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# Noseband sensor validation and behavioural indicators for assessing beef cattle grazing on extensive pastures☆

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ABSTRACT

Advances in on-animal sensor technologies to monitor location and activity have enhanced the ability to study foraging decisions of free-ranging herbivores. Sensors monitoring jaw movements that quantify ingestive behaviours, such as the RumiWatch (RW) noseband sensor system, have primarily been used in indoor animal housing systems or structurally homogeneous, small pasture (paddock) environments. Continuously monitoring these ingestive behaviours in extensive and heterogeneous rangelands has not been previously conducted. We evaluated the accuracy of the RW noseband sensor system for two grazing seasons in 130-ha pastures (paddocks) composed of native, mixed-species plant communities in a semiarid environment. The noseband sensor was used to compare ingestive behavior at different sites and seasons characterized by varying sward complexity, stocking rate, and levels of forage limitation. We evaluated the noseband sensor against direct visual observations of yearling steers grazing with two different validation studies. First, the time duration of grazing recorded by the sensor was compared to direct visual observation data (Validation Study 1). A high correlation ($r_s = 0.95$) for hourly grazing time resulted between the RW system and visual observations. Second, we examined the ability of the RW system to measure prehension bite rates in distinct plant communities varying in height and leaf angle (Validation Study 2). The accordance between direct observation and measurement by the RW system for bite rate improved from 2019 (Concordance Correlation Coefficient (CCC) = 0.71) to 2020 (CCC = 0.80) after modifications to improve the fit of the halter supporting the noseband sensor. Correlations between the sensor and visual observations increased by ~17 % with this modification for grazing bouts in mixed-species and midgrass-dominated swards; correlations remained ~10 % lower in shortgrass-dominated swards. Our results show that the RW system is an effective tool for monitoring free-ranging cattle grazing activity and quantifying bite rates in a heterogeneous rangeland ecosystem. Bite rate measurements are more accurate in swards with vertically oriented stems and leaves compared to lawn-like prostrate swards. Grazing bout length and rumination chew rate may represent behavioral indicators employed in managing animal performance in semiarid rangelands. Our validation study and experimental investigation indicate that the RW noseband sensor is a useful animal-borne sensor technology for research demanding sustained ingestion measurements across mixed-species forage communities.

## 1. Introduction

Advances in using animal-borne sensors to measure domestic and wild herbivore behaviour have revolutionized the study of ungulate foraging behaviour. However, most studies employing these technologies to study the foraging behaviour of free-ranging herbivores are

*Abbreviations:* CCC, concordance correlation coefficient; CI, confidence interval; GPS, global positioning system.

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limited by the inability to distinguish the rate at which herbivores access forage, and instead focus on binary determinations of grazing (yes/no) and grazing duration. For instance, global positioning system (GPS) collars configured with activity sensors permit the separation of foraging locations and locations devoted to other activities such as bedding or traveling (Ganskopp and Bohnert, 2009; Augustine and Derner, 2013; Bailey et al., 2018). Although grazing time can be derived by summing the sensor's recorded time spent with an animal's head in a downward position (Ungar et al., 2005), the rate at which animals ingest plant material is not available. An initial step to accurately measure intake rate, which is the product of bite mass and bite rate, is to measure the number of prehension bites taken in a given amount of time. Advances are needed to monitor the rate that such bites accumulate in space and time. Similarly, an improved understanding of how herbivores shape vegetation dynamics, ecosystem processes, and patterns often entails knowledge of forage utilization within an area across time, rather than merely the number of herbivores and their distribution.

The development of animal-borne sensors to discriminate ingestive behaviours has long been a goal of animal scientists (Duckworth and Shirlaw, 1955; Chambers et al., 1981; Ungar and Rutter, 2006). Knowledge of such behaviours provides insight into the relationship between the internal state of a ruminant (e.g., nutritional requirements or fertility; Simpson et al., 1997) and their environment (e.g., forage offer, sward state, or climate; Rutter, 2004; Simpson et al., 2010; Carvalho, 2013). Continuous monitoring of jaw movements, for example, can provide information on circadian grazing patterns (Linnane et al., 2001; Gregorini et al., 2006), animal health disorders (Gonzalez et al., 2008), and forage deficiencies (Werner et al., 2019). This list highlights the utility of continuous monitoring for quantifying physiological and behavioural activities that previously incurred substantial labor and time for observations.

Efforts to continuously monitor ingestive behaviour have improved since the IGER Behavior Recorder (IBR) system, which measured jaw movement by electrical resistance for a maximum period of 24 h (Rutter et al., 1997; Ungar and Rutter, 2006). Along with the limited data recording timespan, this tool required analysis via the "GRAZE" software, which proved to be arduous (Rutter, 2000). New technologies, including the RumiWatch (RW) noseband sensor system, which can be deployed for multiple days and provides almost immediate results through validated analysis software, may potentially improve instantaneous and longer-term behavioural data capture (Nydegger et al., 2010).

Evaluations of the RW noseband sensor system (hereafter RW system) have centered on dairy cows in indoor animal housing systems (Zehner et al., 2012; Pahl et al., 2016; Ruuska et al., 2016) and in very small (~0.15 ha in size) pastures (paddocks) with homogenous sward architecture (~0.15 ha in size; Werner et al., 2018, 2019). Since its inception, the RW system has undergone several modifications to refine the algorithms used by the RW Converter to analyze the raw signal (Zehner et al., 2012). Validation of different software versions occurred against direct visual observations in indoor animal housing systems (Zehner et al., 2017) and improved pastures (Werner et al., 2018). However, the applicability of the RW system for free-ranging livestock in extensive landscapes remains unclear. For example, forage architecture (Soder et al., 2009), which varies vertically and horizontally in mixed-species rangeland environments, may affect the RW system's accuracy. Therefore, rigorous measures are needed to quantify how foraging behavior varies in relation to plant phenology, plant community composition, and architecture, and cattle management strategies (e.g., varying stocking rates).

Our objectives were to (1) conduct a validation study for free-ranging beef steers in heterogenous swards and (2) evaluate the degree to which foraging behavior quantified by the RW system varies with plant phenology, community composition, and cattle stocking rate. Specifically, we assessed the ability of the RW system to quantify 1) the time an animal spent grazing and 2) the number of prehension bites taken during grazing bouts in structurally heterogenous swards in a semi-arid rangeland ecosystem. Our investigation did not intend to examine correspondence in timing and behavioural classification at the individual jaw movement event level. Instead, validation analyses occurred at higher-level aggregations of jaw movements occurring at the spatiotemporal scale of several sequential feeding stations (fine-scale: 10 min sum of 1 min records) and at a coarser scale of hourly records (Senft et al., 1987). We then report on the degree to which ingestive behaviors quantified by the RW system at a scale of days to weeks vary in relation to forage conditions and stocking rate during years with near-average and below-average forage production.

## 2. Methods

This research follows the Institutional Animal Care and Use Committee (IACUC) protocol (#CPER-4) approved March 2019 by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS), Fort Collins, Colorado, United States.

### 2.1. Site and study design

We studied yearling beef steers grazing 130-ha pastures containing mixed-species swards at the Central Plains Experimental Range (40°50′N, 104°43′W). Mean annual precipitation is 340 mm and mean growing season (April - August) precipitation is 241 mm. Topography consists of slightly undulating plains. Study pastures were dominated either by the Loamy Plains (Ecological Site ID: R067BY002CO, see https://esis.sc.egov.usda.gov/) or Sandy Plains (ID: R067BY024CO) ecological site (USDA, 2007a;2007b). Ecological sites are distinct types of land with specific soil and physical composition unique in their ability to produce distinct types and amounts of vegetation with an inherent ability to respond similarly to natural disturbances and management actions (NRC, 1994). On the Loamy Plains ecological site, $C_4$ shortgrasses blue grama (*Bouteloua gracilis* (Willd. Ex Kunth) Lag. ex Steud) and buffalograss (*B. dactyloides* (Nutt.) J. T. Columbus) are dominant species, $C_3$ mid-height grasses are subdominant species and scarlet globemallow (*Sphaeralcea coccinia* (Nutt) Rydb.) is the most abundant forb. Mean annual aboveground herbaceous production (ANHP) is 798 $kg{\cdot}ha^{-1}$ for 2013−2020. On the Sandy Plains ecological site, the $C_3$ mid-height grasses (hereafter, midgrass) western wheatgrass (*Pascopyrum smithii*) and needle-and-thread (*Hesperostipa comata*) dominate the plant community with blue grama subdominant, and a sparse shrub layer of fourwing saltbush (*Atriplex canescens*) is present (USDA, 2007b). Mean ANHP is 1086 $kg{\bullet}ha^{-1}$ for 2013−2020.

### 2.2. Animals and treatments

RW system deployments and associated direct visual observations took place in June to August and September 2019 and June to July and August to September 2020 (Table 1), with different yearling steers studied each year. Steers were crossbred, British-breed *Bos taurus*. All steers were identifiable by numbered ear tags. Over each grazing season, steers increased in live weight from approximately 275 kg–415 kg. Study animals were weighed at the beginning of each deployment and then reweighed within 28 days.

We randomly chose four steers from a herd of 24–28 yearlings in each 130-ha pasture (see details below) to be fitted with RW systems (Table 1). Each deployment extended over three weeks with an adjustment period to the RW system of one day before the start of direct visual observations. To acclimate steers to human observers before RW system deployments, we walked with the herds during morning grazing sessions for one week before each deployment. Additionally, observers wore identical clothes that differentiated them from site managers (Bonnet et al., 2015). A water tank was provided in each 130-ha pasture.

**Table 1**
Experimental design, annual aboveground net herbaceous production (ANHP), perennial $C_3$ midgrass and $C_4$ shortgrass percentage of total ANHP, stocking information, and Validation Study sample size for 2019-2020 at the USDA ARS Central Plains Experimental Range, near Nunn, Colorado.

| Year | Deployment | Dates | Ecological site (Pasture) | ANHP (kg ha$^{-1}$) | $C_3$ grass (%) | *Bouteloua sp.* (%) | Stocking rate (AUD ha$^{-1}$) | # of steer | # of focal steer | Study 1 - hourly | Study 2 - grazing bouts |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2019 | Early | 6/14–8/7 | Loamy Plains (15E) | 1370 | 12 | 31 | 18.77 | 23 | 4 | – | 96 |
| | Late | 9/6–9/26 | | | | | 18.77 | 23 | 3 | – | 15 |
| | Early | 6/14–8/7 | Sandy Plains (19 N) | 1733 | 19 | 6 | 22.05 | 26 | 4 | – | 91 |
| | Late | 9/6–9/26 | | | | | 22.05 | 26 | 2 | – | 13 |
| | Late | 9/6–9/26 | Loamy Plains (23E) | 1171 | 21 | 65 | 31.09 | 34 | 3 | – | 31 |
| 2020 | Early | 6/11–7/8 | Loamy Plains (15E) | 354 | 25 | 57 | 20.62 | 24 | 3 | 23 | 134 |
| | Late | 8/20–9/16 | | | | | 20.62 | 24 | 2 | – | 116 |
| | Early | 6/11–7/8 | Sandy Plains (19 N) | 437 | 58 | 18 | 21.43 | 24 | 2 | 13 | 62 |
| | Late | 8/20–9/16 | | | | | 21.43 | 24 | 2 | – | 6 |

### 2.3. Sensor technology

The RW system is associated with software packages for managing the sensor (RW Manager) and analyzing raw data (RW Converter). A halter that fits the individual animal's head incorporates the RW sensors, consisting of a noseband pressure sensor, a three-axis accelerometer to detect three-dimensional head movements, and a data logger. The noseband pressure sensor connects to a tube filled with propylene glycol to detect jaw movements and lays in a belt on the animal's nose bridge—the pressure inside the tube changes due to jaw movement, which records in 10 Hz resolution. Raw data is stored on an integrated 4 GB SD card. A protective box that holds the data logger is located on the halter's right side, while on the left side, a similar protective box contains a two 3.6 V battery power supply. Battery life spanned approximately 100 days of raw data logging. Varying pressure signatures of jaw movements are recorded via the noseband pressure sensor and later identified and classified into prehension bites, mastication chews, and rumination chews using the RW Converter (Nydegger et al., 2010). Additional technical aspects of the noseband pressure sensor are found in Zehner et al. (2017) and Werner et al. (2018).

Study steers were fit with RW systems (Itin + Hoch GmbH, Liestal, Switzerland; www.rumiwatch.ch) that weighed 0.91 kg. Nylon halters, which supported the noseband sensor, included a buckle that allowed rapid placement around the nose and neck of steers when restrained in a chute. We replaced the nylon neck strap with a "break-a-way" leather strap and buckle in case an individual animal was caught in fencing to meet animal safety protocol. Once the halter was on the steer, we examined the fit around the nose and neck, and adjusted the length of the halter to ensure 3–5 cm of movement space between the animal's nose bridge and the inside of the noseband sensor (Fig. S1). This distance between the nose bridge and sensor aims to ensure the best possible detection of jaw movements by the pressure sensor (Rombach et al., 2018). After the animal returned to a pasture, observers noted whether the noseband sensor was appropriately affixed to a focal animal's nose bridge. If misplaced, we did not conduct observations until sensor placement was refit.

We used the RW Manager 2 (V.2.1.0.0) and the RW Converter (V.0.7.3.36) to manage and translate raw data provided by the RW noseband system. The Converter provided two different analysis approaches for time resolutions. First, the Converter categorized 1-min summary data into different focal behaviour classifications. In addition, the Converter also created numerical values based on a calculation of the time spent (min per period of interest) in each behavioural classification in each of the selected time resolutions, i.e., 1-min, 1-h summaries. Resultant summary data are the product of the RW Converter (V.0.7.3.36) applied to 1-min (600 measurements per min or ten measurements per sec, i.e., 10 Hz resolution) or 1-hr (36,000 measurements) intervals of raw data (10 Hz resolution).

The RW Converter (V.0.7.3.36) used three parameters to monitor and compute grazing time, and two output variables to describe grazing time. EAT1TIME represents the estimated amount of time grazing with head position down, and EAT2TIME represents estimated time grazing with head position up, measured via the three-axis accelerometer housed within the halter. Furthermore, output from the RW Converter includes the estimated number of grazing bouts per time period of interest. The start of a grazing bout start was defined as a switch from non-grazing behavior to at least seven continuous min of grazing, and the end of a grazing bout as a switch to at least seven consecutive min of non-grazing behaviour (Perez-Ramirez et al., 2009; Wolfger et al., 2015).

### 2.4. Validation Study 1: hourly grazing time

In 2020, we conducted hourly grazing time validation measurements in a single deployment in two 130-ha pastures moderately stocked at ~21 Animal Unit Days (AUD) ha$^{-1}$ (Table 1). One pasture contained the Loamy Plains ecological site, whereas the other contained the Sandy Plains ecological site (USDA-NRCS, 2007a,2007b); neither pasture contained more than one ecological site. We collected behavioural data by direct visual observation with previously trained observers monitoring steer behaviours from distances of ~25 m in each study pasture. We conducted visual observations on one or two individual steers in each pasture during daylight hours (0600–1400) of ten observation days. Observations spanned morning hours until early afternoon to encompass grazing, resting and/or bedding bouts within a given day and lasted an average of 4.2 h d$^{-1}$.

For Validation Study 1, direct visual observations followed the method of Ganskopp and Bohnert (2009). Observers used a hand-held GPS device to record time to ensure synchrony with the RW system clock. Before activating the RW system, we synchronized both the computer used to activate the halter and the GPS device time stamps. Activity was classified as grazing (including grazing while walking if the head position down and the animal was consuming forage), traveling (walking without head down and grazing), standing in place (head-up chewing or loitering), bedding, grooming, drinking or licking a salt block. We recorded activity every 30-sec. When an animal switched from one activity to another, observers mentally noted the particular transition time. We recorded the transition if the new activity persisted for more than 15-sec within a given 30-sec interval. If the animal resumed its prior action in less than 15-sec, then we ignored the switch in activity. We logged data on a manual spreadsheet in the field.

Using this method, we conducted direct observations on five different steers with RW systems for a total of 36 complete hour-long periods (2160 min) in 2020 (Table 1). The RW Converter (V.0.7.36 [FW00.56]) processed the raw data into summaries of grazing activity over 1-min and 1-h intervals. We, therefore, summarized direct visual observations in terms of (1) grazing versus not grazing at 1-min intervals (where a 1-min interval in which one 30-sec interval was recorded as grazing and one as not grazing was classified as a grazing interval), and (2) the time duration of different activities occurring within each 1-h interval, and (3) the number of times a grazing bout started and stopped for each 1-h period. The Converter's calculation of grazing time (GRAZINGTIME) is the sum of the duration of EAT1TIME (grazing while head position down) and EAT2TIME (feeding with head position up). The choice of a 1-h interval resolution in this experiment reflects a 1) standard time period of investigation for noseband validation studies in dairy settings (Werner et al., 2018, 2019; Steinmetz et al., 2020) and an interval aligned with collective behaviors enacted at the level of the plant community-soil plant association (Senft et al., 1987).

### 2.5. Validation Study 2: bite rate

This study examined the RW system's accuracy in measuring the number of prehension bites taken by yearling beef steers at 1-min resolution. This fine temporal resolution is 1) commonly evaluated in similar validation studies in dairy or improved pasture settings (Rombach et al., 2018; Werner et al., 2018; Steinmetz et al., 2020) and 2) approximates feeding station-level ingestive behavior (Senft et al., 1987). Due to difficulty in visually classifying pure bites, chews, and chew-bites at all times during a direct observation of a focal animal, we focus this evaluation on prehension bites (pure bites) – the act of grasping and severing food items. A prehension bite is defined as a combination of jaw, tongue, and neck movement to remove plant tissue accompanied by a biting sound (Bailey et al., 1996). In both 2019 and 2020, two previously trained observers conducted direct visual observations of grazing bouts of haltered steers for four days of each week of deployment. Observers monitored an individual steer for 10-min periods to record the number of prehension bites taken. During each 10-min observation, observers recorded the number of bites taken in each of five consecutive 2-min periods. We summed values from the 2-min periods to evaluate total prehension bites 10 $min^{-1}$. These observation bouts occurred between 05:00 and 21:00 h. On any given day, we observed each of the four steers wearing a RW system in each of the study pastures for at least three different 10-min observation bouts (12 total observation bouts per herd per day), with observers standing $\leq 2.5$ m from focal animal and taking a 90-sec break between bouts.

Following Bonnet et al. (2015), we developed a coding grid using site-level botanical knowledge and preliminary foraging behavior observations to denote sward identity and height variation. We assigned a height class to each prehension bite taken along 10-min grazing bout paths for each of the six plant functional groups: forbs, shortgrass, western wheatgrass (*Pascopyrum smithii*), mid-grasses other than western wheatgrass, sub-shrubs, and shrubs. Each plant functional group represents a type of plant architecture that entails different prehension tactics by grazers. Height classes for each plant functional group consisted of 2–5, 5–8, 8–12, 12–20, and >20 cm without including plant inflorescence. We recorded prehension bite numbers separately for each height class and plant functional group combination during the bout. Within grazing bouts, for instance, steers sometimes grazed both shortgrass and midgrass interspersed among shortgrass swards; therefore, we recorded the number of prehension bites of each plant functional group and their accompanying height. Sward-type of an observation bout was assigned when > 50 % of prehension bites were taken from a single plant functional group. Otherwise, a sward received a "mixed" designation in our analysis.

In total, we conducted 614, 10-min observation bouts over two grazing seasons. For analyses, we excluded bouts where two different behaviour types (grazing bites with head down and rumination chews with head up) occurred within one 10-min period and excluded bouts where no grazing bites occurred, resulting in 564, 10-min grazing bouts for analyses. We summarized raw data logged at 1-min intervals using the RW Converter (V.0.7.3.36). Then, we summed prehension bites 1-$min^{-1}$ interval into 10-min intervals that aligned with visual observation periods. As in Validation Study 1, the RW system timestamp and observer timepiece synchronization occurred before RW system deployment.

### 2.6. Spatiotemporal variation in grazing behaviors

To illustrate how forage productivity and phenology varied within and among our study pastures, we calculated normalized difference vegetation index (NDVI) time series for each study year and pasture. We used the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM; Gao et al., 2006) to combine satellite imagery from the Landsat sensor (16-day repeat cycle, 30 m spatial resolution) and MODIS Terra and Aqua sensors (combined 1-day repeat cycle, 250 m spatial resolution) to obtain daily NDVI observations at a 30-m spatial resolution (Gaffney et al., 2018). We then calculated daily mean NDVI at the pasture scale. To depict the performance of study animals during each deployment, we present the associated average daily gain (ADG) determined from 28-day weight measurements and grazing season weight gain.

#### 2.6.1. Seasonal and yearly behavioural variation in two contrasting ecological sites

To provide insight into variation in ingestive behavior by yearling steers in rangeland environments, we contrasted behavioral results derived from the RW system for steers exposed to varying swards, forage conditions and stocking rates. We evaluated ingestive and rumination metrics at three temporal scales: an entire 24-h day, within daylight hours only, and within nighttime hours only, where daylight hours were defined as the time between sunrise and sunset. For ingestive behavior, we examined time spent grazing per day, prehension bite rate, and mean daily grazing bout length. For rumination, we examined ruminate chew rate, rumination chews per bolus, mean daily rumination bout length, and time spent ruminating per day. We compared these metrics between a pasture containing the Loamy Plains ecological site and one containing the Sandy Plains ecological site during a year of average forage production (2019) and below-average forage production (2020). In each year and ecological site, we additionally compared ingestive and rumination behavior early in the growing season, when vegetation was near peak biomass, versus late in the growing season, when vegetation biomass was low and senescing (as quantified by the NDVI curve for each year). A nearby weather station at Nunn, Colorado, provided daily sunrise and sunset times.

#### 2.6.2. Grazing beaviour with moderate vs. heavy stocking

To assess potential effects of stocking rate on foraging behavior, we deployed the RW system in a moderately stocked pasture and a paired heavily stocked pasture, both of which contain the Loamy Plains ecological site. Both of these pastures are part of a long-term stocking rate study, where each have been consistently managed at a moderate versus a heavy stocking rate annually since 1939 (see Porensky et al., 2017 for details). We only conducted this comparison late in the 2019 growing season when forage was senescing, and cattle were likely limited by forage quantity. Similar to the ecological site comparison

(Loamy Plains vs. Sandy Plains) under moderate stocking, we evaluated behaviours at the 24-h day scale, daytime only, and nighttime only.

### 2.7. Statistical analysis

We performed statistical analysis using R version 4.0.1 (R Development Core Team, 2020). We carried out the following analyses to evaluate the agreement between the RW system and visual observations, contingent on the type and temporal resolution of data analyzed by the RW Converter.

#### 2.7.1. Validation study 1 and 2

In Validation Study 1, we computed Cohen's Kappa (K) to evaluate the agreement between the RW system and visual observations at a 1-min resolution for grazing activity (Cohen, 1960). If we observed grazing for at least 30 s within a given minute, the minute was classified as grazing to align with the 1-min summaries generated by the Converter. We computed K-values using the R package *irr* (Gamer et al., 2019) which we interpreted as follows– poor: $K < 0.00$, slight: $K = 0.00-0.20$, fair: $K = 0.21 - 0.40$, moderate: $K = 0.41 - 0.60$, substantial: $K = 0.61 - 0.80$, and almost perfect: $K = 0.81–1.00$ (Landis and Koch, 1977). Following Martin and Bateson (2007), we computed the percentage of agreement (PA) of the 1-min resolution data for grazing and non-grazing behaviour as:

$$PA\% = \frac{total\ numbers\ of\ agreement}{total\ numbers\ of\ agreement + total\ numbers\ of\ disagreement} \text{ x } 100$$

We assessed grazing time $h^{-1}$ and prehension bites 10 $min^{-1}$ to gauge agreement between the RW system and visual observations. We subjected the continuous behavioural data from the sensor system and visual observations to three measures of agreement. First, the Spearman's rank correlation coefficient ($r_s$) was calculated with base R function *cor* for measured and observed pairs of observations as data followed a non-normal distribution. Second, a concordance correlation coefficient (CCC) was calculated with R package *DescTools* (Signorell et al., 2016), using U-statistics for non-normality (Carrasco et al., 2007). CCC provides a reliability measure between two observers of the Euclidean distance from the concordance line (Lin, 1989). The strength of correlation for $r_s$-values and CCC were based on criteria established by Hinkle et al. (2003) as follows: negligible = 0.00−0.30, low = 0.31 – 0.50, moderate = 0.51−0.70, high = 0.71 – 0.90, and very high = 0.91 – 1.00. Last, we performed a graphical analysis in a Bland-Altman-Plot and Bland-Altman-Analysis for limits of agreement statistics using R package *blandr* (Datta, 2017).

Bland-Altman-Plots demonstrated the agreement between the RW system and visual observations conducted by plotting the differences (automated measurement – visual observation) against the means of automated measurement and visual observation. A measure of bias (mean differences) between the paired, automatically recorded and visually observed values, along with 95 % confidence intervals (CI), were provided by Bland-Altman analysis (Bland and Altman, 1986; Giavarina, 2015). In addition, this analysis offers limits of agreement, as calculated as ± 1.96 *x* standard deviation from mean difference, which represent prediction limits for the difference between pairs of future measurements (Carstensen et al., 2008). We considered bias (or mean difference) as significant when the line of equality was outside of the 95 % CI of the mean difference. Considerable under- or over-estimation of measurement occurred when the line of equality was not within the 95 % CI of the mean difference. We computed corrected values for bias difference for time spent grazing $h^{-1}$ in Validation Study 1 and grazing bites 10-$min^{-1}$ in Validation Study 2 with approximated 95 % CI using the Delta method following Oehlert (1992).

For the number of grazing bouts that started or ceased within each 1-h period (Validation Study 1), values varied between 0 and 2; hence data were treated as an ordinal variable. We examined agreement for grazing bouts using Cohen's Kappa statistics and percentage agreement. For the number of bites per 10-min period (Validation Study 2), we assessed agreement for counts between the RW system and observers using Spearman's Rank Correlation, CCC, and Bland-Altman analysis.

#### 2.7.2. Spatiotemporal variation in grazing behaviours

Seasonal and yearly variation in two contrasting ecological sites was evaluated by comparing ingestive and rumination behavior enacted in moderately stocked pastures containing contrasting ecological sites, Loamy Plains vs. Sandy Plains. Using a linear mixed effect model with yearling steer identity as a random intercept, we evaluated whether behaviour differed by year, seasonal deployment, and ecological sites for each time period of interest. We used the 'lmer' function from R package '*lme4*' in this analysis (Bates et al., 2015).

We compared behavior between moderately and heavily stocked pastures containing the same ecological site, Loamy Plains, to evaluate the effect of stocking rate on ingestive and rumination behavior. We used base R function '*aov*' to conduct an analysis of variance (ANOVA) on the same behaviour variables in our Loamy Plains vs. Sandy Plains ecological site comparison for assessing the effect of stocking rate on behavioral variation. Before analyses, grazing time and prehension bite rates were not corrected for bias, as validation data was not available for each deployment and ecological site. We report exact *P* values to allow readers to distinguish between significant effects ($P < 0.05$) and marginally significant effects that may still warrant attention ($0.05 < P < 0.15$).

## 3. Results

### 3.1. Validation Study 1: hourly grazing time

Categorical data for grazing vs. non-grazing behaviour at a 1-min resolution demonstrated substantial agreement between visual observations and the RW system. The Cohen's Kappa value was $K = 0.79$ and 0.77 for the grazing and non-grazing activity measurements, respectively. The percentage of agreement was between 88.4 % and 89.6 % for these activity measurements.

For analyses of time spent grazing at a 1-h temporal resolution, we found that RW system slightly overestimated grazing minutes $hr^{-1}$ (as measured by the GRAZINGTIME parameter calculated by the RW Converter software; Fig. 1). The Spearman's Rank Correlation ($r_s = 0.95$) and a concordance correlation coefficient (CCC = 0.93) classify as very high for determining grazing minutes $hr^{-1}$ (Table S1). According to Bland-Altman statistics, the mean difference between visual observations and the RW system was 4.2 min $hr^{-1}$ (solid line in Fig. S2). In contrast to the results based on the Converter's GRAZINGTIME output (i.e., the sum of EAT1TIME and EAT2TIME), the EAT1TIME metric (which estimates time spent grazing with head position down) showed a higher

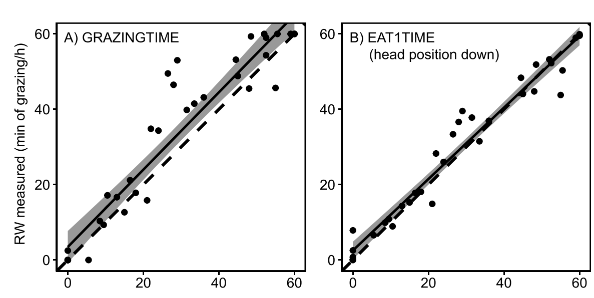


**Fig. 1.** Scatter plot of RW-estimated versus "true" (observed) grazing time (A) and eating time (B). Spearman's rank correlations (±SE) of RW system measurements and visual observations of feeding behaviour in 1-h periods for RW Converter (V.0.7.3.36) parameter A) GRAZINGTIME and B) EAT1TIME (head position down) are also depicted. Dashed line denotes perfect 1:1 relationship.

correlation with visual observations, and less bias than the GRAZINGTIME metric. The percentage of agreement for number of grazing bout starts and ends within 1-h periods was 94.4 % and 86.1 %, respectively. Cohen's Kappa values showed near perfect agreement for grazing bouts started (K = 0.89) and substantial agreement for grazing bouts finished (K = 0.70) between visual observations and the RW system measurements.

Spearman's Rank Correlation and CCC were 7 and 5% lower, respectively, for time spent grazing per hour in the Loamy Plains pasture, which is dominated by $C_4$ shortgrasses, compared to the Sandy Plains pasture dominated by midgrasses (Table S1). Grazing minutes $hr^{-1}$ were overestimated by 4.8 min with the RW system in the shortgrass-dominated pasture (i.e., Loamy Plains ecological site). In contrast, grazing minutes $hr^{-1}$ were neither overestimated nor underestimated with the RW system in the midgrass-dominated sward (i.e., Sandy Plains ecological site). Bias-correction resulted in a daily grazing time increase of approximately 30 min (Table S2). In midgrass-dominated pasture (Sandy Plains) correction increased daily grazing time by approximately a half-hour, while correction in shortgrass-dominated pasture (Loamy Plains) resulted in three-fourths of an hour increase in daily grazing time.

### 3.2. Validation Study 2: bite rate

#### 3.2.1. Overall

Across all deployments and pastures (n = 564), visually observed prehension bite rates ranged from 17 to 733 10-$min^{-1}$, with a median of 252 bites 10-$min^{-1}$. The RW Converter's estimates of prehension bite rate ranged from 1 to 833 10-$min^{-1}$, with a median of 286 bites 10-$min^{-1}$. Overall, agreement of prehension bite estimates between visual and automated counts was high, with $r_s = 0.80$ and CCC = 0.75. The Bland-Altman statistics for all 564, 10-min observation periods showed that the RW Converter slightly overestimated bite rate (Table S3). A bias of 28 prehension bites 10-$min^{-1}$, with a lower 95 % limit of agreement of -203 bites 10-$min^{-1}$ and an upper 95 % limit of 259 bites 10-$min^{-1}$, confirmed this overestimation.

To evaluate the degree to which the agreement between prehension bite rate estimates by the RW system versus visual counts varied among plant swards of varying architectural complexity, we assessed the agreement for four types of plant functional group swards (Fig. S3a-d). Forb, midgrass, and shortgrass swards comprised observation bouts where greater than 50 % of prehension bites originated from the respective sward types. We also evaluated agreement for steers prehending mixed swards, where no one functional group comprised >50 % of bites observed. The lowest bias in agreement occurred when steers were grazing swards not dominated by a single functional group, i.e., mixed swards. In these mixed swards (n = 299 observations), we found a bias of 22 bites 10-$min^{-1}$, with lower and upper 95 % limits of agreement of -196 and 239 bites 10-$min^{-1}$ (Fig. S4a). The second-most common sward consumed by steers was that dominated by shortgrass (n = 133 observations). Within these short-statured, lawn-like swards (Fig. S4b), we found a bias of 38 bites 10-$min^{-1}$, with lower and upper 95 % limits of agreement of -252 and 327 bites 10-$min^{-1}$, indicating slight overestimation of shortgrass prehension bite rate by the RW system. We note that in Fig. S4a-b, the largest errors occurred when steers were taking many bites on a homogenous patch of short, prostrate leaves. In swards dominated by midgrass (n = 90 observations; Fig. S4c), we found a bias of 33 bites 10-$min^{-1}$, with lower and upper 95 % limits of agreement of -134 and 200 bites 10-$min^{-1}$, again indicating slight overestimation of prehension bite rate by the RW system in this sward type (Table S3). In total, we observed 41 grazing bouts dominated by prehension bites of forbs (Fig. S4d). A bias of 40 bites 10-$min^{-1}$, with lower and upper 95 % limits of agreement of -182 and 262 bites 10-$min^{-1}$ (Table S3), confirmed slight overestimation of bites observed in forb-dominated swards. Correlation between the RW system algorithm and visual counts (Fig. S5a-d), as denoted by both Spearman's Rank Correlation and CCC, was moderate for forb and shortgrass swards (correlation <0.70) and high for midgrass and mixed swards (correlation > 0.70; Table S3).

#### 3.2.2. Yearly

In 2020, we replaced the non-adjustable cheek strap with an adjustable nylon one to improve fit of the RW system above the nose bridge. To assess potential improvement in prehension bite detection, we examined the agreement between automated measurements from the RW system and visual observations for steers grazing each sward type for which we conducted observations in both 2019 and 2020. We could not compare prehension bite rates in forb-dominated swards because forbs were rare in 2020. Correlation between the RW system and visually observed prehension bite rates per 10-min period across the remaining sward types increased from 2019 to 2020 (Fig. 2), with $r_s$ increasing by 3.8 % and CCC by 12.7 % (Table 2). The CCC for mixed species and midgrass swards increased between 2019 and 2020 by 25.8 % and 19.7 %, respectively. In contrast, we did not find an increase in the CCC value from 2019 to 2020 in shortgrass-dominated swards, and correlation decreased slightly by 1.6 % (Table S4).

The Bland-Altman plot showed overall bias (or mean difference) decreased by 85 % from 55 (2019) to 8 (2020) bites 10-$min^{-1}$ (Fig. S6a, b; Table 2). Unlike 2019, where the line of equality was not within the 95 % CI, the bias of eight grazing bites 10-$min^{-1}$ (95 % CI of -2 to 18) demonstrated a much closer agreement in 2020 between the RW system and visual observations. Bias (or mean difference) also declined between 2019 and 2020 in each sward type studied. Bias for mixed-species and midgrass swards decreased by 44.6 % (Fig. S6c,d) and 8.7 % (Fig. S6g, h), respectively. In addition, bias of 12 bites 10-$min^{-1}$ along with the 95 % CI of -1 and 25 for mixed swards in 2020 indicates an almost perfect agreement (Table 2). In contrast, Bland-Altman statistics for shortgrass demonstrates significant overestimation by the RW system for prehension bite rate in 2019, and underestimation in 2020 (Fig. S6e, f). Comparison of absolute values for bias in 2019 and 2020 for shortgrass swards showed a 25.8 % reduction in bias for bites 10-$min^{-1}$ in shortgrass. The median deployment length with the RW system appropriately fitted on the nose bridge was 13 days (range: 5–27) in 2019 and 19 days (range: 3–28) in 2020.

### 3.3. Spatiotemporal variation in grazing behaviours

#### 3.3.1. Seasonal and yearly variation in two contrasting ecological sites

As depicted in NDVI times series (Fig. 3a), plant greenness in 2019 peaked at twice the level observed in 2020 in both Loamy and Sandy Plains ecological site pastures. Steers gained weight across the 2019 grazing season in both study pastures, while weight gain reached a plateau in the final weeks of the 2020 season. We observed no clear variation for mean average daily gain (ADG) across ecological sites, deployment periods, or years. Mean ADG of haltered steers remained above zero for each deployment (Fig. 3a). Variation in the time spent grazing during the day and at night indicated that yearlings spent most of their time grazing during the day (Fig. 3b), while time spent ruminating occurred mostly at night (Fig. 4a). Using a linear mixed model, we found total cumulative grazing time $d^{-1}$ in 2020 was greater than 2019 ($F_{1,14} = 2.81$, $P = 0.01$; Table S5). However, we observed no difference between ecological sites or deployment periods, nor did the cumulative grazing time $d^{-1}$ depend on the interactive effects of the ecological site and deployment period. In 2019, the mean number of prehension bites $h^{-1}$ was greater than 2020 ($F_{1,14} = -2.29$, $P = 0.04$; Table S5). Steers in the Loamy Plains pasture exhibited a greater bite rate than steers in the Sandy Plains pasture ($F_{1,14} = -4.02$, $P = 0.001$; Fig. 3c). The cumulative mean grazing bout length was longer during the late-season deployment across years and pastures ($F_{1,14} = 3.00$, $P = 0.01$). Grazing bout length extended for a longer period in 2020 compared to 2019, irrespective of the deployment period or pasture ($F_{1,14} = 2.96$, $P = 0.01$; Fig. 3d). Cumulative rumination time per day

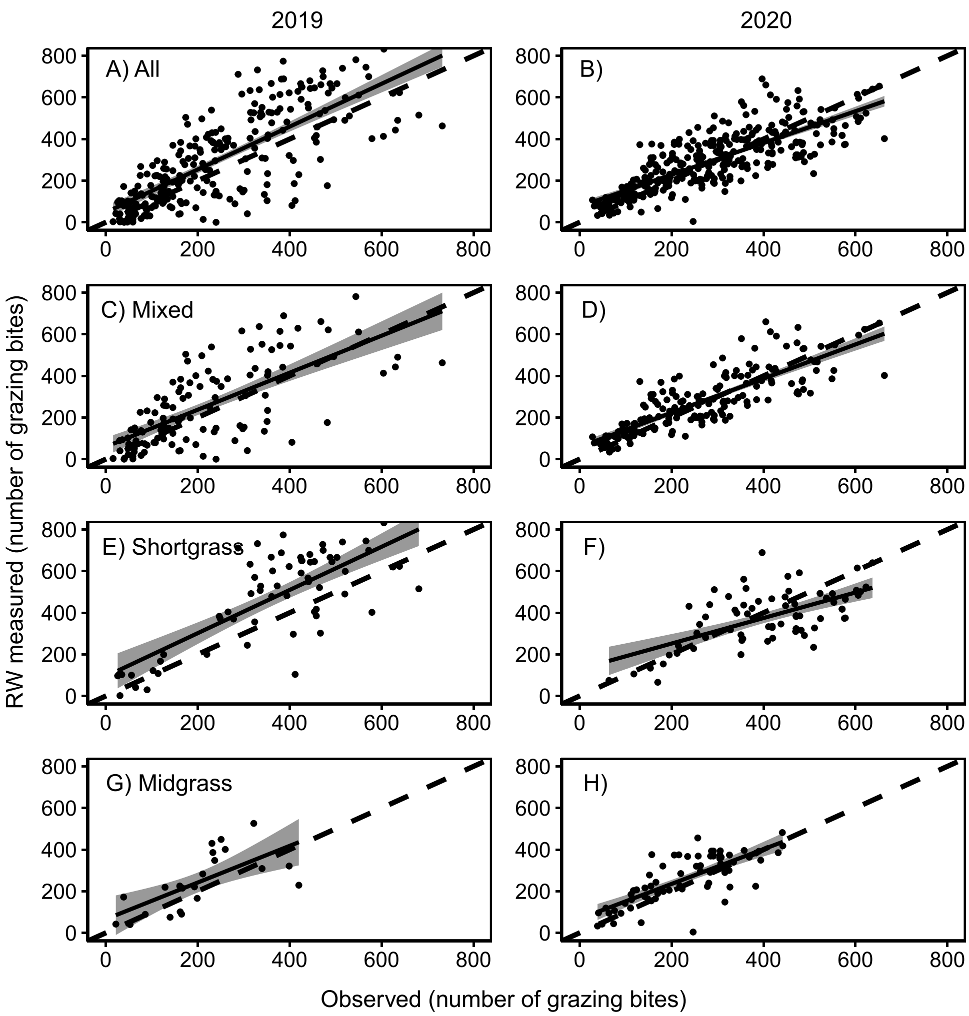


**Fig. 2.** Scatter plot of RW-estimated versus "true" (observed) prehension bites across years and sward-types. Spearman's rank correlations (±SE) of RW system measurements and visual observations of prehension bites in 10-min periods for 2019 (A, C, E, G) and 2020 (B, D, F, H) are also depicted. Sward types were defined as greater than 50 % of bites observed in the 10-min period. Mixed swards (C, D) were denoted as those where no plant functional group made more than 50 % of bites in an observation. Dashed line denotes perfect 1:1 relationship.

**Table 2**
Mean sward height (standard deviation), Spearman's rho ($r_s$), Concordance Correlation Coefficient (CCC), and Bland-Altman-Statistics (Bias, upper and lower 95 % limits of agreement [LOA] with 95 % CI) of the RW system versus visual observations of grazing bites 10-min$^{-1}$.

| Year | Sward | Height (cm) | $r_s$ | CCC | Bias (95 % CI) | Lower LOA (95 % CI) | Upper LOA (95 % CI) |
|---|---|---|---|---|---|---|---|
| 2019 | All (n = 246) | 8.83 (3.01) | 0.79 | 0.71 | 55.05 (37.71; 72.39) | −215.62 (-245.30; -185.94) | 325.72 (296.04; 355.40) |
| | Mixed (n = 121) | 9.57 (3.29) | 0.72 | 0.66 | 21.59 (8.96; 34.21) | −195.86 (-217.46; -147.26) | 239.03 (217.43; 260.63) |
| | Shortgrass (n = 64) | 5.67 (1.82) | 0.63 | 0.63 | 37.52 (12.22; 62.82) | −251.56 (-294.91; -208.22) | 326.60 (283.26; 369.94) |
| | Midgrass (n = 22) | 10.60 (3.62) | 0.80 | 0.61 | 32.88 (15.00; 50.76) | −134.45 (-165.13; -103.78) | 200.21 (169.54; 230.88) |
| 2020 | All (n = 318) | 5.67 (1.55) | 0.82 | 0.80 | 8.19* (-2.11; 18.49) | −174.78 (-192.40; -157.16) | 191.16 (173.54; 208.78) |
| | Mixed (n = 178) | 5.52 (1.61) | 0.86 | 0.83 | 11.97* (-0.60; 24.54) | −154.63 (-176.15; -133.10) | 178.57 (157.04; 200.10) |
| | Shortgrass (n = 69) | 4.64 (1.05) | 0.54 | 0.62 | −27.86 (-55.65; -0.06) | −254.61 (-302.34; -206.89) | 198.90 (151.18; 246.63) |
| | Midgrass (n = 68) | 7.14 (1.91) | 0.75 | 0.73 | 30.03 (11.06; 49.00) | −123.61 (-156.20; -91.03) | 183.67 (151.09; 216.26) |

* = no significant over-estimation or under-estimation between automated system and visual observation.

declined in 2020 compared to 2019 ($F_{1,14}$ = -2.33, $P$ = 0.04; Fig. 4; Table S6). Whole-day rumination chew rate was reduced in 2020 ($F_{1,14}$ = -3.14, $P$ = 0.01), as was the number of rumination chews per bolus ($F_{1,14}$ = -2.59, $P$ = 0.02). Late-season rumination chew rate was reduced in comparison to early-season rumination chews ($F_{1,14}$ = 3.89, $P$ = 0.03). Rumination bout length did not differ between seasons, years, or pastures. Interactive effects for rumination time, chew rate, chews per bolus, and rumination bout length across years, deployment periods, and pastures were not significant ($P$ > 0.05).

Time spent grazing during daytime hours was greater in 2020 than 2019 ($F_{1,14}$ = 4.51, $P$ = 0.001; Table S5). Steers spent less time grazing during the day in late-season deployment than the first deployment ($F_{1,14}$ = -3.65, $P$ = 0.002; Fig. 3b). Similar to findings for the entire day, steers in 2020 took fewer bites h$^{-1}$ during daytime than in 2019 ($F_{1,14}$ = -2.26, $P$ = 0.04) and fewer prehension bites h$^{-1}$ in the Sandy Plains versus the Loamy Plains pasture ($F_{1,14}$ = -4.07, $P$ = 0.001; Fig. 3c). The length of daytime grazing bouts in Loamy Plains was longer than Sandy Plains during the late-season deployment, as revealed by a significant deployment period *x* ecological site (pasture-type) interaction ($F_{1,14}$ = -2.30, $P$ = 0.04; Fig. 3d). Daytime grazing bout length was longer in 2020 than 2019 ($F_{1,14}$ = 3.03, $P$ = 0.01; Table S5). Time spent ruminating during daytime was less during the late-season ($F_{1,14}$ = -2.35, $P$ = 0.03). Rumination time in 2020 was lower than 2019 in the daytime ($F_{1,14}$ = -3.29, $P$ = 0.01; Fig. 4a, Table S6). Likewise, daytime rumination chew rate in 2020 was reduced when compared 2019 ($F_{1,14}$ = -2.75, $P$ = 0.02) and late-season rumination chew rate was less than the early-

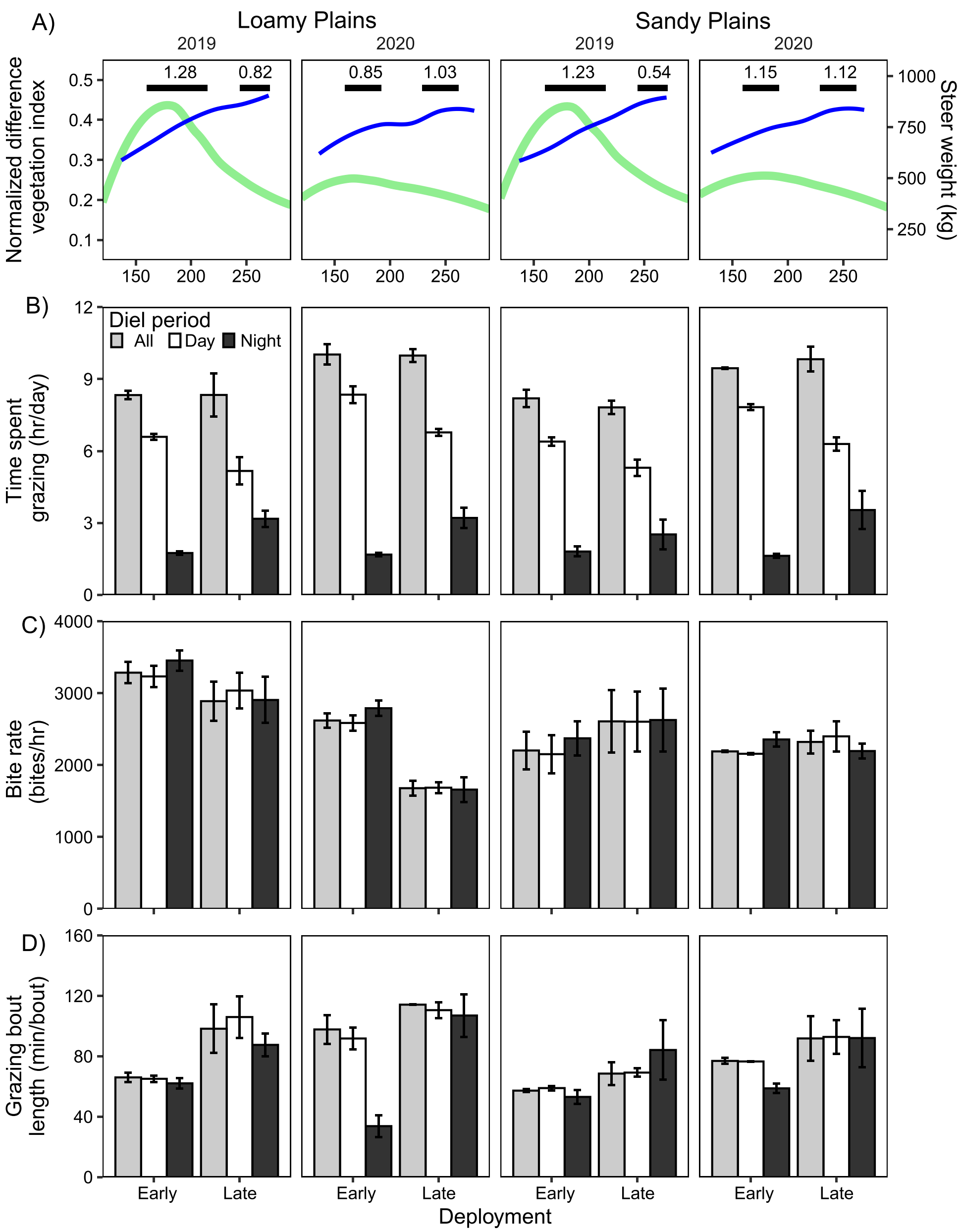


**Fig. 3.** A) Normalized difference vegetation index (NDVI; green line), steer weight gain from mid-May to end of September (blue line), black horizontal lines denote length deployment period, and numbers above black horizontal lines denote average daily gain (ADG) from 28-day weights, B) mean (±SE) time spent grazing per day, C) bites per hour, and D) grazing bout length for entire day, daytime and nighttime hours of each deployment for moderately-stocked pastures representing Loamy Plains and Sandy Plains ecological sites in 2019 and 2020. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

season rate ($F_{1,14}$ = -4.18, $P$ = 0.02; Fig. 4b). Rumination chews per bolus ($F_{1,14}$ = -2.05, $P$ = 0.06) and bout length ($F_{1,14}$ = -1.77, $P$ = 0.10) in daytime tended to be lower in 2020 than 2019 (Fig. 4c,d). However, we observed no difference between ecological sites or deployment periods during daytime, nor did the chews per bolus or rumination bout length depend on the interactive effects of the year, ecological site and deployment period.

Steers spent more time grazing at night later compared to early in the season ($F_{1,14}$ = 4.01, $P$ = 0.004; Table S5). Night grazing time, however, did not differ between ecological sites or years (Fig. 3b). Steers took more prehension bites $h^{-1}$ at night in the Loamy Plains than the Sandy Plains pasture ($F_{1,14}$ = -3.69, $P$ = 0.001; Fig. 3c). In 2020, steers grazing at night took fewer bites $h^{-1}$ than in 2019 ($F_{1,14}$ = -2.25, $P$ = 0.04). A marginally significant deployment period $x$ ecological site interaction suggests prehension bite rate was greater at night in the Sandy Plains versus the Loamy Plains pasture during the late-season deployment ($F_{1,14}$ = 1.80, $P$ = 0.09). Nighttime grazing bout length tended to be shorter early in the season during 2020 in the Loamy Plains than the Sandy Plains pasture, as revealed by a three-way interaction ($F_{1,10.4}$ = -2.64, $P$ = 0.02; Fig. 3d). This finding corresponds with increased nighttime prehension activity in the Loamy Plains pasture, indicating less search time or selectivity when grazing shortgrass- versus midgrass-dominated swards early in the season. Time spent ruminating and time engaged in a rumination bout at nighttime were not different across years, deployment periods, or pastures, while interaction terms did not suggest dependence on a particular time or pasture level ($P$ > 0.05; Table S6). In contrast, nighttime late-season rumination chew rate ($F_{1,14}$ = -4.19, $P$ = 0.02) and 2020 chew rate ($F_{1,14}$ = -3.03, $P$ = 0.01) were significantly lower than chew rate shown in the early-season deployments and during 2019, respectively (Fig. 4b). The number of chews per bolus at nighttime were lower in 2020 than 2019 ($F_{1,14}$ = -2.38, $P$ = 0.03; Fig. 4c), while nighttime rumination bout length did not differ by year, deployment period, or pasture ($P$ > 0.05; Fig. 4d).

### 3.3.2. *Grazing behaviour with moderate vs. heavy stocking*

An evaluation of grazing behaviours under moderate and heavy stocking rate in Loamy Plains pastures indicated behavioural shifts to counter forage limitation (Fig. 5a) were relatively minimal. In 2019, the

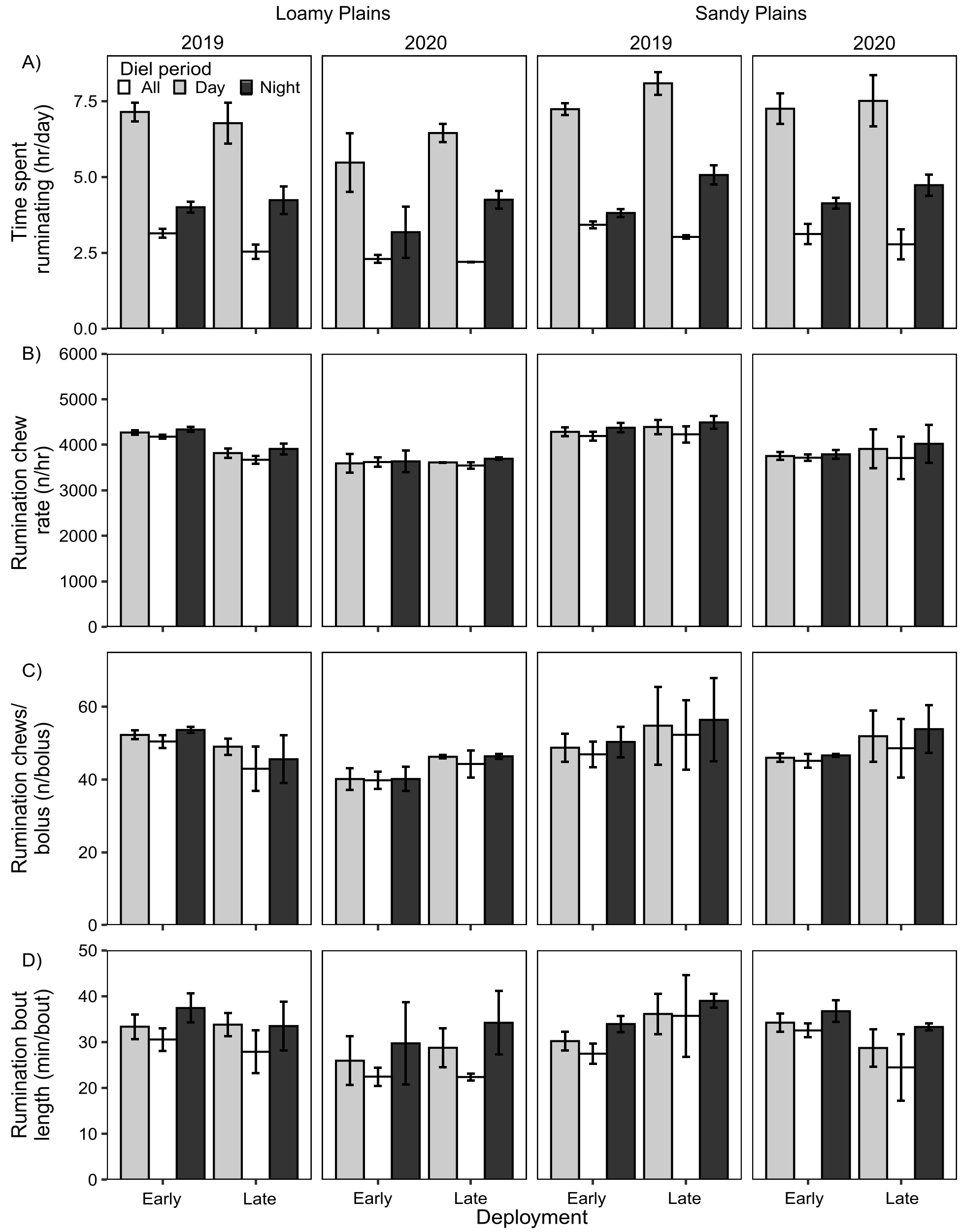


**Fig. 4.** A) Mean (±SE) time spent ruminating per day, B) rumination chews per hour, C) rumination chews per bolus, and D) rumination bout length for entire day, daytime and nighttime hours of each deployment period for moderately-stocked pastures representing Loamy Plains and Sandy Plains ecological sites in 2019 and 2020.

amount of time spent grazing $h^{-1}$ during the second deployment period in the heavy stocked pasture did not differ from the moderately stocked pasture during daytime (ANOVA; $F_{1,4} = 2.40$, $P = 0.20$) or nighttime ($F_{1,4} = 1.05$, $P = 0.36$; Fig. 5b; Table S7). Daily grazing time tended to extend longer under heavy stocking ($F_{1,4} = 1.89$, $P = 0.13$). Prehension bites $h^{-1}$ did not differ between stocking rates across entire days ($F_{1,4} = 0.09$, $P = 0.78$), during daytime ($F_{1,4} = 0.01$, $P = 0.94$) or at night ($F_{1,4} = 0.05$, $P = 0.83$; Fig. 5c, Table S7). Grazing bout length did not differ with stocking rate during the entire day or during daytime ($P > 0.05$), while nighttime grazing bout length tended to extend longer with heavy stocking ($F_{1,4} = 1.80$, $P = 0.15$; Fig. 5d). Rumination-associated behaviours were similar between stocking rates for each diel period ($P > 0.05$; Fig. S7).

## 4. Discussion

Our assessment in shortgrass steppe rangeland showed that RW noseband sensors measure time spent grazing on an hourly basis with very high accuracy and measure bite rates while grazing various plant functional groups with moderate to high accuracy. We noted better correlations for hourly grazing time from swards with more vertically than horizontally oriented grass blades, where individual bites are more distinct. At the bite level, we found prehension bite rate was more difficult to measure when steers were grazing short-statured swards where bites are small and rapid compared to midgrass-dominated swards where bites are larger and more distinct.

Our investigation included growing seasons characterized by average (2019) and below-average (2020) forage production, which facilitated comparisons of ingestive behaviour in response to forage limitation within seasons and across years. We found that cattle

 

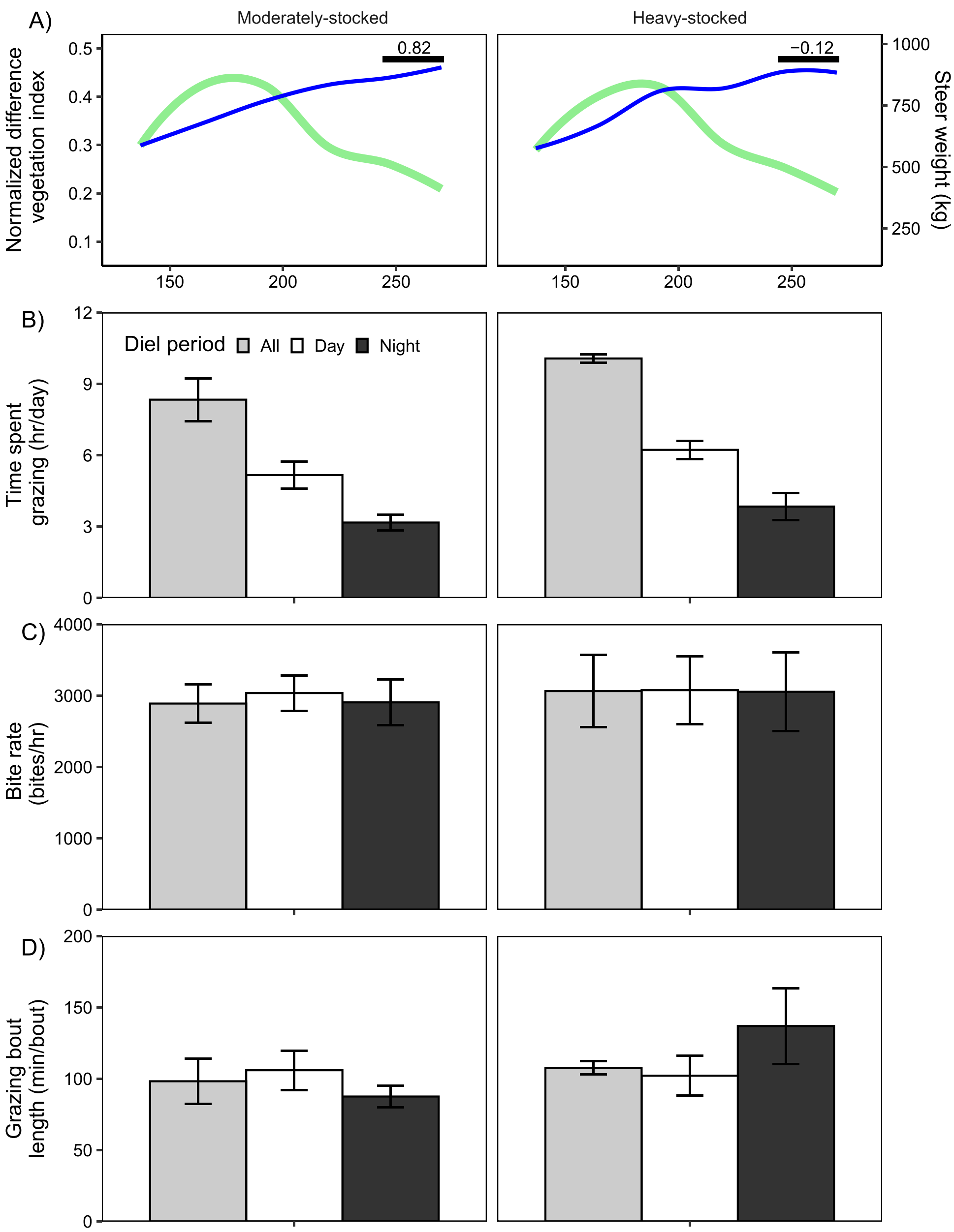


**Fig. 5.** A) Normalized difference vegetation index (NDVI; green line), steer weight gain from mid-May to end of September (blue line), black horizontal lines denote length of deployment period, and numbers above black horizontal lines denote average daily gain (ADG) measured from 28-day weights, B) mean (±SE) time spent grazing per day C) bites rate per hour, and D) grazing bout length for entire day, daytime and nighttime hours for moderately- and heavy-stocked pastures representing Loamy Plains ecological site in September 2019. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

increased daily grazing time and grazing bout length during a drought year with low forage production (2020). In addition, cattle reduced prehension bite rates and rumination chew rates when grazing low-biomass swards, compared to rates under average-production conditions (2019). Steers gained less weight in the drought year (2020), indicating that fine-scale measures of prehension bite rate, grazing bout length, and rumination time and chew rate may provide an indicator of conditions leading to declining animal performance. This research outcome would otherwise not be possible through other measurements such as time spent grazing per hour or day. Corresponding indicators of low forage availability influencing grazing behaviors (increased daily grazing time and grazing bout length, decreased daytime rumination chew rate) and lower weight gain occurred with the heavy compared to the moderate stocking rate. Collectively, these results indicate that the RW system robustly quantifies ingestive behaviours in semiarid rangeland environments and identifies when foraging processes change in a manner that potentially leads to reduced animal performance.

### 4.1. Validation Study 1: hourly grazing time

A very high accuracy for estimating grazing time per hour in semiarid rangeland ($r_s$ = 0.95; CCC = 0.93) is similar to that reported for dairy cattle in Europe fitted with the same RW noseband system and Converter algorithm ($r_s$ = 0.96, CCC = 0.96; Werner et al., 2018). Also consistent with Werner et al. (2018), we found the RW system slightly overestimated grazing time compared to visual observation. We found that the output for 'EAT1TIME' (head position down) was more highly correlated to direct observations ($r_s$ = 0.98 and CCC = 0.98) than GRAZINGTIME. Moreover, the mean difference between visual observation and the RW system estimate of EAT1TIME decreased by 3 min of grazing $h^{-1}$. Thus, we infer the variable 'EAT2TIME' (head position up) incorporates some actions that should not be considered ingestive behaviours (e.g., licking). Our findings support the contention of Werner et al. (2018), who suggested that the RW Converter output should include greater specificity of behaviours at the course 1-hr resolution.

Algorithms employed by the RW Converter differ depending on the selected output time resolution, but the accuracy of both 1-min and 1-h summaries was substantial. For 1-min summaries, the algorithm evaluates each minute independently without plausibility checks that use time periods before or after the measured minute of interest. As a result, we expected error detected between the RW system and visual observations would be greater with 1-min compared to 1-h summaries. We did find slightly lower accordance for 1-min (0.89) versus 1-h (0.93) summaries, suggesting there is room for improvement in the finer-scale temporal resolution algorithm. Research applications benefit from the 1-min resolution data summaries, which can gauge fine-scale changes in foraging behaviour as an animal moves among different patches within complex plant communities. In addition, the RW system allows increased data collection during night hours when direct visual observations are nearly impossible.

### 4.2. Validation Study 2: bite rate

The accordance between visual observations and the RW system for prehension bite estimates improved substantially in all sward types after modification in the halter fit. This outcome suggests that the noseband sensor system is very sensitive in detecting pressure differences (Rombach et al., 2018; Werner et al., 2018) and modifications of the halter for cattle snout sizes other than European dairy cows improves application of the RW system outside dairy settings. To estimate prehension bite rates, the sensor produced slight overestimates relative to visual observations, which agrees with findings from milk production systems where cattle grazed homogenous swards (e.g., Rombach et al., 2018; Werner et al., 2018). We found the greatest discrepancy between prehension bite estimates from visual observations versus the RW system remained after halter modification for cattle prehending lawn-like, shortgrass swards at rates of >400 prehension bites 10-min$^{-1}$ (Fig. 4g, h). Underestimation by the RW system in these conditions most likely arises because sensor sensitivity was inadequate to detect the very rapid bites by steers in consuming this low-statured plant community supporting horizontally aligned leaves. Under these conditions, the RW system could not effectively distinguish among the nearly continuous biting of leaves by the grazing animals. Because non-uniformity occurred in correlation among the distinct plant functional group swards, we suggest that this technology is most robust for prehension bite detection when there is some vertical orientation of leaves/plant parts in the plant community. At the same time, overall accordance rates were high across all sward types after halter modification. The degree to which plant architecture impacts the accuracy of grazing behaviour measurements by automatic jaw movement recorders is critical to broadening the applicability of this technology in heterogenous swards. Our findings exemplify how jaw movement measurements in mixed-species swards in drier environments differ from uniform vertical forage heights in improved pasture systems of more temperate climates. Such discrepancies in sward specific-bite rate estimates should be taken under careful consideration when employing RW-produced data to estimate intake.

A key potential application of sensors that monitor grazing and rumination behaviors is detecting when animals begin to experience forage intake limitations that result in reduced animal weight gain. Even prior to our modification of the halter fit, we found that the RW system detected an increase in grazing bout length at night for cattle under heavy versus moderate stocking on the Loamy Plains ecological site (Fig. 5). The heavily stocked pasture contains greater dominance of shortgrasses (Table 1), which were senescing and had declined in height to only 1−2 cm by the time we conducted the RW system trial in September of 2019. Cattle grazing lush swards at peak NDVI in June of 2019 versus prehending lower biomass, senescent swards in September of 2019 (both at the same moderate stocking rate) showed increased grazing bout length (for 24-hr and at night on both ecological sites) when forage availability was in decline. The increase in grazing bout length was particularly evident at night. In contrast, rumination metrics did not show any notable changes in response to declining biomass in September of 2019, as revealed by the lack of significant deployment period *x* year interactions.

After the halter modification, we were fortunate to compare RW system measurements under even lower biomass conditions in the drought of 2020. Comparing grazing behavior metrics at peak NDVI in June versus low NDVI in September again showed a significant increase in grazing bout length (Fig. 3), but few changes in rumination metrics (Fig. 4). Furthermore, for both ecological sites, we detected maximal values for grazing bout length late in the 2020 grazing season compared to both early-season 2020 and both early- and late-season of 2019. Collectively, results suggest grazing bout length could be a predictor of forage limitation, as cattle begin to graze less selectively and increase the length of periods in which they continuously prehend bites to maintain intake (Mezzalira et al., 2012), particularly during nighttime grazing bouts. Further research to quantify when grazing bout length increases to levels (i.e., thresholds) indicative of declining cattle performance is needed.

## 5. Conclusion

Technologies such as the RW system provide week to month-long measurement of behavioural parameters for ingestive behaviour research. In our study with free-ranging animals handled infrequently (only every 28 days in these experiments), the RW systems remained functional and affixed to a steer's nose bridge from 3 to 28 days. The median length of functionality increased from 13 to 19 days with the modification of an adjustable cheekpiece to enhance affixation to the nose bridge of the steer. This extension of available recording time provides longer-term digital logging of foraging mechanics to measure responses more robustly to changes in habitat use, feeding patterns, and food selection (Fortin et al., 2015; Raynor et al., 2015). For example, one can more rigorously assess selective foraging in spatially distinct plant communities (e.g., heightened bite rate in riparian areas; Provenza et al., 2015) to inform fine-scale linkages in trophic and community interactions (Warne et al., 2019).

Further, rates of ingestion and concomitant patterns across days or longer, for instance, impart more insight into the biology of ruminants than 24-h totals derived from binary (grazing or not) investigations. Animal-borne sensors provide opportunities to elucidate foraging mechanisms underlying animal performance in free-ranging livestock production enterprises and open new opportunities in animal movement research. Our initial results suggest grazing bout length could be a valuable indicator of changes in forage conditions affecting animal performance. Coupling animal-borne noseband sensors with high temporal and spatial GPS devices provides pathways to precision livestock and rangeland management strategies, including measuring and modifying animal location and movement rate for accessing forage in extensive landscapes.

## Data statement

The research data is confidential.

## Declaration of Competing Interest

The authors report no declarations of interest.

## Acknowledgments

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.applanim.2021.105402.

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Supplemental material for

# Noseband sensor validation and behavioural indicators for assessing beef cattle grazing on extensive pastures

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Table S1. Spearman's rho ($r_s$), Concordance Correlation Coefficient (CCC), and Bland-Altman-Statistics (Bias, upper and lower 95% limits of agreement [LOA] with 95% CI) of the RW system versus visual observations for duration of grazing time in a 1-h resolution for RW Converter (V.0.7.3.36) parameter GRAZINGTIME (sum of duration of grazing head position down [EAT1TIME] and feeding head position up [EAT2TIME]) and EAT1TIME (grazing head position down).

| Ecological site (Pasture name) | Behaviour (min/h) | $r_s$ | CCC | Bias (95% CI) | Lower LOA (95% CI) | Upper LOA (95%CI) |
|---|---|---|---|---|---|---|
| All | GRAZINGTIME | 0.95 | 0.93 | 4.21 (1.75; 6.67) | -10.04 (-14.28; -5.80) | 18.45 (14.21; 22.70) |
| | EAT1TIME | 0.98 | 0.98 | 1.03* (-0.36; 2.42) | -7.04 (-9.44; -4.63) | 9.09 (6.69; 11.49) |
| Loamy Plains (15E) | GRAZINGTIME | 0.92 | 0.91 | 4.87 (1.34; 8.40) | -11.13 (-17.25; -5.01) | 20.87 (14.75; 26.99) |
| | EAT1TIME | 0.97 | 0.97 | 1.33 (-0.65; 3.32) | -7.64 (-11.08; -4.21) | 10.31 (6.88; 13.75) |
| Sandy Plains (19N) | GRAZINGTIME | 0.99 | 0.96 | 3.04* (-0.25; 6.33) | -7.62 (-13.40; -1.85) | 13.70 (7.93; 19.47) |
| | EAT1TIME | 0.99 | 0.99 | 0.48* (-1.46; 2.43) | -5.83 (-9.25; -2.41) | 6.80 (3.38; 10.22) |

* = no significant over-estimation or under-estimation between automated system and visual observation.

Table S2. Estimates of total amount of time spent grazing per day based on the RW system measurements, as calculated from GRAZINGTIME and EAT1TIME (head position down) and bias corrected values after validation for Validation Study 1, June-July 2020.

| Ecological site (Pasture name) | GRAZINGTIME (h/day) | GRAZINGTIME without bias (h/day) | EAT1TIME (h/day) | EAT1TIME without bias (h/day) |
|---|---|---|---|---|
| All | 8.90 (8.74; 9.06) | 9.52 (9.17; 9.87) | 8.20 (8.04; 8.37) | 8.34 (8.16; 8.53) |
| Loamy Plains (15E) | 9.12 (8.92; 9.31) | 9.85 (9.35; 10.35) | 8.48 (8.28; 8.66) | 8.66 (8.39; 8.93) |
| Sandy Plains (19N) | 8.57 (8.35; 8.81) | 9.00 (8.57; 9.44) | 7.81 (7.59; 8.01) | 7.87 (7.64; 8.10) |

Table S3. Mean sward height (standard deviation), Spearman's rho ($r_s$), Concordance Correlation Coefficient (CCC), and Bland-Altman-Statistics (Bias, upper and lower 95% limits of agreement [LOA] with 95% CI) of the RW sensors versus visual observations of grazing bites in 10-min periods for each sward type and all observations.

| Sward | Sward Height (cm) | $r_s$ | CCC | Bias (95% CI) | Lower LOA (95% CI) | Upper LOA (95% CI) |
|---|---|---|---|---|---|---|
| All (n = 564) | 7.05 (2.19) | 0.80 | 0.75 | 28.63 (18.93; 38.33) | -201.18 (-217.76; -184.59) | 258.43 (241.85; 275.02) |
| Mixed (n = 299) | 7.16 (2.29) | 0.79 | 0.75 | 21.59 (8.96; 34.21) | -195.86 (-217.46; -147.26) | 239.03 (217.43; 260.63) |
| Shortgrass (n = 133) | 5.13 (1.42) | 0.53 | 0.61 | 37.52 (12.22; 62.82) | -251.56 (-294.91; -208.22) | 326.60 (283.26; 369.94) |
| Midgrass (n = 90) | 7.97 (2.33) | 0.74 | 0.70 | 32.88 (15.00; 50.76) | -134.45 (-165.13; -103.78) | 200.21 (169.54; 230.88) |
| Forb (n = 41) | 10.45 (3.58) | 0.67 | 0.64 | 40.07 (4.29; 75.85) | -182.10 (-243.75; -120.45) | 200.21 (200.60; 323.90) |

Table S4. RW system measurement of grazing bites and bias-corrected grazing bites across plant functional group swards in Validation Study 2, 2019 and 2020.

| Year | Sward | Bites (bites 10-min$^{-1}$) | Bites without bias |
|---|---|---|---|
| 2019 | All | 303 (275; 330) | 358.00 (263; 373) |
| | Mixed | 251 (216; 285) | 286.74 (240; 311) |
| | Shortgrass | 471 (415; 528) | 579.01 (398; 615) |
| | Midgrass | 243 (180; 305) | 285.07 (241; 329) |
| | Forb | 221 (171; 272) | 256.45 (220; 292) |
| 2020 | All | 294 (278; 310) | 302.21 (292; 312) |
| | Mixed | 273 (251; 295) | 285.04 (272; 297) |
| | Shortgrass | 379 (347; 411) | 351.18 (324; 378) |
| | Midgrass | 260 (232; 239) | 290.04 (248; 308) |

Table S5. Linear mixed model results for grazing behaviors in moderately-stocked Loamy Plains versus Sandy Plains ecological sites during all day, daytime, and nighttime periods, 2019 and 2020.

| Behavior | Diel Period | Variable | *β* | *SE* | *F* | *P* |
|---|---|---|---|---|---|---|
| Grazing (h) | All | Intercept | 8.33 | 0.40 | 21.14 | <0.0001 |
| | | Pasture (Sandy Plains) | -0.14 | 0.56 | -0.24 | 0.81 |
| | | Period (Late-season) | 0.01 | 0.60 | 0.01 | 0.99 |
| | | Year (2020: drought) | 1.69 | 0.60 | 2.81 | 0.02 |
| | | Pasture x Period | -0.38 | 0.91 | -0.48 | 0.68 |
| | | Pasture x Year | -0.44 | 0.91 | -0.48 | 0.64 |
| | | Period x Year | -0.05 | 0.93 | -0.05 | 0.96 |
| | | Pasture x Period x Year | 0.80 | 1.40 | 0.57 | 0.58 |
| | Day | Intercept | 6.58 | 0.26 | 25.82 | <0.0001 |
| | | Pasture (Sandy Plains) | -0.20 | 0.36 | -0.55 | 0.59 |
| | | Period (Late-season) | -1.42 | 0.39 | -3.65 | 0.003 |
| | | Year (2020: drought) | 1.76 | 0.39 | 4.51 | 0.001 |
| | | Pasture x Period | 0.33 | 0.59 | 0.56 | 0.58 |
| | | Pasture x Year | -0.32 | 0.59 | -0.55 | 0.59 |
| | | Period x Year | -0.15 | 0.61 | -0.25 | 0.81 |
| | | Pasture x Period x Year | -0.29 | 0.90 | -0.32 | 0.75 |
| | Night | Intercept | 1.76 | 0.25 | 6.91 | <0.0001 |
| | | Pasture (Sandy Plains) | 0.05 | 0.36 | 0.13 | 0.90 |
| | | Period (Late-season) | 1.42 | 0.35 | 4.01 | 0.004 |
| | | Year (2020: drought) | -0.08 | 0.39 | -0.21 | 0.84 |
| | | Pasture x Period | -066 | 0.53 | -1.26 | 0.25 |
| | | Pasture x Year | -0.10 | 0.59 | -0.17 | 0.87 |
| | | Period x Year | 0.09 | 0.54 | 0.17 | 0.87 |
| | | Pasture x Period x Year | 1.07 | 0.84 | 1.27 | 0.23 |
| Bites (bites/h) | All | Intercept | 3285.70 | 190.20 | 17.27 | <0.0001 |
| | | Pasture (Sandy Plains) | -1085.50 | 269.10 | -4.02 | 0.001 |
| | | Period (Late-season) | -396.50 | 290.60 | -1.36 | 0.19 |
| | | Year (2020: drought) | -665.40 | 290.60 | -2.29 | 0.04 |
| | | Pasture x Period | 801.50 | 439.40 | 1.82 | 0.09 |
| | | Pasture x Year | 652.60 | 439.40 | 1.49 | 0.16 |
| | | Period x Year | -545.10 | 452.90 | -1.20 | 0.25 |
| | | Pasture x Period x Year | 271.80 | 677.10 | 0.40 | 0.69 |
| | Day | Intercept | 3233.40 | 187.90 | 17.21 | <0.0001 |
| | | Pasture (Sandy Plains) | -1081.70 | 265.70 | -4.07 | 0.001 |
| | | Period (Late-season) | -1.96.60 | 287.00 | -0.69 | 0.50 |
| | | Year (2020: drought) | -647.40 | 287.00 | -2.26 | 0.04 |
| | | Pasture x Period | 648.60 | 433.90 | 1.50 | 0.16 |
| | | Pasture x Year | 653.10 | 433.90 | 1.51 | 0.15 |
| | | Period x Year | -703.90 | 447.20 | -1.57 | 0.14 |
| | | Pasture x Period x Year | 494.00 | 668.60 | 0.74 | 0.47 |
| | Night | Intercept | 3454.8 | 193.20 | 17.88 | <0.0001 |
| | | Pasture (Sandy Plains) | -1082.00 | 273.30 | -3.96 | 0.001 |
| | | Period (Late-season) | -548.70 | 295.20 | -1.86 | 0.08 |
| | | Year (2020: drought) | -663.70 | 295.20 | -2.25 | 0.04 |
| | | Pasture x Period | 803.00 | 446.20 | 1.80 | 0.09 |
| | | Pasture x Year | 647.40 | 446.20 | 1.45 | 0.17 |
| | | Period x Year | -583.30 | 460.00 | -1.27 | 0.23 |
| | | Pasture x Period x Year | 168.20 | 687.70 | 0.25 | 0.81 |

Table S5 (continued). Linear mixed model results for grazing behaviors in moderately-stocked Loamy Plains vs. Sandy Plains ecological sites during all day, daytime, and nighttime periods, 2019 and 2020.

| Behavior | Diel Period | Variable | *β* | *SE* | *F* | *P* |
|---|---|---|---|---|---|---|
| Grazing bout (min) | All | Intercept | 65.98 | 7.04 | 9.38 | <0.0001 |
| | | Pasture (Sandy Plains) | -8.76 | 9.95 | -0.88 | 0.39 |
| | | Period (Late-season) | 32.25 | 10.75 | 3.00 | 0.01 |
| | | Year (2020: drought) | 31.76 | 10.75 | 2.96 | 0.01 |
| | | Pasture x Period | -20.96 | 16.25 | -1.29 | 0.22 |
| | | Pasture x Year | -12.09 | 16.25 | -0.74 | 0.47 |
| | | Period x Year | -15.83 | 16.75 | -0.95 | 0.36 |
| | | Pasture x Period x Year | 19.43 | 25.04 | 0.78 | 0.45 |
| | Day | Intercept | 65.06 | 5.77 | 11.28 | <0.0001 |
| | | Pasture (Sandy Plains) | -6.16 | 8.15 | -0.76 | 0.46 |
| | | Period (Late-season) | 40.89 | 8.81 | 4.64 | 0.0004 |
| | | Year (2020: drought) | 26.69 | 8.81 | 3.03 | 0.01 |
| | | Pasture x Period | -30.63 | 13.32 | -2.30 | 0.04 |
| | | Pasture x Year | -9.06 | 13.32 | -0.68 | 0.51 |
| | | Period x Year | -22.13 | 13.73 | -1.61 | 0.13 |
| | | Pasture x Period x Year | 28.12 | 20.52 | 1.37 | 0.19 |
| | Night | Intercept | 75.49 | 7.48 | 10.09 | <0.0001 |
| | | Pasture (Sandy Plains) | -17.88 | 10.67 | -1.68 | 0.12 |
| | | Period (Late-season) | 19.32 | 9.66 | 2.00 | 0.11 |
| | | Year (2020: drought) | 5.95 | 11.54 | 0.52 | 0.61 |
| | | Pasture x Period | 8.87 | 14.33 | 0.62 | 0.57 |
| | | Pasture x Year | 11.55 | 17.51 | 0.66 | 0.52 |
| | | Period x Year | 23.25 | 14.54 | 1.60 | 0.20 |
| | | Pasture x Period x Year | -34.49 | 23.56 | -1.46 | 0.18 |

Table S6. Linear mixed model results for rumination-associated behaviors in moderately-stocked Loamy Plains vs. Sandy Plains ecological sites during all day, daytime, and nighttime periods, 2019 and 2020.

| Behavior | Diel Period | Variable | *β* | *SE* | *F* | *P* |
|---|---|---|---|---|---|---|
| Ruminating (h) | All | Intercept | 7.14 | 0.47 | 15.24 | <0.0001 |
| | | Pasture (Sandy Plains) | 0.09 | 0.66 | 0.14 | 0.89 |
| | | Period (Late-season) | -0.37 | 0.72 | -0.52 | 0.61 |
| | | Year (2020: drought) | -1.67 | 0.72 | -2.33 | 0.04 |
| | | Pasture x Period | 1.22 | 1.08 | 1.13 | 0.28 |
| | | Pasture x Year | 1.68 | 1.08 | 1.56 | 0.14 |
| | | Period x Year | 1.34 | 1.12 | 1.21 | 0.25 |
| | | Pasture x Period x Year | -1.94 | 1.68 | -1.16 | 0.26 |
| | Day | Intercept | 3.15 | 0.17 | 18.67 | <0.0001 |
| | | Pasture (Sandy Plains) | 0.28 | 0.24 | 1.18 | 0.26 |
| | | Period (Late-season) | -0.60 | 0.26 | -2.35 | 0.03 |
| | | Year (2020: drought) | -0.85 | 0.26 | -3.29 | 0.01 |
| | | Pasture x Period | 0.20 | 0.39 | 0.52 | 0.61 |
| | | Pasture x Year | 0.54 | 0.39 | 1.39 | 0.18 |
| | | Period x Year | 0.51 | 0.40 | 1.27 | 0.23 |
| | | Pasture x Period x Year | -0.45 | 0.60 | -0.75 | 0.47 |
| | Night | Intercept | 4.00 | 0.35 | 11.53 | <0.0001 |
| | | Pasture (Sandy Plains) | -0.19 | 0.49 | -0.39 | 0.70 |
| | | Period (Late-season) | 0.23 | 0.53 | 0.44 | 0.67 |
| | | Year (2020: drought) | -0.83 | 0.53 | -1.56 | 0.14 |
| | | Pasture x Period | 1.02 | 0.80 | 1.28 | 0.24 |
| | | Pasture x Year | 1.14 | 0.80 | 1.43 | 0.18 |
| | | Period x Year | 0.82 | 0.82 | 1.01 | 0.35 |
| | | Pasture x Period x Year | -1.48 | 1.23 | -1.20 | 0.26 |
| Chew (chew/h) | All | Intercept | 4224.29 | 126.14 | 33.49 | <0.0001 |
| | | Pasture (Sandy Plains) | 60.49 | 185.34 | 0.33 | 0.75 |
| | | Period (Late-season) | -388.43 | 100.00 | -3.89 | 0.03 |
| | | Year (2020: drought) | -631.82 | 201.24 | -3.14 | 0.01 |
| | | Pasture x Period | 346.05 | 143.34 | 2.44 | 0.09 |
| | | Pasture x Year | 100.88 | 309.55 | 0.33 | 0.75 |
| | | Period x Year | 243.95 | 143.81 | 1.70 | 0.19 |
| | | Pasture x Period x Year | -48.77 | 324.09 | -0.15 | 0.88 |
| | Day | Intercept | 4135.89 | 117.82 | 35.10 | <0.0001 |
| | | Pasture (Sandy Plains) | 57.14 | 172.37 | 0.33 | 0.75 |
| | | Period (Late-season) | -428.97 | 102.72 | -4.18 | 0.02 |
| | | Year (2020: drought) | -514.74 | 187.06 | -2.75 | 0.02 |
| | | Pasture x Period | 332.48 | 148.11 | 2.25 | 0.11 |
| | | Pasture x Year | 38.01 | 287.20 | 0.13 | 0.90 |
| | | Period x Year | 269.20 | 148.75 | 1.81 | 0.17 |
| | | Pasture x Period x Year | -179.12 | 311.19 | -0.58 | 0.58 |
| | Night | Intercept | 4287.34 | 133.88 | 32.02 | <0.0001 |
| | | Pasture (Sandy Plains) | 87.98 | 197.89 | 0.45 | 0.66 |
| | | Period (Late-season) | -373.82 | 89.19 | -4.19 | 0.02 |
| | | Year (2020: drought) | -651.38 | 215.04 | -3.03 | 0.01 |
| | | Pasture x Period | 329.23 | 127.49 | 2.58 | 0.08 |
| | | Pasture x Year | 66.93 | 331.59 | 0.20 | 0.84 |
| | | Period x Year | 220.96 | 127.77 | 1.73 | 0.18 |
| | | Pasture x Period x Year | 55.28 | 331.02 | 0.17 | 0.87 |

Table S6 (continued). Linear mixed model results for rumination-associated behaviors in moderately-stocked Loamy Plains versus Sandy Plains ecological sites during all day, daytime, and nighttime periods, 2019 and 2020.

| Behavior | Diel Period | Variable | *β* | *SE* | *F* | *P* |
|---|---|---|---|---|---|---|
| Chews/bolus | All | Intercept | 51.99 | 2.87 | 18.10 | <0.0001 |
| | | Pasture (Sandy Plains) | -3.27 | 4.22 | -0.77 | 0.45 |
| | | Period (Late-season) | -2.43 | 2.28 | -1.06 | 0.34 |
| | | Year (2020: drought) | -11.88 | 4.58 | -2.59 | 0.02 |
| | | Pasture x Period | 7.83 | 3.28 | 2.39 | 0.08 |
| | | Pasture x Year | 9.11 | 7.05 | 1.29 | 0.22 |
| | | Period x Year | 6.18 | 3.29 | 1.88 | 0.13 |
| | | Pasture x Period x Year | -5.67 | 7.39 | -0.77 | 0.46 |
| | Day | Intercept | 51.04 | 3.54 | 14.41 | <0.0001 |
| | | Pasture (Sandy Plains) | -4.14 | 5.08 | -0.81 | 0.43 |
| | | Period (Late-season) | -7.77 | 4.24 | -1.83 | 0.11 |
| | | Year (2020: drought) | -11.27 | 5.50 | -2.05 | 0.06 |
| | | Pasture x Period | 12.80 | 6.24 | 2.05 | 0.08 |
| | | Pasture x Year | 9.48 | 8.37 | 1.13 | 0.28 |
| | | Period x Year | 10.93 | 6.31 | 1.73 | 0.13 |
| | | Pasture x Period x Year | -12.49 | 10.67 | -1.17 | 0.27 |
| | Night | Intercept | 54.01 | 3.76 | 14.38 | <0.0001 |
| | | Pasture (Sandy Plains) | -3.70 | 5.37 | -0.69 | 0.50 |
| | | Period (Late-season) | -8.51 | 4.66 | -1.83 | 0.11 |
| | | Year (2020: drought) | -13.88 | 5.81 | -2.38 | 0.03 |
| | | Pasture x Period | 14.11 | 6.88 | 2.05 | 0.08 |
| | | Pasture x Year | 10.18 | 8.84 | 1.15 | 0.27 |
| | | Period x Year | 13.25 | 6.97 | 1.90 | 0.10 |
| | | Pasture x Period x Year | -11.65 | 11.54 | -1.01 | 0.33 |
| Rumination bout | All | Intercept | 32.82 | 2.61 | 12.55 | <0.0001 |
| | | Pasture (Sandy Plains) | -2.62 | 3.88 | -0.68 | 0.51 |
| | | Period (Late-season) | 1.05 | 1.53 | 0.69 | 0.54 |
| | | Year (2020: drought) | -6.89 | 4.22 | -1.63 | 0.13 |
| | | Pasture x Period | 2.19 | 2.18 | 1.01 | 0.38 |
| | | Pasture x Year | 10.91 | 6.51 | 1.68 | 0.12 |
| | | Period x Year | -2.14 | 2.18 | -0.98 | 0.39 |
| | | Pasture x Period x Year | -6.62 | 6.32 | -1.05 | 0.31 |
| | Day | Intercept | 30.73 | 3.02 | 10.18 | <0.0001 |
| | | Pasture (Sandy Plains) | -3.26 | 4.32 | -0.76 | 0.46 |
| | | Period (Late-season) | -3.05 | 3.66 | -0.83 | 0.43 |
| | | Year (2020: drought) | -8.26 | 4.68 | -1.77 | 0.10 |
| | | Pasture x Period | 9.63 | 5.39 | 1.79 | 0.13 |
| | | Pasture x Year | 13.33 | 7.12 | 1.87 | 0.08 |
| | | Period x Year | 1.97 | 5.45 | 0.36 | 0.73 |
| | | Pasture x Period x Year | -16.61 | 9.15 | -1.81 | 0.10 |
| | Night | Intercept | 37.47 | 3.76 | 9.97 | <0.0001 |
| | | Pasture (Sandy Plains) | -3.54 | 5.48 | -0.65 | 0.53 |
| | | Period (Late-season) | -3.99 | 3.52 | -1.13 | 0.32 |
| | | Year (2020: drought) | -7.75 | 5.94 | -1.30 | 0.22 |
| | | Pasture x Period | 7.01 | 5.10 | 1.38 | 0.24 |
| | | Pasture x Year | 10.55 | 9.11 | 1.16 | 0.27 |
| | | Period x Year | 3.05 | 5.12 | 0.60 | 0.58 |
| | | Pasture x Period x Year | -9.51 | 10.17 | -0.94 | 0.37 |

Table S7. Linear mixed model results for grazing bites taken for moderately-stocked vs. heavy-stocked Loamy Plains ecological sites during all, daytime, and nighttime periods of the day during the second deployment in 2019.

| Behavior | Diel Period | Variable | *β* | *SE* | *F* | *P* |
|---|---|---|---|---|---|---|
| Grazing (h) | All | Intercept | 8.34 | 0.65 | 12.84 | 0.0002 |
| | | Pasture (Heavy) | 1.73 | 0.92 | 1.89 | 0.13 |
| | Day | Intercept | 5.17 | 0.48 | 10.66 | 0.0004 |
| | | Pasture (Heavy) | 1.06 | 0.69 | 1.55 | 0.20 |
| | Night | Intercept | 3.17 | 0.47 | 6.84 | 0.002 |
| | | Pasture (Heavy) | 0.67 | 0.66 | 1.03 | 0.36 |
| Bites (bites/h) | All | Intercept | 2889.20 | 407.20 | 7.10 | 0.002 |
| | | Pasture (Heavy) | 175.30 | 575.80 | 0.30 | 0.78 |
| | Day | Intercept | 3036.83 | 380.18 | 7.99 | 0.001 |
| | | Pasture (Heavy) | 40.64 | 537.66 | 0.08 | 0.94 |
| | Night | Intercept | 2906.10 | 451.50 | 6.44 | 0.003 |
| | | Pasture (Heavy) | 148.10 | 638.50 | 0.23 | 0.83 |
| Grazing bout length (min) | All | Intercept | 98.23 | 11.79 | 8.33 | 0.001 |
| | | Pasture (Heavy) | 9.34 | 16.68 | 0.56 | 0.61 |
| | Day | Intercept | 105.95 | 13.82 | 7.67 | 0.002 |
| | | Pasture (Heavy) | -3.84 | 19.54 | -0.20 | 0.85 |
| | Night | Intercept | 96.16 | 20.41 | 4.71 | 0.01 |
| | | Pasture (Heavy) | 42.49 | 28.86 | 1.47 | 0.21 |
| Ruminating (h) | All | Intercept | 6.77 | 0.74 | 9.10 | 0.001 |
| | | Pasture (Heavy) | 0.61 | 1.05 | 0.58 | 0.59 |
| | Day | Intercept | 2.54 | 0.30 | 8.41 | 0.001 |
| | | Pasture (Heavy) | 0.03 | 0.43 | 0.06 | 0.95 |
| | Night | Intercept | 4.42 | 0.45 | 9.34 | 0.001 |
| | | Pasture (Heavy) | 0.58 | 0.64 | 0.91 | 0.41 |
| Chews (chews/h) | All | Intercept | 3818.62 | 77.92 | 49.01 | <0.0001 |
| | | Pasture (Heavy) | -159.03 | 110.20 | -1.44 | 0.22 |
| | Day | Intercept | 3670.63 | 66.03 | 55.59 | <0.0001 |
| | | Pasture (Heavy) | -175.63 | 93.38 | -1.88 | 0.13 |
| | Night | Intercept | 3909.93 | 89.22 | 43.82 | <0.0001 |
| | | Pasture (Heavy) | -148.79 | 126.18 | -1.18 | 0.30 |
| Chews/bolus (n/bolus) | All | Intercept | 49.00 | 2.57 | 19.05 | <0.0001 |
| | | Pasture (Heavy) | 0.90 | 3.64 | 0.25 | 0.82 |
| | Day | Intercept | 42.94 | 4.69 | 9.15 | 0.001 |
| | | Pasture (Heavy) | 5.16 | 6.64 | 0.78 | 0.48 |
| | Night | Intercept | 45.55 | 5.13 | 8.88 | 0.0001 |
| | | Pasture (Heavy) | 5.23 | 7.26 | 0.72 | 0.51 |
| Rumination bout length (min) | All | Intercept | 33.79 | 6.77 | 5.00 | 0.01 |
| | | Pasture (Heavy) | 5.67 | 9.57 | 0.59 | 0.59 |
| | Day | Intercept | 27.88 | 6.66 | 4.19 | 0.01 |
| | | Pasture (Heavy) | 5.22 | 9.42 | 0.55 | 0.61 |
| | Night | Intercept | 33.49 | 8.02 | 4.18 | 0.01 |
| | | Pasture (Heavy) | 11.66 | 11.34 | 1.03 | 0.36 |

Figure S1. British breed yearling steer wearing a RumiWatch Halter (Itin and Hoch GmbH, Liestal, Switzerland). Belt around the nose includes a pouch with a propylene glycol-filled tube and the pressure sensor. Waterproof plastic protection box (left side: battery; right side: triaxial-accelerometer, data logger, and secure digital memory card). Animal is also wearing a global positioning system (GPS) collar.

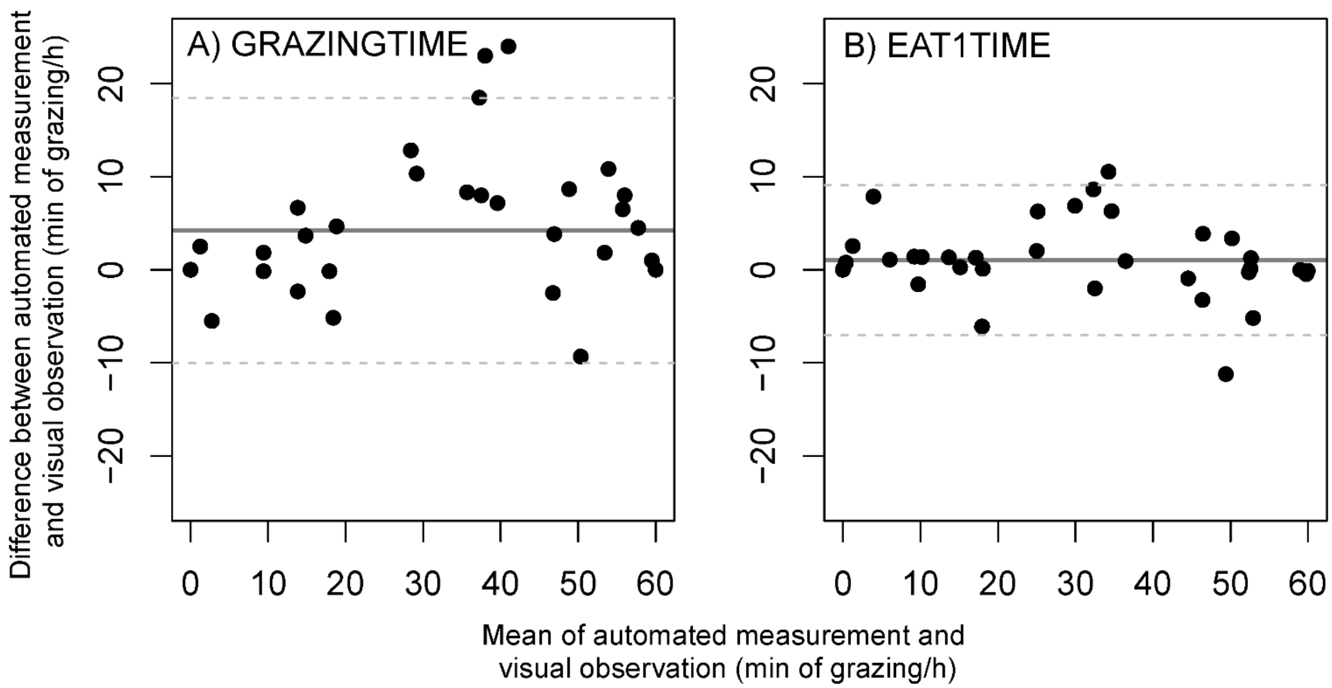


Figure S2. Agreement between RW system measurements and visual observations of feeding behavior in 1-h periods for based on RW Converter (V.0.7.3.36) outputs A) GRAZINGTIME and B) EAT1TIME (head position down), displayed in Bland-Altman plots (solid line indicates the mean difference; dashed lines indicate upper and lower 95% limits of agreement).

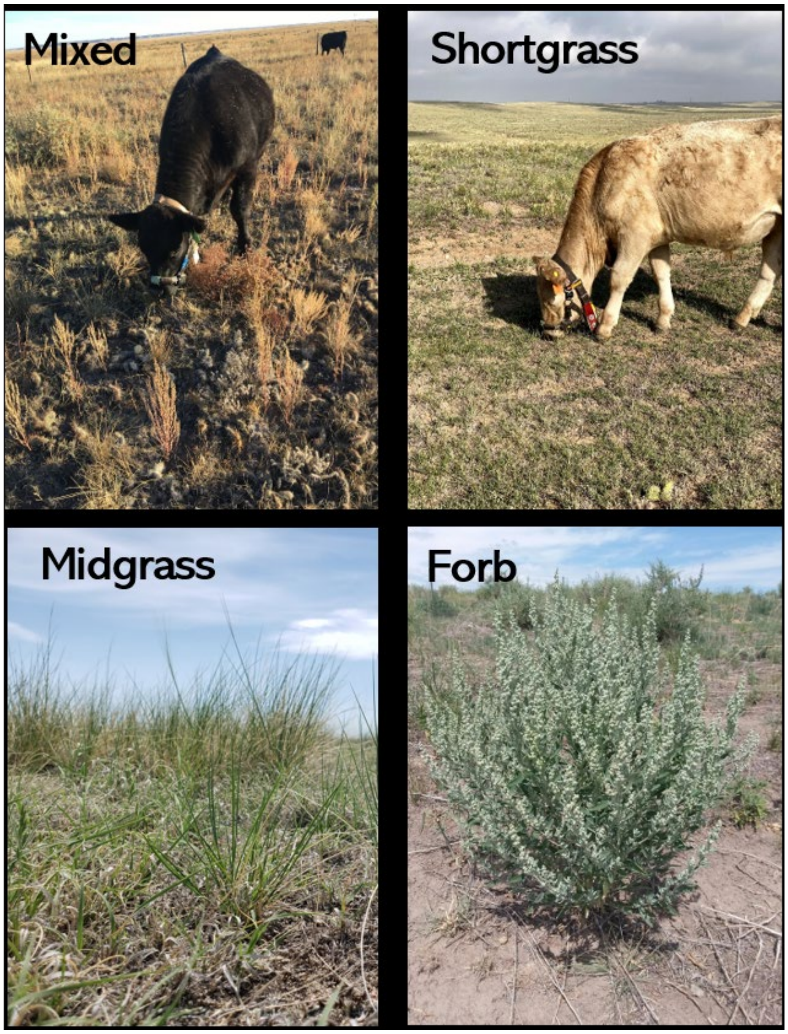


Figure S3. A) Mixed, B) shortgrass, C) midgrass, and D) forb swards observed in observation bouts of yearling steers at the Central Plains Experimental Range, near Nunn, Colorado.

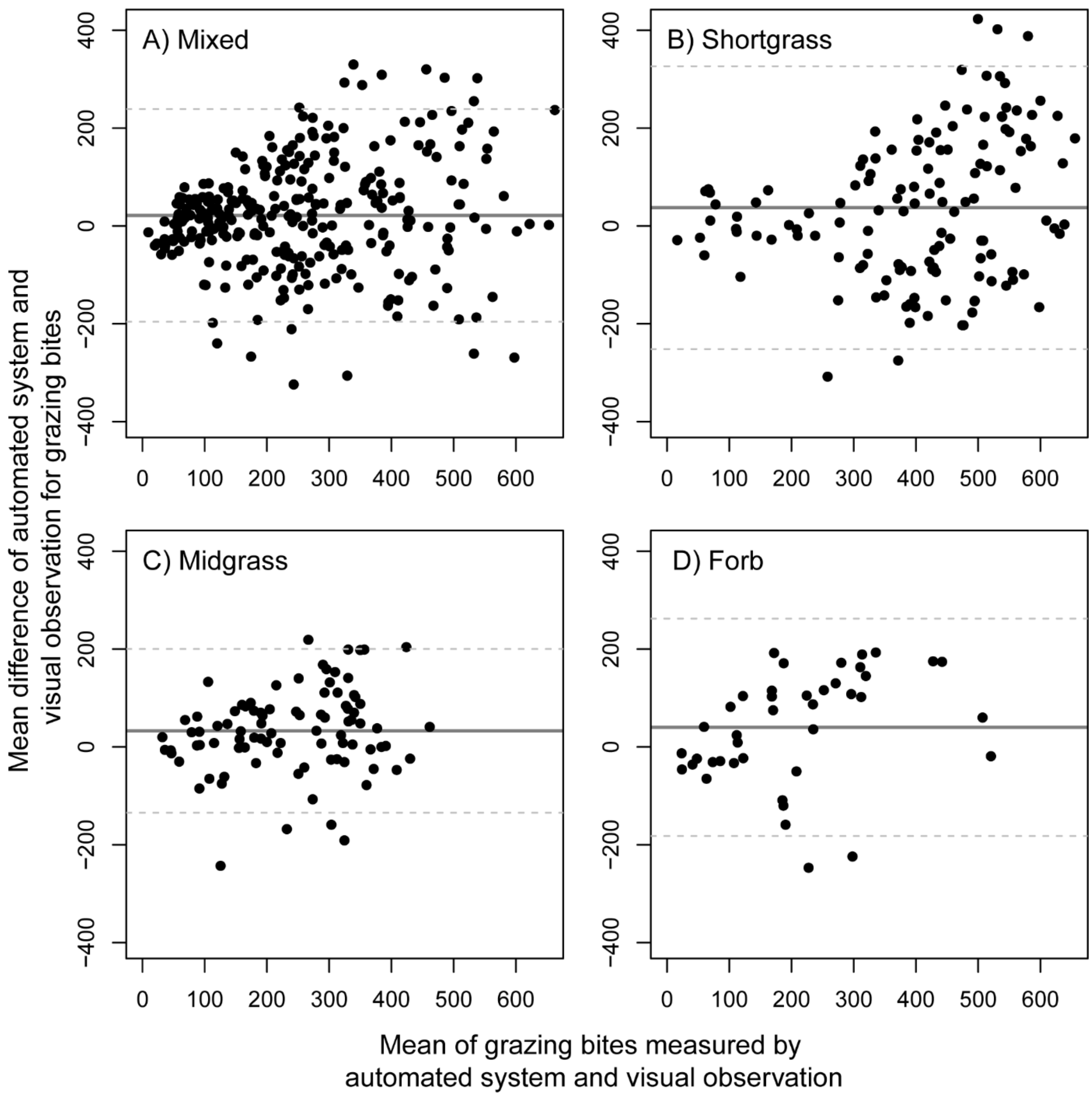


Figure S4. Agreement between RW system measurements and visual observations of grazing bites in 10-min periods, displayed in Bland-Altman-Plots (solid line indicates the mean difference; dashed lines indicate upper and lower 95% limits of agreement). Sward types were defined as greater than 50% of bites observed in the 10-min period. Mixed swards (A) were denoted as those where no plant functional group made more than 50% of bites in an observation bout.

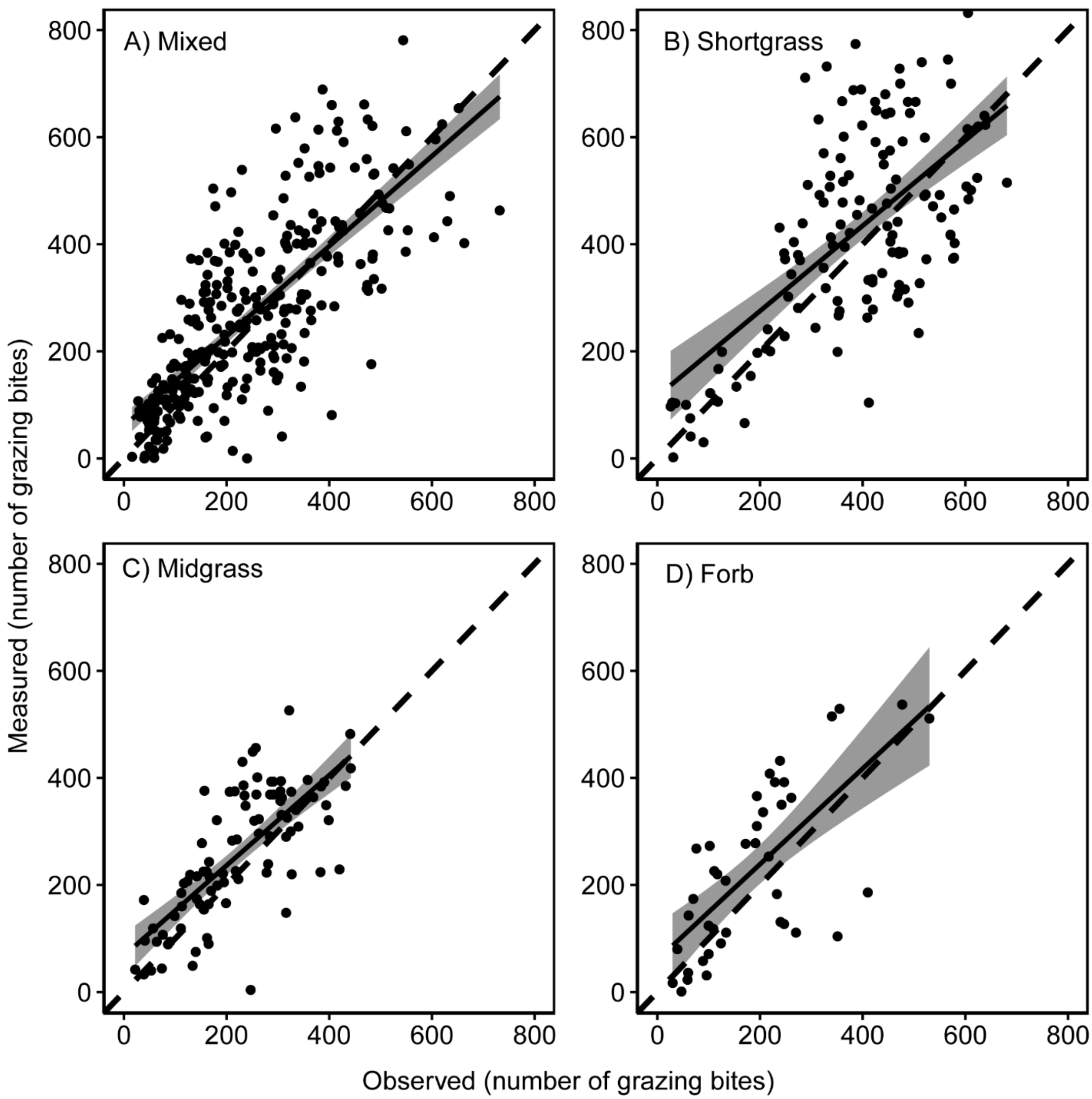


Figure S5. Spearman's rank correlations between RW system measurements and visual observations of grazing bites in 10-min periods. Sward types were defined as greater than 50% of bites observed in the 10-min period. Mixed swards were denoted as those where no plant functional group made more than 50% of bites in an observation. Dashed line denotes perfect 1:1 relationship.

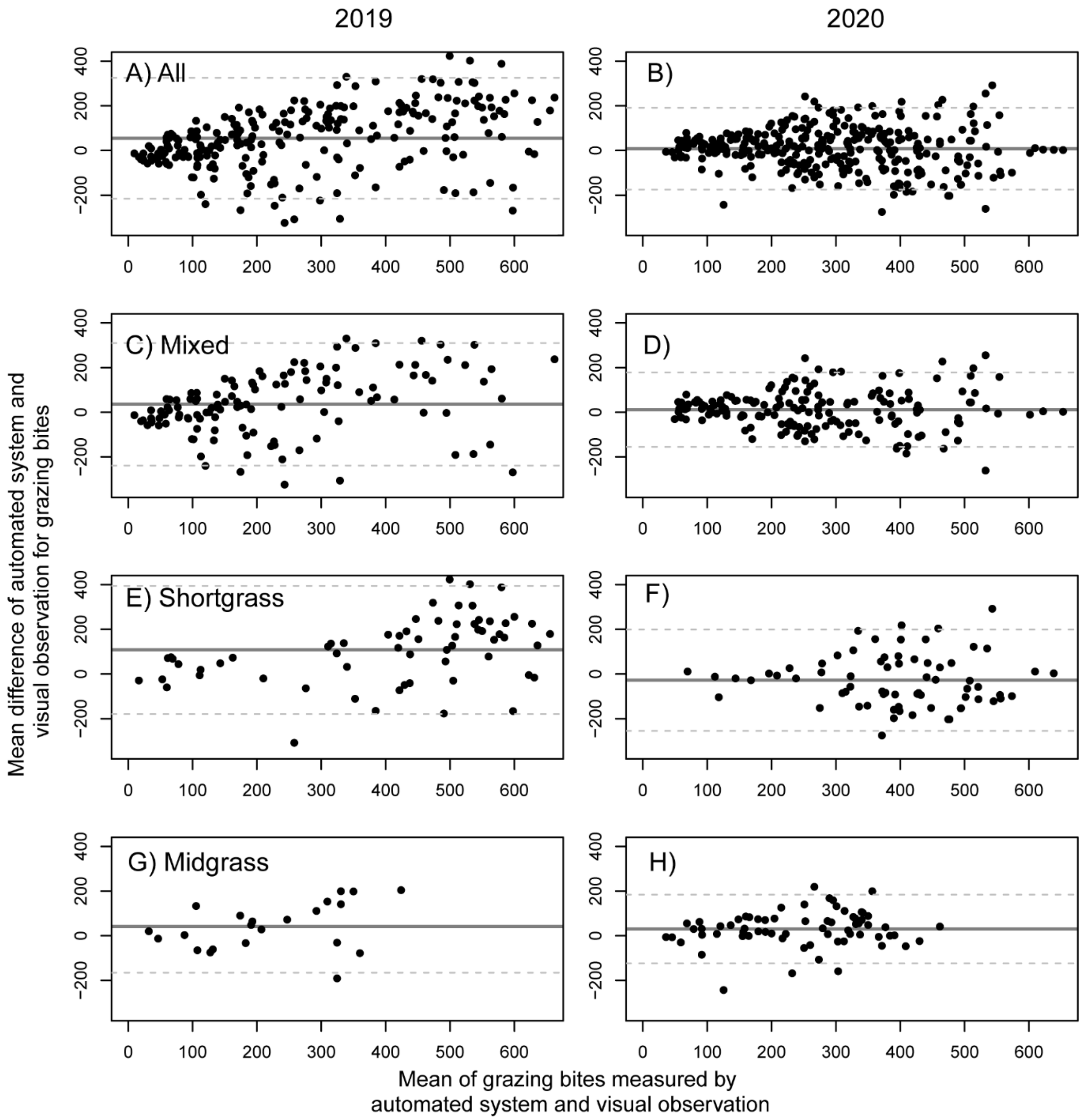


Figure S6. Agreement between RW system measurements and visual observations of grazing bites in 10-min periods for 2019 (A, C, E, G) and 2020 (B, D, F, H), displayed in Bland-Altman-Plots (solid line indicates the mean difference; dashed lines indicate upper and lower 95% limits of agreement). Sward types were defined as greater than 50% of bites observed in the 10-min period. Mixed swards (C,D) were denoted as those where no plant functional group made more than 50% of bites in an observation bout.

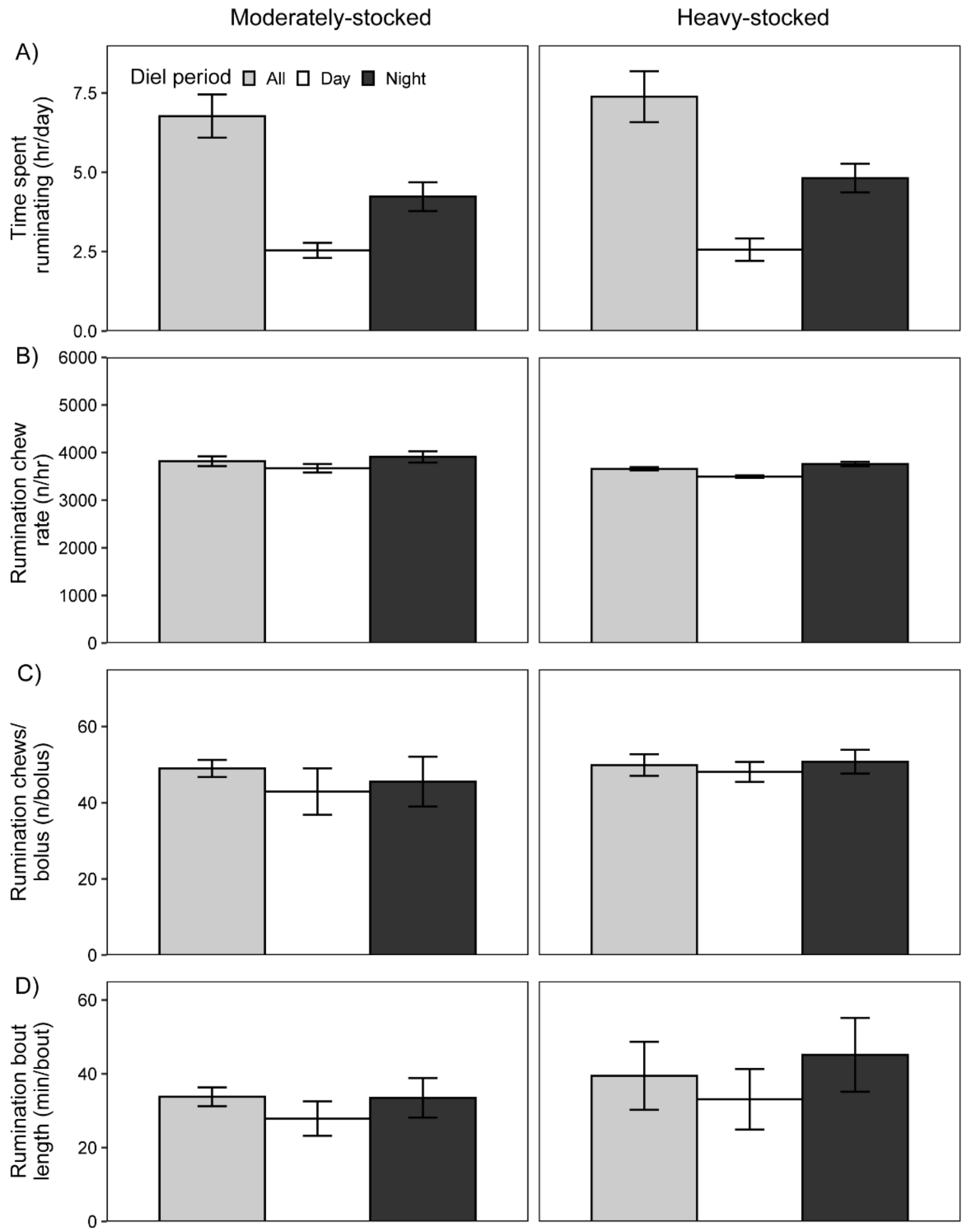


Figure S7. A) Mean (±SE) time spent ruminating per day, B) rumination chew rate per hour, C) rumination chews per bolus, and D) rumination bout length for entire day, daytime and nighttime hours for moderately- and heavy-stocked pastures representing Loamy Plains ecological site in September 2019.