Published February 14, 2019

Harvesting Oat Forage at Late Heading Increases Milk Production per Unit of Area

Jeremie R. Favre, Kenneth A. Albrecht, Lucia Gutierrez, and Valentin D. Picasso*

Forage & Grazinglands

Abstract

Oat (*Avena sativa* L.) is a widely used forage crop in the USA and globally, often integrated in dairy systems where it provides the benefits of diversifying crop rotations. As the forage harvest occurs at a later date, forage yield is expected to increase while nutritive value is expected to decrease. To determine the optimal maturity stage to maximize milk production, a 2-year experiment with two forage-oat cultivars (ForagePlus and Laker) and four harvest times (boot stage, 2 days after boot stage, heading, and 5 days after heading) was established in a randomized complete block design with three replications at two locations in Wisconsin, USA. Laker reached the boot stage 4 days earlier and headed 3 days earlier than ForagePlus. Relative forage quality decreased at the same rate with increasing growing degree-days for both locations, years, and cultivars. Therefore, to maximize milk production per cow through feeding the highest nutritive value forage, harvesting oat at boot stage is recommended. Forage yield increased linearly with increasing growing degree-days for both locations, years, and cultivars, with steeper slope in Arlington than Madison due to precipitation differences. Model estimates of milk production per hectare in both cultivars increased linearly across the four harvest dates in Arlington. In Madison, milk production per hectare did not change significantly with harvest date. Harvesting oat for forage at late heading can therefore increase milk production per hectare, since the greater forage yield compensates for the reduction in forage nutritive value.

Core Ideas

- Oat forage harvested in late heading increases yield and milk production per hectare.
- Oat cultivar Laker reached boot and heading 3-4 days earlier than ForagePlus.
- Thermal units (GDD) should be used to report maturity time instead of calendar date.

Global Relevance of Oat Forage

Oat is the most widely used cool-season annual forage in the Northern Great Plains of the USA and represents a major source of forage for livestock around the globe (Fraser and McCartney, 2004). In recent years, 1.3 million ha (3.2 million acres) have been planted with oat in the United States and 61% were harvested for forage (USDA-NASS, 2017). Oat was also grown for forage on 1.25 million ha (3.1 million acres) in Brazil (Harper et al., 2017) and 1.3 million ha (3.2 million acres) in China (Wang, 2004). Large-scale production in Europe, Australia, Japan, northern Africa, the Himalayas, and Pakistan also has been reported by Suttie and Reynolds (2004). Additionally, diversifying corn and soybean-dominated rotations with cereals such as oat has the potential to reduce pests, weeds, and disease pressure and increase farm sustainability by reducing chemical inputs and erosion (Faé et al., 2009; Liebman and Schulte,

Agronomy Dep., Univ. of Wisconsin-Madison, Madison, WI 53706. *Corresponding author (picassorisso@wisc.edu).

Received 15 June 2018.
Accepted 4 Dec. 2018.

Conversions: For unit conversions relevant to this article, see Table A.

Crop Forage Turfgrass Manage.
5:180046 doi:10.2134/cftm2018.06.0046

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source: https://doi.org/10.24451/arbor.10030 | downloaded: 18.4.2024

Table A. Useful conversions.

To convert Column 1 to Column 2, multiply by	Column 1 Suggested Unit	Column 2 SI Unit
0.304	foot, ft	meter, m
25.4	inch	millimeter, mm (10^{-2} m)
0.405	acre	hectare, ha
1.12	pound per acre, lb/acre	kilogram per hectare, kg/ha
5/9 (°F – 32)	Fahrenheit, °F	Celsius, °C

2015; Sindelar et al., 2016). Oat forage can be grown for hay, pasture, or silage, which can be incorporated in dairy rations for high-producing cows, where it can replace corn silage in 10% of the diet (Harper et al., 2017) or fed in large quantities to beef cattle (Stevens et al., 2004). In the US Midwest, oat can be used in a double-cropping system where it is harvested as dairy-forage and followed in summer by soybean, pearl millet or sorghum, hence maximizing annual forage production (McMillan, 2016).

What Is the Optimal Maturity Stage for Harvesting Oat Forage?

The existence of a trade-off between forage dry matter (DM) yield and forage nutritive value is well known and affects every grass as the leaf-to-stem ratio decreases when the plant matures (Nelson and Moser, 1994). The nutritional value of oat forage follows the same trend (Erickson et al., 1977; Fraser and McCartney, 2004) and scientists have traditionally recommended that dairy producers harvest oat forage at the boot stage based on the assumption that forage nutritive value should be prioritized above forage DM yield (Schrickel et al., 1992; Fraser and McCartney, 2004). This idea is well established among farmers and actively spread by extension services (Rankin, 2014; Barnhart, 2011). Whereas forage nutritive value is an important factor for high-producing dairy cows, milk production per hectare- and not per ton– can be an alternative metric for dairy producers using oat as the main source of feed for their milking cows, dry cows, and heifers. We therefore combined selected forage nutritive value parameters and forage DM yield using the "MILK2016" model from Undersander et al. (2016) to answer the question of the optimal maturity stage to harvest oat forage for maximizing milk production per unit of area.

Oat Cultivars

Considering the interest in dairy-grade oat forage in the USA, especially in the upper Midwest, it is necessary to address this question with modern cultivars. ForagePlus is a forage-type oat cultivar released in 2001 and is described as exceptionally high yielding (WCIA, 2017). It was the top yielding forage cultivar of the Wisconsin Oat and Barley Performance Tests from 2013 to 2017 with a forage DM yield of 9002 kg/ha (8030 lb/acre) at heading in 2017 (Mochon and Conley, 2013, 2014, 2015; Gutierrez and Conley, 2016, Gutierrez et al., 2017). Laker is a newer forage-type oat cultivar released in 2017. It is described as very high yielding with similar nutritive value as ForagePlus, and had a forage DM yield of 7892 kg/ha (7040 lb/acre) at heading in 2017, not different from ForagePlus (Gutierrez and Conley, 2016, Gutierrez et al., 2017).

Experimental Design and Treatments

Both cultivars were grown as part of the 2016 and 2017 Wisconsin Oat and Barley Performance Tests comparing 16 cultivars (Gutierrez and Conley, 2016, Gutierrez et al., 2017) at the Arlington (43.30′ N, 89.21′ W) and West Madison (43.06′ N, 89.53′ W) Agricultural Research Stations in Wisconsin, USA, on Troxel silt loam soil of moraine origin and Plano silt loam soil of till plain origin, respectively. The previous crop at both locations was soybean and no fertilizer was applied to the oat, following extension recommendations (Ruark and Wood, 2011; Mallarino et al., 2015). Research fields were prepared for planting with conventional tillage and seeded in rows 0.15 m (6 inches) apart and at a density of 90 kg/ha (80 lb/acre). In 2016, planting was performed with a Wintersteiger four-row planter on 23 April at Madison and with a hand-pushed, single-row planter on 27 April at Arlington. The 2017 planting was performed with a 10-row planter on 9 April at Arlington and on 10 April at Madison. Weeds were controlled chemically at both locations and years with a mix of 2,4-D (46.5% a.i.) and Harmony Extra (50% a.i.) at the rate of 110 g/ha (1.57 oz/acre) and 17 g/ha (0.24 oz/acre), respectively.

The experimental design was a randomized complete block with three replications and treatments arranged as a complete factorial with two factors: (1) cultivar, with two levels: ForagePlus and Laker; and (2) maturity stage at harvest with four levels: boot stage, 2 days after boot stage, heading, and 5 days after heading. Boot stage was reached when 50% of the reproductive stems in the plots reached the R0 stage from Moore et al. (1991), which corresponds to Feekes 10 and Zadoks 45 (Feekes, 1941; Zadoks et al., 1974). Heading was reached when 50% of the reproductive stems in the plots reached the R3 stage from Moore et al. (1991), which corresponds with Feekes 10.5 and Zadoks 59. The plots were 0.6 m wide by 1.5 m long (2 ft by 5 ft) in 2016 and 1.5 m wide by 5 m long (5 ft by 15 ft) in 2017. Alleys were 2.4 m (8 ft) wide between blocks and 0.3 m wide (1 ft) between plots.

Forage was hand-harvested from two 1-m rows in the center of each plot in 2016 (0.3 m^2) and from four 1-m center rows in 2017 (0.6 m^2), at a stubble height of 5 cm (2 inches).

The four harvest dates ranged between 15 June and 1 July in Madison and between 21 June and 2 July 2016 in Arlington. In 2017, harvest dates ranged between 19 June and 3 July at both locations. Harvested plants were placed in paper bags and dried in a forced-air dryer set at 55°C (130°F) directly after harvest and weighed after a 5-days drying period to extrapolate forage DM yields based on the harvested area. Samples were sent to the University of Wisconsin Soil and Forage Laboratory (Marshfield, WI) where they were ground to pass a 1-mm screen with a Christy hammer mill (Christy-Turner Ltd, Ipswich, England) and analyzed for nutritive value composition using Near Infra-Red Spectroscopy (NIRS) with an equation calibrated for grass hay. Parameters of interest included acid detergent fiber (ADF), neutral detergent fiber (NDF), NDF digestibility after 48 h (NDFD), and crude protein (CP), all expressed on a percentage of the dry-matter basis. The model fit (R^2) for the NIRS predictions for ADF, NDF, NDFD, and CP was 0.93, 0.96, 0.87, and 0.98, respectively, over 700 samples (Stammer, personal communication, 2018). The relative forage quality (RFQ) is an index that estimates the nutritive value of forages relative to that of fresh full-bloom alfalfa; it was calculated according to Undersander et al. (2001) by combining forage DM intake with total digestible nutrients, both calculated from NIRS-estimated parameters (NDF, NDFD, CP, ether extract). A RFQ of 100 indicates a nutritive value equal to that of full-bloom alfalfa before preservation. Milk production per ton of forage was calculated with the MILK2016 equation from Undersander et al. (2016), which calculates the amount of energy available to the cow for milk production after subtracting the maintenance energy from the total ingested energy, estimated from CP, NDF digestibility (48h), and non-fiber carbohydrate. Our central parameter, the calculated milk production per hectare, was then estimated by multiplying forage DM yield per hectare (in tons) and milk per ton of forage. A key assumption of our approach was that oat forage was the only forage in the ration for the dairy cows, which is not true for most dairy systems in the region where oat forage is mixed with corn silage, alfalfa hay, and other forages. However, our approach allows for a comparison of the total amounts of nutrients harvested per unit of land allocated to oat, to guide land use decisions for farmers.

Statistical Analyses

A mixed model analysis was performed for seven dependent variables (calculated milk per hectare, forage yield, RFQ, ADF, NDF, NDFD, and CP, referred as ***Y*** in the model below) with the following effects: cultivars (C), harvest maturity stages (H), location (L), Year (Y), and blocks (B- nested within location and years) as well as their respective two, three, and four-way interactions. They were considered fixed effects except blocks which were considered random, and included in the following mixed model: ***Y*** = C + H + L + Y + <u>B(L,Y)</u> + CxH + CxL + CxY + HxL + HxY + LxY + CxHxL + CxHxY + CxLxY + HxLxY + CxHxLxY. No three or four-way interactions were found significant ($P < 0.05$) for any variable and they were later removed from the model. The model assumptions, i.e., the normal distribution of the residuals and the homogeneity of their variance, were graphically tested with a scatter and qq-plot, and statistically tested with the test of Shapiro-Wilk and Levene test, respectively. All assumptions were met. A location by harvest maturity stage interaction was found for most variables, and therefore analyses were conducted by location. Differences between least squared means for cultivars among maturity stages were further investigated using Tukey's multiple-comparison test.

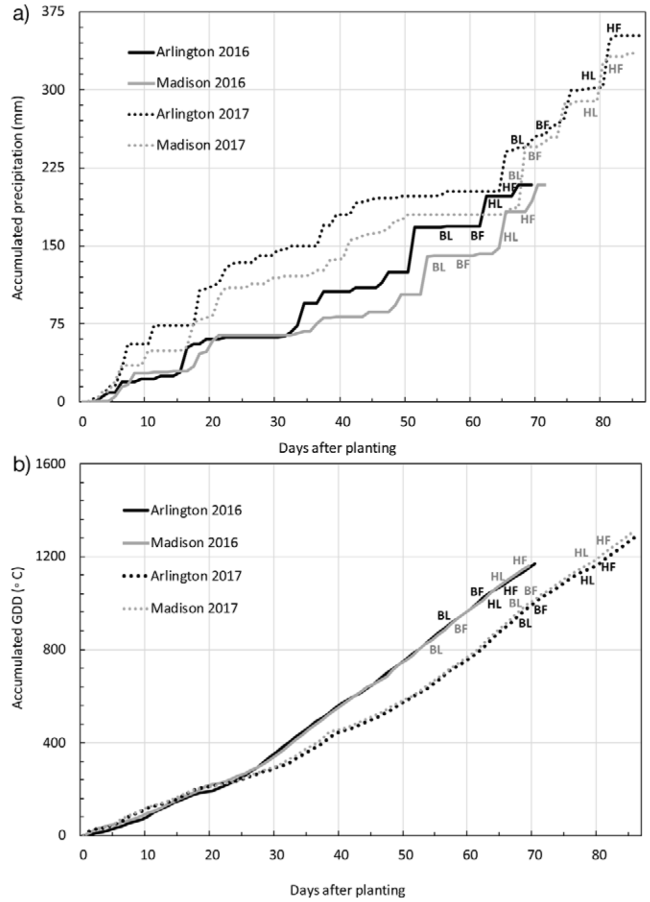

Fig. 1. (a) Accumulated precipitation and (b) growing degree-days from planting date to final harvest date in 2016 and 2017 at Arlington and Madison Agricultural Research Stations, Wisconsin. Days after planting when the boot (B) stage and heading (H) were reached for the oat cultivars Laker (L) and ForagePlus (F) in each location and year are marked with corresponding letters next to each line.

The thermal time accumulation from planting to harvest was calculated based on the average daily temperature records from the National Weather Service (NWS, 2018) and the equation from McMaster and Wilhelm (1997), with a base temperature of 0°C (32°F). To study the changes in calculated milk production, forage DM yield and nutritive value over time, another mixed-model analysis was performed with all independent variables using GDD (instead of harvest maturity stage), cultivar, location and year as fixed effects, blocks as random effect and all two, three, and four-way

Table 1. Degrees of freedom (df) and *P*-values from the analysis of variance of calculated milk per area, forage yield and nutritive value parameters, for the effect of location (Arlington and Madison, Wisconsin, USA), year (2016 and 2017), oat cultivar (ForagePlus and Laker), maturity stage (Boot, Boot +2 days, Heading, Heading +5 days), and their two-way interactions.

	df	Milk per area †	Forage DM yield	ADF	NDF	NDFD	CP	RFQ
Location	1	0.08	**< 0.01**	**< 0.01**	**< 0.01**	**0.01**	0.53	0.32
Year	1	0.06	**0.03**	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**	**0.01**
Cultivar	1	**< 0.01 ‡**	**0.01**	0.24	0.90	**< 0.01**	0.87	**< 0.01**
Maturity stage	3	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**
Location × Year	1	**< 0.01**	**0.03**	**0.03**	0.11	**0.01**	0.26	0.96
Location × Cultivar	1	0.24	0.47	0.75	0.75	0.64	0.71	0.99
Location × Maturity stage	3	**0.01**	**0.01**	0.06	0.12	0.19	0.23	0.10
Year × Cultivar	1	**0.02**	**< 0.01**	0.12	0.50	0.01	0.28	0.10
Year × Maturity stage	3	0.82	0.71	0.40	0.72	0.13	0.17	0.33
Cultivar × Maturity stage	3	0.12	**0.03**	**< 0.01**	0.06	0.17	0.81	**0.01**

† Milk per area: calculated milk production per hectare using MILK16 model (in kg/ha); Forage DM yield: forage dry matter yield (in kg/ha); RFQ: relative forage quality; ADF: acid detergent fiber (% DM); NDF: neutral detergent fiber (% DM); NDFD, neutral detergent fiber digestibility (%DM); CP: crude protein (% DM).

‡ Bold numbers highlight p-values < 0.05.

interactions. After studying the relevant interactions, linear and quadratic regressions were fit with treatment means for each variable against GDD. Both linear and quadratic models were compared based on the adjusted R^2.

Environmental Conditions

During the 2016 growing season, precipitation was 209 mm (8.2 inches) at Arlington and 193 mm (7.6 inches) at Madison (Fig. 1). These values are similar to the 30-year average of 210 and 200 mm (8.3 and 7.9 inches) for the months of May and June at Arlington and Madison (NWS, 2018). Precipitation during the 2017 growing season was 352 mm (13.9 inches) in Arlington and 335 mm (13.1 inches) in Madison, more than 130 mm greater than the 30-year average. Both locations had the same accumulation of GDD over the course of each growing season (Fig. 1). The recorded temperature average in 2016 was 18°C (64°F) and 16.7°C (62°F) in 2017, which is greater than the historical average of 16°C (61°F). The drier weather conditions in Madison and the different soils explain the consistent yield gap observed between both locations in the annual Wisconsin Oat and Barley Performance Tests and indicates that Arlington represents an environment with greater yield potential (Mochon and Conley, 2013, 2014, 2015; Gutierrez and Conley, 2016, Gutierrez et al., 2017). Therefore, Arlington represents an environment with greater yield potential.

Milk Production and Forage Yield

Because a significant interaction was found between maturity stage and location (Table 1), results for calculated milk production per area and forage DM yields are presented by location. Milk production and forage DM yields were usually greater in Arlington than in Madison (Table 2). Forage DM yield increased from the boot stage to late heading in both locations, but the increase was steeper in Arlington than in Madison, probably due to greater precipitation (Table 2). Milk production per area increased for both cultivars in Arlington, but did not change in Madison for ForagePlus (Table 2).

Calculated milk production per hectare increased in Arlington from boot stage to heading + 5 days for both cultivars. It was greater for ForagePlus than Laker at boot and late boot stages but no differences between cultivars were detected at heading and heading + 5 days. Calculated milk production per hectare was maximal at heading + 5 days, with an average of 10,170 kg/ha (9080 lb/acre; Table 2). In Madison, a similar increase was detected for Laker but calculated milk production remained stable across harvest maturity stages for ForagePlus. Despite differences between cultivars at heading at the latter location, ForagePlus and Laker performed similarly at heading + 5 days with an average of 7816 kg/ha (6979 lb/acre). Forage DM yield also increased from the boot stage to the late heading stage for both cultivars and both locations, and it was maximum at the late heading stage with an average of 9870 kg/ha (8812 lb/acre) and 7513 kg/ha (6709 lb/acre) between cultivars in Arlington and Madison, respectively (Table 2). Our results were similar to Coblentz et al. (2011) who reported a maximum forage yield of 8100 kg/ha (7300 lb/acre) for ForagePlus harvested at the late heading stage in the fall in Wisconsin. Our yields were greater than those reported by Contreras-Govea and Albrecht (2006) measured in an experiment at two similar Wisconsin locations and may be the result of a greater growing degree-day accumulation of 200 in the present study.

Nutritive Value

As expected, acid detergent fiber and NDF increased for both cultivars, locations, and years from the boot stage to late heading while NDFD decreased (Table 2). Averaged between cultivars, locations, and years ADF increased from 36.5% at the boot stage to 40.8% 5 days after heading, NDF increased from 55.1 to 60.8%, respectively, and NDFD decreased from

Table 2. Calculated milk production per unit of area, forage yield, and nutritive value parameters of two oat cultivars (ForagePlus and Laker) at four maturity stages grown in Arlington and Madison, WI, USA over two growing seasons (2016 and 2017).

Location	Cultivar	Maturity stage	Milk per area	Forage DM yield	ADF	NDF	NDFD	CP	RFQ
			kg/ha	kg/ha	%DM	%DM	%DM	%DM	
Arlington	ForagePlus	B †	7570 cd ‡	5946 de	40.0 cd	59.3 bc	63.9 a	11.7 ab	128 ab
	Laker	B	5717 e	4358 f	37.9 e	56.5 d	63.4 a	12.2 a	136 a
	ForagePlus	B+2	8571 bc	6620 d	39.2 d	58.0 cd	64.3 a	11.6 ab	131 ab
	Laker	B+2	6314 de	5018 ef	39.0 de	57.5 cd	62.6 a	12.6 a	130 ab
	ForagePlus	H	10494 a	8783 bc	39.9 cd	61.0 b	55.4 ab	10.8 bc	121 b
	Laker	H	8829 bc	8251 c	41.8 b	61.1 ab	60.8 bc	10.6 bc	102 c
	ForagePlus	H+5	10556 a	9555 ab	40.9 bc	60.9 b	56.6 bc	10.4 bc	108 c
	Laker	H+5	9783 ab	10183 a	43.3 a	63.2 a	51.5 c	9.5 c	90 d
Madison	ForagePlus	B	6919 abcd	4875 cd	34.4 cd	52.9 de	63.8 a	13.0 ab	149 a
	Laker	B	5586 d	4069 d	33.6 d	51.8 e	63.6 a	13.3 a	147 a
	ForagePlus	B+2	7347 abc	5522 c	36.1 bc	55.0 cd	62.1 ab	12.5 ab	137 ab
	Laker	B+2	6390 cd	5097 cd	36.0 bc	55.4 cd	54.4 abc	11.8 bc	127 bc
	ForagePlus	H	8318 a	6927 ab	36.9 b	56.5 bc	56.9 abc	10.7 cd	122 c
	Laker	H	6543 bcd	6226 bc	39.9 a	59.9 a	54.5 abc	10.5 d	101 d
	ForagePlus	H+5	7644 abc	7263 ab	39.7 a	60.2 a	53.3 bc	9.6 d	99 d
	Laker	H+5	7988 ab	7764 a	39.3 a	58.8 ab	52.4 c	10.0 d	98 d

† B: Boot stage, B+2: 2 days after boot stage, H: heading, H+5: 5 days after heading. Milk per area: calculated milk production per hectare using MILK16 model; Forage DM yield: forage dry matter yield; RFQ: relative forage quality; ADF: acid detergent fiber; NDF: neutral detergent fiber; NDFD, neutral detergent fiber digestibility; CP: crude protein.

‡ Means with the same letters within each location and across cultivars and maturity stage are not different at alpha = 0.05.

63.7 to 53.5%, respectively. Crude protein decreased with harvest maturity stage (Table 2) from 12.6% at boot stage to 9.9% at late heading, when data were averaged over cultivars, locations, and years. Therefore, RFQ also decreased with maturity stage (Table 2). Averaged between cultivars, locations, and years, RFQ decreased from 140 at the boot stage to 99 at late heading. Therefore, when the goal is to maximize milk production per cow through feeding forage with the highest possible nutritive value (Broderick, 2003), harvesting at the boot stage is recommended. ForagePlus and Laker had similar nutritive value in most maturity stages, except at heading, where ForagePlus was superior (Table 2). Results for nutritive parameters are similar to those reported by Contreras-Govea and Albrecht (2006) and follow the same trend described by Erickson et al. (1977), Cherney and Marten (1982) and Khorasani et al. (1997) who observed ADF of oat forage plateau after heading. In the present study, ADF concentration of ForagePlus remained stable from the boot to late heading stage and confirms its particularly slow-maturing characteristic, as described by Contreras-Govea and Albrecht (2006).

Change in Calculated Milk Production, Forage Yield, and Nutritive Value over Time

Treatment means for calculated milk production per hectare, forage DM yield and nutritive value parameters were regressed over the accumulation of GDD since the date of planting. A significant location by GDD effect was detected for milk production per area ($P = 0.02$) and forage DM yield ($P < 0.01$), regressions were analyzed separately by location for these two variables (Table 3). No interactions with GDD were found for nutritive value parameters, so these regressions are shown for all locations, cultivars, and years together (Table 3). Forage DM yield increased linearly over time with a simultaneous linear decrease in nutritive value. In Arlington, the steep increase in forage DM yield compensated for the decrease in relative forage quality, leading to an increase in calculated milk production per area from the boot stage to late heading (Fig. 2). In Madison, precipitation was consistently lower than in Arlington by 30 mm, forage DM yield increased with a smaller slope, and calculated milk production per unit of area remained stable despite the decrease in nutritive value, but it did not increase (Fig. 2).

A significant agronomic difference between ForagePlus and Laker lies in their different thermal time (growing degree-days) requirement to reach the boot and heading stage ($P < 0.01$). Laker was consistently earlier than ForagePlus, reaching the boot stage 4 days or 77 GDD earlier than ForagePlus, and reaching heading 3 days or 54 GDD earlier than ForagePlus. Considering their similar yields, planting Laker allows farmers to harvest earlier and plant the next crop sooner (if weather is suitable), therefore helping to maximize annual productivity. On the other hand, the slower rate of maturity and greater stability in calculated milk production observed for ForagePlus indicates a greater flexibility of harvest.

Table 3. Linear regression equations, model fit (R^2), and p-values for calculated milk production per area, forage yield, and nutritive value parameters against accumulated thermal time since date of planting (x: growing degree-days) of oat harvested for forage from two locations (Arlington and Madison, Wisconsin, USA), two cultivars (ForagePlus and Laker) and two growing seasons (2016 and 2017).

Variable	Units	Location	Regression equation ‡	R^2	*P*-value
Milk per area †	kg/ha	Arlington	Y = - 12509 + 19.3x	0.70	< 0.01
		Madison	Y = + 7092 + 0.00x	–	0.11
Forage DM yield	kg/ha	Arlington	Y = - 15515 + 21x	0.91	< 0.01
		Madison	Y = - 3152 + 8.5x	0.61	< 0.01
RFQ	–		Y = + 272 -14x	0.68	< 0.01
ADF	% DM		Y = + 16.4 + 0.02x	0.47	< 0.01
NDF	% DM		Y = + 28.6 + 0.03x	0.57	< 0.01
CP	% DM		Y = + 23.9 - 0.01x	0.74	< 0.01

† Milk per area: calculated milk production per hectare using MILK16 model; Forage DM yield: forage dry matter yield; RFQ: relative forage quality; ADF: acid detergent fiber; NDF: neutral detergent fiber; CP: crude protein.

‡ *N* = 8 for milk per area and forage DM yield, and *N* = 16 for RFQ, ADF, NDF and CP.

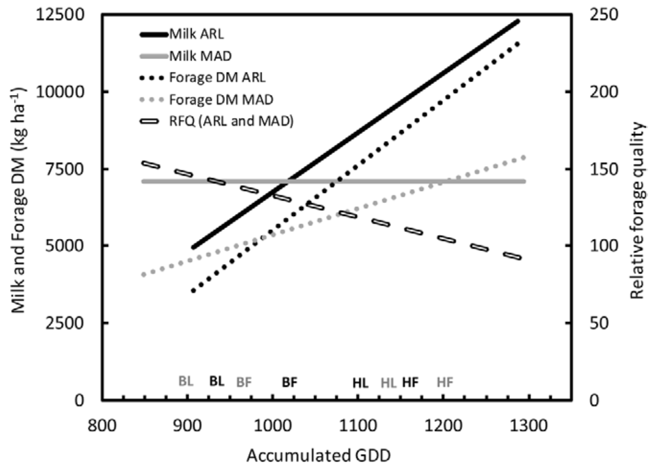

Fig. 2. Linear regressions for calculated milk production per area (kg/ha), forage DM yield (kg/ha), and relative forage quality (RFQ) of oat harvested for forage at two locations (ARL: Arlington and MAD: Madison) in Wisconsin, against the accumulation of growing degree days since planting date. Data represents the means of two cultivars (ForagePlus and Laker) and 2 years (2016 and 2017) over four maturity stages (from boot to late heading), whereas RFQ represents the mean between Arlington and Madison. Regression parameters are shown in Table 3. Accumulated GDD to reach the boot (B) and heading (H) stages for Laker (L) and ForagePlus (F) oat in each location are marked with corresponding letters.

Time from planting to harvest is generally reported in a number of calendar days (Khorasani et al., 1997, Contreras-Govea and Albrecht, 2006; Coblentz et al., 2011) and we argue that thermal units offer a more relevant scale to determine phenological stage of development. Development of oat is best described as a function of daily temperatures and solar radiation, not time (Hughes et al., 1984; Lobell and Ortiz-Monasterio, 2007). This would allow for a more objective comparison of results between publications. Average temperatures in Arlington during the month of May can fluctuate in a range of 15°C (25°F) (NWS, 2018). This makes calendar days a variable and therefore inaccurate time scale. Few publications report forage DM accumulation as a function of GDD (see for instance Martini et al., 2009; Iannucci et al., 2015) and no previous research has, to our knowledge, linked the changes in nutritive value parameters with thermal units for modern oat cultivars.

Optimal Maturity Stage for Harvesting Oat forage

Nutritive value of both forage-oat cultivars followed a similar decreasing trend in Arlington and Madison. Therefore, to maximize milk production per cow, harvesting at boot stage is recommended. Calculated milk production per area and forage DM yield differed between locations. Superior rainfall in Arlington was associated with a steeper increase in forage DM yield and a continuous increase in calculated milk production per hectare across all harvest maturity stages (Fig. 2). The lower amount of precipitation in Madison reduced the rate of forage DM accumulation, leading to stable milk production per area of approximately 7092 kg/ha. These results suggest that forage DM yield is the main driver for milk production per hectare, and indicate that harvesting oat for forage at the late heading stage can maximize milk production per unit of area where fertile soils and adequate rainfall are present. In environments with below-average yield potential, milk production per hectare can be expected to remain stable over time and producers are advised to base their harvest-timing decisions on forage nutritive value. Finally delaying harvest into or past the flowering stage will make oat forage difficult to incorporate in a balanced dairy ration since CP falls rapidly after heading while NDF increases until physiological maturity in oat (Erickson et al., 1977; Khorasani et al., 1997; Nelson and Moser, 1994). Further research is needed to determine with precision when milk production per unit of area will drop after late heading.

This model of estimation of milk production assumed that lower quality forage can fit into a balanced ration, with non-forage components providing much of the protein and energy required. Even if a lower quality forage produces more milk per unit of land, the cost of all the other feeds required to balance such a ration will determine whether more milk per unit of land is economically attractive to the farmer. In this study, we did not include any of these economic considerations, and we only focused on forage and milk productivity estimations. Therefore, farmers must consider additional factors in their decision-making process for harvesting oat for forage in each particular system. For instance, they must consider the cost of forages and concentrates used to balance the ration, the category of livestock for which forage is most needed, and the need to open land for manure application or double-cropping. The range of dairy cattle categories available in the herd is another relevant consideration, because heifers, dry cows, and late lactation cows can utilize the less digestible forage, and therefore make better use of the oat forage harvested in late heading. All these considerations are important to decide which metric to optimize when deciding when to harvest oat forage.

In conclusion, as the forage was harvested at later dates between boot and late heading, oat forage DM yield increased linearly while nutritive value decreased linearly with growing degree-days. The interpretation of this trade-off between forage yield and nutritive value depends on the goals of the dairy farmer, their feeding system, cost of forages and concentrates, and animal categories, among other factors. If the goal is to maximize milk production per cow through feeding the highest nutritive value forage to lactating dairy cows, harvesting at the boot stage is optimal. If the goal is to maximize milk production per unit of area feeding a range of dairy categories, in environments with high forage DM yield potential, harvesting oat for forage at late heading may be desirable, since increased forage DM yield can compensate for the reduction in forage nutritive value. These results must be evaluated in economic perspective considering each particular farm system.

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