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# Evaluation and Development of a Nutrition Model to Predict Intake and Growth of Suckling Calves

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**Abstract:** The objective of this study was to evaluate and develop equations to predict forage intake and growth of calves throughout the suckling period of beef calves grazing on forage or dairy calves fed harvested forage. Milk and forage intake and body weight data for individual animals were collected from published theses (one using bottle-fed dairy calves and one using suckling beef calves). A nutrition model was constructed using milk and forage intake equations and growth equations. Additional datasets were compiled from the literature to develop equations to adjust the original nutrition model for forage digestibility, milk composition, and growth. In general, the original nutrition model predicted the forage intake and body weight of dairy calves with moderate-to-high precision (CCC = 0.234 to 0.929) and poor accuracy (MB = −341.16 to −1.58%). Additionally, the original nutrition model predicted forage intake and body weight in beef calves with poor-to-moderate precision (CCC = 0.348 to 0.766) and accuracy (MB = 6.39 to 57.67%). Adjusted nutrition models performed better with the best model precisely (CCC = 0.914) predicting forage intake and precisely (CCC = 0.978) and accurately (MB = 2.83%) predicting body weight in dairy calves. The best adjusted nutrition model predicted forage intake and body weight with high precision (CCC = 0.882 and 0.935) and moderate accuracy (MB = −7.01 and −7.34) in beef calves. Nutrition models were able to adequately predict the forage intake and growth of calves with adjustments made to standard milk energy concentrations and growth equations.

**Keywords:** beef calves; dairy calves; empty body composition; empty body gain; forage digestibility; milk composition

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## 1. Introduction

The cow–calf sector of the beef industry has a disproportional impact on the environmental sustainability of beef production [1]. Additionally, grazing management, which is most applicable in the cow–calf sector, has the potential to sequester carbon in the soil, offsetting a substantial portion of the greenhouse gas emissions from forage-fed cattle [2]. Grassland-beef systems are complex, involving the biological processes of soil, plants, and animals, and the impact of management practices are dependent upon characteristics (soil type, forage species, climate, etc.) of the ecosystem [3]. The future sustainability of beef production depends upon developing a better understanding of the interactions between ecosystem characteristics and management practices, to develop optimal grassland-beef systems specific to the ecosystem.

The multifactorial nature of grassland-beef systems and the long-time horizons for detecting significant changes in soil parameters creates substantial difficulties in designing and performing field experiments to understand the interactions between ecosystem characteristics and management practices. Computer simulation models have been used extensively to evaluate complex biological systems [4]. Process-based soil and plant computer models have been used to evaluate effects of animal grazing on soil parameters [5–9], and to predict the performance of growing and finishing cattle from nutrition and environmental conditions [10,11]. A recent dynamic, stochastic cow herd model has been developed to evaluate the sustainability of management decisions over long time horizons [12,13], but the current model is inadequate in predicting the growth of suckling beef calves consuming forage.

Extensive research has been performed in the postweaning growing and finishing phases of cattle production systems to determine their feed intake, growth, and chemical body composition [14–21], but few studies have evaluated the feed intake and growth of preweaned calves [22–24]. The available equations from the literature to predict the forage intake and/or growth of suckling calves are inaccurate and imprecise [25]; however, this analysis used data accumulated over the 240-day suckling period that was compiled over three decades with calves fed a mixed diet in drylot, which may not accurately represent forage grazing and nutritive value dynamics experienced by suckling calves on pasture. Additionally, most forage intake equations were developed using data from Holstein dairy calves fed in hutches rather than with grazing beef calves. Thus, the objective of this study was to evaluate and develop equations to predict forage intake and growth throughout the suckling period of beef calves grazing on forage or dairy calves fed harvested forage.

## 2. Materials and Methods

### *2.1. Base Model*

A nutrition model, which operated on a daily time step from birth to 240 days of age, was built in Microsoft Excel® (Version 2312 Build 16.0.17126.20132) using published equations. The diet was a daily-adjusted intake of milk and forage. Similar to Lancaster et al. [25], daily milk intake was predicted using 1 of 2 equations. The first set of equations was that from the National Academies of Science, Engineering, and Medicine [10] (NASEM):

$$\mathrm{MY} = \frac{\mathrm{w}}{\mathrm{a} \times \mathrm{e}^{\mathrm{kw}}} \tag{1a}$$

$$\mathrm{a} = \frac{1}{\mathrm{PKYD} \times \mathrm{k} \times \mathrm{e}} \tag{1b}$$

$$\mathrm{k} = \frac{1}{\mathrm{T}} \tag{1c}$$

where MY is milk yield (kg/d) at week w; w is the week of lactation after parturition; PKYD is peak milk yield (kg/d); T is the week of peak milk yield; and a and k are the parameters of the equation.

The second set of equations was that of Wood [26] (WOOD) as described by Tedeschi and Fox [25]:

$$\mathrm{MY} = \frac{\left[\mathrm{A} \times (\mathrm{t}+14)^{\mathrm{b}} + e^{-\mathrm{i} \times (\mathrm{t}+14)}\right] \times \mathrm{YP}}{10} \tag{2a}$$

$$\mathrm{A} = 5.30 - 0.075 \times \mathrm{L} \tag{2b}$$

$$\mathrm{L} = \mathrm{YP} + 40 \tag{2c}$$

$$\mathrm{b} = \frac{\mathrm{Ln}(10) - \mathrm{Ln}(\mathrm{A})}{\mathrm{Ln}(\mathrm{L}+14) - 1} \tag{2d}$$

$$\mathrm{c} = \frac{\mathrm{b}}{\mathrm{L}+14} \tag{2e}$$

where MY is milk yield (kg/d) on day t; t is the day of lactation after parturition; A, b, and c are the parameters of the Wood's equation; YP is peak milk yield (kg/d); and L is the day of peak milk yield.

Daily forage intake was predicted using 1 of 5 equations: (1) (Eq91) equations from Tedeschi et al. [27], (2) (Eq67) equations from Baker et al. [22], (3) (Eq25) quation from Tedeschi and Fox [24], (4) (Eq17) equation from Tedeschi and Fox [24], and (5) (Eq21) equation from Holloway et al. [23]. These equations were selected because of the inclusion of adjustments for forage quality (DE concentration; Eq25, Eq17, Eq21), developed with data from different breeds (Holsteins − Eq91, Eq25, Eq17; Hereford × Holstein − Eq67; Angus − Eq21), and based on a constant DE intake per kg of BW (Eq17, Eq21).

$$\text{Eq91: FDMI} = a + b \times BW + c \times DIM + d \times BW \times DIM + e \times MY + f \times BW \times MY + g \times DIM \times MY + h \times BW \times DIM \times MY; \quad (3)$$

If PKM = 2.72 kg/d, a = 5.95, b = −0.008, c = −0.019, d = 0, e = −1.272, f = 0.010, g = 0.027, and h = 0; if PKM = 5.44 kg/d, a = −1.147, b = 0.025, c = 0.221, d = −0.005, e = 0.496, f = −0.008, g = −0.226, and h = 0.005; if PKM = 8.16 kg/d, a = −0.196, b = 0.004, c = 0.108, d = −0.002, e = −0.423. f = 0.007, g = −0.066, and h = 0.001; if PKM = 10.88 kg/d, a = 0.183, b = −0.004, c = −0.023, d = 0, e = 0.031, f = 0.001, g = 0.006, and h = 0; if PKM = 13.6 kg/d, a = 0.025, b = −0.001, c = −0.002, d = 0, e = 0.033, f = 0, g = −0.002, and h = 0; and if DIM is greater than the day of peak milk yield, FDMI = (30.313 × BW − 753.76 × MY − 11.704 × BW × MY − 190.316 × PKM + 0.499 × BW × PKM + 112.106 × MY × PKM − 0.085 × BW × MY × PKM)/1000, where FDMI is forage DMI (kg/d); BW is the current calf body weight (kg); DIM is days in milk (d); MY is the current daily milk yield (kg/d); and PKM is the peak milk yield (kg/d).

$$\text{Eq67: FOMI} = a + b \times \text{MOMI} \quad (4)$$

If the month of lactation = 1 or 2, a = 0 and b = 0; if the month of lactation = 3, a = 35.6 and b = −3.11; if month of lactation = 4, a = 26.7 and b = −2.12; if the month of lactation = 5, a = 24.1 and b = −2.19; if the month of lactation = 6, a = 17.9 and b = −1.71; if the month of lactation = 7, a = 22.8 and b = −2.21; and if the month of lactation ≥ 8, a = 22.4 and b = −2.60.

Where FOMI is the forage organic matter intake (g/kg BW) and MOMI is the milk organic matter intake (g/gk BW). FOMI and MOMI were converted to DMI using the forage and milk organic matter concentrations of 87.8% and 91.1% DM, respectively.

$$\begin{aligned}\text{Eq25: FDMI} = {} & (1/DE_F^2) \times ((BW^{(-0.3895 - 0.0197 \times PKM2)}) \times e^{(BW \times (-0.00244 - 0.00337 \times PKM) - 1.3594 \times PKM)} \\ & \times ((BW^{(0.4477 \times PKM)}) \times (-32.5704 + (27.9016 - 7.66732 \times DE_F) \times DE_F) \\ & \times e^{((0.0588 + 0.00018 \times BW) \times PKM2)} + (BW^{(1.3895 + 0.0197 \times PKM2)}) \times e^{(BW \times (0.00244 + 0.00337 \times PKM) + 1.3594 \times PKM)} \times \\ & (0.4738 + DE_F \times (-0.4059 + DE_F \times (0.11154 - 0.003273 \times PKM) + 0.01191 \times \\ & PKM) - 0.0139046 \times PKM) + (BW^{(0.3895 + 0.0197 \times PKM2)}) \times \\ & e^{(BW \times (0.00244 + 0.00337 \times PKM) + 1.3594 \times PKM)} \times (-10.3049 + DE_F \times (8.82778 + DE_F \times (-2.42586 + \\ & 0.362681 \times PKM) - 1.31981 \times PKM) + 1.54065 \times PKM)))\end{aligned} \quad (5)$$

where *FDMI* is forage DMI (kg/d); $DE_F$ is the digestible energy concentration of forage (Mcal/kg DM); BW is current calf body weight (kg); and PKM is peak milk yield (kg/d).

$$\text{Eq17: DEI} = -2.127 + 0.318 \times PKM + 0.0978 \times BW - 0.00287 \times PKM \times BW \quad (6a)$$

$$FDMI = \frac{\text{DEI} - 4.87 \times \text{MDMI}}{DE_F} \quad (6b)$$

$$\text{RFDMI} = \frac{\left(0.1317 - 0.1128 \times DE_F + 00031 \times DE_F^2\right) \div DE_F}{0.027185} \quad (6c)$$

where DEI is digestible energy intake (Mcal/d); PKM is peak milk yield (kg/d); BW is current calf body weight (kg); FDMI is forage DMI (kg/d); MDMI is milk DMI (kg/d); $DE_F$

is the digestible energy concentration of forage (Mcal/kg DM); and RFDMI is the relative DMI of forage adjustment for forage DE (kg/d).

$$\text{Eq21: } DEI_F = 0.042 + 3.749 \times \frac{DEI_M}{BW} - 24.324 \times \left(\frac{DEI_M}{BW}\right)^2 - 0.082 \times DE_F + 0.031 \times DE_F^2 - 1.027 \times \left(\frac{DEI_M \times DE_F}{BW}\right) \quad (7)$$

where $DEI_F$ is forage digestible energy intake (Mcal/kg BW); $DEI_M$ is milk digestible energy intake (Mcal/d); $DE_F$ is the digestible energy concentration of forage (Mcal/kg DM); and BW is current calf body weight (kg).

Net energy required for maintenance was computed using Eq. 19-1 from National Academies of Science, Engineering and Medicine [10], assuming no lactation, body composition, or temperature acclimatization factor. Feed required for maintenance was computed as net energy required divided by the net energy for maintenance concentration of the diet (Equation 19-5 from [10]). Retained energy was computed as the total intake (milk + forage) minus feed required for maintenance multiplied by the net energy for gain concentration of the diet (Equation 19-48 from [10]). Shrunk weight gain was computed from shrunk body weight and retained energy using the following equations from National Academies of Science, Engineering and Medicine [10].

$$EBG = 12.341 \times EQEBW^{-0.6837} \times RE^{0.9116} \quad (8a)$$

$$EQEBW = 0.891 \times EQSBW \quad (8b)$$

$$EQSBW = SBW \times (SRW/FSBW) \quad (8c)$$

$$RE = (DMI - FFM) \times NEg \quad (8d)$$

$$FFM = (SBW^{0.75} \times 0.077) \div NEm \quad (8e)$$

where EBG is empty body gain (kg/d); EQEBW is equivalent empty body weight (kg); RE is retained energy (Mcal/d); EQSBW is equivalent shrunk body weight (kg); SBW is current shrunk body weight (kg); SRW is the standard reference weight (kg); FSBW is the observed final shrunk body weight at the selected fat endpoint (kg); DMI is dry matter intake (kg/d); FFM is feed for maintenance (kg/d); NEg is the net energy for gain concentration of the diet (Mcal/kg DM); and NEm is the net energy for maintenance concentration of the diet (Mcal/kg DM).

Final daily shrunk body weight was computed as the initial daily shrunk body weight plus shrunk weight gain. The initial daily shrunk body weight was equal to the final shrunk body weight from the previous day.

### *2.2. Model Evaluation Data*

#### 2.2.1. Dairy Calf Intake and Body Weight Dataset

Milk and forage intake and body weight data of 40 Holstein steer calves were acquired from Abdelsamei [28]. Calves were housed individually and fed a milk replacer with a metabolizable energy concentration of 4.68 Mcal/kg DM twice daily. Calves were offered alfalfa hay with a dry matter digestibility of 72.1% daily. Body weight and milk and forage intake were recorded approximately every 14 d along with calf age. Calves were fed until slaughter, and the observed final shrunk body weight at 28% empty body fat was obtained from Abdelsamei [28]. The SRW used was 478 kg. The advantage of using this dataset to evaluate the nutrition model was that the milk and forage intake were measured directly. The descriptive statistics of the dairy calf intake and body weight dataset are presented in Table 1.

**Table 1.** Descriptive statistics of the dairy calf intake and body weight dataset used to evaluate forage intake and growth models.

| Item | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|
| Birth date, Julian d | 208.70 | 24.35 | 170 | 257 |
| Birth weight, kg | 44.9 | 9.0 | 36.0 | 57.0 |
| 30-d BW, kg | 61.6 | 12.3 | 35.0 | 92.0 |
| 30-d milk intake, kg/d | 6.65 | 2.75 | 2.50 | 12.08 |
| 30-d forage intake, kg DM/d | 0.08 | 0.09 | 0.00 | 0.41 |
| 60-d BW, kg | 85.0 | 17.0 | 49.0 | 117.0 |
| 60-d milk intake, kg/d | 7.25 | 3.15 | 2.50 | 12.69 |
| 60-d forage intake, kg DM/d | 0.29 | 0.30 | 0.00 | 1.33 |
| 90-d BW, kg | 115.8 | 23.1 | 71.0 | 165.0 |
| 90-d milk intake, kg/d | 7.27 | 3.51 | 2.37 | 12.83 |
| 90-d forage intake, kg DM/d | 0.88 | 0.57 | 0.16 | 2.14 |
| 115-d BW, kg | 142.6 | 26.7 | 84.0 | 184.0 |
| 115-d milk intake, kg/d | 6.65 | 3.04 | 2.14 | 11.83 |
| 115-d forage intake, kg DM/d | 1.55 | 0.64 | 0.39 | 2.58 |
| 145-d BW, kg | 168.1 | 29.8 | 104.0 | 220.0 |
| 145-d milk intake, kg/d | 5.90 | 2.99 | 1.84 | 10.46 |
| 145-d forage intake, kg DM/d | 2.26 | 0.66 | 1.08 | 3.33 |
| 165-d BW, kg | 187.2 | 33.9 | 117.0 | 239.0 |
| 165-d milk intake, kg/d | 5.27 | 2.67 | 1.60 | 9.34 |
| 165-d forage intake, kg DM/d | 2.98 | 0.71 | 1.22 | 4.79 |
| 195-d BW, kg | 212.2 | 38.0 | 127.0 | 269.0 |
| 195-d milk intake, kg/d | 4.44 | 2.27 | 1.34 | 8.45 |
| 195-d forage intake, kg DM/d | 3.83 | 0.52 | 2.55 | 4.84 |

2.2.2. Beef Calf Intake and Body Weight Dataset

Milk and forage intake and body weight of 51 Hereford steer calves were acquired from Boggs [29]. Calves were born in March and April and suckled their dams while grazing native bluestem pastures near Manhattan, KS, USA. Calves were weaned on September 29. Milk consumption was measured monthly from April through September using the weigh-suckle-weigh technique. Milk energy concentration was assumed to be 0.72 Mcal/kg of fluid milk [10], and the calculated metabolizable energy concentration was 5.47 Mcal/kg dry matter [25]. Forage intake was measured monthly from May through September using the chromic oxide marker technique. In vitro dry matter digestibility of forage samples was determined using the method of Tilley and Terry [30], and forage intake was determined as fecal output divided by indigestibility. Body weight was recorded at birth and monthly from April through September. Calves were not fed to slaughter weight; thus, 465 kg was used as the final shrunk body weight at 28% empty body fat based on finishing trials with cattle from the same herd at Kansas State University [31,32]. The SRW used was 462 kg. The value of using this dataset to evaluate the nutrition model was that the conditions match those of typical beef calves. The descriptive statistics of the beef calf intake and body weight dataset are presented in Table 2.

**Table 2.** Descriptive statistics of the beef calf intake and body weight dataset used to evaluate forage intake and growth models.

| Item | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|
| Birth date, Julian | 86.75 | 12.84 | 60 | 122 |
| Birth weight, kg | 34.8 | 3.4 | 23.1 | 41.8 |
| April BW, kg | 61.0 | 9.7 | 40.0 | 80.6 |
| April milk yield, kg/d | 6.43 | 1.49 | 3.40 | 9.99 |
| May BW, kg | 78.3 | 11.3 | 55.4 | 99.0 |
| May milk yield, kg/d | 5.90 | 1.49 | 3.13 | 10.44 |
| May forage intake, kg DM/d | 0.47 | 0.21 | 0.20 | 10.16 |
| June BW, kg | 96.8 | 13.4 | 68.5 | 119.8 |
| June milk yield, kg/d | 4.95 | 1.44 | 1.32 | 8.40 |
| June forage intake, kg DM/d | 1.45 | 0.69 | 0.47 | 3.14 |
| July BW, kg | 120.1 | 16.6 | 83.5 | 148.4 |
| July milk yield, kg/d | 4.82 | 1.45 | 2.27 | 8.40 |
| July forage intake, kg DM/d | 1.85 | 0.72 | 0.92 | 5.05 |
| Aug. BW, kg | 145.9 | 18.9 | 103.5 | 177.9 |
| Aug. milk yield, kg/d | 3.38 | 0.95 | 1.35 | 6.81 |
| Aug. forage intake, kg DM/d | 2.62 | 0.64 | 1.45 | 4.36 |
| Sept. BW, kg | 165.3 | 21.1 | 116.1 | 202.5 |
| Sept. milk yield, kg/d | 3.61 | 1.12 | 1.13 | 5.90 |
| Sept. forage intake, kg DM/d | 3.57 | 0.84 | 2.36 | 6.14 |

### *2.3. Model Adjustment Data*

#### 2.3.1. Calf Growth

A literature search was performed to identify experiments measuring the empty body weight, empty body weight gain, empty body fat gain, and empty body protein gain of growing/finishing cattle, especially cattle lighter than typical weaning weights, using PubMed and Google Scholar. Search terms included the combinations of cattle, empty body, empty body weight, chemical composition, and empty body fat, and excluded the terms sheep, goat, lamb, and pigs. Searches returned between 160 and 600 records depending upon the search engine and search term combination and were screened first by title and second by the type of reported data. Records on various breeds were included and categorized into beef and dairy categories; studies and treatments using breed crosses of these categories were excluded. Records on growing/finishing steers and heifers were included in the dataset, but studies or treatments using mature cows or bulls were excluded. The final dataset contained 232 treatment means from 53 studies published between 1960 and 2010. Treatment means were further categorized as preweaning or postweaning based on the initial and final empty body weight; a final empty body weight of less than 200 kg was categorized as preweaning, and an initial empty body weight of greater than 200 kg was categorized as postweaning. Retained energy was calculated from empty body fat and protein gain, assuming 9.39 and 5.55 Mcal/kg of gain, respectively [33,34]. The initial dataset was divided into two serial slaughter datasets based on breed type: beef or dairy. Mature weight was not known for cattle in these studies; thus, the observed, rather than the equivalent, empty body weight was used in equation evaluation and development.

The growth Equation (8a) was evaluated in both the beef and dairy cattle serial slaughter datasets using the evaluation metrics described below. Additionally, the correlation of empty body protein and fat gain with empty body weight gain was evaluated between cattle classified as preweaning and postweaning using the *cor.test* function in base R statistical software (version 4.2.1) [35]. The accuracy and precision of growth Equation (8a) were evaluated in cattle that were classified as preweaning or postweaning.

A new growth equation was developed by evaluating 3 functions using fixed effect (*nls* function in base R) and mixed effect (*nlmer* function in *lme4* package of R) models.

$$EBG = a \times RE^{b} \quad (9)$$

$$EBG = a \times (RE/EBW^{0.75})^{b} \quad (10)$$

$$EBG = a \times RE^{b} \times EBW^{c} \quad (11)$$

where EBG is empty body weight gain in kg/d, RE is retained energy in Mcal/d, EBW is empty body weight in kg; a is the intercept, and b and c are power coefficients. Mixed effect models included study as a random variable affecting the intercept. The best model was determined using Akaike's Information Criteria (AIC). Cross-fold validation was performed on the final model using the leave-one-group-out method where group is equal to study. The *groupKFold* and *train* functions in the *caret* package of R statistical software were used to perform cross-fold validation.

#### 2.3.2. Forage Digestibility

A literature search was performed to identify experiments measuring in vitro and in vivo forage digestibility using PubMed and Google Scholar. Search terms included the combinations of cattle, sheep, forage, dry matter digestibility, in vitro, and in vivo. Searches returned several thousand records that were screened first by title, second by location, and third by the in vitro method. Records from international locations using forages not typically grown in the USA were excluded. Records that did not report at least 2 methods (in vitro and in vivo) or 2 measures (dry matter and organic matter) of digestibility were excluded. Records and treatment means using in vitro methods other than the technique by Tilley and Terry [30] were excluded. Additionally, records were excluded where the digestibility of the forage alone could not be determined such as when a grain or protein supplement was being fed. The final forage digestibility dataset contained 185 treatment means from 35 studies. The relationships among in vitro and in vivo dry matter and organic matter forage digestibility were evaluated using the evaluation metrics described below.

A second literature search was performed to identify previously published equations relating in vitro with in vivo forage digestibility using PubMed and Google Scholar with the same search terms mentioned above. Records without an equation relating in vitro with in vivo forage digestibility were excluded. This resulted in 8 records having 14 equations relating in vitro with in vivo dry matter digestibility [30,36–42]. The forage digestibility dataset was used to evaluate the previously published equations relating in vitro with in vivo forage digestibility estimates. The previously published equations were evaluated using the evaluation metrics described below.

Using the forage digestibility dataset, a new equation relating in vitro dry matter digestibility with in vivo organic matter digestibility was developed. As the new equation must be robust across forage species, and that all studies used the Tilley and Terry [30] technique to determine in vitro dry matter digestibility, a fixed effect linear model (*lm* function in base R) without a random effect of study was used. Cross-fold validation was performed on the final model using the leave-one-out method in the *train* function of the *caret* package in R statistical software.

#### 2.3.3. Milk Composition

A literature search was performed to identify experiments measuring milk yield and composition (fat, protein, lactose) in beef cows using PubMed and Google Scholar. Search terms included the combinations of cattle, milk yield, milk production, milk composition, and milk fat, and excluded the terms dairy, sheep, goat, lamb, and pigs. Searches returned 1000 to 1500 records depending upon the search engine and search term combination and were screened first by title and second by the type of data reported. Records where the days in milk for yield and composition measurements could not be determined were excluded. Records where all variables (days in milk, yield, fat, protein, lactose) were not available were excluded. Records on various breeds were included and categorized into Taurus, Taurus Cross, Zebu, and Zebu Cross categories. Additionally, the method used to determine milk yield (machine or weigh-suckle-weigh) was recorded. The final milk composition dataset contained 125 treatment means from 13 studies. Milk energy was computed as the sum of milk fat multiplied by 9.39 Mcal/kg, milk protein multiplied by 5.55 Mcal/kg, and milk lactose multiplied by 4.00 Mcal/kg, which are gross energy values reported for fat, protein, and carbohydrates [33,34,43].

The milk composition dataset was used to evaluate the effect of days in milk and milk yield on milk composition, and to develop an equation to predict milk energy from yield and days in milk. Mixed effect models were developed for milk fat, protein, lactose, and energy using the *lmer* function of the *lme4* package in R statistical software where study was a random intercept in the model. Breed type and the method of milk yield determination were included in the model regardless of significance. The models were developed using a manual backwards stepwise approach where the predictor variable of milk yield, days in milk, and the interaction with the greatest *p*-value was removed, and the model was re-evaluated until all predictor variables were significant. The interactions of breed type and method with milk yield and days in milk were evaluated but were not significant at $p \leq 0.05$. Cross-fold validation was performed on the final models using the leave-one-group-out method where group is equal to study. The *groupKFold* and *train* functions in the *caret* package of R statistical software were used to perform cross-fold validation.

### *2.4. Model Evaluation*

Evaluation of the nutrition model was accomplished in sequential steps. First, the prediction of milk intake was evaluated, and the best equation to predict milk intake was established for the dairy and beef calf intake and body weight datasets. Second, forage intake and body weight were predicted simultaneously using the original nutrition model, and the results were compared with the observed values. Third, forage intake and body weight were predicted separately using the original nutrition model, where the observed body weight or the observed forage intake were used, respectively, and the results were compared with the observed values. Fourth, adjustments were made to milk energy, forage digestibility, and calf growth equation in the nutrition model using the model adjustment datasets and analyses described above to assess the ability to improve the prediction of forage intake and body weight.

#### 2.4.1. Evaluation Metrics

Evaluation of the nutrition model was performed using R statistical software. Linear regression of observed values on predicted values was performed using the *lm* function of the base statistical package. The statistical model was considered significant at $p \leq 0.05$. The intercept and the slope of the linear regression model were tested equal to zero and one, respectively, using 95% confidence intervals, and the linear hypothesis test simultaneously testing intercept equal to zero and slope equal to one was performed using the *linearHypothesis* function. The mean bias (MB), concordance correlation coefficient (CCC), and bias correction factor (Cb) were computed between the observed and the predicted values using the *epiR* package.

#### 2.4.2. Milk Intake

Milk intake was predicted using the NASEM and WOOD milk yield equations, by iteratively solving for the peak milk yield and the week of peak yield where the sum of the absolute difference between the observed and the predicted milk yield was minimized. Peak milk yield is the greatest kg of milk produced on any day of lactation, typically around day 49 of lactation. This was accomplished using the Solver function in Microsoft Excel (Version 2312 Build 16.0.17126.20132). The predicted milk yield from the nutrition model was recorded at each day of age where the observed milk intake was measured. The predicted milk intake was compared with the observed milk intake using the evaluation metrics discussed above. For the dairy calf intake and body weight dataset, the deviation from observed milk intake was also evaluated based on the peak milk treatment applied by Abdelsamei [28]. A 'best' equation was determined for each of the dairy and beef calf intake and body weight datasets and used for all further predictions of forage intake and body weight.

#### 2.4.3. Forage Intake

Forage intake was predicted using the 5 equations outlined above (Eq91, Eq67, Eq25, Eq17, Eq21). The predicted forage intake from the nutrition model was recorded at each day of age where the observed forage intake was measured. The predicted forage intake was compared with the observed forage intake using the evaluation metrics discussed above. When forage intake was predicted separately from body weight using the nutrition model, and the observed body weight was used in the model, a linear regression equation relating body weight with the day of age was developed for each individual calf to predict its body weight at each daily time step in the model.

#### 2.4.4. Body Weight

Body weight was predicted using the growth Equation (8a–e). The predicted body weight from the nutrition model was recorded at each day of age where the observed body weight was measured. The predicted body weight was compared with the observed body weight using the evaluation metrics discussed above. When body weight was predicted separately from the forage intake using the nutrition model, and the observed forage intake was used in the model, a polynomial regression equation relating forage intake with the day of age was developed for each individual calf to predict forage intake at each daily time step in the model.

In the nutrition model, body weight is predicted from retained energy estimated from milk and forage intake; thus, the prediction of body weight is not only affected by the prediction of milk and forage intake but also by the energy concentration of milk and forage. For the dairy calf intake and body weight dataset, the metabolizable energy value of milk replacer was reported by Abdelsamei [28]; thus, no adjustment was made to the energy intake from milk for changing milk composition. For the beef calf intake and body weight dataset, milk composition was not measured and only milk yield was reported by Boggs [29]. The results from the analysis of the milk composition dataset were used to adjust the milk energy concentration and energy intake for milk yield and days in milk for the beef calf intake and body weight dataset. Milk energy intake was a function of milk intake and the milk energy concentration; thus, adjusting the milk energy concentration did not affect the prediction of milk intake.

For the dairy calf intake and body weight dataset, the dry matter digestibility of alfalfa forage was reported by Abdelsamei [28]; thus, no adjustment was made to the energy concentration of forage in the nutrition model. For the beef calf intake and body weight dataset, the estimated energy concentration of the grazed forage was adjusted based on the equation relating in vitro dry matter digestibility to in vivo organic matter digestibility developed from the forage digestibility dataset. The observed forage intake was then adjusted based on the new forage digestibility estimate at each time point by the following equations:

$$\text{FO} = \text{observed fDMI} \times (100 - \text{original digestibility}) \quad (12a)$$

$$\text{New observed fDMI} = \text{FO} \div (100 - \text{new digestibility}) \quad (12b)$$

where FO = fecal dry matter output in kg/d, fDMI = forage dry matter intake in kg/d, and original or new digestibility in %. Thus, changing the forage digestibility did affect the prediction of forage intake, and the predicted forage intake was compared with the new observed forage intake when evaluating the nutrition model results.

For both the dairy and beef calf intake and body weight datasets, the calculation of empty body weight gain in the nutrition model was adjusted using the newly developed equations relating empty body gain with retained energy and empty body weight for growing/finishing dairy and beef cattle, respectively. The predicted body weight was compared with the observed body weight when evaluating the model results.

Changes in the calculation of milk energy concentration, forage digestibility, and empty body weight gain were first evaluated individually using the observed forage intake in the nutrition model to predict body weight using the evaluation metrics described above. Second, the combination of the changes in the calculation of milk energy concentration, forage digestibility, and empty body weight gain were evaluated in predicting forage intake and body weight using the evaluation metrics described above. Finally, the deviation between the observed and predicted forage intake and body weight was evaluated based on the birth date of calves. Calf birth date was categorized into 3 periods as was used by Boggs [29] in their analysis: Period 1 was 1 March to 20 March, Period 2 was 21 March to 31 March, and Period 3 was 1 April to 1 May. The *lm* function from the base R statistical package was used to model the effect of birth period on the deviation between the observed and predicted values with forage intake or body weight as covariates.

## 3. Results

### *3.1. Dairy Calf Intake and Body Weight Dataset*

#### 3.1.1. Milk Intake

Both the NASEM and WOOD milk yield equations predicted milk intake with similar precision (CCC = 0.951 and 0.954) and accuracy (MB = 6.44 and −4.14%) (Table 3). Additionally, the intercept and slope were similar between the predicted and observed values for both equations; however, neither met the criteria for linearity ($p < 0.0001$). Upon further evaluation, the sum of the absolute difference between the observed and predicted values was lesser ($p \leq 0.05$) for WOOD at peak milk yield less than 10.88 kg/d but was lesser ($p \leq 0.05$) for NASEM at peak milk yield greater than 10.88 kg/d (Table S1). Using the WOOD equation when the predicted peak milk yield was less than 10 kg/d and the NASEM equation when the predicted peak milk yield was greater than or equal to 10 kg/d resulted in an improved prediction of milk intake (Figure 1). The CCC (0.969) when using both equations was only slightly improved compared with using only NASEM or WOOD milk yield equations, but the MB (−0.74%) was substantially improved. Additionally, the intercept was closer to zero and the slope was closer to one than with either equation alone. The predicted daily milk yield from the combination of NASEM and WOOD milk yield equations was used as the daily milk intake in all subsequent nutrition model evaluations.

**Table 3.** Comparison of milk yield equations to predict milk intake in the dairy calf intake and body weight dataset.

| Item [1] | NASEM | WOOD | Both |
|---|---|---|---|
| CCC | 0.951 | 0.954 | 0.969 |
| Cb | 0.991 | 0.996 | 1.000 |
| MB (SD), kg/d | 0.393 (0.919) | −0.253 (0.927) | −0.045 (0.771) |
| MB, % | 6.44 | −4.14 | −0.74 |
| Intercept ± SE | 0.9094 ± 0.0753 | 0.2690 ± 0.0842 | 0.1622 ± 0.0728 |
| Slope ± SE | 0.9096 ± 0.0115 | 0.9179 ± 0.0118 | 0.9662 ± 0.0106 |
| Pr > F | <0.0001 | <0.0001 | 0.0025 |

[1] NASEM = milk yield Equation (1a–c); WOOD = milk yield Equation (2a–e); CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; SD = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = *p*-value for linear hypothesis test.

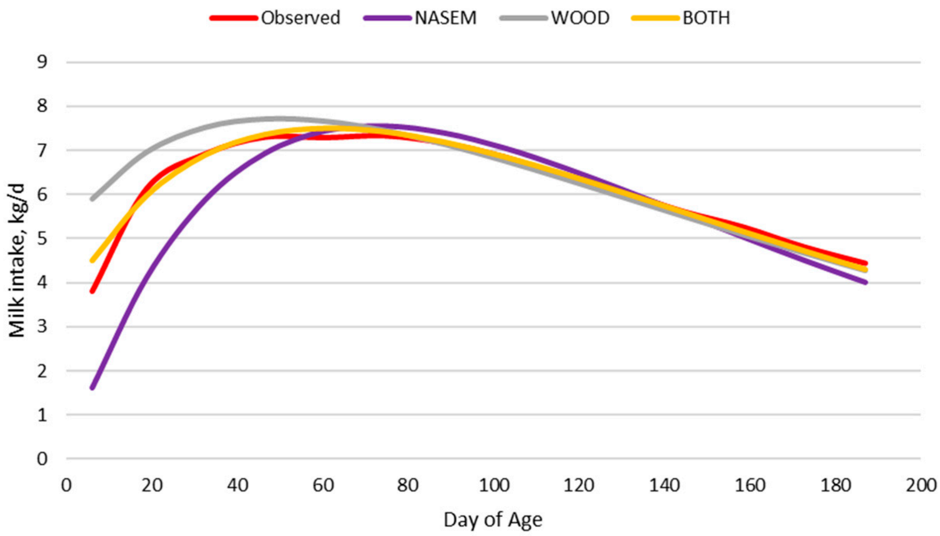



**Figure 1.** Observed milk intake and predicted milk yield using milk yield equations over the suckling period in the dairy calf dataset. NASEM = milk yield Equation (1a–c); WOOD = milk yield Equation (2a–e); and BOTH = combination of NASEM used when estimated peak milk yield was > 10 kg/d and WOOD used when estimated peak milk yield was ≤ 10 kg/d.

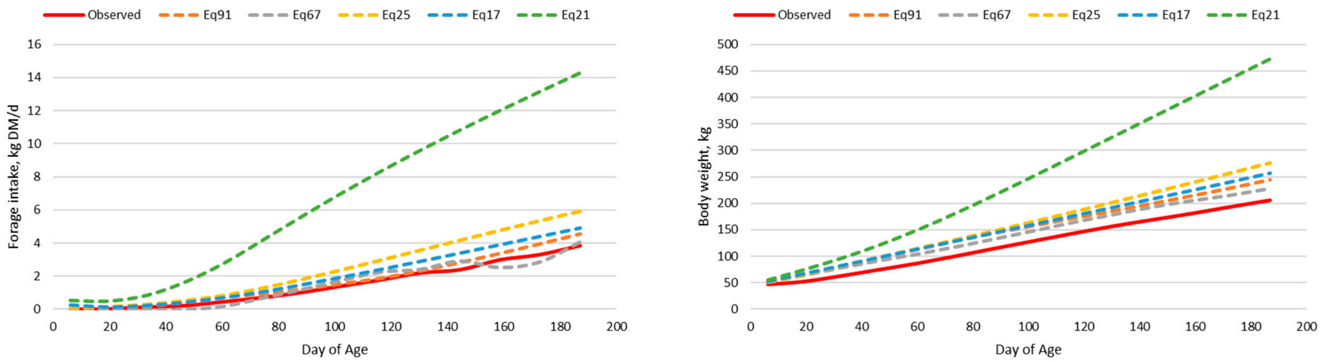
### 3.1.2. Original Nutrition Model

When forage intake and body weight were predicted simultaneously, the precision of predicting forage intake was similar (CCC = 0.874 to 0.920) for Eq91, Eq67, and Eq17, whereas Eq25 and especially Eq21 had poorer precision (Table 4). The MB was good for Eq67 (−1.58%), but poor for Eq91, Eq25, Eq17, and Eq21 (−341.16 to −17.49%), which is surprising given that Eq91, Eq25, and Eq17 were developed from this same dataset of Abdelsamei [28]. Additionally, Eq67 had a slope closer to one than the other equations, but Eq25 had the intercept closest to zero. Figure 2a illustrates the observed and predicted forage intake for the five equations over the suckling period.

**Table 4.** Comparison of original models using 5 forage intake equations to predict forage intake and body weight simultaneously in the dairy calf intake and body weight dataset.

| Item | Eq91 [1] | Eq67 | Eq25 | Eq17 | Eq21 |
|---|---|---|---|---|---|
| Forage Intake | | | | | |
| CCC [2] | 0.878 | 0.920 | 0.729 | 0.874 | 0.234 |
| Cb | 0.957 | 0.999 | 0.797 | 0.921 | 0.257 |
| MB (SD), kg/d | −0.259 (0.722) | −0.023 (0.546) | −0.954 (0.984) | −0.527 (0.580) | −5.055 (3.698) |
| MB, % | −17.49 | −1.58 | −64.4 | −35.6 | −341.16 |
| Intercept ± SE | 0.2266 ± 0.0326 | 0.1322 ± 0.0332 | 0.0135 ± 0.0360 | −0.0563 ± 0.0283 | −0.1712 ± 0.0397 |
| Slope ± SE | 0.7188 ± 0.0134 | 0.8956 ± 0.0163 | 0.6005 ± 0.0113 | 0.7639 ± 0.0109 | 0.2513 ± 0.0049 |
| Pr > F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Body Weight | | | | | |
| CCC | 0.876 | 0.929 | 0.819 | 0.864 | 0.402 |
| Cb | 0.908 | 0.951 | 0.833 | 0.878 | 0.423 |
| MB (SD), kg | −26.439 (16.932) | −18.005 (15.271) | −36.952 (23.855) | −30.847 (17.077) | −122.473 (84.252) |
| MB, % | −21.54 | −14.67 | −30.1 | −25.13 | −99.78 |
| Intercept ± SE | −7.9868 ± 1.6539 | 1.8476 ± 1.2441 | 7.0021 ± 1.0362 | −0.5910 ± 1.0313 | 25.1856 ± 1.5894 |
| Slope ± SE | 0.8763 ± 0.0102 | 0.8589 ± 0.0080 | 0.7248 ± 0.0058 | 0.8030 ± 0.0061 | 0.3978 ± 0.0057 |
| Pr > F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

[1] Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7).
[2] CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; SD = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = $p$-value for linear hypothesis test.




(**a**) (**b**)

**Figure 2.** Observed and predicted forage intake (**a**) and body weight (**b**) for the 5 forage intake equations over the suckling period in the dairy calf intake and body weight dataset using the original model. Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7).

The precision of predicting body weight was similar (CCC = 0.819 to 0.929) for Eq91, Eq67, Eq25, and Eq17, but poor for Eq21. However, the MB was poor (MB = −99.78 to −14.67%) for all equations. Additionally, Eq17 had the intercept closest to zero and Eq67 had the slope closest to one; however, none of the equations met the criteria for linearity ($p < 0.0001$). As with forage intake, Eq21 had very poor predictive ability. Figure 2b illustrates the overprediction of body weight by all five equations throughout the suckling period.

When the observed body weight was used in the nutrition model to predict forage intake separately from body weight (Table 5), the observed body weight was estimated from a linear regression equation relating body weight with the day of calf age for each individual calf to complete the daily timestep of the nutrition model since body weight was not measured daily. The regression equation was highly precise (CCC = 0.980) and moderately accurate (MB = −6.23%) in estimating body weight. The five equations performed much better in predicting forage intake separately when the observed body weight was used in the nutrition model. Model precision was high (CCC = 0.935 to 0.964) for Eq91, Eq67, Eq25, and Eq17, and moderate for Eq21. Model accuracy was high for Eq91 (MB = −0.55%), moderate for Eq67 and Eq17, and poor for Eq25 and Eq21. Additionally, the intercepts were closer to zero and the slopes closer to one in general, although, none of the equations met the criteria for linearity ($p < 0.0001$). These results indicate that imprecision and inaccuracy of body weight prediction may be negatively affecting the prediction of forage intake.

When the observed forage intake was used in the nutrition model to predict body weight separately from forage intake (Table 6), the observed forage intake was estimated from a polynomial regression equation relating forage intake with the day of calf age for each individual calf to complete the daily timestep of the nutrition model since forage intake was not measured daily. The regression equation was highly precise (CCC = 0.988) and accurate (MB = −0.41%) in estimating forage intake. Model precision (CCC = 0.926) and accuracy (MB = −17.08%) in predicting body weight separately were similar to when forage intake and body weight were predicted simultaneously. Additionally, the criteria for linearity were not met ($p < 0.0001$) similar to when forage intake and body weight were predicted simultaneously. This result further indicates that the imprecision and inaccuracy in the nutrition model is related to the prediction of body weight.

**Table 5.** Comparison of original models using 5 forage intake equations to predict forage intake separately in the dairy calf intake and body weight dataset when observed body weight was used in the model [1].

| Item [3] | Eq91 [2] | Eq67 | Eq25 | Eq17 | Eq21 |
|---|---|---|---|---|---|
| CCC | 0.935 | 0.936 | 0.958 | 0.964 | 0.640 |
| Cb | 0.998 | 0.997 | 0.99 | 0.995 | 0.690 |
| MB (SD), kg/d | −0.008 (0.503) | 0.097 (0.471) | −0.176 (0.366) | −0.131 (0.342) | −1.366 (1.171) |
| MB, % | −0.55 | 6.57 | −11.9 | −8.83 | −92.26 |
| Intercept ± SE | 0.1745 ± 0.0288 | 0.1655 ± 0.0287 | −0.0298 ± 0.0224 | −0.0328 ± 0.0216 | −0.0674 ± 0.0340 |
| Slope ± SE | 0.8763 ± 0.0140 | 0.9503 ± 0.0150 | 0.9109 ± 0.0103 | 0.9387 ± 0.0102 | 0.5416 ± 0.0093 |
| Pr > F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

[1] Linear regression of observed body weight on day of age was used to predict body weight for the dairy calf intake and body weight dataset (CCC = 0.980; Cb = 0.987; MB, kg = −8.662; MB, % = −6.23). [2] Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7). [3] CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; SD = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = *p*-value for linear hypothesis test.

**Table 6.** Comparison of original and adjusted models to predict body weight separately in the dairy calf intake and body weight dataset when observed forage intake was used in the model [1].

| Item [2] | Original EBG Equation | New EBG Equation |
|---|---|---|
| CCC | 0.926 | 0.992 |
| Cb | 0.938 | 0.999 |
| MB (SD), kg/d | −20.966 (11.365) | −0.135 (7.368) |
| MB, % | −17.08 | −0.11 |
| Intercept ± SE | −6.4356 ± 1.0076 | −1.7250 ± 0.7569 |
| Slope ± SE | 0.8989 ± 0.0064 | 1.0129 ± 0.0056 |
| Pr > F | <0.0001 | 0.0643 |

[1] Polynomial linear regression of observed forage intake on day of age was used to predict forage intake for the dairy calf dataset (CCC = 0.988; Cb = 0.999; MB, kg/d = −0.01; MB, % = −0.41). [2] EBG = empty body weight gain; CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; SD = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = *p*-value for linear hypothesis test.

#### 3.1.3. Adjusted Nutrition Model

Since the milk energy concentration and the forage digestibility were reported in the dairy calf intake and body weight dataset, the likely issue with the prediction of body weight in the nutrition model is the precision and accuracy of the empty body weight gain equation. The descriptive statistics of the dairy calf serial slaughter dataset used to evaluate the empty body weight gain Equation (8a) are presented in Table S2. The mean (SD) empty body weight, empty body weight gain, and retained energy were 103.7 (97.6) kg, 0.65 (0.25) kg/d, and 1.933 (1.311) Mcal/d, respectively. Overall, the prediction of empty body weight gain by Equation (8a) was imprecise (CCC = 0.329) and inaccurate (MB = 61.47%), with the intercept and slope being significantly different than zero and one, respectively (Table S3). Upon further evaluation, the published equation was highly precise (CCC = 0.934) and moderately accurate (MB = 5.14%) in postweaning (>200 kg initial empty body weight) dairy cattle, but imprecise (CCC = 0.314) and inaccurate (MB = 75.62%) in preweaning (<200 kg final empty body weight) dairy cattle.

Based on the imprecision and inaccuracy of predicting empty body weight gain in preweaning dairy cattle, a new equation was developed using the entirety of the dairy calf serial slaughter dataset, not just the preweaning cattle data. Mixed effect models to estimate empty body weight gain from the combinations of retained energy and empty body weight had a lesser AIC than those of fixed effect models (Table S4). The inclusion of empty body weight in the model (Model 5 and Model 6 vs. Model 4 (Table S4)) did not improve the AIC, but Model 6 was determined to be the best model to follow the equation convention used by the National Academies of Science, Engineering and Medicine [10] (2016). The final equation was as follows:

$$\text{EBG} = 0.78621 \times \text{RE}^{0.78512} \times \text{EBW}^{-0.14361} \quad (13)$$

where EBG is empty body weight gain in kg/d, RE is retained energy in Mcal/d, and EBW is mean empty body weight in kg. Cross-fold validation of the final model resulted in a small root mean square error (0.060 kg/d), a large coefficient of determination ($R^2$ 0.825), an intercept not different from zero, and a slope not different from one (Table S5).

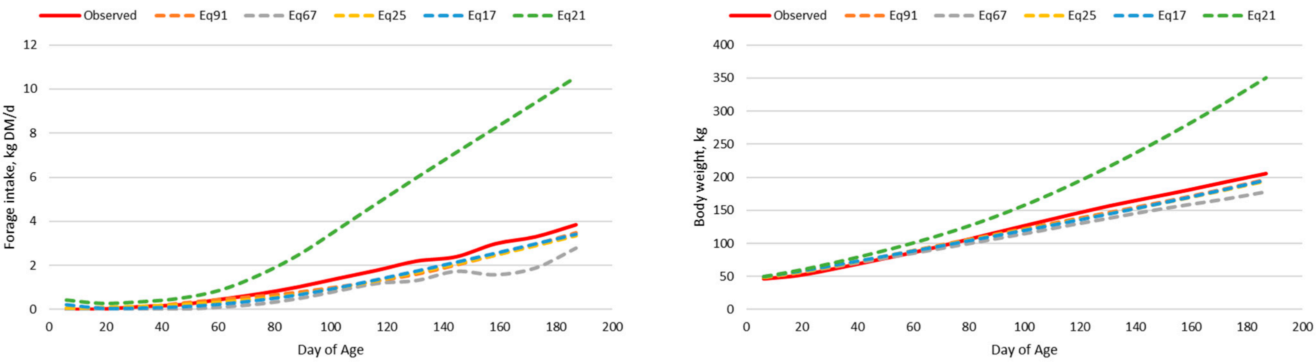
The original nutrition model was adjusted by replacing the empty body weight gain Equation (8a) with Equation (13). The observed forage intake was used in the adjusted nutrition model to predict body weight resulting in a highly precise (CCC = 0.992) and accurate (MB = −0.11%) prediction of body weight (Table 6). Additionally, linearity criteria were met ($p$ = 0.0643) indicating the simultaneous equivalency of intercept not being different from zero and the slope not being different from one.

Predicting forage intake and body weight simultaneously with the adjusted nutrition model resulted in improved precision and accuracy compared with the original nutrition model (Table 7). Forage intake was predicted with high precision (CCC = 0.881 to 0.914) for Eq91, Eq25, and Eq17, but with lesser precision for Eq67 and Eq21. Model accuracy was poor in predicting forage intake by all equations, but Eq91, Eq25, and Eq17 had better accuracy (MB = 15.47 to 18.11%) than Eq67 and Eq21 (MB = 40.53 and −172.88%, respectively). The slope coefficients for Eq91, Eq25, and Eq17 were closer to one in the adjusted nutrition model, but the intercepts were further from zero, and none of the equations met the criteria for linearity ($p$ < 0.0001) compared to the original nutrition model. Although not highly accurate, Eq91, Eq25, and Eq17, which were developed from this same dataset, were the most precise and accurate in predicting forage intake. Figure 3a illustrates the prediction of forage intake for the five equations in the adjusted nutrition model.

**Table 7.** Comparison of adjusted models using 5 forage intake equations to predict forage intake and body weight simultaneously using the new empty body weight gain Equation (13) in the dairy calf intake and body weight dataset.

| Item | Eq91 [1] | Eq67 | Eq25 | Eq17 | Eq21 |
|---|---|---|---|---|---|
| Forage Intake | | | | | |
| CCC [2] | 0.914 | 0.766 | 0.881 | 0.901 | 0.412 |
| Cb | 0.984 | 0.825 | 0.967 | 0.973 | 0.451 |
| MB (SD), kg/d | 0.229 (0.500) | 0.600 (0.594) | 0.268 (0.561) | 0.252 (0.513) | −2.561 (2.527) |
| MB, % | 15.47 | 40.53 | 18.11 | 17.02 | −172.88 |
| Intercept ± SE | 0.2588 ± 0.0298 | 0.3072 ± 0.0294 | 0.2037 ± 0.0343 | 0.1928 ± 0.0312 | 0.1269 ± 0.0347 |
| Slope ± SE | 0.9761 ± 0.0167 | 1.3382 ± 0.0231 | 1.0539 ± 0.0206 | 1.0489 ± 0.0184 | 0.3328 ± 0.0064 |
| Pr > F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Body Weight | | | | | |
| CCC | 0.978 | 0.940 | 0.968 | 0.969 | 0.701 |
| Cb | 0.991 | 0.973 | 0.995 | 0.995 | 0.739 |
| MB (SD), kg/d | 3.472 (10.701) | 10.934 (15.392) | 4.749 (13.263) | 4.807 (13.190) | −47.540 (48.220) |
| MB, % | 2.83 | 8.91 | 3.87 | 3.92 | −38.73 |
| Intercept ± SE | −9.6804 ± 0.9940 | 0.7530 ± 1.5226 | 2.4086 ± 1.3481 | 2.7352 ± 1.3383 | 29.2959 ± 1.5428 |
| Slope ± SE | 1.1103 ± 0.0077 | 1.0911 ± 0.0124 | 1.0198 ± 0.0104 | 1.0176 ± 0.0103 | 0.5488 ± 0.0078 |
| Pr > F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

[1] Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7). [2] CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; SD = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = $p$-value for linear hypothesis test.




(**a**) (**b**)

**Figure 3.** Observed and predicted forage intake (**a**) and body weight (**b**) for the 5 forage intake equations over the suckling period in the dairy calf intake and body weight dataset using the adjusted model. Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7).

Body weight was predicted with high precision (CCC = 0.968 to 0.978) and accuracy (MB = 2.83 to 3.92%) by Eq91, Eq25, and Eq17, but with poorer precision and accuracy by Eq67 and Eq21 (Table 7). Additionally, the intercepts were very near zero, and the slopes were very close to one for Eq25 and Eq17; although neither met the criteria for linearity ($p < 0.0001$). Using Eq91, Eq25, and Eq17, which were developed from this same dairy calf intake and body weight dataset, provided precise and accurate prediction of body weight in the adjusted nutrition model. Figure 3b illustrates the prediction of body weight for the five equations in the adjusted nutrition model.

### *3.2. Beef Calf Intake and Body Weight Dataset*

#### 3.2.1. Milk Intake

The prediction of milk intake was evaluated using the NASEM and WOOD milk yield equations. Both equations predicted milk intake with high precision (CCC = 0.796 and 0.820, respectively), but the WOOD equation had improved accuracy (MB = 1.31 vs. 4.29%) compared to the NASEM equation (Table 8). Additionally, the intercept and slope were closer to zero and one, respectively, for the WOOD equation compared to the NASEM equation, and the WOOD equation met the criteria for linearity ($p = 0.1673$), whereas the NASEM equation did not ($p < 0.0001$). Figure 4 illustrates the observed and predicted milk intake during the suckling period in the beef calf intake and body weight dataset. Thus, the predicted daily milk yield from the WOOD equation was used as the daily milk intake for all subsequent nutrition model evaluations.

**Table 8.** Comparison of milk yield equations to predict milk intake in the beef calf intake and body weight dataset.

| Item [1] | NASEM | WOOD |
|---|---|---|
| CCC | 0.796 | 0.820 |
| Cb | 0.993 | 0.991 |
| MB (SD), kg/d | 0.206 (1.078) | 0.063 (0.969) |
| MB, % | 4.29 | 1.31 |
| Intercept ± SE | 1.0875 ± 0.1719 | 0.3321 ± 0.1850 |
| Slope ± SE | 0.8087 ± 0.0350 | 0.9433 ± 0.0371 |
| Pr > F | <0.0001 | 0.1673 |

[1] NASEM = milk yield Equation (1a–c); WOOD = milk yield Equation (2a–e); CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; SD = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = $p$-value for linear hypothesis test.

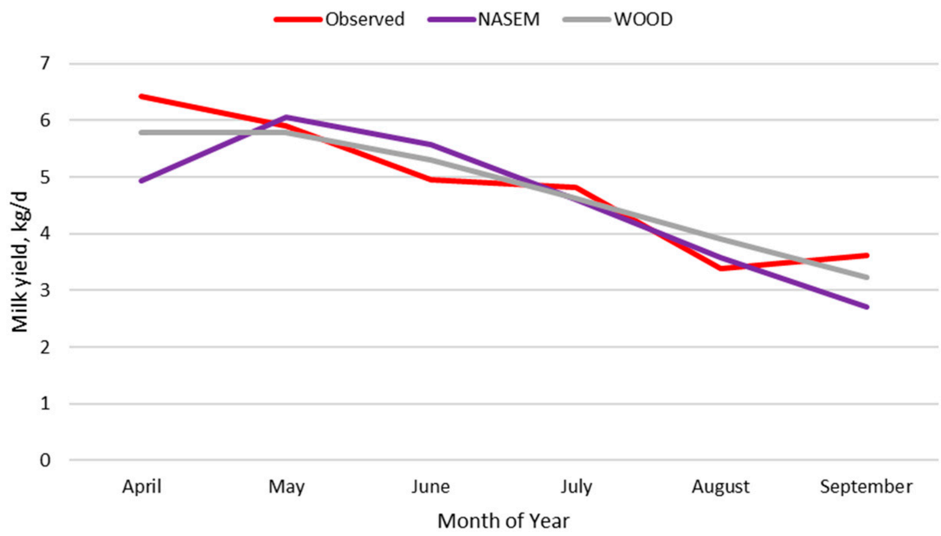



**Figure 4.** Observed and predicted milk intake using milk yield equations over the suckling period in the beef calf intake and body weight dataset. Calves were born in March and April. NASEM = milk yield Equation (1a–c) and WOOD = milk yield Equation (2a–e).

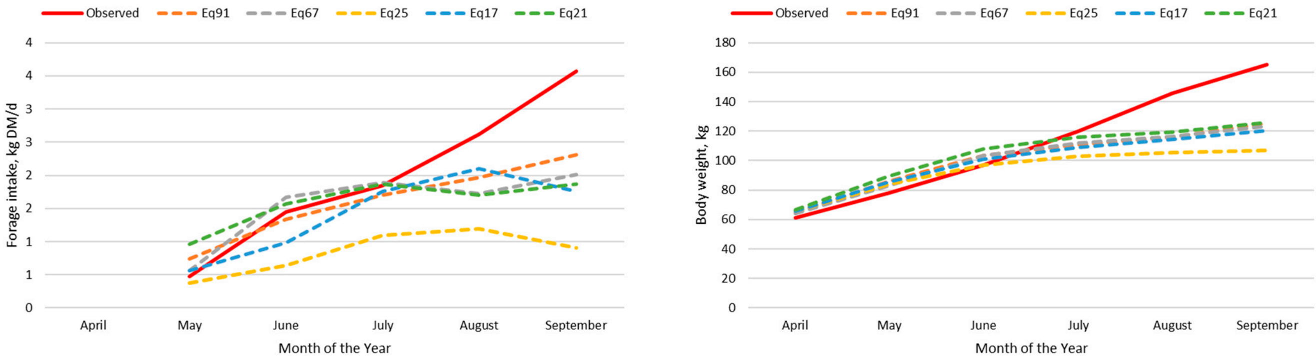
### 3.2.2. Original Nutrition Model

The simultaneous prediction of forage intake and body weight resulted in poor-to-moderate precision and poor-to-moderate accuracy. Forage intake predicted by Eq91 was moderately precise (CCC = 0.613), but its prediction by other equations had poor precision (CCC < 0.60) (Table 9). All equations predicted forage intake with poor accuracy (MB > 10%). Some equations (Eq67, Eq25, and Eq17) had intercepts close to zero, but all equations had slopes greater than one, indicating that forage intake was underpredicted to a greater extent as the observed forage intake increased, which can be seen in Figure 5a.

**Table 9.** Comparison of original models using 5 forage intake equations to predict forage intake and body weight simultaneously in the beef calf intake and body weight dataset.

| Item | Eq91 [1] | Eq67 | Eq25 | Eq17 | Eq21 |
|---|---|---|---|---|---|
| Forage Intake | | | | | |
| CCC [2] | 0.613 | 0.476 | 0.167 | 0.491 | 0.348 |
| Cb | 0.745 | 0.752 | 0.278 | 0.706 | 0.608 |
| MB (SD), kg/d | 0.389 (0.802) | 0.433 (0.963) | 1.160 (1.064) | 0.565 (0.910) | 0.409 (1.037) |
| MB, % | 19.36 | 21.51 | 57.67 | 28.07 | 20.33 |
| Intercept ± SE | −0.6318 ± 0.1251 | 0.1182 ± 0.1605 | 0.1346 ± 0.1714 | 0.0939 ± 0.1391 | −0.3867 ± 0.2296 |
| Slope ± SE | 1.6294 ± 0.0720 | 1.1992 ± 0.0940 | 2.2045 ± 0.1873 | 1.3254 ± 0.0878 | 1.4965 ± 0.1374 |
| Pr > F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Body Weight | | | | | |
| CCC | 0.762 | 0.76 | 0.574 | 0.766 | 0.766 |
| Cb | 0.899 | 0.898 | 0.757 | 0.874 | 0.909 |
| MB (SD), kg/d | 10.224 (21.910) | 10.946 (21.887) | 17.594 (26.833) | 11.911 (23.166) | 7.114 (22.379) |
| MB, % | 9.18 | 9.83 | 15.79 | 10.69 | 6.39 |
| Intercept ± SE | −11.3177 ± 4.5786 | −8.3620 ± 4.5074 | −11.4078 ± 6.2286 | −10.2020 ± 4.9313 | −18.4033 ± 4.9166 |
| Slope ± SE | 1.2129 ± 0.0436 | 1.1922 ± 0.0432 | 1.3092 ± 0.0645 | 1.2223 ± 0.0479 | 1.2447 ± 0.0457 |
| Pr > F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

[1] Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7).
[2] CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; SD = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = *p*-value for linear hypothesis test.




(**a**) (**b**)

**Figure 5.** Observed and predicted forage intake (**a**) and body weight (**b**) for 5 forage intake equations over the suckling period in the beef calf intake and body weight dataset using the original model. Calves were born in March and April. Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7).

The prediction of body weight was moderately precise by Eq91, Eq67, Eq17, and Eq21 with CCC of approximately 0.76 (Table 9). The prediction was moderately accurate (MB = 6.39 to 9.83%) by Eq91, Eq67, and Eq21, but Eq17 had poor accuracy. Body weight prediction by Eq25 was imprecise and inaccurate, having CCC of 0.574 and MB of 15.79%. None of the equations met the criteria for linearity ($p < 0.0001$) with intercepts lesser than zero and slopes greater than one, indicating that body weight was overpredicted at lighter weights and underpredicted at heavier weights, which can be seen in Figure 5b.

When forage intake and body weight were predicted separately, the observed body weight was estimated from a linear regression equation relating body weight with the day of calf age for each individual calf to complete the daily timestep of the nutrition model since body weight was not measured daily (Table 10). The regression equation was highly precise (CCC = 0.992) and accurate (MB = 0.72%) in estimating body weight. The forage intake predicted by Eq91 was highly precise (CCC = 0.834) and accurate (MB = 0.81%), Eq67 and Eq17 were moderately precise and accurate, Eq25 was moderately precise and poorly accurate, and Eq21 was poorly precise and accurate. Additionally, Eq91 and Eq67 met the criteria for linearity ($p = 0.8283$ and 0.0854, respectively), whereas Eq25, Eq17, and Eq21 did not ($p < 0.001$). The prediction of forage intake was more precise and accurate than when the forage intake and body weight were predicted simultaneously. These results indicate that the prediction of body weight may be hindering the precise and accurate prediction of forage intake.

When body weight was predicted separately using the observed forage intake in the nutrition model, the observed forage intake was estimated from a polynomial regression equation relating forage intake with the day of calf age for each individual calf to complete the daily timestep of the nutrition model since forage intake was not measured daily. The regression equation was highly precise (CCC = 0.972) and accurate (MB = −0.53%) in estimating forage intake (Table 11). The prediction of body weight was highly precise (CCC = 0.821) and moderately accurate (MB = 9.69%); but the intercept was lesser than zero and the slope was greater than one, indicating overprediction at lighter body weight and underprediction at heavier body weight. The prediction of body weight separately was more precise than when forage intake and body weight were predicted simultaneously, indicating that the prediction of body weight is hindering the precision and accuracy of the nutrition model.

**Table 10.** Comparison of original models using 5 forage intake equations to predict forage intake separately in the beef calf intake and body weight dataset when observed body weight was used in the model [1].

| Item | Eq91 [2] | Eq67 | Eq25 | Eq17 | Eq21 |
|---|---|---|---|---|---|
| CCC [3] | 0.834 | 0.725 | 0.630 | 0.738 | 0.528 |
| Cb | 0.983 | 0.953 | 0.830 | 0.959 | 0.727 |
| MB (SD), kg/d | 0.016 (0.653) | 0.112 (0.800) | 0.555 (0.806) | 0.196 (0.787) | 0.418 (0.894) |
| MB, % | 0.81 | 5.58 | 27.56 | 9.73 | 20.76 |
| Intercept ± SE | −0.0222 ± 0.0915 | 0.0721 ± 0.1176 | 0.4491 ± 0.1001 | 0.2499 ± 0.1061 | −0.3290 ± 0.1520 |
| Slope ± SE | 1.0193 ± 0.0408 | 1.0211 ± 0.0557 | 1.0723 ± 0.0590 | 0.9701 ± 0.0515 | 1.4684 ± 0.0891 |
| Pr > F | 0.8283 | 0.0854 | <0.0001 | 0.0005 | <0.0001 |

[1] Linear regression of observed body weight on day of age was used to predict body weight for the beef calf intake and body weight dataset (CCC = 0.992; Cb = 0.999; MB, kg = 0.722; MB, % = 0.72). [2] Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7). [3] CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; SD = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = *p*-value for linear hypothesis test.

**Table 11.** Comparison of original models to predict body weight in the beef calf intake and body weight dataset when observed forage intake was used in the model [1].

| Item | Original [2] | New Forage Digestibility | New Milk Energy | New EBG Equation | New Combination |
|---|---|---|---|---|---|
| CCC [3] | 0.821 | 0.883 | 0.863 | 0.901 | 0.931 |
| Cb | 0.913 | 0.957 | 0.946 | 0.981 | 0.985 |
| MB (SD), kg/d | 10.796 (18.441) | 7.260 (16.097) | 6.998 (17.324) | 1.757 (16.143) | −5.965 (13.045) |
| MB, % | 9.69 | 6.52 | 6.28 | 1.58 | −5.35 |
| Intercept ± SE | −11.0374 ± 3.5433 | −7.8853 ± 3.0152 | −13.3124 ± 3.3515 | −10.5959 ± 3.1486 | −8.3616 ± 2.5005 |
| Slope ± SE | 1.2170 ± 0.0338 | 1.1454 ± 0.0277 | 1.1945 ± 0.0308 | 1.1127 ± 0.0275 | 1.0204 ± 0.0203 |
| Pr > F | <0.0001 | < 0.0001 | <0.0001 | < 0.0001 | <0.0001 |

[1] Polynomial linear regression of observed forage intake on day of age was used to predict forage intake for the beef calf intake and body weight dataset (CCC = 0.972; Cb = 1.000; MB, kg/d = −0.011; MB, % = −0.53). [2] Original = model using observed in vitro forage dry matter digestibility, standard milk energy concentration (0.72 Mcal/kg), empty body weight gain Equation (8a); New Forage Digestibility = adjusted model substituting estimated in vivo forage organic matter digestibility for observed in vitro forage dry matter digestibility; New Milk Energy = adjusted model substituting estimated daily milk energy concentration for the standard milk energy concentration; New EBG Equation = adjusted model substituting the developed empty body weight gain equation for the original empty body weight gain Equation (8a); New Combination = adjusted model combining the changes of New Forage Digestibility, New Milk Energy, and New EBG Equation. [3] CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; Sd = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = *p*-value for linear hypothesis test.

### 3.2.3. Adjusted Nutrition Model

Unlike the dairy calf intake and body weight dataset, the composition of milk was not known, and the forage digestibility was estimated from the in vitro method in the beef calf intake and body weight dataset, both of which affect the estimated energy intake of the calf. The descriptive statistics of the forage digestibility dataset are presented in Table S6. The mean (SD) in vitro dry matter digestibility, in vitro organic matter digestibility, in vivo dry matter digestibility, and in vivo organic matter digestibility were 57.9 (9.23), 54.22 (10.09), 56.66 (7.85), and 56.17 (10.93) %. Comparison of in vitro with in vivo dry matter digestibility indicated poor precision (CCC = 0.495) and high accuracy (MB = −2.75%) (Table S7). The prediction of in vivo dry matter digestibility did not meet the criteria for linearity ($p < 0.0001$), having an intercept considerably greater than zero and a slope considerably lesser than one. Comparison of in vitro with in vivo organic matter digestibility indicated high precision (CCC = 0.887) and accuracy (MB = 3.97%), but the prediction of in vivo organic matter digestibility did not meet the criteria for linearity ($p = 0.0021$), although the intercept and the slope were closer to zero and one, respectively, than those of dry matter digestibility.

Comparison of in vitro dry matter digestibility with in vitro organic matter digestibility resulted in a highly precise and accurate prediction of organic matter digestibility (Table S8). Additionally, comparison of in vivo dry matter digestibility with in vivo organic matter digestibility resulted in a highly precise and accurate prediction of organic matter digestibility. The relationship of in vivo dry matter with organic matter digestibility had an intercept closer to zero and a slope closer to one than those for in vitro digestibility, but neither met the criteria for linearity ($p < 0.001$).

In the beef calf intake and body weight dataset, in vitro forage dry matter digestibility values are reported. However, as mentioned above, the linear relationship between in vitro and in vivo forage dry matter digestibility is poor. Previously published equations were evaluated to predict in vivo forage dry matter digestibility from in vitro forage dry matter digestibility using the Tilley and Terry [30] technique (Table S9). The prediction of in vivo dry matter digestibility was imprecise (CCC < 0.550) for all 14 evaluated equations (Table S10); however, all the equations were at least moderately accurate (MB < 10%) with some being highly accurate (MB < 5%). For all equations, the criteria for linearity were not met ($p < 0.001$), with intercepts being considerably greater than zero and slopes being considerably lesser than one, except for Equation (14; Table S10) which had an intercept considerably lesser than zero and a slope considerably greater than one.

Based on the poor prediction by previously published equations, a new equation relating in vivo forage organic matter digestibility to in vitro forage dry matter digestibility was developed. In vitro dry matter digestibility was used to predict in vivo organic matter digestibility for two reasons: (1) Boggs [29] only reported in vitro dry matter digestibility values of the forage, and (2) in vitro dry matter digestibility had a better relationship with in vivo organic matter digestibility (r = 0.95) than in vivo dry matter digestibility (r = 0.51). The new equation was as follows:

$$\text{OMD} = 7.7718 + 0.8937 \times \text{IVDMD} \quad (14)$$

where OMD is in vivo organic matter digestibility in %, and IVDMD is in vitro dry matter digestibility in %. Cross-fold validation of the new equation resulted in a root mean square error of 3.087% units, a coefficient of determination of 0.8706, an intercept not different from zero, and a slope not different from one (Table S11).

The original beef calf nutrition model was adjusted to incorporate the new estimated in vivo forage organic matter digestibility predicted from Equation (14) above, which was assumed to be equal to total digestible nutrients. The prediction of body weight when the observed forage intake was used in the adjusted nutrition model was highly precise (CCC = 0.883) and moderately accurate (MB = 6.52%), which is an improvement over the original nutrition model (Table 11). Additionally, the intercept was closer to zero and the slope closer to one than for the original model, although the adjusted model did not meet the criteria for linearity ($p < 0.0001$).

In the original beef calf nutrition model, milk energy was assumed to be 0.72 Mcal/kg of fluid milk, which may not be consistent across yield and days in milk. The descriptive statistics for the milk composition dataset are presented in Table S12. The mean (SD) of milk yield, fat, protein, lactose, and energy were 7.37 (2.06) kg/d, 4.65 (1.43)%, 3.32 (0.33)%, 4.90 (0.25)%, and 0.82 (0.14) Mcal/kg, respectively. The final statistical models for the prediction of fat, protein, lactose, and energy are presented in Table S13. Milk fat percentage varied with days in milk, yield × days in milk interaction, and breed type. The model explained 52.8% of the variation after adjusting for the variation explained by the random effect of study. Milk protein percentage varied with yield and days in milk with the final model explaining 44.6% of the variation. Milk lactose percentage varied with yield, which accounted for 26.9% of the variation. Milk energy concentration followed a similar model as milk fat percentage varying with days in milk, yield × days in milk interaction, and breed type with the final model accounting for 49.7% of the variation.

Cross-fold validation of the final models for predicting milk composition resulted in small root mean square errors, moderate coefficients of determination, and intercepts and slopes not different from zero and one, respectively (Table S14). The new equation to predict milk energy concentration is as follows:

$$EN = 0.7285 + 0.00070 \times DIM - 0.00012 \times Yield \times DIM \quad (15)$$

where EN is milk energy concentration in Mcal/kg of fluid milk, DIM is days in milk in d, and Yield is milk yield in kg/d. Cross-fold validation of the final model to predict milk energy concentration had a root mean square error of 0.034 Mcal/kg, a coefficient of determination of 0.497, and intercepts and slopes not different from zero and one, respectively.

The beef calf nutrition model was adjusted to incorporate Equation (15) to predict milk energy concentration with the observed forage intake used to predict body weight. The prediction of body weight was highly precise (CCC = 0.863) and moderately accurate (MB = 6.28%), which was improved compared to the original nutrition model and had similar values to the adjusted nutrition model with the new forage digestibility estimates (Table 11). However, the intercept and slope of the linear regression of observed on predicted values are similar to the original nutrition model.

Like the dairy calf nutrition model, the prediction of empty body weight gain by Equation (8a) was evaluated using the beef cattle serial slaughter dataset. The descriptive statistics for the dataset are presented in Table S15. The mean (SD) empty body weight, empty body weight gain, and retained energy were 342.9 (71.8) kg, 1.03 (0.43) kg/d, and 4.54 (2.10) Mcal/d, respectively. Overall, the prediction of empty body weight gain was moderately precise (CCC = 0.777) and poorly accurate (MB = −13.56%); however, even though the criteria for linearity were not met ($p < 0.0001$), the intercept and slope were close to zero and one, respectively (Table S16). Separating pre- (<200 kg final empty body weight) and postweaning (>200 kg initial empty body weight) data indicated that the prediction of empty body weight gain had similar precision (CCC = 0.843 and 0.770) but was more accurate in postweaning than preweaning beef cattle (MB = −14.46 vs. 24.33%). Additionally, the intercept and slope of linear regression were closer to zero and one, respectively, for postweaning beef cattle than preweaning beef cattle, even though neither met the criteria for linearity ($p < 0.05$).

Based on the inaccuracy of predicting empty body weight gain in preweaning beef cattle, a new equation was developed using the entirety of the beef cattle serial slaughter dataset, not just the preweaning cattle data. Mixed effect models to estimate empty body weight gain from combinations of retained energy and empty body weight had lesser AIC than those of fixed effect models (Table S17) except for Model 6 versus Model 3. The inclusion of empty body weight in the model (Model 5 and Model 6 vs. Model 4) did not improve the AIC, but Model 5 was determined to be the best model to follow the equation convention used by the National Academies of Science, Engineering and Medicine [10]. The final equation is as follows:

$$EBG = 7.92787 \times (RE \div EBW^{0.75})^{0.70834} \quad (16a)$$

which is equivalent to the following,

$$EBG = 7.92787 \times RE^{0.70834} \times EBW^{-0.53126} \quad (16b)$$

where EBG is empty body weight gain in kg/d, RE is retained energy in Mcal/d, and EBW is empty body weight in kg. Cross-fold validation of the final model resulted in a root mean square error of 0.115 kg/d, a coefficient of determination ($R^2$) of 0.777, an intercept not different from zero, and a slope not different from one (Table S18).

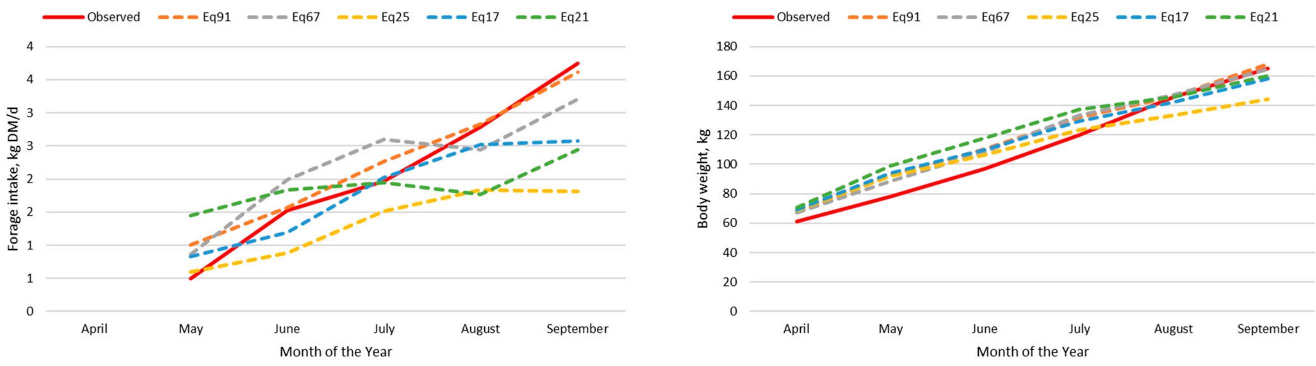
The original beef calf nutrition model was adjusted to incorporate Equation (16b) to predict empty body weight gain with the observed forage intake used to predict body weight. The prediction of body weight was highly precise (CCC = 0.901) and accurate (MB = 1.58%), which is an improvement over the original nutrition model as well as the nutrition models adjusted for the new forage digestibility and new milk energy (Table 11). The slope of the linear regression was closer to one compared to the original nutrition model; however, the intercept was similar to the original nutrition model. The original beef calf nutrition model was adjusted with the combination of the new forage digestibility, new milk energy concentration, and new empty body weight gain equation. When predicting body weight using the observed forage intake, the adjusted nutrition model was highly precise (CCC = 0.931), which is slightly better than each of the adjusted nutrition models alone, and moderately accurate (MB = −5.35%), which is similar to the adjusted nutrition models with the new forage digestibility and milk energy concentration, but poorer than the adjusted nutrition model with the new empty body weight gain equation alone. However, when comparing the intercept and slope of linear regression, the combination adjusted nutrition model had an intercept similar to the other adjusted nutrition models but had a slope closer to one than the other adjusted nutrition models. However, none of the adjusted nutrition models met the criteria for linearity ($p < 0.0001$). It was determined that the combination adjusted nutrition model was the best model.

Forage intake and body weight were predicted simultaneously using the combination adjusted beef calf nutrition model. The prediction of the forage intake was highly precise for Eq91, moderately precise for Eq67 and Eq17, and imprecise for Eq25 and Eq21 (Table 12). The model was moderately accurate for Eq91 and Eq67, but was poorly accurate for Eq25, Eq17, and Eq21. Additionally, Eq67 had an intercept closest to zero and a slope closest to one and met the criteria for linearity ($p = 0.1603$) compared with the other equations. Figure 6a illustrates the predicted and observed forage intake from the adjusted model. Body weight was predicted with high precision by all equations, and high accuracy by Eq25, and moderate accuracy by Eq91, Eq67, Eq17, and Eq21. Eq67 had an intercept closest to zero, and Eq91, Eq67, Eq17, and Eq21 had slopes closer to one than Eq25. Figure 6b illustrates the predicted and observed body weight from the adjusted nutrition model. The precision and accuracy of forage intake and body weight prediction is improved for the adjusted nutrition model compared to the original nutrition model.

**Table 12.** Comparison of adjusted models using 5 forage intake equations to predict forage intake and body weight simultaneously in the beef calf intake and body weight dataset using the combination of new forage digestibility, milk energy concentration, and empty body weight gain equation.

| Item | Eq91 [1] | Eq67 | Eq25 | Eq17 | Eq21 |
|---|---|---|---|---|---|
| Forage Intake | | | | | |
| CCC [2] | 0.822 | 0.670 | 0.434 | 0.686 | 0.380 |
| Cb | 0.956 | 0.951 | 0.546 | 0.842 | 0.628 |
| MB (SD), kg/d | −0.149 (0.674) | −0.107 (0.879) | 0.783 (0.925) | 0.281 (0.809) | 0.233 (1.078) |
| MB, % | −7.01 | −5.08 | 39.87 | 13.24 | 10.96 |
| Intercept ± SE | −0.4464 ± 0.1063 | −0.1010 ± 0.1427 | −0.4021 ± 0.1337 | −0.4482 ± 0.1263 | −1.0047 ± 0.2712 |
| Slope ± SE | 1.1309 ± 0.0429 | 0.9969 ± 0.0588 | 1.8840 ± 0.0924 | 1.3958 ± 0.0634 | 1.6545 ± 0.1391 |
| Pr > F | <0.0001 | 0.1603 | <0.0001 | <0.0001 | <0.0001 |
| Body Weight | | | | | |
| CCC | 0.935 | 0.938 | 0.896 | 0.926 | 0.886 |
| Cb | 0.978 | 0.985 | 0.972 | 0.98 | 0.956 |
| MB (SD), kg/d | −8.173 (11.663) | −6.918 (12.128) | −0.104 (16.267) | −5.956 (13.310) | −10.486 (14.937) |
| MB, % | −7.34 | −6.21 | −0.09 | −5.35 | −9.41 |
| Intercept ± SE | −6.6719 ± 2.1851 | −3.2861 ± 2.2109 | −19.3587 ± 3.2651 | −13.6285 ± 2.6198 | −16.0307 ± 3.0696 |
| Slope ± SE | 0.9875 ± 0.0174 | 0.9693 ± 0.0178 | 1.1727 ± 0.0282 | 1.0654 ± 0.0214 | 1.0455 ± 0.0242 |
| Pr > F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

[1] Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7).
[2] CCC = concordance correlation coefficient; Cb = bias correction factor; MB = mean bias; SD = standard deviation; Intercept = intercept coefficient of linear regression of observed on predicted values; SE = standard error; Slope = slope coefficient of linear regression of observed on predicted values; and Pr > F = $p$-value for linear hypothesis test.




(**a**) (**b**)

**Figure 6.** Observed and predicted forage intake (**a**) and body weight (**b**) for 5 forage intake equations over the suckling period in the beef calf intake and body weight dataset using the adjusted model. Calves were born in March and April. Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7).

### 3.2.4. Exploration of Model Deviation

Even though the adjusted nutrition model prediction is improved, the lack of a clearly distinct best forage intake equation is concerning. Additionally, Figure 6b clearly illustrates the overprediction of body weight through much of the suckling period; thus, a further evaluation of the deviation of the observed and predicted values was undertaken. In the beef calf intake and body weight dataset, calves were born from March 1 to May 2; however, the first milk intake measurement was not undertaken until the end of April and the first forage intake measurement was not undertaken until the end of May such that some calves were 2 to 3 months old before assessing nutrient intake, which may skew the precision and accuracy of the nutrition model.

For the deviation between the observed and predicted forage intake, there was a birth period × forage intake interaction ($p \leq 0.05$) for all forage intake equations except Eq17 (Table 13). For Eq91 and Eq67, the deviation between the observed and predicted forage intake was closer to zero for calves in birth period 3, those born closer to the initial measurement, at lesser forage intake values. However, as calves grew and forage intake was greater, the deviation between the observed and predicted forage intake was similar among birth periods.

**Table 13.** Effect of birth period with the covariate of forage intake on deviation between observed and predicted forage intake from the adjusted model using the combination of new forage digestibility, milk energy concentration, and empty body weight gain equation in the beef calf intake and body weight dataset.

| | | Birth Period [1] | | | | *p*-Value [2] | | |
|---|---|---|---|---|---|---|---|---|
| **Equation [3]** | **Covariate Level** | **1** | **2** | **3** | **SEM** | **BP** | **Cov** | **BP × Cov** |
| Eq91 | 0.75 kg/d | −0.62 [a] | −0.46 [a] | −0.06 [b] | 0.09 | 0.01 | 0.01 | 0.01 |
| | 1.50 kg/d | −0.37 [a] | −0.22 [a] | 0.02 [b] | 0.06 | | | |
| | 2.25 kg/d | −0.11 | 0.02 | 0.10 | 0.06 | | | |
| | 3.00 kg/d | 0.15 | 0.26 | 0.19 | 0.07 | | | |
| | 3.75 kg/d | 0.40 | 0.50 | 0.27 | 0.10 | | | |
| Eq67 | 0.75 kg/d | −1.08 [a] | −0.75 [a] | −0.22 [b] | 0.10 | 0.01 | 0.01 | 0.01 |
| | 1.50 kg/d | −0.61 [a] | −0.39 [a] | 0.02 [b] | 0.07 | | | |
| | 2.25 kg/d | −0.13 [a] | −0.03 [a] | 0.27 [b] | 0.07 | | | |
| | 3.00 kg/d | 0.34 | 0.34 | 0.52 | 0.08 | | | |
| | 3.75 kg/d | 0.82 | 0.70 | 0.76 | 0.11 | | | |

**Table 13.** *Cont.*

| Equation [3] | Covariate Level | Birth Period [1] | | | SEM | *p*-Value [2] | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | | BP | Cov | BP × Cov |
| Eq25 | 0.75 kg/d | −0.72 [a] | −0.55 [ab] | −0.32 [a] | 0.10 | 0.47 | 0.01 | 0.05 |
| | 1.50 kg/d | −0.37 | −0.26 | −0.13 | 0.07 | | | |
| | 2.25 kg/d | −0.02 | 0.03 | 0.06 | 0.07 | | | |
| | 3.00 kg/d | 0.33 | 0.32 | 0.25 | 0.08 | | | |
| | 3.75 kg/d | 0.66 | 0.61 | 0.44 | 0.11 | | | |
| Eq17 | 0.75 kg/d | −0.64 [a] | −0.55 [a] | −0.24 [b] | 0.09 | 0.17 | 0.01 | 0.08 |
| | 1.50 kg/d | −0.34 | −0.27 | −0.07 | 0.07 | | | |
| | 2.25 kg/d | −0.03 | 0.01 | 0.09 | 0.07 | | | |
| | 3.00 kg/d | 0.27 | 0.29 | 0.26 | 0.08 | | | |
| | 3.75 kg/d | 0.58 | 0.57 | 0.43 | 0.11 | | | |
| Eq21 | 0.75 kg/d | −1.11 [a] | −1.02 [a] | −0.54 [b] | 0.09 | 0.01 | 0.01 | 0.01 |
| | 1.50 kg/d | −0.50 [a] | −0.54 [a] | −0.20 [b] | 0.07 | | | |
| | 2.25 kg/d | 0.10 | −0.05 | 0.14 | 0.07 | | | |
| | 3.00 kg/d | 0.71 [a] | 0.43 [b] | 0.47 [ab] | 0.08 | | | |
| | 3.75 kg/d | 1.31 [a] | 0.92 [b] | 0.81 [b] | 0.11 | | | |

[1] Birth Period 1 = March 1 to March 20; Birth Period 2 = March 21 to March 31; and Birth Period 3 = April 1 to May 2. [2] BP = *p*-value for birth period effect; Covariate = *p*-value for forage intake covariate effect; and BP × Cov = *p*-value for birth period × covariate interaction. [3] Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7). [ab] Mean deviations without a common superscript within a row differ at $p \leq 0.05$.

Like the results for forage intake, there was a birth period × body weight interaction ($p \leq 0.05$) for all forage intake equations (Table 14). The deviation between the observed and predicted body weight was closer to zero for calves in birth period 3 at lesser body weight for all equations. Interestingly, the deviation was closer to zero for calves in birth periods 2 and 3 at heavier body weights for Eq25, Eq17, and Eq21. Even though body weight was overpredicted early in the suckling period, the nutrition model was more accurate than average for those calves with measurements shortly after birth, indicating that the nutrition model is reasonably accurate.

**Table 14.** Effect of birth period with covariate of body weight on deviation between observed and predicted body weight from the adjusted model using the combination of new forage digestibility, milk energy concentration, and empty body weight gain equation in the beef calf intake and body weight dataset.

| Equation [3] | Covariate Level | Birth Period [1] | | | SEM | *p*-Value [2] | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | | BP | Cov | BP × Cov |
| Eq91 | 60 kg | −11.6 [a] | −6.1 [a] | 2.2 [b] | 1.7 | 0.01 | 0.01 | 0.01 |
| | 90 kg | −5.8 [a] | −3.5 [a] | 2.2 [b] | 1.2 | | | |
| | 120 kg | −0.1 | −0.8 | 2.3 | 1.1 | | | |
| | 150 kg | 5.6 | 1.9 | 2.3 | 1.5 | | | |
| Eq67 | 60 kg | −11.7 [a] | −6.4 [a] | 1.6 [b] | 1.7 | 0.01 | 0.01 | 0.01 |
| | 90 kg | −5.8 [a] | −3.6 [a] | 2.1 [b] | 1.2 | | | |
| | 120 kg | 0.1 | −0.8 | 2.5 | 1.1 | | | |
| | 150 kg | 5.9 | 1.9 | 3.0 | 1.6 | | | |

**Table 14.** *Cont.*

| Equation [3] | Covariate Level | Birth Period [1] | | | SEM | p-Value [2] | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | | BP | Cov | BP × Cov |
| Eq25 | 60 kg | −15.3 [a] | −10.5 [a] | 0.8 [b] | 2.1 | 0.01 | 0.01 | 0.01 |
| | 90 kg | −6.3 [a] | −6.1 [a] | 1.4 [b] | 1.5 | | | |
| | 120 kg | 2.7 | −1.7 | 2.1 | 1.5 | | | |
| | 150 kg | 11.7 [a] | 2.7 [b] | 2.7 [b] | 1.9 | | | |
| Eq17 | 60 kg | −12.7 [a] | −7.8 [a] | 1.7 [b] | 1.9 | 0.01 | 0.01 | 0.01 |
| | 90 kg | −5.6 [a] | −4.6 [a] | 1.8 [b] | 1.3 | | | |
| | 120 kg | 1.5 | −1.4 | 1.9 | 1.2 | | | |
| | 150 kg | 8.6 [a] | 1.8 [b] | 2.0 [b] | 1.7 | | | |
| Eq21 | 60 kg | −18.5 [a] | −8.2 [b] | 1.7 [c] | 2.1 | 0.01 | 0.01 | 0.01 |
| | 90 kg | −8.9 [a] | −4.4 [a] | 1.9 [b] | 1.4 | | | |
| | 120 kg | 0.7 | −0.7 | 2.1 | 1.4 | | | |
| | 150 kg | 10.3 [a] | 3.0 [b] | 2.3 [b] | 1.8 | | | |

[1] Birth period 1 = March 1 to March 20; Birth Period 2 = March 21 to March 31; and Birth Period 3 = April 1 to May 2. [2] BP = *p*-value for birth period effect; Cov = *p*-value for body weight covariate effect; and BP × Cov = *p*-value for birth period × covariate interaction. [3] Eq91 = Equation (3); Eq67 = Equation (4); Eq25 = Equation (5); Eq17 = Equation (6a–c); and Eq21 = Equation (7). [ab] Mean deviations without a common superscript within a row differ at $p \leq 0.05$.

## 4. Discussion

The measurement of forage intake by grazing cattle is fraught with errors regardless of the indirect method used [44–49], making the prediction of forage intake difficult. Many factors affect the intake of grazed forage, i.e., selective grazing [50–53], sward structure [50,54–56], forage species [45,57], and changing plant morphology and nutritive value affects the forage intake during the growing season [45,49,57,58]. In suckling calves, the animal has multiple choices of nutrients, milk, and forage, further complicating the prediction of forage intake. Numerous studies [22,59–68] have demonstrated that forage intake has a negative relationship with milk intake. Additionally, Webb et al. [69] demonstrated that calves preferentially consume the available milk supply before consuming forage. The negative relationship of forage intake with milk intake and the preferential consumption of milk allows development of equations to predict forage intake on the assumption that the available milk produced by the dam is consumed first, and subsequently forage intake can be predicted from the negative relationship between milk and forage intakes.

Milk production and milk intake are in dynamic balance. Tedeschi and Fox [24] reported that calves offered milk at high peak milk curves based on Wood [26] milk yield equation did not consume all the milk shortly after birth. Dams giving birth to heavier calves produce more milk than those giving birth to lighter calves, possibly due to the greater suckling stimulus and milk intake early in the lactation by heavier calves [70–73]. Additionally, milk production is influenced by the nutrient intake of the dam [74–76], resulting in varying levels of milk production in the same dams across years, and possibly affecting the shape of the lactation curve [76,77]. In dairy cattle, milk composition is also dynamic in that the concentration of components varies with breed, milk yield, and the stage of lactation [78–80]; however, a constant energy value of 0.72 Mcal/kg fluid milk is typically used in beef cattle [10]. Evaluation of the relationship of milk yield and days in milk with milk components indicated that milk composition is not constant in beef cows of various breed types. Breed type influenced the average milk composition but did not interact with milk yield or days in milk such that all breed types followed a similar pattern. In dairy cattle, milk fat and protein are at the greatest concentrations in the first few days after calving, declining steadily until peak milk yield is reached, after which concentrations increase steadily through late lactation such that component yield (milk yield × component concentration) is virtually constant throughout lactation [78]. The results from the current analysis of milk composition indicate similar relationships of milk yield and days in milk with milk components in beef cows as previously reported in dairy cows. Several studies [81–83] have reported increasing concentration of milk components in late lactation of beef cows. Similarly, Peischel [60] reported that milk protein and digestible energy consumed (kg/d) by suckling beef calves was relatively constant across 7 months of lactation. Increasing energy concentration in late lactation as part of the nutrition model significantly changed the predicted energy intake and growth of calves in late lactation to better align with the observed body weight values.

Throughout the lactation period, milk intake declines but calf body weight increases. Heavier calves will consume more forage and thus the nutrition model must be dynamic to reflect the ever-changing relationship between milk intake, body weight, and forage intake, which complicates the prediction of forage intake and calf growth. The dairy calf intake and body weight dataset with the direct measurements of milk and forage intake and energy concentrations allowed a better evaluation of these relationships, where the model performed reasonably well in predicting forage intake. However, predicting alfalfa hay intake is not the same as predicting grazed forage intake. Forage digestibility influences the rate of fermentation and thus passage rate out of the rumen [84]; thus, as forage plants mature, the decreasing digestibility results in less forage intake as a percentage of body weight [10]. Of the forage intake equations evaluated, Eq25, Eq17, and Eq21 adjust for digestibility of the forage; however, these were the least precise and accurate to predict forage intake in the beef calf intake and body weight dataset with changing forage digestibility throughout the grazing season. This could be due to the inaccurate estimates from the in vitro methods of determining forage digestibility used by Boggs [29]. Most published equations relating in vitro forage dry matter digestibility with in vivo forage dry matter digestibility have an intercept greater than zero and a slope lesser than one [36–41], indicating that in vivo forage digestibility is underpredicted at lesser forage digestibility and overpredicted at greater forage digestibility. Forages with lesser digestibility ferment at slower rates, resulting in longer rumen residence times, and forages with greater digestibility ferment at faster rates, resulting in shorter rumen residence times, whereas in vitro methods use a constant rumen fluid incubation time, which does not account for the differing rumen residence times. Bryan [62] used serial in situ incubation times (12, 24, 36, 48, and 72 h) for forage samples collected from pastures grazed by suckling calves: in vivo forage digestibility throughout the grazing season was best estimated by differing incubation times. The average intercept and slope of the published equations is 8.075 and 0.861, respectively, which is similar to the intercept and slope of the newly developed equation; thus, the new equation may be robust across forage species and maturities.

Sequentially dissecting the model into the prediction of forage intake and body weight separately allowed the determination of the aspects leading to imprecision and inaccuracy of the nutrition model. For both the dairy and beef calf intake and body weight datasets, when observed body weight was used in the nutrition model, and thus body weight did not depend upon the prediction from retained energy, the prediction of forage intake was greatly improved. However, when the observed forage intake was used and predicted body weight did depend upon the prediction from retained energy, body weight prediction was imprecise and inaccurate. Thus, indicating that the relationship between retained energy and empty body weight gain may not be the same for very lightweight preweaned calves compared to heavier postweaned cattle. The relationship of retained energy and empty body weight gain is dependent upon the composition of gain [10,14,15], which was the reason for multiple equations based on sex and frame size in the 1984 Nutrient Requirements of Beef Cattle [85] and the equivalent empty body weight concept in the 2000 Nutrient Requirements of Beef Cattle [86]. However, these equations were built on data from postweaned cattle. Hildebrand et al. [87] reported that the relationship between retained energy and empty body weight gain was different between pre- and postweaned cattle and between beef and dairy type cattle, likely due to the different relationships of empty body weight gain with protein and fat gain. Hildebrand et al. [87] reported that empty body protein gain had a stronger correlation with empty body weight gain than empty body fat gain in preweaning calves (r = 0.971 vs. 0.839), but empty body protein gain had similar correlation as fat gain with empty body weight gain in postweaning calves (r = 0.805 and 0.807). Additionally, the exponent of the equation relating empty body weight gain with retained energy was significantly greater in preweaned versus postweaned cattle and beef versus dairy cattle (0.718, 1.124, 0.356, and 0.762 for preweaned dairy, preweaned beef, postweaned dairy, and postwean beef cattle, respectively). Adjustment of the nutrition model with the new empty body weight gain equations based on pre- and postweaned dairy or beef cattle greatly improved the prediction of body weight in both the dairy and beef calf intake and body weight datasets, indicating that further evaluation of the relationship between empty body weight gain and retained energy from birth to slaughter may be warranted.

The final adjusted beef calf nutrition model had less precision and accuracy than expected; however, further evaluation indicated that calves born earlier relative to the initial milk and forage intake measurements had greater deviation from model predictions. The reason for this is unclear, but not collecting milk intake measurements near birth could have skewed the prediction of milk intake, leading to an inaccurate prediction of forage intake and body weight. Additionally, calves born in March in the Kansas Flint Hills with warm-season native prairie forages may not consume as much forage in the first couple of months after birth, resulting in overprediction by the model. Baker and Barker [59] reported that forage intake of high nutritive value perennial ryegrass pasture (average in vitro organic matter digestibility = 80.3%) by milk-fed calves was decreased when herbage allowance was less than 40 g/kg LW/day, suggesting that March-born calves in the Kansas Flint Hills may not consume much low-quality forage during the first 2 months of age. Peischel [60] reported a negative regression coefficient between calf age and grazed Kansas Flint Hills native prairie forage intake in July and August for calves born between March 1 and May 1, indicating that older calves consumed less forage. However, even Eq67, which assumes calves consume no forage in the first 2 months after birth, overpredicted forage intake for calves in birth periods 1 and 2. Bottle-fed dairy calves that consume less starter feed early in life do not have the same extent of rumen development and feed digestion capacity as those that consume more starter feed [88–92]. Thus, calves born in early spring may not consume much forage prior to new-growth grass being available, possibly due to the lower nutritive value of hay, and thus may not consume as much forage as expected even at 2 to 3 months of age after lush grass is available. In the dataset from Boggs [29], calves born in April consumed more forage at 60 days of age in June than March-born calves at 60 days of age in May. Thus, further adjustments to the nutrition model may be needed for calf age relative to the availability of lush grass.

Variation among individual animals in diet digestibility exists [93–96]; thus, assuming a constant forage digestibility based on in vitro techniques can result in a significant error (−16 to +25%) in estimating intake [46]. Additionally, the nutrition model which uses the in vitro forage dry matter digestibility assumes that calves can digest forage equally well in the first couple of months after birth compared with 5 to 6 months after birth. Preston et al. [97] reported that milk-fed Holstein calves had similar digestibility of a high-quality forage (average dry matter digestibility = 74.6%) at 3 to 6 weeks of age as the same calves at 7 to 10 weeks of age. McCullough and Sisk [98] reported no difference in alfalfa pellet dry matter digestibility (average = 55%) from 6 to 12 weeks of age in milk-fed calves even though calves younger than 10 weeks of age consumed only small amounts of alfalfa pellets. Godfrey [99] reported that pasture digestibility (average organic matter digestibility = 75.8%) was similar in 5-, 8-, 11-, and 14-week-old milk-fed dairy calves. Additionally, calves fed an all-milk diet until 8 weeks of age achieved rumen digestive function equal to milk-fed calves allowed to graze pasture since 2 weeks of age in approximately 1 week. Broesder et al. [63] reported that younger calves (72 days of age) had greater particulate passage rate and shorter rumen retention times, but greater ruminal forage dry matter digestibility than older calves (108 to 151 days of age) when fed alfalfa hay ad libitum. Similarly, Lamothe et al. [100] reported similar microbial crude protein efficiency in suckling calves from June to September, suggesting that rumen fermentation was equally efficient as in younger suckling calves. Thus, it seems that the capability to digest forage is developed rapidly upon the consumption of forage and that in vitro dry matter digestibility values can be applied to all ages in the nutrition model.

For the dairy calf intake and body weight dataset, Eq91, Eq25, and Eq17 had the greatest precision and accuracy in predicting forage intake and body weight simultaneously in the adjusted nutrition model. This is expected provided that these forage intake equations were developed using this same dataset; however, an adjustment to the empty body weight gain equation for dairy type cattle was necessary to achieve this level of precision and accuracy.

For the beef calf intake and body weight dataset, Eq91 and Eq67 had the best combination of precision and accuracy in predicting forage intake and body weight simultaneously in the adjusted nutrition model. Both equations were developed from bottle fed calves; however, Eq91 was developed from data on Holstein steer calves fed alfalfa hay in confinement, whereas Eq67 was developed with Hereford x Holstein cross steer calves grazing perennial ryegrass pastures through the summer months. The precision of predicting forage intake was lesser with Eq67 than Eq91, but the intercept and the slope for Eq67 were not different than zero and one, respectively, for the prediction of forage intake. Additionally, Eq67 had an intercept not different from zero and a slope near one for the prediction of body weight.

## 5. Conclusions

The original nutrition model was inadequate to predict forage intake and body weight of both milk-fed dairy and suckling beef calves. The direct measurements of milk and forage intakes and milk and forage energy concentrations in the dairy calf intake and body weight dataset provided a more accurate means to evaluate the nutrition model. Dissecting the nutrition model indicated that the original equation relating empty body weight gain with retained energy was inadequate to predict body weight from milk and forage energy intake in dairy type cattle. Incorporating a new empty body weight gain equation into the nutrition model resulted in a highly precise and accurate prediction of body weight, and a highly precise but poorly accurate prediction of forage intake. The forage intake equations with the greatest precision and accuracy in predicting forage intake and body weight simultaneously in the adjusted nutrition model were Eq91, Eq25, and Eq17, which were developed from the same dairy calf intake and body weight dataset.

The beef calf intake and body weight dataset included indirect measurements of milk and forage intakes and forage energy concentration, and the original model assumed a constant milk energy concentration. Dissecting the nutrition model indicated that the prediction of body weight was inadequate, leading to the evaluation of milk and forage energy concentrations and the relationship between empty body weight gain and retained energy in preweaned beef calves. The evaluation of the relationship between in vitro and in vivo forage dry matter digestibility indicated inadequate prediction by previously published equations, prompting the development of a new equation. Milk composition is known to vary with milk yield and the stage of lactation in dairy cattle, leading to an analysis of milk composition in beef cows that resulted in a new equation to predict milk energy concentration throughout lactation. Like the dairy calf nutrition model, the original equation relating empty body weight gain with retained energy was inadequate to predict body weight from milk and forage energy intakes in preweaned beef calves. Incorporating the new estimates of forage digestibility, milk energy concentration, and the empty body weight gain equation into the nutrition model resulted in improved precision and accuracy of the prediction of forage intake and body weight of beef calves. The forage intake equations with the greatest precision and accuracy in predicting forage intake and body weight simultaneously in the adjusted nutrition model were Eq91 and Eq67.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ruminants4010004/s1, Table S1: Sum of the absolute difference between observed and predicted milk yield between milk yield equations at different peak milk yield groups in the dairy calf dataset; Table S2: Descriptive statistics of the dairy cattle serial slaughter dataset used to evaluate the empty body weight gain Equation (8a) and develop a new equation; Table S3: Evaluation of the empty body weight gain Equation (8a) in the dairy cattle serial slaughter dataset; Table S4: Significance of model coefficients and fit statistics for equations developed to predict empty body weight gain in the dairy cattle serial slaughter dataset; Table S5: Cross-validation of the final mixed effect equation (EBG = a $\times$ $RE^b$ $\times$ $EBW^c$) to predict empty body weight gain in the dairy cattle serial slaughter dataset; Table S6: Descriptive statistics of the forage in vitro/in vivo digestibility dataset used to develop and evaluate forage digestibility equation; Table S7: Evaluation of in vitro versus in vivo digestibility in the forage digestibility dataset; Table S8: Evaluation of dry versus organic matter digestibility in the forage digestibility dataset; Table S9: Published equations evaluated to predict in vivo dry matter digestibility from in vitro dry matter digestibility in the forage digestibility dataset; Table S10: Evaluation of published equations to predict in vivo DMD from in vitro DMD in the forage digestibility dataset; Table S11: Cross-validation of the final equation (OMD = a + b $\times$ IVDMD) to predict in vivo organic matter digestibility in the forage digestibility dataset; Table S12: Descriptive statistics of the milk composition dataset used to develop milk energy equation; Table S13: Regression coefficients ($\pm$SE), least square means, and fit statistics for mixed model equations developed to predict milk composition in beef cows; Table S14: Cross-validation of the final mixed effect models to predict milk composition in beef cows; Table S15: Descriptive statistics of the beef cattle serial slaughter dataset used to evaluate the empty body weight gain Equation (8a) and develop a new equation; Table S16: Evaluation of the empty body weight gain Equation (8a) in the beef cattle serial slaughter dataset; Table S17: Fit statistics for equations developed to predict empty body weight gain (kg/d) in beef cattle serial slaughter dataset; Table S18: Cross-validation of the final mixed effect equation (EBG = a $\times$ $(RE/EBW^{0.75})^b$) to predict empty body weight gain in the beef cattle serial slaughter dataset.

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