of starting harvest early in the autumn and not idling the mowers would be the reduction in the number of people needed and the ability to provide them more payable time over a longer period, providing economic incentives to attract labor. These advantages would need to be balanced against the economic impact of shorter stand life and lower yield that might occur due to early harvest.

Conclusions

Harvest start date and the mower idled constraint had greater impact on harvest progression than the type of harvest system. The most promising harvest system involved the use of intensive conditioning (IC), where cutting started in the early autumn and continued independent of how much crop was already cut but not baled (i.e., no mower idled constraint). Compared to conventional conditioning (CC), this system had less crop exposed to rain and considerably less area left to be baled in the spring. There were only slight economic and labor differences between the two systems. Despite the faster drying rate, tedding either the CC or IC system provided little additional benefit and would require an additional raking operation prior to baling, adding to costs. The impact of losses that might occur when the crop, after cutting, is exposed to prolonged periods of inclement weather needs further study as does the impact of shorter stand life and lower yield that might occur due to early harvest.

Two alternative harvest management strategies could be used to address these concerns. First, the issue of stand degradation associated with early autumn harvesting could be alleviated by harvesting individual fields in early autumn only once every 3 years. For example, harvesting could be scheduled over a 3-year cycle where autumn harvest occurs on 33% of the fields to extend the harvest window, while still harvesting 67% of the total acres after killing frost. By harvesting each field in early autumn only once every 3 years, stand persistence could be maintained and extend the life of the stand. Second, rather than harvesting and leaving the crop on the ground over winter, a small percentage of the total acres or of each field (~5%) could be left standing over winter to provide critical over-wintering wildlife habitat. This would eliminate the areas left to be baled in the spring. The standing crop could then be harvested with the rest of the field the following autumn and new wildlife habitat islands left standing the following year. This strategy would require additional area be established in switchgrass to meet the biorefinery annual needs.

$AB_{autumn,\ spring}$, area baled in the autumn or spring (ha); A_{rain}, fraction of material cut and rained on during fall (decimal); $A_{SPW,\ LSB}$, area harvested by SPW or LSB (ha); $AP_{SPW,\ LSB}$, area productivity of SPW or LSB (ha h^{-1}) (see Table 1); CD, binary conditioning coefficient; 0 for conventional conditioning; 1 for intensive conditioning; D, duration of the harvest season (days); JD, Julian date; k, drying rate constant (h^{-1}); LSB, large-square baler; M_0, wet basis standing crop moisture at time zero (decimal); M_t, dry basis moisture content at time t (decimal); M_{t-1}, dry basis moisture content at previous time $t-1$ (decimal); M_e, dry basis equilibrium moisture content (decimal); MS_{annual}, dry mass harvested per year per harvesting team (Mg); MS_{total}, total dry mass required per year by the biorefinery (Mg); N_{fleet}, total number of both SPW and LSB required to complete harvest; P, precipitation (mm); RH, relative humidity (decimal); RK, binary raking coefficient; 1 on day of raking, otherwise 0; SD, swath density ((g DM) m^{-2}); SI, solar insolation (W m^{-2}); SPW, self-propelled windrower; t, length of drying period (h); VPD, vapor pressure deficit (kPa) [40]; WR, moisture absorption rate (4 g·(m^{-2} h^{-1}) for dew rewetting and 150 g·(m^{-2} h^{-1}) for rain rewetting); WS, wind speed (m s^{-1}); Y_{fall}, switchgrass dry basis yield in the autumn (Mg ha^{-1})

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