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Yield prediction of grassland swards using specific equations for Rising Plate Meter

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Accurate prediction of grassland yield is essential for efficient management and sustainable use. The Rising Plate Meter (RPM) is a device widely used in pasture management to measure the height of growth considering sward density to calculate biomass yield. This can be transferred to the use of grassland for mowing. The key is to adapt the prediction equation, which calculates the dry matter yield from the measured compressed sward height. The accuracy can be further improved by using specific prediction equations. The equations consider (1) temporal, (2) spatial and (3) sward-specific factors. To develop the specific equations, RPM measurements were carried out for two regions, the dry matter yield of the plots was determined and the data were analyzed using linear regression. The results show that the application of the specific equations improves the mean deviation from 31% (RMSE = 738 kg/ha) to 18% (RMSE = 570 kg/ha). These improvements allow farmers to predict yield already during the growing phase, providing a reliable basis for site-specific grassland management and optimizing forage production.

Keywords
Grassland, yield prediction, rising plate meter, precision farming

Globally, grassland is the most important form of vegetation, accounting for almost 70% of agricultural land (FAO 2021). In Europe, and particularly in Germany, the proportion of grassland in the total utilized agricultural area is much lower at 28%, although the proportion of mown grassland has increased steadily over the last four years to 12% (Statistisches Bundesamt 2024). Grassland management is particularly important for small farms in southwest Germany (Statistisches Landesamt Baden-Württemberg 2022).

In order to plan storage, efficient grazing or the introduction of Precision Farming management methods, it is very important to have sub-area accurate grassland yield data. Digital measurement technologies can be used to measure parameters during both the growth and harvesting phases to determine biomass yield at sub-field level. The measurement of parameters during the growth phase is a yield prediction, as the harvest takes place at a later date. In contrast, the measurement of yield-relevant parameters during the harvesting process can be described as yield measurement, as the parameters are measured after the plant material has been cut.

The development of yield measurement systems is at an advanced stage and is available on the market for forage harvesters (Worek and Thurner 2021). However, adoption in agricultural practice has so far been low due to high investment costs and restrictive harvesting conditions (Riehl 2020). The dominant form of yield determination on small-scale farms is the visual estimation of yield based on the number of bales or the volume of silage filled (Köhler et al. 2016).

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Yield prediction is currently the subject of intense research. For example, radar, multispectral or meteorological data are collected by satellites, unmanned aerial systems or ground-based sensors and processed into a prediction model using machine learning techniques (Viljanen et al. 2018, Bretas et al. 2021, Murphy et al. 2021c, Stumpe et al. 2024).

One method of predicting yield that has been studied for some time and was originally used to determine available forage on grazed grassland is the use of the Rising Plate Meter (Earle and McGowan 1979, Tucker 1980, Scrivner et al. 1986, Harmoney et al. 1997). This involves measuring the height of the plant population during the growing season, from which biomass can be calculated using a predictive equation (Murphy et al. 2021c). This method can be applied to mowed grassland to predict its yield at mowing.

Currently, a standardized equation developed in Ireland based on intensively managed and homogeneous grassland swards is always used for prediction across regions regardless of sward composition. It has not been published by the manufacturer of the RPM, so it is not known. When the equation is applied, only the two parameters (1) target cutting height, and (2) subjectively estimated dry matter content are adjusted to determine the dry matter yield. Studies have shown that this equation is not suitable for species-rich grassland swards such as those found in southwest Germany (Dillard et al. 2016, Hart et al. 2020, Stumpe et al. 2021).

Specific prediction equations that consider other factors affecting grassland sward development are one way to improve this. The literature identifies three main factors that require specific adjustment of the prediction equation. As a result of previous studies, the need for (1) temporal, (2) spatial, and (3) sward-dependent adjustments to the prediction equations has emerged. For the temporal adjustment, the vegetation period of one year is subdivided into further growth periods, taking into account the typical growth curve of grassland plants (Lile et al. 2001, Nakagami and Itano 2014, La Guardia Nave and Corbin 2019, Murphy et al. 2021b). Spatial adjustment can be made by dividing geographical areas into regions where climatic conditions, altitude and soil types are similar within a region (Rennie et al. 2009, Hart et al. 2019, Stumpe et al. 2021). The physiological characteristics of the plant community have a major influence on the relationship between height and dry matter yield. Classifying grassland swards into sward types based on the yield proportions of the plant groups takes these characteristics into account and allows sward-specific adaptation (Milsom et al. 2019, Rayburn 2020, Murphy et al. 2021b, McSweeney et al. 2022, Chapa et al. 2023).

At present, neither agricultural practice nor research uses this specific adjustment of the prediction equations to take these factors into account. The necessary equations are not available. As a result, yield predictions using the Rising Plate Meter in southwest Germany and the Alpine region are imprecise compared to yield predictions for intensively managed grasslands (Hart et al. 2019, Stumpe et al. 2021). Especially for the grassland intensive regions like the Southern Black Forest and Upper Swabia, an adaptation is necessary to provide a precise method for yield prediction that is easy to implement in a small-scale region.

Based on these research gaps, the aim of the study is the determination of temporal, spatial and sward-dependent adjusted equations for the prediction of dry matter yield of grassland swards in two model regions in southwest Germany. Furthermore, it is to be investigated how the prediction performance of a Rising Plate Meter changes with the use of the specific prediction equations compared to the use of a general prediction equation. The prediction performance is to be evaluated using statistical metrics and compared with previous research results.

Material and methods

The two model regions, Southern Black Forest and Upper Swabia, were examined in 2020 and 2021 and are located in southwestern Germany in the state of Baden-Württemberg. The location in Germany and the location of the study sites within the model regions are shown in Figure 1. The Southern Black Forest region is located east of the city of Freiburg and is typical of a low mountain range region in Germany. The altitude of the four experimental plots in this region is between 800 and 1100 m above sea level. The region of Upper Swabia extends between the city of Ulm and Lake Constance. The three experimental fields assigned to this region are located between 500 and 600 m above sea level.

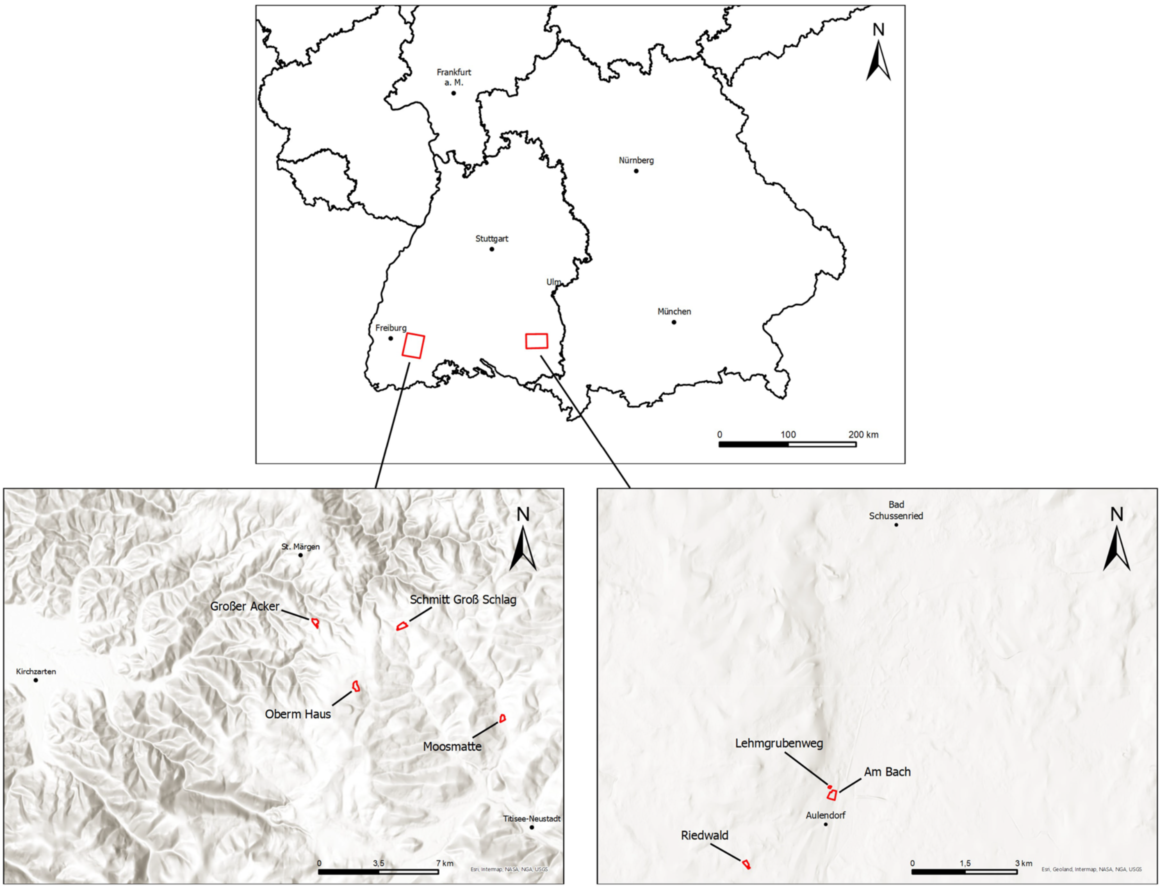

Figure 1: Geographical representation of the model regions within Germany (top) and the experimental fields in the model regions Southern Black Forest (left) and Upper Swabia (right)

Both regions are characterized by a high proportion of grassland in the agricultural area. The Southern Black Forest region is climatically characterized by an average annual precipitation of 1258.5 mm. The average annual temperature is 8.0 °C. With an average annual precipitation of 938 mm and an average annual temperature of 9.6 °C, the region of Upper Swabia has less precipitation and is warmer in comparison. This difference is also evident in the number of vegetation days. The Southern Black Forest region has an average of 223 vegetation days per year and the Upper Swabia region has an average of 247 vegetation days per year (Landwirtschaftliches Technologiezentrum Augustenberg 2024).

The size of the experimental fields in the Southern Black Forest model region is between 3.5 and 6.1 ha. The soil type for the fields *Großer Acker*, *Oberm Haus* and *Schmitt Groß Schlag*, which are located on the ridges of the Black Forest, is brown earth. The soil type for the *Moosmatte*, which is located in a valley, is different with fen and anmoorgley. With a size of between 0.2 and 2.0 ha, the experimental fields in the Upper Swabia region are smaller than those in the Southern Black Forest region. The soil type differs between the three experimental fields and can be seen in Table 1.

Table 1: Overview of the experimental fields with assignment to the model regions and description of the altitude, area size and soil type

Name of the experimental field	Region	Height above sea level in m	Field size in ha	Soil type
Großer Acker	Southern Black Forest	858.9	4.4	Brown earth
Moosmatte	Southern Black Forest	861.5	3.5	Fen and Gley
Oberm Haus	Southern Black Forest	1053.5	5.7	Brown earth
Schmitt Groß Schlag	Southern Black Forest	1013.7	6.1	Brown earth
Am Bach	Upper Swabia	558.0	2.0	Gley
Lehmgrubenweg	Upper Swabia	565.3	0.2	Gley
Riedwald	Upper Swabia	592.0	0.9	Para-brown earth

Soil type according to: Regierungspräsidium Freiburg, Landesamt für Geologie, Rohstoffe und Bergbau (2021)

The intensity of use of the grasslands differs for the selected model regions. The experimental fields in the Southern Black Forest region are managed according to organic standards and mowed three times a year. The fields in the Upper Swabia region, on the other hand, are managed conventionally and mowed five to seven times a year.

The plant community of the experimental fields is influenced not only by soil type but also by altitude, climate, land use intensity and management practices. According to Deutsche Landwirtschafts-Gesellschaft e. V. (2004), three sward types can be distinguished (Table 2). They allow the plant communities to be assessed and categorized into defined groups. Using the method published by Klapp and Stählin in Voigtländer and Voss (1979), the yield share is determined for each experimental plot (1 m^2) on the basis of the mass percentages in the dry state. At the same time, the main grassland species are recorded and listed in Table 2.

Table 2: Classification of sward types according to Deutsche Landwirtschafts-Gesellschaft e. V. (2004)

Sward type	Grass content	Main grassland species
Rich in grasses (RG)	> 70%	Perennial ryegrass (*Lolium perenne*), Orchard grass (*Dactylis glomerata*), False oat-grass (*Arrhenatherum elatius*)
Balanced (B)	50–70%	Perennial ryegrass (*Lolium perenne*), Meadow fescue (*Festuca pratensis*), Ribwort plantain (*Plantago lanceolata*), Red clover (*Trifolium pratense*)
Rich in clover and herbs (RCH)	< 50%	Red clover *(Trifolium pratense),* White clover *(Trifolium repens*), Ribwort plantain (*Plantago lanceolata*), Common dandelion (*Taraxacum officinale*)

The growing periods are obtained by dividing the growing season of a year into three parts based on the meteorological seasons. The first growing period (1) is from the beginning of vegetation to the beginning of summer. This is followed by the second growing period (2), which includes the summer months of June, July and August. The third growing period (3) spans from the beginning of fall to the end of vegetation. The growing season is therefore divided into three growing periods for further data analysis.

Depending on the size and sward heterogeneity of the field, each experimental field comprises between four and ten randomly distributed plots. The number of plots increases with both the size and heterogeneity of the field. The size of the plots is one square meter. This square meter is fully covered by the Rising Plate Meter by recording nine points of compressed sward height in a standardized pattern and sequence. The mean value of the compressed sward height per test plot is calculated from the nine measuring points. The compressed sward height is measured using a Rising Plate Meter type Grasshopper. The dimensions and components of the measuring instrument are shown in the schematic illustration in Figure 2.

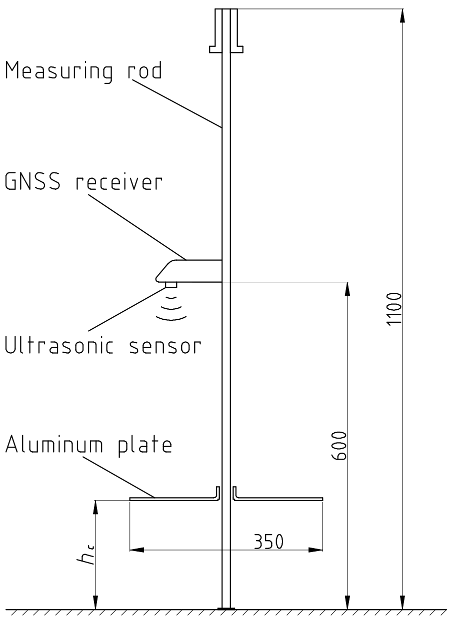

Figure 2: Rising Plate Meter type Grasshopper

The aluminium plate can be displaced vertically along the measuring rod and has a mass of 0.4785 kg. To take a measurement, the rod is passed vertically through the plants to the soil surface, and at the same time, the plants prevent the aluminium plate from sinking to the surface. The mass of the plate generates a pressure of 49 N m^{-2}, which compacts the plants of the sward. Thus, the distance between the aluminium plate and the soil surface is equal to the compressed sward height (h_c). In addition to plant height, the compressed sward height takes into account the density of the sward as it also affects how far the aluminium plate sinks.

To determine h_c, an ultrasonic sensor is used to measure the distance between the aluminium plate and the sensor position. This value is subtracted from the maximum distance between the ultrasonic sensor and the aluminium plate to determine h_c. The average error of the ultrasonic sensor distance measurement is 0.18 mm (McSweeney et al. 2019). Additionally, the Global Navigation Satellite System (GNSS) receiver determines the position with an average error of up to seven meters for each measurement (Office of the Department of Defense 2020).

After measuring the compressed sward height, the plant material within the test plot is cut manually at a cutting height of 7 cm and the fresh matter yield is determined. The dry matter yield is obtained after oven drying at 60 °C until the mass remains constant and extrapolated to the yield per hectare. This provides a dry matter yield value for each plot that can be related to the previously measured compressed sward height. Plots on which the plants were not erected prior to RPM measurement were excluded from further evaluation.

Statistical evaluation

To investigate the relationship between compressed sward height and dry matter yield, correlation analysis is used based on previous research (Itano et al. 2012, Dillard et al. 2016, La Guardia Nave and Corbin 2019). The coefficient of determination R^2 is used to analyze the regression line and thus the correlation between the two variables. It allows the comparison of different regression lines and, with the extreme values $R^2 = 0$ and $R^2 = 1$, indicates how well they describe the dependence of the dependent variable dry matter yield (Y_{DM}) on the independent variable compressed sward height (h_c).

Different statistical metrics are used to evaluate prediction performance, allowing for absolute and relative assessment of accuracy, as well as comparability of predictions for data sets with different variance. Stumpe et al. (2024) recommend Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMSE), Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) for the evaluation of prediction models. The definitions of the statistical metrics used in this study can be found in Equations 1–4. P is the predicted value, O is the measured value, and n is the number of samples.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (P_i - O_i)^2} \qquad \text{(Eq. 1)}$$

$$\mathrm{NRMSE_{mean}} = \frac{\mathrm{RMSE}}{\bar{O}} \qquad \text{(Eq. 2)}$$

$$\mathrm{MAE} = \frac{1}{n} \cdot \sum_{i=1}^{n} |P_i - O_i| \qquad \text{(Eq. 3)}$$

$$\mathrm{MAPE} = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{|P_i - O_i|}{O_i} \qquad \text{(Eq. 4)}$$

The definition of NRMSE is not standardized in the literature. The mean, the range, or the standard deviation are optionally used as reference values for the RMSE. In this study, the mean is used as the reference value because this definition is recommended in the literature (Priesack et al. 2006, Yang et al. 2014), and the mean is the most commonly used reference value in comparable studies (Stumpe et al. 2024).

Results

The data set under consideration contains a total of 814 samples, which are distributed across two regions, seven fields, and two years. The descriptive statistics (mean, standard deviation σ, minimum value, maximum value) for the measured parameters of sward height and dry matter yield are presented in Table 3. The distribution of the measurements across the subcategories of sward type and growing period is also included in the table.

Table 3: Descriptive statistics of the dataset

Variable		**Mean**	**σ**	**Min**	**Max**	**Number of samples**
Sward height	in mm	137.48	44.43	48.25	234.00	-
Dry matter yield	in kg/ha	2415.26	1554.01	105.09	6931.13	-
Sward type						
Rich in grasses (RG)		-	-	-	-	183
Balanced (B)		-	-	-	-	126
Rich in clover and herbs (RCH)		-	-	-	-	505
Growing period						
1 (March – May)		-	-	-	-	311
2 (June – August)		-	-	-	-	275
3 (September – November)		-	-	-	-	228

A prediction equation for an RPM describes the relationship between the measured compressed sward height (h_c) in mm and the related dry matter yield (Y_{DM}) in kg/ha. A linear equation is determined from the available measurement data using correlation analysis. The general form of a prediction equation is shown in Equation 5. m describes the slope of the straight line and b indicates the intercept.

$$Y_{\mathrm{DM}} = m \cdot h_c - b \qquad \text{(Eq. 5)}$$

By considering the entire data set, a general prediction equation can be derived which is adapted to the mowing use of species-rich grassland swards in southwest Germany. No distinction is made between model regions, growing seasons and sward types. The totality of all 814 measurements and the general prediction equation derived from them for southern German conditions are shown in Figure 3.

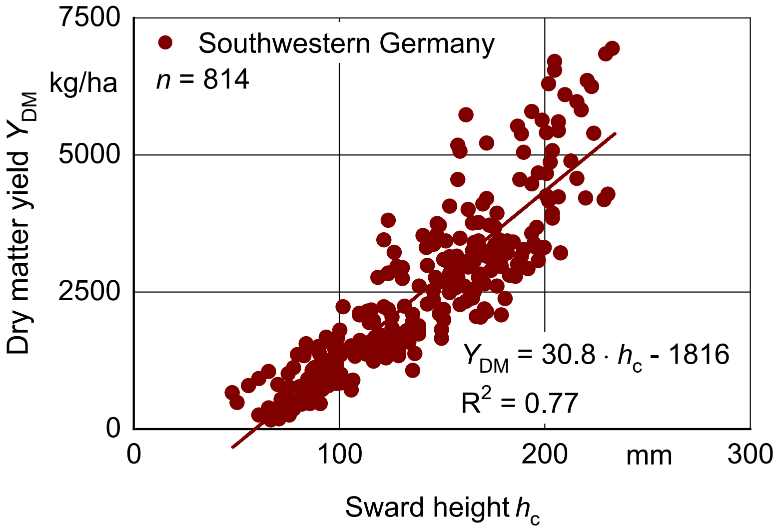

Figure 3: Measurement results (h_c; Y_{DM}) and general prediction equation for the entire data set (two regions, three growing periods, three sward types)

It can be seen that the measurements above a compressed sward height of 150 mm are spread more widely around the regression line than in the range below. Overall, the general equation results in a positive slope of 30.8 and a negative intercept of −1816. The coefficient of determination of this equation to describe the dependence of dry matter yield on sward height for southwest Germany is $R^2 = 0.77$.

To develop specific prediction equations, the data set is divided by (1) region, (2) sward type, and (3) growing period. With two experimental regions, three sward types and three growing periods, there are a total of 18 specific prediction equations.

The measured data and the results of the correlation analysis for the Southern Black Forest (SBF) region are shown in Figure 4, Figure 5 and Figure 6 separately for the sward types (RG, B and RCH) defined in Table 2. The numbers (1, 2 and 3) relate to the growing periods that have been predefined on the basis of the meteorological seasons. A compressed sward height of 204 mm corresponds to the maximum for the Southern Black Forest region. The yield per hectare reaches a maximum value of 3840 kg/ha in this region. These maximum values are reached in the first growing period and decrease in the further course of the growing season. Especially in the third growing period, lower compressed sward heights and dry matter yields are observed. The comparison of the measured data of the different sward types for the same growing period shows that the values for the compressed sward height and the dry matter yield of the different sward types are in a similar range.

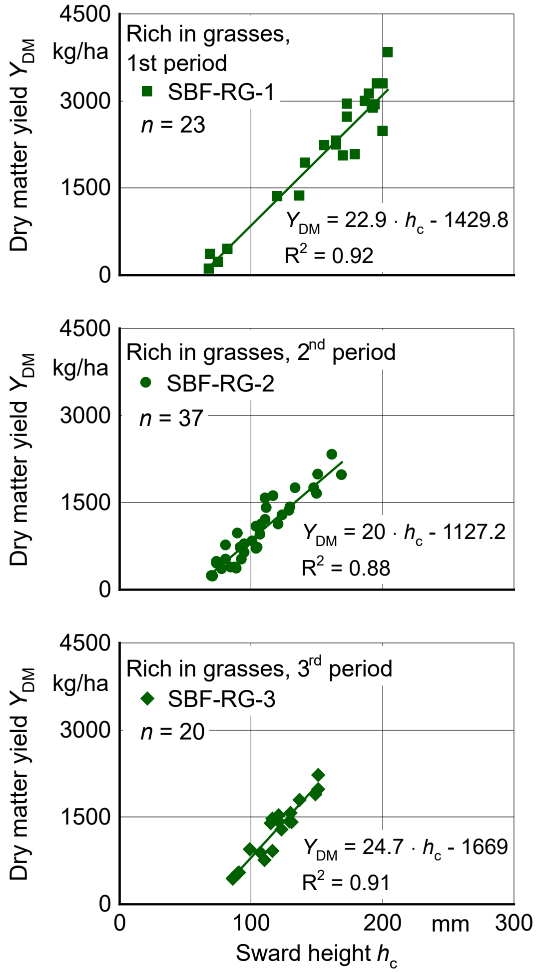

Figure 4: Measurement results and prediction equations for the Southern Black Forest region, sward type rich in grasses, subdivided according to the growing period

Correlation analysis provides linear equations for each combination of sward type and growing period that describe the relationship between compressed sward height and dry matter yield. For each of the nine specific equations, the slope is positive and ranges from 18.7 to 27.8. The intercept is negative in all cases and ranges from −1775 to −899.6. The coefficients of determination for the linear equation lines range from R^2 = 0.86 to R^2 = 0.98.

A comparison of the regression line equations for different sward types in the same growing period shows that the values for slope and ordinate intercept are similar for swards rich in grasses and balanced swards in the first two growing periods. For swards rich in clover and herbs, the straight line for the second growing period is steeper and the value for the ordinate intercept is smaller compared to the other two sward types. In the third growing period, however, the slope of the straight line for swards rich in grasses is steeper and the ordinate intercept is lower than for balanced swards and swards rich in clover and herbs. This shows the different relationship between dry matter yield and the compressed sward height depending on the sward type and growing period.

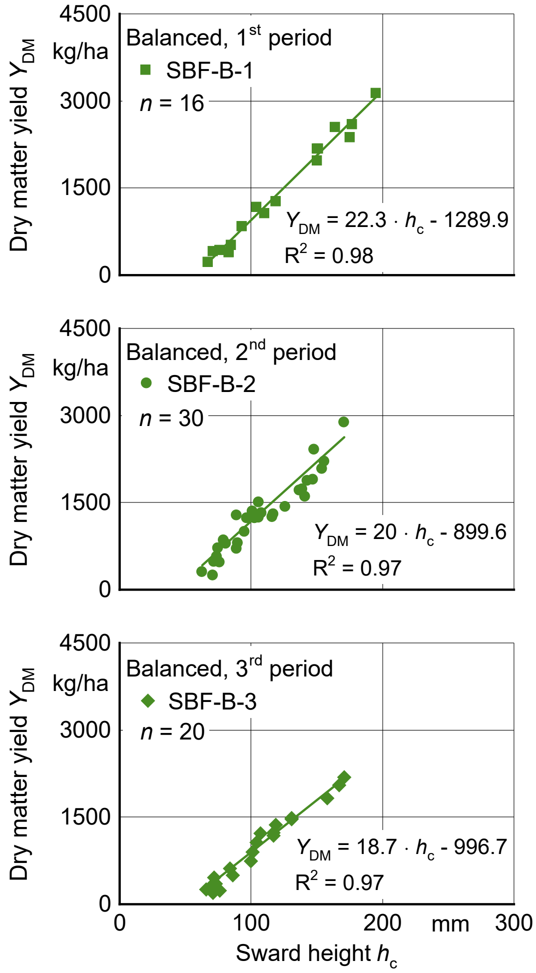

Figure 5: Measurement results and prediction equations for the Southern Black Forest region, sward type balanced, subdivided according to the growing period

An examination of the prediction equations for the Southern Black Forest region shows that the SBF-RCH-2 equation has a significantly greater slope than the corresponding equations for the two other sward types. Clover and herbs, which dominate for this sward type, are easier to compact compared to grass and lead to a comparatively high dry matter yield due to their leaf mass. Clover and herbs are particularly dominant over grasses during dry periods, for example during the summer depression in the second growing period. For the SBF-RG-3 equation, a greater slope can also be observed compared to the two equations of the other sward types and compared to the previous growing period. This can be explained by the fact that precipitation increases in the third growing period and the grass swards become denser. Balanced swards and swards rich in clover and herbs, on the other hand, are more sensitive to more frequent mowing. Therefore, these two sward types result in less dense swards in the third growing period with a lower slope.

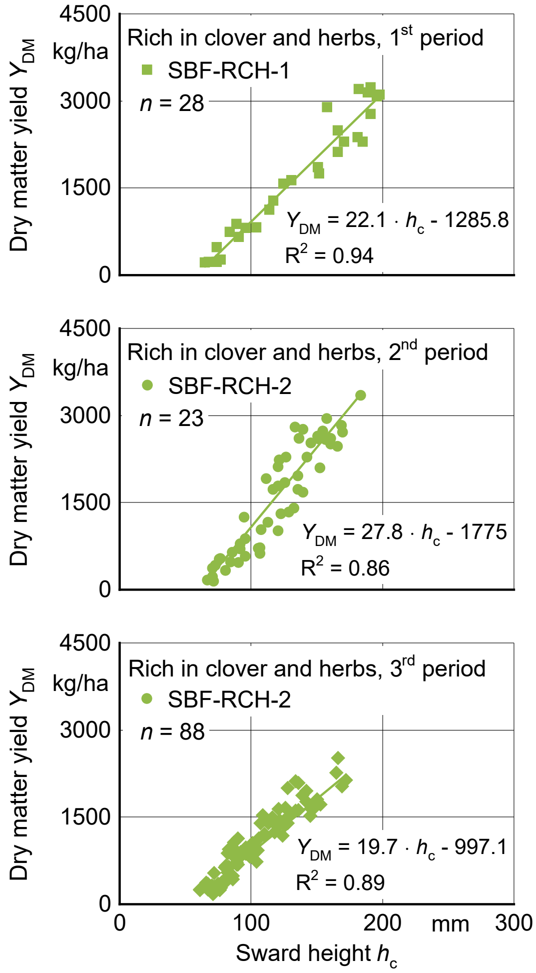

Figure 6: Measurement results and prediction equations for the Southern Black Forest region, sward type rich in clover and herbs, subdivided by growing period

For the region of Upper Swabia (US), the measured data and the results of the correlation analysis are presented in the same form in Figure 7, Figure 8 and Figure 9. The maximum sward height of 234 mm is higher than the comparable value for the Southern Black Forest region, and the maximum dry matter yield of 6931 kg/ha is also higher in the Upper Swabia region. The maximum values are reached in the first growing period. The yield level decreases in the course of the growing season for all sward types. There is no discernible difference between the sward types for the same growing period in terms of compressed sward height and dry matter yield.

Compared to the first experimental region, there is a stronger decrease in the yield level from the first to the third growing period. As a result, the equations of the regression lines differ more strongly from each other. The slope of the straight lines is between 10.6 and 31.8 and the ordinate intercept of the straight line is between −1704.6 and 348.4. The coefficients of determination of the specific equations for the region of Upper Swabia lie in a range between R^2 = 0.46 and R^2 = 0.67.

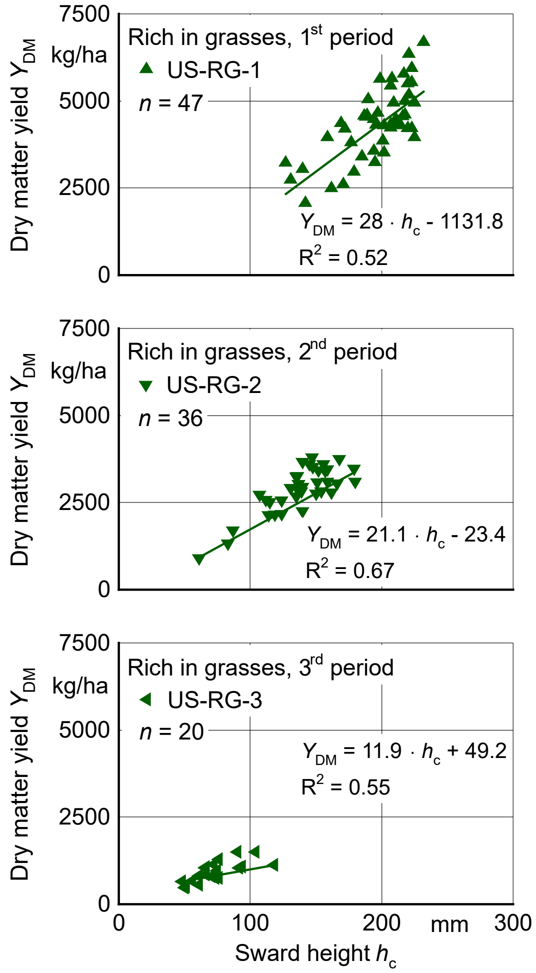

Figure 7: Measurement results and prediction equations for the Upper Swabia region, sward type rich in grasses, subdivided according to the growing period

Regardless of the sward type, it can be seen that the slope decreases from the first to the third growing period, thereby causing the straight line to flatten. There is a difference between the equations for the sward types in each growing period.

In the region of Upper Swabia, the comparison by sward type shows in most cases the greatest slope for the equations of the sward type rich in grasses. This may be due to the soil structure, which, compared to the soils of the Southern Black Forest region, is better able to compensate for dry periods, so that the summer depression of grass growth is weakened. The equations for the third growing period of the region of Upper Swabia generally show a positive intercept with a flatter curve. This can be explained by a younger sward and a higher water content, resulting in a lower dry matter content, which in turn leads to a flatter curve.

A comparison of the measured data for the regions studied shows that a higher yield level with higher maximum values for the compressed sward height is achieved in the region of Upper Swabia. A possible factor is the warmer climate with a higher average annual temperature and more growing days per year. Cultivation intensity also has an influence, which is higher in Upper Swabia with more intensive fertilization and more frequent mowing.

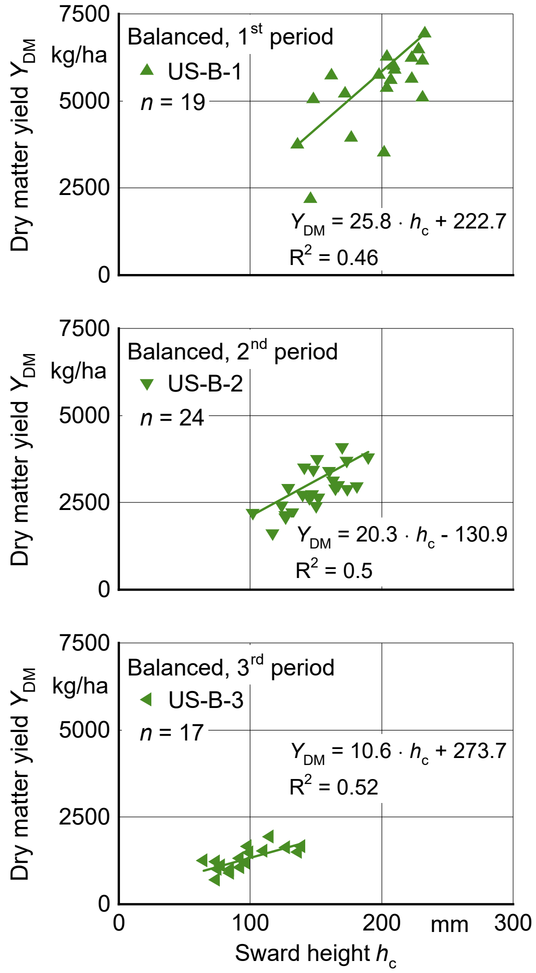

Figure 8: Measurement results and prediction equations for the Upper Swabia region, sward type balanced, subdivided according to the growing period

Looking at the specific equations for the two experimental regions, it can be seen that the slope is greater in the Upper Swabian region for the first growing period, comparable in the second growing period, and greater in the Southern Black Forest region for the third growing period. This may be due to the different plant species per sward type in the two regions, which have different compaction properties. A comparison of the intercepts does not show results that are similar to those obtained for the slope.

The comparison of the coefficients of determination for the regression lines of the two experimental regions shows that the coefficients of determination for the region of Upper Swabia are on a lower level. Thus, the linear equations described for the region of Upper Swabia do not represent the relationship between compressed sward height and dry matter yield as well as the equations for the region of Southern Black Forest.

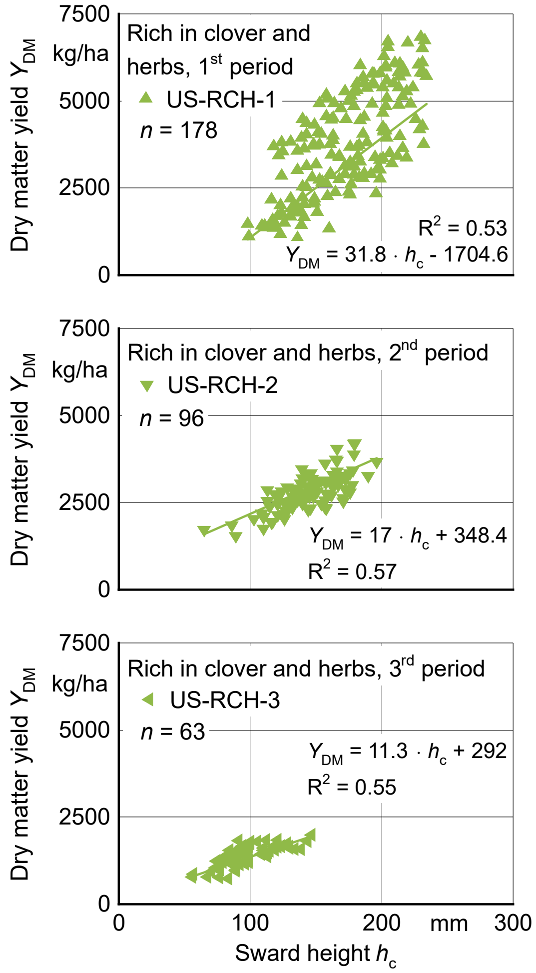

Figure 9: Measurement results and prediction equations for the Upper Swabia region, sward type rich in clover and herbs, subdivided according to the growing period

The developed equations, both general and specific, can be applied to the available data set to predict dry matter yield. The deviation of the predicted DM yield from the measured DM yield can then be calculated. The statistical metrics presented in the previous chapter can be used to evaluate the prediction performance. Table 4 provides a comparative overview of the application of a general dry matter yield prediction equation for the entire data set versus the application of the 18 specific prediction equations developed.

Table 4: Comparative description of the statistical metrics for the evaluation of the prediction results of the general and specific prediction equation

Prediction equation applied	**RMSE** in kg/ha	**$NRMSE_{mean}$** in %	**MAE** in kg/ha	**MAPE** in %
General	738.09	30.56	580.01	30.85
Specific	570.23	23.61	388.01	18.26

The application of the general prediction equation, which has not been specifically adapted to the three factors, gives an average deviation of 738.09 kg/ha (RMSE) or 580.01 kg/ha (MAE) between the predicted yield and the actual measured yield. Relative to the mean of the measurements ($NRMSE_{mean}$) and to each individual measurement (MAPE), this results in a relative deviation of 30.56% and 30.85%, respectively.

Using the specific prediction equations, absolute deviations of 570.23 kg/ha (RMSE) and 388.01 kg/ha (MAE) are achieved. This results in relative deviations of 23.61% ($NRMSE_{mean}$) and 18.26% (MAPE).

Discussion

Compared to a general prediction equation, the specific prediction equations better represent the relationship between compressed sward height and dry matter yield. Therefore, predicting dry matter yield with a Rising Plate Meter using specific equations is more accurate, as can be seen from the statistical metrics. Both the absolute and relative prediction errors for the prediction using the specific prediction equation are lower than the corresponding value for the general equation. The absolute prediction error is reduced by 160 to 570.23 kg/ha (RMSE) and the relative error is reduced by about 12 to 18% (MAPE).

For comparison with other studies, the absolute error measured as RMSE is the most frequently reported value. Gargiulo et al. (2020) achieve prediction errors of 45 to 160 kg/ha with the help of linear regression, which is not reached or beaten by any comparable study. Klingler et al. (2020) report an RMSE of 434 kg/ha for prediction, which is in a similar range to this study. With RMSE values between 880 and 1170 kg/ha, the prediction error of Reddersen et al. (2014) is significantly higher. The results of the present study are therefore in the range of results of methodologically comparable studies for other regions. The differences can be explained by the heterogeneity of the considered swards and the size of the captured samples.

When evaluating the accuracy of yield prediction with a Rising Plate Meter, the limitations of the system must also be considered. Especially for laying swards, the RPM does not provide reliable results, because the relationship between compressed sward height and dry matter yield cannot be described by the equations for other conditions. In addition, sward heights that are too high are difficult to measure correctly with the RPM and tend to lodge. In the case of highly gapped swards, there is also the problem that the measurement positions do not correctly reflect the heterogeneity of the sward (Murphy et al. 2018).

In addition to the accuracy of the prediction, cost is a critical factor in the practical application of the technology. For the Rising Plate Meter, the running costs of the application are more important than the investment costs (Kiefer et al. 2024). They are strongly influenced by the density of the measurement points and the sampling pattern (Hart et al. 2022). The pattern, in turn, affects the spatial resolution of the data and therefore the quality of the yield prediction. There is therefore a trade-off between the cost of measurement and the quality of the data. To resolve this conflict, the number of measurement points has been studied and a recommendation has been made as to how many measurement points are required under which crop conditions (Hutchinson et al. 2016). A tool can also be used to distribute the points over the field, taking into account the shape of the field (Murphy et al. 2020).

A further refinement of the prediction equation to account for the grassland sward under investigation offers a potential avenue for more precise predictions. A comprehensive evaluation has revealed that further distinctions within a sward type, particularly the sward type rich in clover and herbs (RCH), could improve the prediction accuracy. This distinction is particularly relevant due to the observed disparities in compressibility between clover and herbs, which can influence the prediction equation. The hypothesis can be confirmed for clover-rich swards due to a larger slope, as evidenced by a comparison of the correlations for samples of the sward type RCH with a high clover content compared to samples with a high herb content.

In order to extend the increase in accuracy to other regions, the development of specific equations for other regions is recommended in the future. To facilitate the application, a database should be established to store the specific equations for the associated regions. To this end, an application should be developed that accesses the database and uses the equation applicable to the conditions under consideration to generate a site-specific yield map based on the compressed sward height data. In addition to compressed sward height, other measurements and data can be used in the prediction, such as weather data, multispectral data, or management data (Murphy et al. 2021a).

Limitations

The findings of this study must be interpreted in consideration of their limitations, as the division of the data set results in smaller data sets for the development of specific prediction equations. To address this, it is necessary to expand the data basis and test the method in other years to account for changing growing conditions. Lodging swards were excluded from the development of specific prediction equations in order to avoid distortion of the correlation. They represent a challenge for the transfer of the method into agricultural practice. The evaluation of the specific prediction equations was carried out on the basis of the fields previously examined, and a future evaluation of the newly developed prediction equations on independent fields in the regions under consideration is recommended to verify the results.

Conclusions

Yield prediction of grassland swards using a Rising Plate Meter provides the opportunity to collect site-specific yield information. Accuracy is increased by applying specific prediction equations adapted to the region, sward composition and growing season. The yield information can be used to match the yield potential of grassland sites to their management intensity and to establish Precision Farming practices.

References

Bretas, I.L.; Valente, D.S.; Silva, F.F.; Chizzotti, M.L.; Paulino, M.F.; D'Áurea, A.P.; Paciullo, D.S.; Pedreira, B.C.; Chizzotti, F.H. (2021): Prediction of aboveground biomass and dry matter content in brachiaria pastures by combining meteorological data and satellite imagery. Grass and Forage Science, pp. 1–13, https://doi.org/10.1111/gfs.12517

Chapa, J.M.; Pichlbauer, B.; Bobal, M.; Guse, C.; Drillich, M.; Iwersen, M. (2023): Field Evaluation of a Rising Plate Meter to Estimate Herbage Mass in Austrian Pastures. Sensors 23(17), https://doi.org/10.3390/s23177477

Deutsche Landwirtschafts-Gesellschaft e.V. (Ed.) (2004): Grobfutterbewertung. Teil A - DLG-Schlüssel zur Bewertung von Grünfutter, Silage und Heu mit Hilfe der Sinnenprüfung

Dillard, S.L.; Hafla, A.N.; Rubano, M.D.; Stout, R.C.; Brito, A.F.; Soder, K.J. (2016): Evaluation of a Rising Plate Meter for Use in Multispecies Swards. Agricultural & Environmental Letters 1(1), pp. 1–4, https://doi.org/10.2134/ael2016.08.0032

Earle, D.F.; McGowan, A.A. (1979): Evaluation and calibration of an automated rising plate meter for estimating dry matter yield of pasture. Australian Journal of Experimental Agriculture 19(98), p. 337, https://doi.org/10.1071/EA9790337

FAO (2021): Land use statistics and indicators statistics. Global, regional and country trends 1990– 2019. FAOSTAT Analytical Brief Series 28

Gargiulo, J.; Clark, C.; Lyons, N.; Veyrac, G. de; Beale, P.; Garcia, S. (2020): Spatial and Temporal Pasture Biomass Estimation Integrating Electronic Plate Meter, Planet CubeSats and Sentinel-2 Satellite Data. Remote Sensing 12(19), https://doi.org/10.3390/rs12193222

Harmoney, K.R.; Moore, K.J.; George, J.R.; Brummer, E.C.; Russell, J.R. (1997): Determination of Pasture Biomass Using Four Indirect Methods. Agronomy Journal 89(4), pp. 665–672, https://doi.org/10.2134/agronj1997.00021962008900040020x

Hart, L.; Oudshoorn, F.; Latsch, R.; Umstätter, C. (2019): How accurate is the Grasshopper® system in measuring dry matter quantity of Swiss and Danish grassland? In: 9th European Conference on Precision Livestock Farming (ECPLF), Animal & Grassland Research and Innovation Centre, 26–29 Aug 2019, Fermoy, Cork

Hart, L.; Quendler, E.; Umstaetter, C. (2022): Sociotechnological Sustainability in Pasture Management: Labor Input and Optimization Potential of Smart Tools to Measure Herbage Mass and Quality. Sustainability 14(12), https://doi.org/10.3390/su14127490

Hart, L.; Werner, J.; Velasco, E.; Perdana-Decker, S.; Weber, J.; Dickhöfer, U.; Umstätter, C. (2020): Reliable biomass estimates of multispecies grassland using the rising plate meter. In: 28th General Meeting of the European Grassland Federation, 19–22 Oct 2020, Helsinki, Wageningen Academic Publishers, pp. 641–643

Hutchinson, K.J.; Scobie, D.R.; Beautrais, J.; Mackay, A.D.; Rennie, G.M.; Moss, R.A.; Dynes, R.A. (2016): A protocol for sampling pastures in hill country. Journal of New Zealand Grasslands 78, pp. 203–209, https://doi.org/10.33584/jnzg.2016.78.511

Itano, S.; Tomimatsu, H.; Nakagami, K.; Maeda, Y. (2012): Incorporating a periodic function into an equation for estimating herbage mass in Zoysia-dominated pastures from rising plate readings. Grassland Science 58(3), pp. 127–132, https://doi.org/10.1111/j.1744-697X.2012.00253.x

Kiefer, A.; Stumpe, C.; Hütt, C.; Bahrs, E. (2024): Comparing economic effects of remote herbage mass estimation in small-scale farms in mountain regions. agricultural engineering.eu 79(1), pp. 1–20, https://doi.org/10.15150/LT.2024.3302

Klingler, A.; Schaumberger, A.; Vuolo, F.; Poetsch, E.M. (2020): Suitability of non-destructive yield and quality measurements on permanent grassland. In: 28th General Meeting of the European Grassland Federation, 19–22 Oct 2020, Helsinki, Wageningen Academic Publishers, pp. 602–604

Köhler, B.; Spiekers, H.; Südekum, K.-H.; Staudacher, W.; Taube, F. (Eds.) (2016): Mengenmäßige Erfassung des wirtschaftseigenen Futters. Definitionen von Mengenbegriffen und Verlustgrößen. DLG-Merkblatt 416, Frankfurt

La Guardia Nave, R.; Corbin, M.D. (2019): Seasonal and diurnal relationship of forage nutritive value and mass in a tall fescue pasture under continuous stocking. Grassland Science 65(3), pp. 162–170, https://doi.org/10.1111/grs.12231

Landwirtschaftliches Technologiezentrum Augustenberg (Ed.) (2024): Agrarmeteorologie Baden-Württemberg. https://www.wetter-bw.de/Agrarmeteorologie-BW/Wetterdaten/Stationskarte, accessed on 26 Mar 2024

Lile, J.A.; Blackwell, M.B.; Thomson, N.A.; Penno, J.W.; Macdonald, K.A.; Nicholas, P.K.; Lancaster, J.; Coulter, M. (2001): Practical use of the rising plate meter (RPM) on New Zealand dairy farms. Proceedings of the New Zealand Grassland Association (63), pp. 159–164, https://doi.org/10.33584/jnzg.2001.63.2425

McSweeney, D.; Coughlan, N.E.; Cuthbert, R.N.; Halton, P.; Ivanov, S. (2019): Micro-sonic sensor technology enables enhanced grass height measurement by a Rising Plate Meter. Information Processing in Agriculture 6(2), pp. 279–284, https://doi.org/10.1016/j.inpa.2018.08.009

McSweeney, D.; Delaby, L.; O'Brien, B.; Ferard, A.; Byrne, N.; McDonagh, J.; Ivanov, S.; Coughlan, N.E. (2022): Dynamic algorithmic conversion of compressed sward height to dry matter yield by a rising plate meter. Computers and Electronics in Agriculture 196, https://doi.org/10.1016/j.compag.2022.106919

Milsom, A.; Bell, O.; Bailey, K.; Brown, S.C.; Barton, R.A.; Moreno Garcia, C.A.; Chen, A.; Bryant, R.H.; Maxwell, T.M.; Eady, C.C. (2019): Assessing the ability of a stationary pasture height sensing device to estimate pasture growth and biomass. Journal of New Zealand Grasslands, pp. 61–68, https://doi.org/10.33584/jnzg.2019.81.384

Murphy, D.J.; Murphy, M.D.; O'Brien, B.; O'Donovan, M. (2021a): A Review of Precision Technologies for Optimising Pasture Measurement on Irish Grassland. Agriculture 11(7), https://doi.org/10.3390/agriculture11070600

Murphy, D.J.; O' Brien, B.; Murphy, M.D. (2020): Development of a grass measurement optimisation tool to efficiently measure herbage mass on grazed pastures. Computers and Electronics in Agriculture 178, https://doi.org/10.1016/j.compag.2020.105799

Murphy, D.J.; O' Brien, B.; Hennessy, D.; Hurley, M.; Murphy, M.D. (2021b): Evaluation of the precision of the rising plate meter for measuring compressed sward height on heterogeneous grassland swards. Precision Agriculture 22(3), pp. 922–946, https://doi.org/10.1007/s11119-020-09765-9

Murphy, D.J.; O' Brien, B.; Murphy, M.D. (2018): Development of a Labour Utilisation Decision Support Tool to Efficiently Measure Grass Herbage Mass Using a Rising Plate Meter. In: ASABE Annual International Meeting, American Society of Agricultural and Biological Engineers, 29 July to 1 Aug 2018, Detroit, American Society of Agricultural and Biological Engineers

Murphy, D.J.; Shine, P.; Brien, B.O.; Donovan, M.O.; Murphy, M.D. (2021c): Utilising grassland management and climate data for more accurate prediction of herbage mass using the rising plate meter. Precision Agriculture 22(4), pp. 1189–1216, https://doi.org/10.1007/s11119-020-09778-4

Nakagami, K.; Itano, S. (2014): Improving pooled calibration of a rising-plate meter for estimating herbage mass over a season in cool-season grass pasture. Grass and Forage Science 69(4), pp. 717–723, https://doi.org/10.1111/gfs.12070

Office of the Department of Defense (Ed.) (2020): Global Positioning System Standard Positioning Service Performance Standard. Washington DC, 5th. ed.

Priesack, E.; Gayler, S.; Hartmann, H.P. (2006): The impact of crop growth sub-model choice on simulated water and nitrogen balances. Nutrient Cycling in Agroecosystems 75(1–3), pp. 1–13

Rayburn, E. (2020): Plate meter calibrations for forage mass follow a continuum of sward basal density. Crop, Forage & Turfgrass Management 6(1), https://doi.org/10.1002/cft2.20009

Reddersen, B.; Fricke, T.; Wachendorf, M. (2014): A multi-sensor approach for predicting biomass of extensively managed grassland. Computers and Electronics in Agriculture 109, pp. 247–260, https://doi.org/10.1016/j.compag.2014.10.011

Regierungspräsidium Freiburg, Landesamt für Geologie, Rohstoffe und Bergbau (Ed.) (2021): LGRB-Kartenviewer. https://maps.lgrb-bw.de/, accessed on 22 Aug 2024

Rennie, G.M.; King, W.M.; Puha, M.R.; Dalley, D.E.; Dynes, R.A.; Upsdell, M.P. (2009): Calibration of the C-DAX Rapid Pasturemeter and the rising plate meter for kikuyu-based Northland dairy pastures. Proceedings of the New Zealand Grassland Association 71, pp. 49–55, https://doi.org/10.33584/jnzg.2009.71.2779

Riehl, G. (2020): Schluss mit dem Schätzen! DLG-Mitteilungen 22(6), pp. 38–41

Scrivner, J.H.; Center, D.M.; Jones, M.B. (1986): A Rising Plate Meter for Estimating Production and Utilization. Journal of Range Management 39(5), pp. 475–477, https://doi.org/10.2307/3899458

Statistisches Bundesamt (Ed.) (2024): Landwirtschaftliche Bodennutzung nach ausgewählten Hauptnutzungsarten. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Feldfruechte-Gruenland/Tabellen/flaechen-hauptnutzungsarten.html, accessed on 22 Aug 2024

Statistisches Landesamt Baden-Württemberg (Ed.) (2022): Anbauflächen aller Kultur- und Nutzungsarten. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/LF-NutzngKultFrucht.jsp, accessed on 22 Aug 2024

Stumpe, C.; Leukel, J.; Zimpel, T. (2024): Prediction of pasture yield using machine learning-based optical sensing: a systematic review. Precision Agriculture 25(1), pp. 430–459, https://doi.org/10.1007/s11119-023-10079-9

Stumpe, C.; Werner, J.; Böttinger, S. (2021): Accuracy improvement of Rising Plate Meter measurements to support management decisions in the Black Forest region. In: 21st Symposium of the European Grassland Federation, European Grassland Federation, 17–19 May 2021, Kassel, pp. 217–219

Tucker, C.J. (1980): A critical review of remote sensing and other methods for non-destructive estimation of standing crop biomass. https://doi.org/10.1111/j.1365-2494.1980.tb01509.x

Viljanen, N.; Honkavaara, E.; Näsi, R.; Hakala, T.; Niemeläinen, O.; Kaivosoja, J. (2018): A Novel Machine Learning Method for Estimating Biomass of Grass Swards Using a Photogrammetric Canopy Height Model, Images and Vegetation Indices Captured by a Drone. Agriculture 8(5), pp. 1–28, https://doi.org/10.3390/agriculture8050070

Voigtländer, G.; Voss, N. (Eds.) (1979): Methoden der Grünlanduntersuchung und -bewertung. Grünland – Feldfutter – Rasen. Stuttgart, Ulmer Verlag

Worek, F.; Thurner, S. (2021): Yield measurement of wilted forage and silage maize with forage harvesters. In: 13th European Conference on Precision Agriculture, 19–22 July 2021, Budapest, Hungary, Wageningen Academic Publishers, pp. 103–110

Yang, J.M.; Yang, J.Y.; Liu, S.; Hoogenboom, G. (2014): An evaluation of the statistical methods for testing the performance of crop models with observed data. Agricultural Systems 127, pp. 81–89, https://doi.org/10.1016/j.agsy.2014.01.008

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