

Original papers

## Handheld NIRS for forage evaluation

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## ABSTRACT

Handheld near infrared reflectance (NIR) instruments are now available for non-scientist operators for on-farm evaluation of forages. There are a variety of instruments with different detector technologies and greatly different NIR scanning ranges. However, there is little public data or independent evaluation of their relative effectiveness in the field. Our objective was to evaluate several hand-held NIR instruments for precision and accuracy of currently available calibrations for dry matter (DM) compared to a state-of-the-art electronic moisture meter, and to evaluate forage nutritive value calibrations available on one instrument. The AuroraNir, NIR4, and SCiO handheld NIR instruments were evaluated, along with the HST-1 electronic impedance moisture probe. Over 600 haylage, corn silage and total mixed ration samples were collected in 2019 and 2020 from 19 dairy farms in NY and WI. After scanning, two subsamples of each sample were dried to determine oven DM. Samples from three of the 19 farms were measured 10 times each, with remixing between measurements, to evaluate precision. The Aurora and NIR4 instruments, with a similar NIR scanning range, were similar in precision for estimating oven DM, while the SCiO and HST-1 instruments were less precise. Using currently available calibrations, accuracy of DM estimations was in the order of AuroraNIR > NIR4 >> SCiO > HST-1, although current calibrations were not sufficiently robust for a range of mixed haylage, corn silage and TMR samples from NY and WI. Calibrations for the AuroraNir did not produce consistently accurate results for nutritive value determinations, particularly when dealing with mixed species haylage.

## 1. Introduction

Near infrared reflectance (NIR) spectroscopy is currently used extensively for routine forage analysis in commercial laboratories. Recently portable spectroscopy has evolved such that successful hand-held instruments can be designed for non-scientist operators (Crocombe, 2018). The drastic reduction in spectrometer size and weight coupled with good performance and high-volume manufacturability has resulted in practical analytical applications in a variety of fields (Yan and Siesler, 2018). Portable NIR spectroscopy can be an effective component of smart agriculture systems (Tang et al., 2021; Wolfert et al., 2017).

Interest in the use of miniaturized hand-held spectrometers for on-farm analysis applications is rapidly increasing (Bec et al., 2020). Portable NIR instruments have been shown to be effective on pre-processed dried, ground forage samples (Acosta et al., 2020; Berzaghi et al. 2021). Portable spectrometers are now routinely installed on forage harvesting equipment and have been adapted to other field equipment such as liquid manure applicators (Bedord, 2019). Hart et al.

(2020) determined that a portable instrument (HarvestLab™ 3000, Deere & Company, Moline, IL, USA) estimated undried mixed forage species quality with systematic but correctable errors. A key component to any successful NIR application is a robust calibration.

Near infrared reflectance calibrations have been evaluated using several criteria (Malley et al., 2005). The coefficient of determination ( $R^2$ ) is the proportion of variability explained by the model. The root mean square error of prediction (RMSEP), also known as the standard error of prediction (SEP), is the average difference between measured and NIR-predicted values, and is used to calculate two additional criteria. The residual prediction variation (RPD) is the standard deviation (SD) of the reference data divided by RMSEP, and is considered a better measure than RMSEP, as it relates RMSEP to the range of the reference measurements (Foster et al., 2013). Additionally, the range of the reference data divided by RMSEP (RER) has been used to assess the success of NIR calibrations (Ward et al., 2011). These evaluation criteria also can be used to assess other forage calibrations, such as those used with electronic moisture meters.

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**Table 1**  
Instruments and their characteristics.

Instrument	Technology	Spectral range	Sample scanning	Scan Area	Number of scans
AuroraNir	Post dispersive diode array	950–1650	Contact	Spot 4 × 6 mm	4 scans
NIR4	Post dispersive diode array	950–1750	Contact	unknown	5 scans
SCiO	Post dispersive optical filter matrix	740–1070	Contact	unknown	7 scans
HST	Electronic impedance	n/a	Probe inserted	n/a	3 insertions



**Fig. 1.** Relative size of instruments used in this study.

**Table 2**  
Validation performance criteria according to Malley et al. (2005).

Level of success	R <sup>2</sup>	RPD	RER
Excellent	> 0.95	> 4.0	> 20
Successful	> 0.90 to 0.95	> 3.0 to 4.0	> 15 to 20
Moderately successful	> 0.80 to 0.90	> 2.25 to 3.0	> 10 to 15
Moderately useful	0.70 to 0.80	1.75 to 2.25	8 to 10

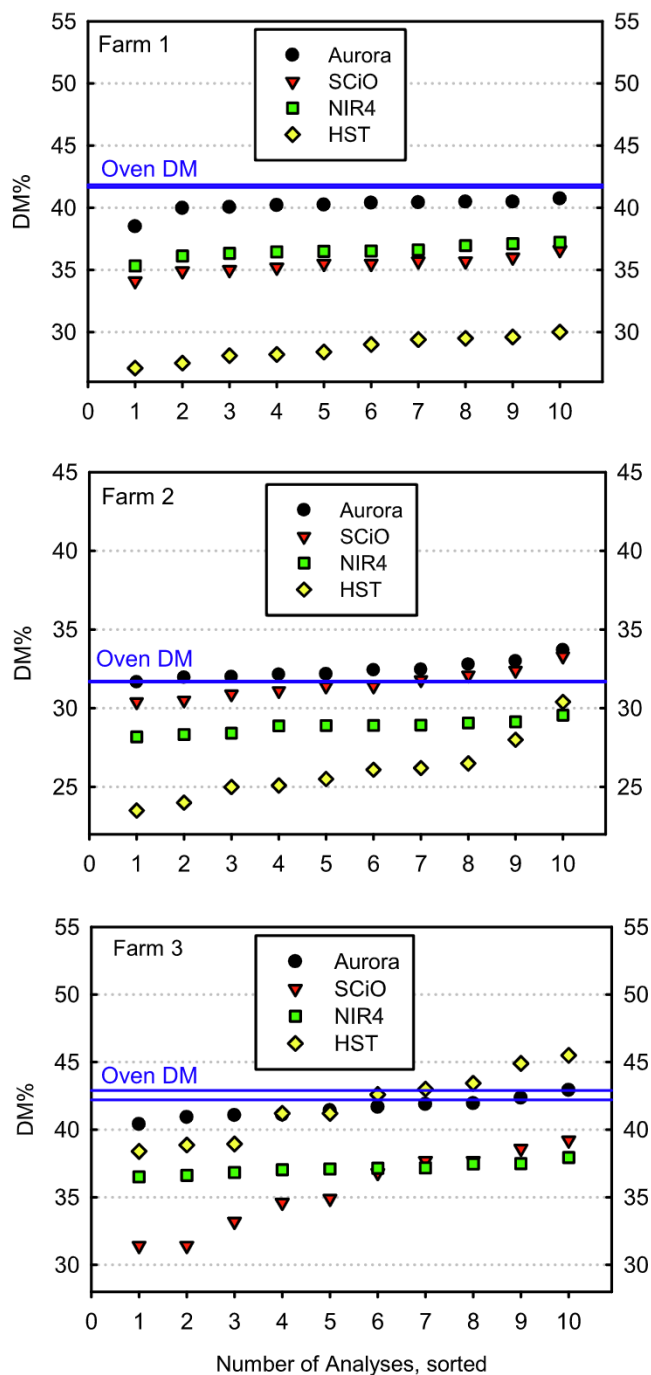
<sup>a</sup> R<sup>2</sup>, coefficient of determination; RPD, residual prediction variation; RER, range of the reference data divided by root mean square error of prediction (RMSEP).

The goal of handheld NIRs for forage use is to analyze samples without any preprocessing, and calibrations are developed using wet, chopped forage. In addition to high moisture content and large particle size forage samples, other challenges for handheld NIRs include signal-to-noise ratio issues, a variable portable power supply, and operation in unfavorable environments. Handheld instruments are currently being used in forage field research studies (Bell et al., 2018) without any independent validation data. In general, there is a paucity of refereed information available on the precision and accuracy of available calibrations for hand-held NIR units. To our knowledge, there have been no published refereed evaluations of hand-held NIR calibrations for forage analysis. Our objective was to evaluate several hand-held NIR instruments for precision and accuracy of currently available calibrations for dry matter (DM) and forage nutritive value.

**2. Materials and methods**

*2.1. Handheld units and scanning procedures*

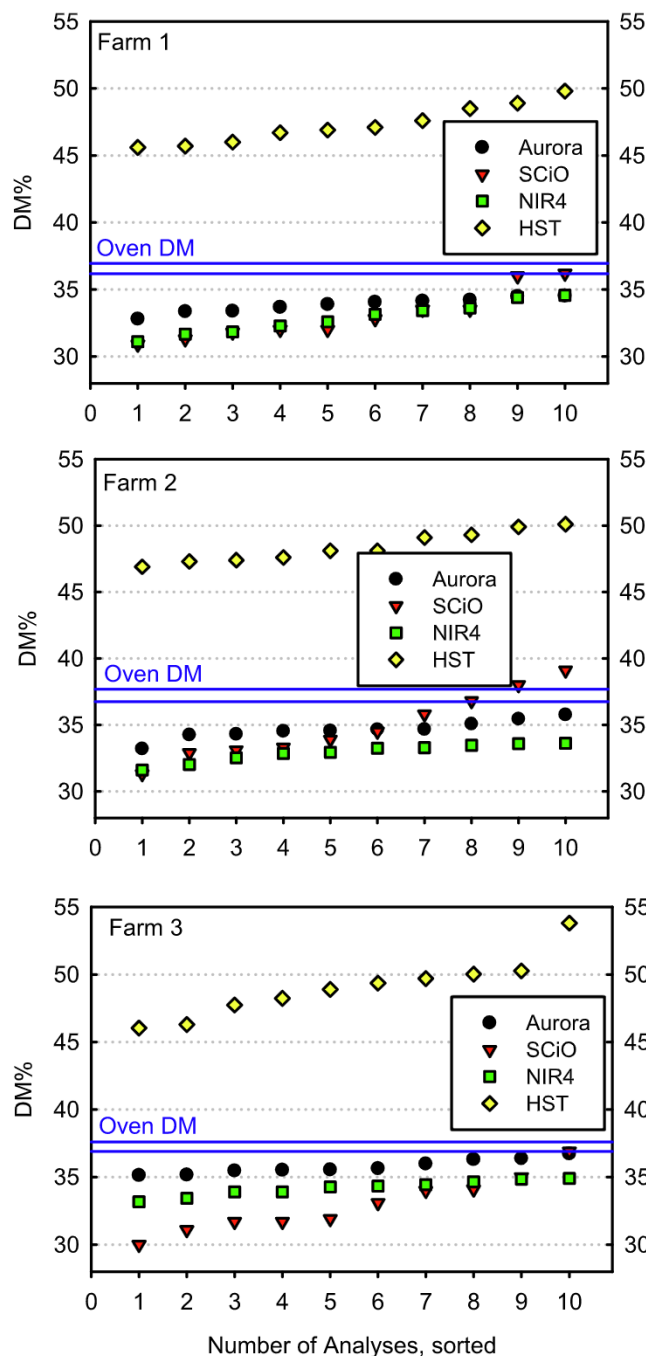
Characteristics of the four instruments evaluated are listed in Table 1



**Fig. 2.** Each point represents an estimate of oven dry matter (DM) of haylage from three farms by four instruments (Aurora, SCiO, NIR4 and HST). Blue lines are duplicate oven DM measurements. Estimates were sorted smallest to largest. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and their relative sizes are shown in Fig. 1. Single scan times for the three NIR instruments were 4–5 s.

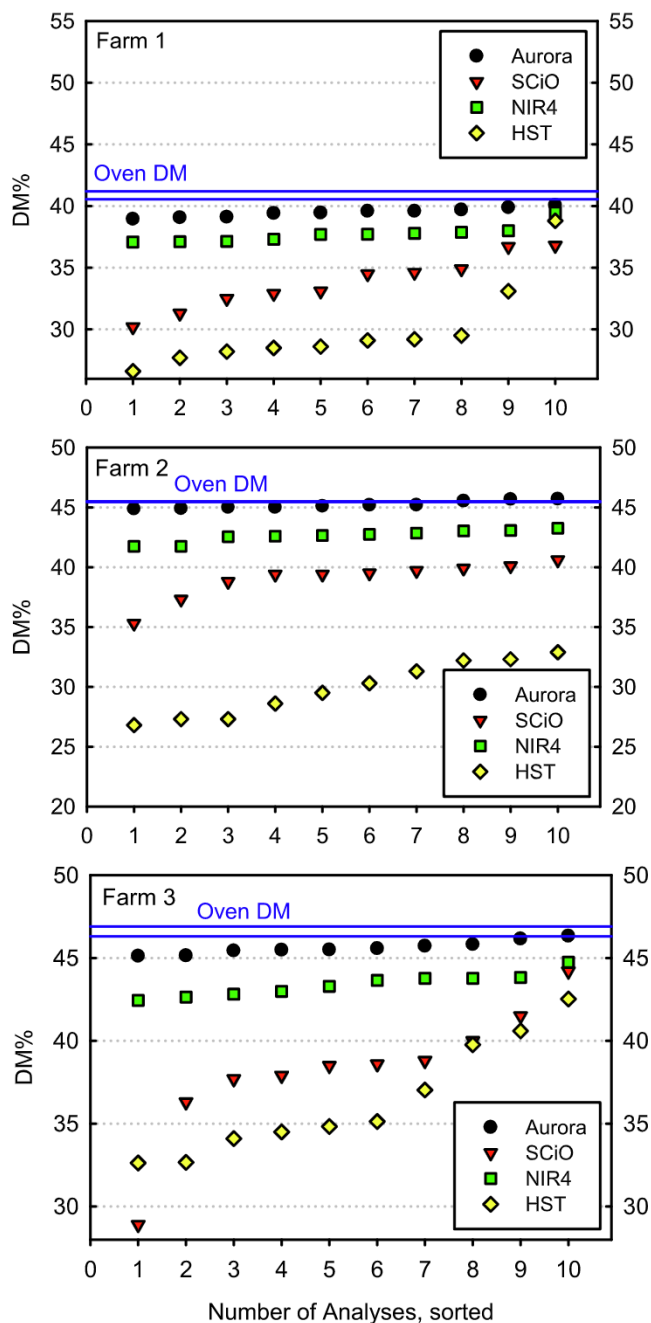
AuroraNir (Grainit s.r.l., Italy). Separate calibrations for haylage, corn silage and TMRs were available (all identified as Ver. 2). Prior to scanning every sample, the lens was covered to prevent external light from entering the device and an internal standard was scanned. Sample was compressed in a rectangular box (10 × 40 cm, 13 cm deep) and the instrument was moved along the forage surface during scanning, maintaining continuous close contact with the surface. Four scans per sample were averaged by the instrument. The abbreviation ‘Aurora’ is



**Fig. 3.** Each point represents an estimate of oven dry matter (DM) of corn silage from three farms by four instruments (Aurora, SCiO, NIR4 and HST). Blue lines are duplicate oven DM measurements. Estimates were sorted smallest to largest. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

used throughout this discussion.

NIR4 (AB Vista, Marlborough, Wiltshire, UK). The only calibration available for testing was a universal moisture calibration [Ver. 0.0.6.724 (6724), last updated 3–6-19], applied to haylage, CS and TMR samples. The instrument was not connected to the internet during the entire experiment, to prevent the calibration from being automatically updated. Prior to scanning every sample, the probe window was covered and an internal standard was scanned. Sample was placed in a round container approximately 25 cm diameter and 15 cm deep, compressed, and the NIR probe was pressed to the surface, sliding along the surface while maintaining continuous close contact with the sample. Five scans



**Fig. 4.** Each point represents an estimate of oven dry matter (DM) of total mixed rations from three farms by four instruments (Aurora, SCiO, NIR4 and HST). Blue lines are duplicate oven DM measurements. Estimates were sorted smallest to largest. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

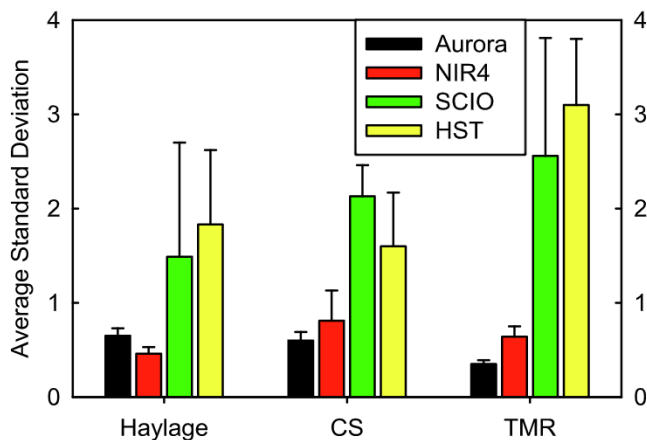
per sample were averaged by the instrument.

SCiO (Consumer Physics, Israel). Moisture calibrations for mixed haylage and corn silage were provided by REVEAL (Cargill Inc. Minneapolis, MN). Because predictions were generated by transmitting NIR scans to the REVEAL website, it is not known whether any calibrations were updated during the experiment. Prior to using the SCiO each day, the internal calibration program was run with the lens covered. Sample was compressed in a rectangular box. A plastic cowl was placed over the end of the instrument, maintaining approximately a 2 cm distance between the sample surface and the sensor window, and excluding external light from the sensor. The SCiO did not have a TMR calibration and TMR samples were evaluated using a mixed haylage calibration.

**Table 3**  
Standard error of the laboratory (SEL) for wet chemistry procedures.

Component	aNDF	ADF	ADL	IVTD	NDFD	CP	Ash	DM
	%DM	%DM	%DM	%DM	%NDF	%DM	%DM	%DM
Haylage	0.501	0.704	0.360	0.670	1.549	0.213	0.269	0.571
N	324	324	324	324	324	56	324	245
CS	0.657	0.532	0.224	0.761	2.356	0.211	0.101	0.348
N	288	288	288	288	288	56	288	208
TMR	0.497	0.657	0.302	0.475	1.899	0.436	0.148	0.424
N	176	176	176	176	176	56	176	111

<sup>a</sup> aNDF, neutral detergent fiber; ADF, acid detergent fiber; ADL, acid detergent lignin; IVTD, in vitro true digestibility at 48 h; NDFD, neutral detergent fiber digestibility at 48 h; CP, crude protein; DM, oven dry matter.



**Fig. 5.** Standard deviation (SD) of oven dry matter (DM) percent of 10 sample DM readings on each of three farms. Values are average SD of the three farms. Vertical error bars are the standard deviation of the values from three farms.

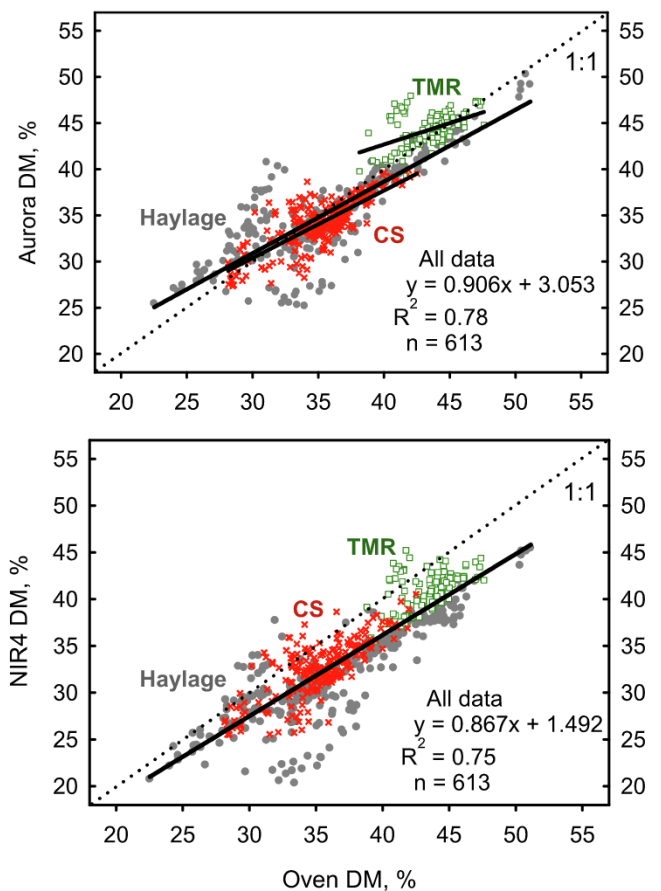
Seven scans per sample were averaged by the instrument.

HST-1 (AgraTronix LLC, Streetsboro, OH) is an electronic impedance 50 cm probe with hay silage and corn silage calibrations and includes both density and temperature compensation. Sample was compressed in a container, and the probe was inserted (minimum of 20 cm) and internal forage temperature was measured prior to moisture determinations to compensate for temperature. Forage density was automatically compensated for based on the force required to insert the probe. HST-1 did not have a TMR calibration and TMR samples were evaluated using the “hay silage” calibration. Three probe readings per sample were averaged by the instrument. The abbreviation ‘HST’ is used throughout this discussion.

These instruments were selected to represent the current available technologies for forage analysis on farm. There is a wide range in cost of these instruments, around \$300 (US) for the HST probe, nearly \$1000 for the SCiO, over \$15,000 for the NIR4, and over \$25,000 for the Aurora. The NIR instruments usually have additional annual usage or routine maintenance and recalibration fees.

**2.2. Precision estimates for oven dry matter**

Haylage, corn silage (CS) and total mixed ration (TMR) samples were collected from three dairy farms and all samples were mixed thoroughly in a large plastic container (Cherney et al., 2021). A representative subsample was transferred to a separate container for each scan or probe, and the subsample was returned to the plastic container afterwards for remixing. This process was repeated 10 times for each instrument, generating 10 separate moisture determinations for each sample/instrument combination. Two subsamples from each sample were dried at 60 °C for 48 h to determine oven dry matter (DM) (Cherney and Cherney, 2003).



**Fig. 6.** Relationship between Aurora and NIR4 dry matter (DM) estimates and oven DM. Black lines for Aurora are individual regression results for forage and total mixed ration (TMR) calibrations. NIR4 has one universal DM calibration and regression line. Gray circle = haylage, Red x = corn silage (CS), Green square = TMR. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**2.3. Accuracy estimates for forage parameters**

Haylage, CS and TMR samples (2 to 5 kg) were collected from 19 dairy farms in NY and WI during 2019 and 2020. A total of 613 samples were collected. The mixed species haylage ranged from mostly alfalfa to mostly grass. Some farms had more than one open haylage or CS bunker, such that the total number of haylage samples does not equal the total number of CS samples. There were fewer TMR samples collected, since they needed to be processed immediately after collection. The TMR samples were scanned the day of collection, some of the haylage and CS samples were vacuum packed in oxygen-limiting polyethylene bags using a commercial vacuum packing machine (Cherney et al., 2007) for scanning at a later date. All samples were mixed well in a large plastic

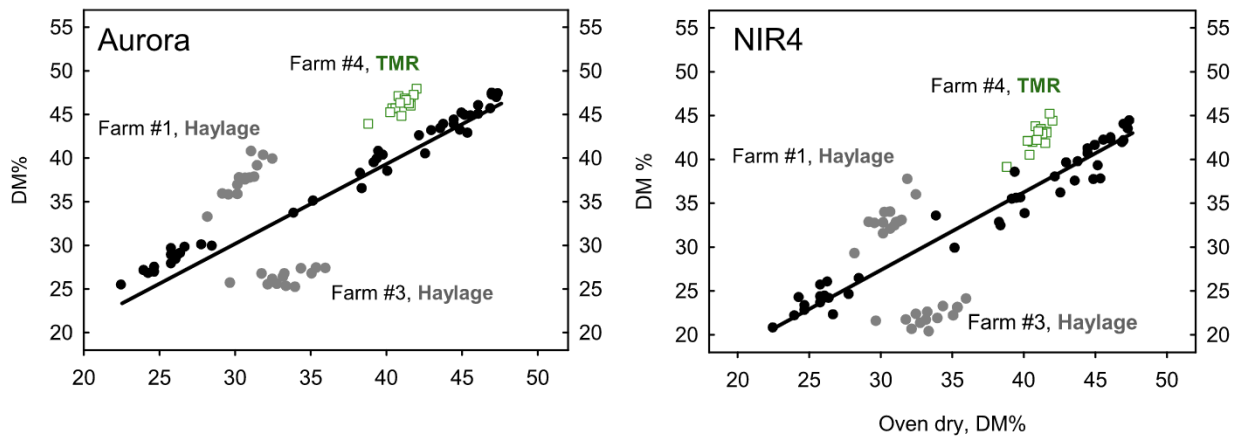


Fig. 7. Outlier sample groups of dry matter (DM) estimations for the second 14-d period of daily bunker sampling, compared to the first 14-d period of daily sampling of haylage and total mixed rations (TMR) on three farms for Aurora and NIR4. Black line is regression equation line for all 613 samples scanned for Aurora and NIR4. Gray circles are haylage and green squares are TMR for the second 14-d period of daily sampling. Black circles are first 14-d period of daily sampling for haylage and TMR of the same bunkers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

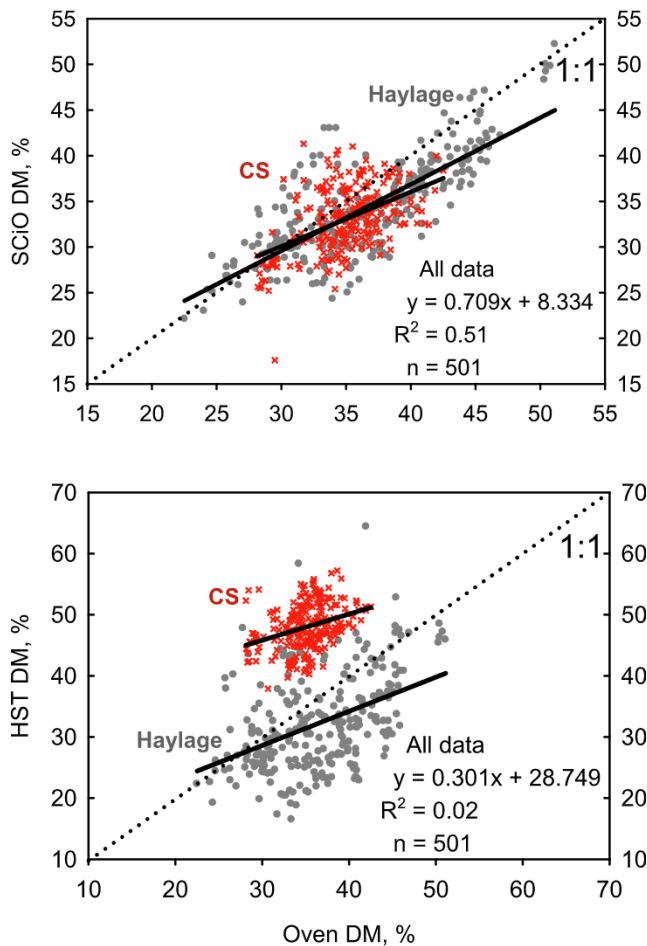


Fig. 8. Relationship between SCiO and HST dry matter (DM) estimates and oven DM. Black lines are individual regression results for haylage and corn silage (CS) calibrations. Gray circle = haylage, Red x = CS. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

bin, prior to scanning and subsampling. After scanning with NIR units and measuring moisture with the moisture probe, two subsamples (approx. 250 g each) for each sample were oven dried (60 °C) for 48 h.

One of the two subsamples was ground in a Wiley mill (Thomas Scientific, Swedesboro, NJ) to pass a 1-mm sieve.

Samples were analyzed using wet chemistry procedures described in Valentine et al. (2019), using sodium sulfite in the neutral detergent solution. Forages were weighed into ANKOM F57 filter bags (ANKOM Technology, Macedon, New York, USA) for aNDF, ADF, ADL and 48 h in vitro digestibility analyses. Filter bags were removed briefly from jars at the start and end of the second day for all in vitro digestion runs and gas buildup was gently expressed, while jars were being purged with CO<sub>2</sub> (Cherney et al. 2021). Neutral detergent fiber digestibility (NDFD) was calculated as the proportion of the total fiber digested, expressed on an NDF basis.

Total ash content was determined by heating samples to 510 °C for four hours. Nitrogen was determined using a combustion process (LECO CN628 analyzer, DairyOne, Ithaca, NY) and CP was calculated as N × 6.25 (AOAC, 1995). All analyses were conducted in duplicate, with the exception of nitrogen, which was determined in duplicate on a subset of samples to calculate a standard error of the laboratory for CP. The standard error of the laboratory (SEL) was determined according to the equation  $SEL = \sqrt{(\sum(d1-d2)^2)/2n}$ , where d1 = duplicate 1, d2 = duplicate 2, and n = number of samples. For NDFD, NDF duplicate sample analyses were randomly associated with one of the two IVTD duplicate analyses (Cherney et al., 2021). The SEL for NDFD were generated by averaging 10 randomizations of duplicates.

The success of NIR predictions were assessed based on the coefficient of determination (R<sup>2</sup>), root mean square error of prediction (RMSEP), residual prediction deviation (RPD) and the ratio of RMSEP to the range of the reference values (RER) (Foster et al., 2013; Ward et al., 2011).  $RMSEP = \sqrt{(\sum(R1-P1)^2)/n}$ , where R1 = reference data set, P1 = predicted data set, and n = number of samples.  $RPD = \text{reference data set standard deviation (SD)} / RMSEP$ .  $RER = \text{Range of the reference data set} / RMSEP$ .

Specific performance criteria for calibrations have been suggested (Malley et al., 2005; Ward et al., 2011) (Table 2). The coefficient of determination (R<sup>2</sup>) is generally not a good measure of model performance because it is highly dependent on the range of the data set (Foster et al., 2013). The RPD and RER both relate RMSEP to the range of reference data, using either the standard deviation or the range of values for the reference data.

**Table 4**

Success of calibration predictions for haylage, corn silage (CS), total mixed ration (TMR) and all samples combined (ALL). The Aurora also had prediction models for chemical species whereas the others were limited to dry matter.

		Aurora					NIR4	SCiO	HST
		aNDF	ADF	CP	Ash	DM	DM	DM	DM
Haylage	R <sup>2</sup>	0.81 <sup>c</sup>	0.50	0.55	0.31	0.73 <sup>c</sup>	0.72 <sup>c</sup>	0.61	0.17
	RMSEP	5.06	3.74	3.08	1.39	3.11	5.48	4.33	8.70
	RPD	1.82 <sup>c</sup>	1.35	1.25	1.21	1.88 <sup>c</sup>	1.07	1.35	0.67
	RER	1.08	5.61	5.59	5.76	9.20 <sup>c</sup>	5.22	6.61	3.29
	n	263	263	263	263	269	269	269	269
CS	R <sup>2</sup>	0.28	0.28	0.32	0.37	0.60	0.57	0.22	0.10
	RMSEP	7.41	2.95	0.50	0.83	2.15	3.42	3.92	13.45
	RPD	0.38	0.69	1.21	0.44	1.35	0.85	0.74	0.21
	RER	1.83	4.30	8.62 <sup>c</sup>	3.01	6.70	4.21	3.67	1.07
	n	224	224	224	224	232	232	232	232
TMR	R <sup>2</sup>	0.03	0.04	0.19	0.01	0.24	0.29	n/a	n/a
	RMSEP	3.87	2.93	1.03	1.31	2.11	3.15	n/a	n/a
	RPD	0.28	0.27	0.86	0.25	2.04 <sup>c</sup>	1.37	n/a	n/a
	RER	1.37	1.42	3.98	1.63	4.50	1.54	n/a	n/a
	n	112	112	112	112	112	112	n/a	n/a
ALL	R <sup>2</sup>	0.83 <sup>c</sup>	0.84 <sup>c</sup>	0.91 <sup>c</sup>	0.93 <sup>c</sup>	0.78 <sup>c</sup>	0.75 <sup>c</sup>	0.51	0.02
	RMSEP	5.88	3.32	2.11	1.19	2.61	4.41	4.15	11.15
	RPD	0.19	0.24	0.42	0.28	2.02 <sup>c</sup>	1.19	1.15	0.43
	RER	7.05	8.81 <sup>c</sup>	10.64 <sup>c</sup>	12.11 <sup>c</sup>	10.96 <sup>c</sup>	6.49	6.89	2.57
	n	599	599	599	599	613	613	501	501

<sup>a</sup> aNDF, neutral detergent fiber; ADF, acid detergent fiber; CP, crude protein; DM, dry matter.

<sup>b</sup> R<sup>2</sup>, coefficient of determination; RMSEP, root mean square error of prediction; RPD, residual prediction deviation; RER, range of the reference data divided by RMSEP.

<sup>c</sup> Meets one of the validation performance criteria listed in Table 2.

### 3. Results and discussion

#### 3.1. Precision estimates for dry matter

Duplicate oven DM determinations for haylage were relatively consistent for this set of samples (Figs. 2-4, Oven DM horizontal line), similar to over 500 samples analyzed in duplicate for oven DM SEL determinations (Table 3). Multiple haylage DM estimates were consistent for the Aurora and NIR4 (Fig. 2). Aurora haylage DM estimates were slightly above or below oven DM, while NIR4 DM estimates were consistently underestimating oven DM for this set of samples. SCiO haylage DM estimates were less consistent than Aurora and NIR4 for Farm C. The HST probe estimates of haylage DM tended to be more variable than repeated NIR estimates (Fig. 2).

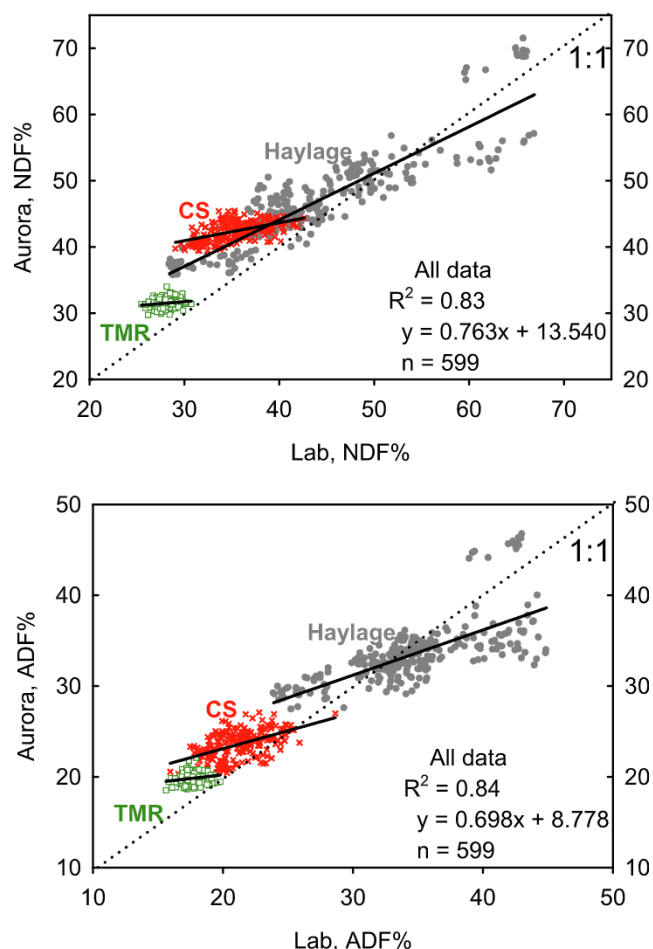
All NIR estimates of DM for CS averaged below oven DM for this set of samples (Fig. 3). The HST probe, however, produced DM estimates for CS that were all well above oven DM. Aurora and NIR4 DM estimates were relatively consistent across multiple readings, with NIR4 estimates slightly lower than that of Aurora. SCiO DM estimates were more variable, ranging from values less than Aurora and NIR4 to greater than Aurora and NIR4 DM estimates. The HST probe was more variable than NIR estimates, particularly for Farm C. The Aurora was consistent and relatively accurate in estimating TMR oven DM for this set of samples (Fig. 4). The NIR4 DM estimates for TMR also were very consistent but several percentage units below that of oven DM. Neither SCiO nor HST were calibrated for TMRs, so “mixed haylage” (SCiO) and “hay silage” (HST) calibrations were applied to TMR samples (Fig. 4). Both SCiO and HST DM estimates for TMRs were variable and well below that of oven DM. A bias was not surprising when using haylage calibrations for TMR samples, but this would not necessarily have reduced precision, which was considerable.

Averaging standard deviations (SD) for DM for three farms, the Aurora and NIR4 were similar in precision across haylage, CS, and TMR samples (Fig. 5). Estimates of DM with SCiO and HST, however, lacked precision with large SD that were variable from farm to farm. Using haylage calibrations for the TMRs for SCiO and HST resulted in SD somewhat greater than for haylage or CS.

#### 3.2. Oven dry matter estimates

The NIR region with the strongest absorption of water is around 1930 nm which is outside the range of all three NIR instruments evaluated. Secondary water NIR absorption peaks between 1400 and 1650 nm are captured by the Aurora and NIR4 but not the SCiO. The Aurora and NIR4 instruments were similar in precision, but the Aurora was somewhat more accurate (Fig. 6). The data pattern was similar for the Aurora and NIR4, and several sample groups that tended to be outliers did so for both instruments (Fig. 7). On four of the farms sampled, haylage, CS, and TMR samples were collected daily for two weeks, and after a two-week pause another set of daily samples were collected for two weeks from the same bunkers (Cherney et al., 2021). Three groups of 14 daily samples from the second collection period were not predicted well by either the Aurora or NIR4 (Fig. 7), however, 14 daily samples collected from the same bunkers were predicted reasonably well for the first sampling period. Both of these NIR instruments detected some subtle differences in the three groups of 14 samples in period two samples which were not present in period one, and these differences apparently were not well represented in the calibration set for either instrument. The correlation coefficient between Aurora and NIR4 DM estimates was 0.95 (n = 613), implying that calibration data sets for the two instruments may be similar. The high correlation between these instruments indicated that our sample mixing procedure was effective, and also that our scanning technique over many different days was very consistent. There is no obvious explanation for the different responses during the two sampling periods. For each sampling period, samples were scanned on 14 different days, resulting in the same anomalies for the Aurora and NIR4 in only three out of 12 sets (3 forage types × 4 farms) of 14 samples collected during the second 14-d period. The two anomalous haylage sets of 14 samples in the second 14-d collection period also were on the edges of the point cloud for the SCiO (Fig. 8), but increased variability made the pattern much less obvious.

The SCiO and HST instruments did not have a TMR calibration, so only haylage and CS DM were evaluated. The SCiO instrument was not as accurate as either the Aurora or NIR4, with haylage and CS producing similar results (Fig. 8). One CS sample was clearly an outlier. The HST moisture probe had poor accuracy and precision with a nearly circular

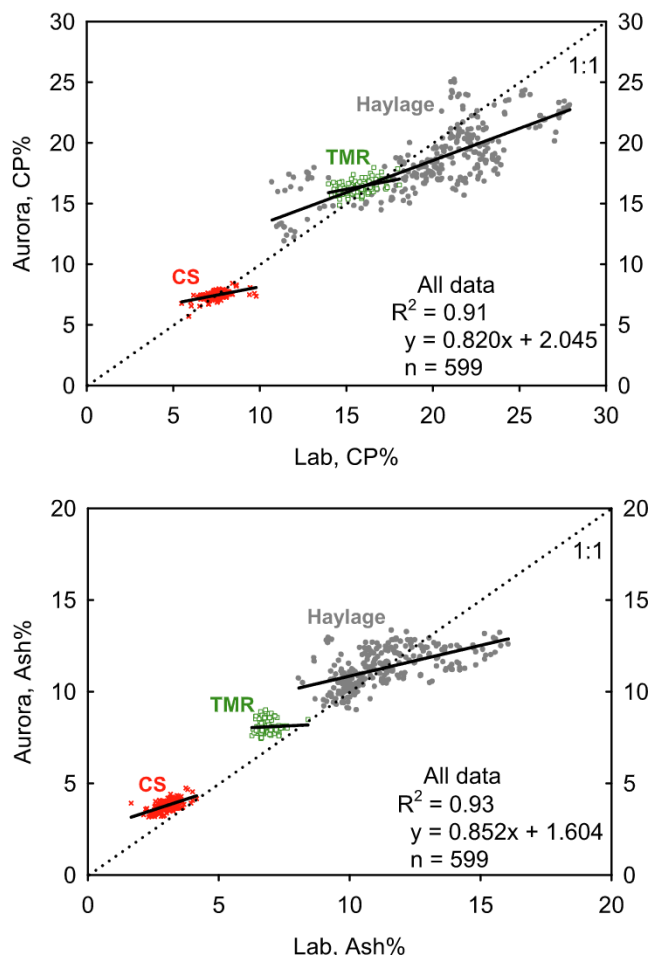


**Fig. 9.** Predicted neutral detergent fiber (NDF) and acid detergent fiber (ADF) by Aurora, compared to wet chemistry determinations. Black lines are individual regression results for forage and total mixed ration (TMR) calibrations. Gray circle = haylage, Red × = corn silage (CS), Green square = TMR. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

point cloud for both haylage and CS (Fig. 8). All CS samples were considerably overpredicted, and several haylage samples were potential outliers for the HST. All four instruments tended to overestimate oven DM at low moisture content and underestimate oven DM at high moisture content. The HST probe overestimated oven DM for all CS samples.

The coefficient of determination ( $R^2$ ) is a relatively poor indicator of model performance but was included in Table 4. The TMR samples with a very narrow range in DM values have extremely poor  $R^2$ . On the other hand, pooling haylage, CS and TMR samples resulted in moderately useful performance based on  $R^2$  for all but SCiO and HST. For SCiO over all samples, range does not correlate well with  $R^2$ , while HST had nearly circular point clouds (Fig. 8) with an almost complete lack of correlation between oven DM and HST DM. None of the DM calibrations for NIR4, SCiO, or HST were even moderately useful (Table 2) based on RPD or RER (Table 4).

The  $R^2$  for NIR4 did exceed 0.70 for haylage and for all samples combined, but primarily due to the relatively large range in haylage reference values. The Aurora DM calibration for haylage was considered moderately useful based on both RPD and RER, and the DM calibration for TMR was moderately useful based on RPD. The Aurora DM calibration was moderately successful for all samples combined based on RER, and moderately useful based on RPD (Table 4).



**Fig. 10.** Predicted crude protein (CP) and Ash by Aurora, compared to wet chemistry determinations. Black lines are individual regression results for forage and total mixed ration (TMR) calibrations. Gray circle = haylage, Red × = corn silage (CS), Green square = TMR. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 3.3. Nutritive value estimates

The Aurora was the only one of the four instruments with nutritive value calibrations, with specific calibrations for haylage, CS and TMR. When combining all samples, a relatively large  $R^2$  was achieved for all four nutritive value parameters (Table 4). Combining all samples resulted in a large range in reference data and moderately useful or moderately successful calibrations based on RER for ADF, CP and Ash. On the other hand, these calibrations were relatively poor based on RPD, which is not strongly influenced by the range of reference data. The haylage aNDF calibration was moderately useful based on RPD, and CS CP calibration was moderately useful based on RER. None of the nutritive value calibrations for TMR were considered useful, in part due to the lack of range in reference data (Figs. 9 & 10).

Corn silage samples had over twice the range in aNDF compared to TMR samples, and haylage had over three times the range of CS for aNDF (Fig. 9). Haylage samples that were grouped and clearly either underpredicted or overpredicted by the Aurora for aNDF tended to originate from the same farm or farms. For example, there are 14 sample points well above the 1:1 line that exceeded 59% Lab NDF (Fig. 9), all originated from 14 consecutive days of sampling the same haylage bunker. There are 16 samples well below the 1:1 line that exceeded 59% Lab NDF, eight of these were collected from one farm and eight were collected from a second farm. This is a demonstration of both precision

and accuracy. The Aurora consistently evaluated samples originating from the same bunker (precision), however, whenever samples were apparently outside the Aurora calibration point cloud it was unable to generate accurate aNDF estimates. The Aurora results for predicting ADF were very similar to that for NDF (Fig. 9). In general, the Aurora underpredicted fiber for haylage with high fiber content, and overpredicted fiber for haylage with low fiber content. In contrast, the Aurora generally overpredicted aNDF and ADF for both CS and TMR.

Despite the poor indicators of success in Table 4, the Aurora appeared to be reasonably accurate for predicting CP and Ash in CS by visual observation (Fig. 10). A similar case could be made for CP in TMR. As with fiber components for haylage, both CP and Ash tended to be underpredicted at higher lab values. Isolated groups of CP haylage samples that were not predicted well originated from one or two farms, as was the case for fiber estimations. All haylage samples exceeding 15% Lab Ash originated from two farms in Wisconsin. These samples were well above the normal range for Ash in haylage and likely contained some soil contamination, which was apparently not represented in the Aurora calibration set.

#### 4. Conclusions

All instruments were evaluated based on averaging the number of scans/probes per sample programmed by the manufacturers. The only instrument evaluated that allows the number of scans per sample to be adjusted by the user is the Aurora. Based on a relatively large set of haylage, corn silage and TMR samples representing a range of dairy farms, we conclude that current DM calibrations for these hand-held NIR units and the HST moisture probe were not sufficiently robust to cover a range of conditions in NY and WI, particularly for mixed species haylage. The Aurora was slightly more accurate for DM estimation than NIR4 and met more of the established calibration performance criteria. The Aurora and NIR4 instruments, with essentially the same NIR scanning range, were very similar in precision for DM with repeatable results from multiple readings of the same sample. The SciO was less precise than the Aurora and NIR4, likely due in part to a much smaller NIR scanning range that does not include either primary or secondary NIR water absorption peaks. The HST moisture probe was less precise than the other three instruments tested. Nutritive value calibrations for the Aurora were not accurate for fiber components of haylage, CS and TMRs, but were relatively accurate for CP in CS and TMRs.

#### CRedit authorship contribution statement

**J.H. Cherney:** Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Project administration. **M.F. Digman:** Conceptualization, Methodology, Formal analysis, Validation, Writing – review & editing. **D.J. Cherney:** Conceptualization, Methodology, Investigation, Writing – review & editing.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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#### Declaration of Interest.

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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