Winter forage producers must choose an optimal stocking rate amid uncertainty about how much forage is available. Adjusting stocking rates can be costly since it can require moving, purchasing, or selling cattle. As stocking rates go up, profits per unit area of land initially increase. However, at some point, there is not enough to eat, so gains and profits decrease (Fales et al., 1995). Overstocking requires supplemental feeding, which is usually expensive (Macdonald et al., 2008). A low stocking rate can lead to poor pasture utilization and low nutritional value of forage if the forage matures. To maximize profit, farmers need to optimally stock each individual field (Fales et al., 1995).

When selecting a stocking rate, farmers are implicitly estimating forage availability (Cuykendall and Casler, 1973). While farmers can use visual assessment to make rough estimates, accurate assessment of forage mass would help in optimally managing grazing systems (Balehegn and Berhe, 2016; Sanderson et al., 2001). Researchers often hand clip and weigh the forage, which is accurate but costly. A rising plate meter, alternatively, can quickly measure forage mass. The rising plate meter measures compressed height and so a calibration equation is needed to convert its measurement to a prediction of forage mass (Nave et al., 2016a, 2016b; Rayburn et al., 2017).

Rising plate meters have been evaluated in New Zealand (Haultain et al., 2014) and California (Scrivner et al., 1986). Studies have dealt mostly with ryegrass (Lolium perenne L.) and clovers (Trifolium repens L.) and have been most interested in grazing for sheep (Balehegn and Berhe, 2016; Sanderson et al., 2001). Researchers often hand clip and weigh the forage, which is accurate but costly. Hand clipping is labor intensive and takes at least 2 d for the leaves to dry (O’Donovan et al., 2002). A rising plate meter, alternatively, can quickly measure forage mass. The rising plate meter measures compressed height and so a calibration equation is needed to convert rising plate meter units (PMU) to forage mass (Nave et al., 2016a, 2016b; Rayburn et al., 2017).

Rising plate meters have been evaluated in New Zealand (Haultain et al., 2014) and California (Scrivner et al., 1986). Studies have dealt mostly with ryegrass (Lolium perenne L.) and clovers (Trifolium repens L.) and have been most interested in grazing for sheep (Bryant et al., 2017; Scrivner et al., 1986). Research has considered ryegrass (Nakagami and Itano, 2014), chicory (Cichorium intybus L.) and plantain (Plantago L.) (Haultain et al., 2014), and a mix of grasses (Dillard et al., 2016). Calibration equations are often estimated separately for month or season (Scrivner et al., 1986; L’Huillier and Thomson, 1988; Nobilly et al., 2013). Litherland et al. (2008) adjusted forage mass predictions for the

Abbreviations: PMU, rising plate meter units.
percentage of dead matter. If the rising plate meter is to be widely adopted, calibration equations are needed for other species and environmental conditions.

As the physical composition of the plants is significantly different, the calibration equations for other forages may not be accurate for wheat (*Triticum aestivum* L.) and rye (*Secale cereale* L.). Since the rye forage cycle is typically a little ahead of wheat (Edmisten et al., 1998; Evers et al., 1998), rye and wheat may need different calibration equations. In winter months (December to mid-March), forage has lower water content, and so calibration equations may also need to differ by season (Gusta and Fowler, 1976).

Therefore, this study estimates wheat and rye calibration equations for a rising plate meter. These equations will help quickly and accurately estimate forage availability. Specifically, we consider crop species, winter seasonality, and tillage effect to estimate forage mass. To achieve our objectives, we used a linear regression model and data from field trials in which the rising plate meter and classical methods (hand clipping and forage weighing) were used.

### Data Collection and Statistical Analysis

Data were collected during the 2012 and 2014 to 2017 production seasons on the Noble Research Institute’s Pasture Research and Demonstration Farm (34°22′ N; 97°21′ W) in Ardmore, OK, and the Red River Research Farm (33°52′ N; 97°16′ W) near Burneyville, OK. From December to January, average temperatures were below 10°C. Total precipitation was adequate to produce good yields during these years. Winter months (December–February) were drier than other months. Wheat and rye were planted using 125 to 135 kg ha⁻¹ for wheat and rye in the fall after emergence. The rye pasture in 2012 received an additional 67 kg ha⁻¹ in February.

The Jengqup (Feilding, New Zealand) model EC09 rising plate meter was used. Data were collected monthly (October–March, every 3–4 wk). Data were collected from a range of forage heights. A 38 × 38-cm quadrant frame was placed directly under the plate meter, and the forage underneath the plate meter was clipped to the ground and bagged. Residual organic material on top of the soil was not included. A wet weight on each individual bag was collected, and the bag was then placed into a forced air dry oven at 60°C for a minimum of 2 d and then weighed. After weighing, dried forages went back into the oven for a day and were reweighed to check if weights were stable. This process was continued until weights were stable.

The plots were grazed by stocker cattle. The cattle were placed in late mid-November to early December at about 250 kg and were removed in April or early May weighing around 400 kg. The soil at the Burneyville site is Yahola fine sandy loam (coarse-loamy, mixed, superactive, calcareous, thermic Udic Ustifluvents). The Ardmore site has Chickasha loam (fine-loamy, mixed, active, thermic Udic Argustolls) (51%), Renfrow silt loam (fine, mixed, superactive, thermic Udertic Paleustolls) (39%), and Normangee loam (fine, smectitic, thermic Udertic Haplustalfs) (14%). The tilled plots were disked twice with a John Deere heavy offset disk followed by a cultipacker and John Deere conventional drill. No-till plots were treated with glyphosate in late May or early June and another as a burn down prior to planting around 15 September.

Past literature usually used a linear functional form, while Rayburn et al. (2017) suggested a quadratic model with no intercept. Dillard et al. (2016) found support for the no-intercept restriction. The two models are non-nested since neither one can be estimated as a special case of the other one. Non-nested tests of the two models are conducted by encompassing (i) the linear and (ii) the quadratic with no intercept into a more general model: (iii) quadratic with an intercept. The encompassing model is

$$\text{FM}_{s,i,t} = \beta_{0,s,t} + \beta_{1,s,t} \cdot \text{PMU}_{s,i,t} + \beta_{2,s,t} \cdot \text{PMU}_{s,i,t}^2 + e_{s,i,t} \quad [1]$$

where FM_{s,i,t} is the forage mass (kg ha⁻¹) for plot i in season s with tillage t.

Pooling tests were used to test whether coefficients varied by species, seasonality, and tillage. All pooling tests were rejected, and so ultimately separate models were estimated for species, season and tillage as shown in Eq. [1]. The PROC REG procedure of SAS (SAS Institute, 2008) was used to estimate the models and calculate the test statistics.

### Results

Total observations were 734: 435 wheat and 299 rye. With the overall non-nested tests, both the linear model (F = 3.89) and the quadratic model with no intercept (F = 3.29) were rejected in favor of the more general model (P < 0.05). With wheat only, however, the null hypothesis of a zero intercept was not rejected (F = 1.49). The null hypothesis of no difference between wheat and rye was rejected (P < 0.05). Thus, separate equations were needed for wheat and rye. The pooling tests of seasonality and tillage were done after separating wheat and rye data. Seasons were modeled as winter and nonwinter. The winter period is from December to mid-March for wheat and December to January for rye. The F-tests of no seasonal difference for wheat (F = 16.04) and rye (F = 28.94) were rejected (P < 0.05). Tillage also affects wheat (F = 8.42) and rye (F = 27.68) (P < 0.05). Therefore, eight calibration equations were estimated.

The winter calibration equation had a higher intercept and slope than the nonwinter equation (Table 1), reflecting the lower water content in winter. Also, tillage showed more forage mass than no-till for given PMUs. The difference in till and no-till may reflect some carryover of plant material on the surface. These regressions, except for the rye nonwinter till case, have R² values above 0.5 (Table 1). The rye nonwinter till case had a major outlier where PMU was low yet forage mass was high; thus, this equation is less reliable than the others (Fig. 1–2).

### Discussion and Conclusion

Based on non-nested test results, the preferred functional form was a quadratic with an intercept. With wheat, however, the intercept was not significant, which matches Rayburn et
al. (2017), who argued for a quadratic with no intercept. The no-till rye parameters had a lower intercept than the model with tillage. The rye no-till had organic matter on the soil surface that was not included in the clippings but did affect the rising plate meter measurements. Calibration equations differed by species, season, and tillage. The conclusions about functional form are based on joint tests. The individual models have less statistical power and show varied responses, with only four of the eight intercepts being significant and only three of the eight quadratic terms significant. As Fig. 1 and 2 show, most of the regressions are close to being linear and many of the intercepts are close to zero. The $R^2$ values were similar to those of previous research such as L’Huillier and Thomson (1988). The rye nonwinter till had an $R^2$ that was low enough to suggest it might not be useful. The other calibration equations can be used along with the rising plate meter to provide more accurate estimates of forage availability than previous estimates that were for different forages and different locations. Field clipping will still be considerably more accurate than the rising plate meter, but the calibration equations used here can help when clipping data are economically infeasible.

### Table 1. Wheat and rye calibration equations.

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Non-winter</th>
<th>Winter</th>
<th>Non-winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Till</td>
<td>No-till</td>
<td>Till</td>
<td>No-till</td>
</tr>
<tr>
<td><strong>Wheat calibration equations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>311.8*</td>
<td>67.98</td>
<td>131.13</td>
<td>–198.76</td>
</tr>
<tr>
<td></td>
<td>(159.45)</td>
<td>(412.31)</td>
<td>(372.58)</td>
<td>(404.26)</td>
</tr>
<tr>
<td>PMU</td>
<td>74.29***</td>
<td>120.23***</td>
<td>41.13***</td>
<td>102.96***</td>
</tr>
<tr>
<td></td>
<td>(16.67)</td>
<td>(46.61)</td>
<td>(39.02)</td>
<td>(46.94)</td>
</tr>
<tr>
<td>PMU$^2$</td>
<td>0.36</td>
<td>–1.12</td>
<td>0.75**</td>
<td>–0.76</td>
</tr>
<tr>
<td></td>
<td>(0.38)</td>
<td>(1.19)</td>
<td>(0.88)</td>
<td>(1.24)</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.6562</td>
<td>0.5686</td>
<td>0.8513</td>
<td>0.5681</td>
</tr>
<tr>
<td><strong>Rye calibration equations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>717.45***</td>
<td>–448.8**</td>
<td>1463.78***</td>
<td>–121.04</td>
</tr>
<tr>
<td></td>
<td>(814.72)</td>
<td>(367.07)</td>
<td>(723.35)</td>
<td>(412.79)</td>
</tr>
<tr>
<td>PMU</td>
<td>70.45***</td>
<td>181.56***</td>
<td>28.35***</td>
<td>86.52***</td>
</tr>
<tr>
<td></td>
<td>(108.63)</td>
<td>(40.35)</td>
<td>(71.65)</td>
<td>(49.07)</td>
</tr>
<tr>
<td>PMU$^2$</td>
<td>2.47*</td>
<td>–2.13***</td>
<td>0.74</td>
<td>–0.26</td>
</tr>
<tr>
<td></td>
<td>(3.41)</td>
<td>(0.99)</td>
<td>(1.64)</td>
<td>(1.34)</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.6613</td>
<td>0.7644</td>
<td>0.2610</td>
<td>0.6913</td>
</tr>
</tbody>
</table>

*, **, *** Significant at $P = 0.05, 0.01$ and 0.001, respectively.

† The dependent variable is kilograms of forage dry matter per hectare. The numbers in parentheses are standard errors.
‡ PMU, rising plate meter unit.
Acknowledgments
The research was primarily funded by the Samuel Roberts Noble Foundation. Brorsen receives funding from the A.J. & Susan Jacques Chair and the Oklahoma Agricultural Experiment Station and USDA National Institute of Food and Agriculture, Hatch Project number OKL02939.

Conflict of Interest
The authors declare no conflict of interest.

References

Fig. 2. Rye forage mass versus rising plate meter unit (PMU) reading.