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# Can Bite rate bridge the gap between cow-wearable tech and real-time pasture management?

Leo Pekar

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# Executive summary

For over a century scientists have been observing cow grazing behavior to understand what cows do when grazing, what changes when dealing with differences in sward architecture (pasture density, length and quality) and how we can benefit from this knowledge. The research has evolved with technology and is shifted from empirical observations to predictive models, but not yet on a commercial scale.

At the moment there's a gap in the integration of cow-wearable derived data, with real-time pasture mass and intake models, which could allow for dynamic grazing management decisions informed by continuous animal behavior data.

This study has been conceived from two premises:

- The understanding that cows increase bite rate when adapting to a shorter sward like a post-grazing residual and
- The hypothesis that bite rate could be detected with a commercially available in-ear sensor (ProTag).

If the premises are confirmed, we would then be able to estimate post-grazing residuals in real-time from the derived sensor data.

Two research questions were proposed and proved or challenged by this study:

1- **Can we identify bite rate with existing cow-wearable technology?**
Yes, Bite Rate can be estimated (±10%) from existing cow-wearable accelerometer data. The sensor signal yields three other independent behavioural channels related with bite strategy and sward characteristics
2- **Can bite rate serve as a proxy for post grazing residual on rotationally grazed pastures?**
Bite Rate is not a good predictor of post-grazing residuals, as satiety and rumen fill influences bite rate negatively, at least in late lactation.

This study despite its small dataset and lack of validation resources, proved a concept and brought forward several positive outcomes that highlight the importance of further research in this field.

Through the duration of this study, the attention shifted from bite rate to bite characteristics and how the cow engages with the sward, as the accelerometer data discriminated between bite rate, angle of approach, effort and lateral sway of cows tackling different patches of heterogeneous sward. This means the data could be used to predict sward characteristics.

There's still a wealth of information encoded on the raw accelerometer data, ripe for its use. If we're able to establish more behaviours from the existing data and combine this with data pools such as rumination, we will increase the reliability of predictive models.

Identification of nuances between animals associated with grazing behaviour could potentially be related to productivity gains and would aid the selection of more efficient animals.

# Contents

# Introduction

In this study I venture on a journey of discovery through three topics to further explore their relationships and potential use:

- Bite rate
- Cow wearable technology
- Post-grazing residual


### Bite rate

Bite Rate (the number of bites a cow takes per minute), is a metric that has been recorded since the 1920s, with the earliest formal field measurements summarized by Hancock (1953). When analyzing cow grazing behavior, researchers have observed cows being very efficient harvesters of posture, adapting for changes in the sward architecture (pasture density, length, and quality) to maximize intake per bite.

This research project is conceived from the theory that, as sward availability declines toward residual levels, cattle modify their bite rate, bite mass, and grazing bout structure in predictable ways (Rook & Penning, 1991; Ungar et al., 2001) that are in principle, detectable by wearable sensors

### Cow wearable technology

The current cow wearable technology adoption apogee is creating a great opportunity to push boundaries. The amount of data collected, and use of machine learning is increasing rapidly the possible utility of data.

This happens at a time in New Zealand's farming industry which is increasingly reliant on overseas workers, farm scale keeps growing and in general terms, the traditional kiwi ingenuity and stockmanship that has been a big part of the industry's success is now perceived to be diminishing. Tools and technology provide oversight and fine-tuning opportunities to potentially fill this void.

While historically, devices have been widely used in research facilities, bite rate remained a topic of study with limited application on farm.

The second theory that this project is based upon is that commercially available cow wearables may offer an opportunity to measure bite rate and explore its potential. This matters because research-grade jaw-movement recorders and acoustic rigs are expensive, fragile, and impractical to deploy across a commercial herd. If a sensor farmers already own for heat detection and health monitoring can also yield bite rate, the marginal cost of adoption is effectively zero the data is already being collected, it is simply a matter of extracting more value from it.

## Post-grazing residual

The management of post-grazing residuals is central to pasture-based dairy systems, particularly in New Zealand where ryegrass (*Lolium perenne*) dominant swards underpin farm productivity. Maintaining residuals at approximately 1,500–1,600 kg dry matter (DM) per hectare following each grazing event optimises the balance between maximising immediate herbage removal and preserving sufficient leaf area for rapid sward recovery (Delagarde & Peyraud, 2011).

On farm, daily feed budgeting remains an art, the vast knowledge we have about cow's feeding requirements and pasture allocation in practical terms gets challenged daily by weather conditions, pasture utilization and difficulties at measuring pastures accurately. At the heart of balancing pasture offer and demand is the daily post-grazing residual, which reconciles offer and demand providing a measurable outcome.

- High residuals are related with higher intake (not linearly) but the leaf material left behind compromises the quality of the regrowth;
- Sweet spot post-grazing residuals is the right balance of finding a point where we achieve a low enough residual to secure good quality re-growth with healthy tillering while not compromising in cow's intake.
- On low post-grazing residuals there's high quality regrowth, but pastures are overgrazed with negative consequences to tillering and regrowth speed.

**This study has been conceived from two premises:**

- The understanding that cows increase bite rate when adapting to a shorter sward like a post-grazing residual and
- The hypothesis that bite rate could be detected with a commercially available in-ear sensor (ProTag).

*If the premises are confirmed, then we would then be able to estimate post-grazing residuals in real-time from the derived sensor data (Figure 1), adding a valuable tool for farmers to aid in the achievement of the sweet spot in post-grazing residuals.*

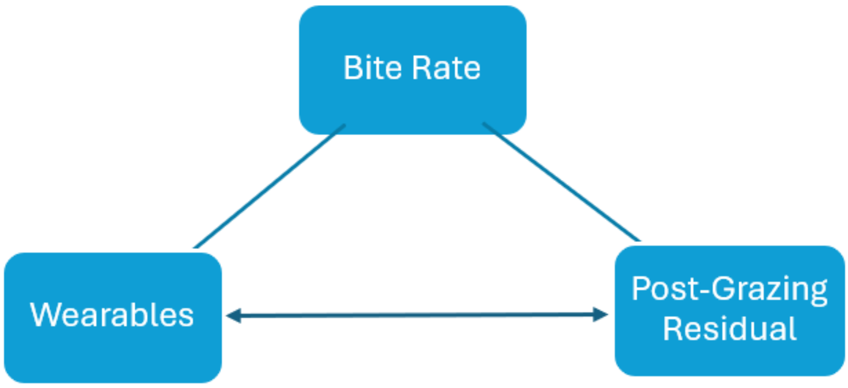



*Figure 1. Potential relationships between parameters*

### The research questions I endeavor to answer:

1- **Can we identify bite rate with existing cow wearable technology?**
2- **Can bite rate serve as a proxy for post grazing residual on intensively grazed pastures?**

# Literature review. Part 1

## Bite Rate in Cattle: A History of Research

*From Early Observations to Modern Precision Grazing Science*

### 1.1 Introduction

Bite rate, the number of bites a grazing animal takes per unit of time stands as one of the most fundamental metrics in the science of animal nutrition, pasture ecology, and livestock production (Boval & Sauvant, 2019, 2021). For cattle, understanding how quickly and efficiently an animal harvests forage has far-reaching implications, from predicting daily dry matter intake to designing optimal grazing management systems. Yet despite its apparent simplicity, bite rate proves to be a surprisingly complex variable shaped by a web of interacting factors including sward structure, bite mass, animal physiology, and behavioural adaptation.

The scientific journey to understand cattle bite rate spans well over a century, evolving from rudimentary field observations and manual tallying by stopwatch to sophisticated electronic jaw movement recorders, GPS-linked accelerometers, and machine-learning algorithms. This document traces that journey, examining how each era of research built upon the last, shifted prevailing assumptions, and opened new questions about how cattle interact with their grazing environment.

### 1.2 Early Foundations: Observations and Descriptive Studies (Pre-1950)

Interest in the feeding behaviour of ruminants predates the formal discipline of animal science. Agricultural observers as far back as the eighteenth century noted that cattle grazing on lush, dense pastures appeared to eat more quickly and with greater satisfaction than those on sparse or drought-affected swards. However, these observations were anecdotal and lacked any systematic quantitative framework.

Researchers conducting pasture utilization studies began to record both the duration of grazing bouts and rough estimates of bite frequency, typically by direct observation and counting, often with the aid of a simple stopwatch. These early counts were painstaking and prone to observer error, but they established a baseline understanding: cattle under typical grazing conditions took somewhere in the range of 40 to 70 bites per minute, a figure that would be refined but not dramatically overturned by later, more rigorous studies.

## 1.3 The Intake Equation: Formalising Bite Rate in the Mid-Twentieth Century (1950s–1960s)

The post-war era brought a revolution in grassland science, driven by the need to intensify agricultural production and by new institutional investment in animal and pasture research. In the United Kingdom, the Grassland Research Institute at Hurley became a leading centre for studies of grazing behaviour. Similarly, institutions in New Zealand, Australia, France, and the Netherlands invested heavily in understanding pasture-animal interactions during this period.

A landmark conceptual advance came with the formalization of what researchers began to call the "intake rate equation," which expressed herbage intake as the product of grazing time, bite rate, and bite mass. This simple multiplicative model had enormous practical and scientific consequences because it implied that animals could compensate for changes in one variable by adjusting another. A cow facing a short sward with small bite mass might increase bite rate or grazing time to maintain adequate intake. Conversely, on a tall, dense sward with large bite mass, bite rate might decline without any penalty to total intake.

$$\text{Intake} = \text{Bite Rate} * \text{Bite Weight} * \text{Grazing Time}$$

Studies by researchers such as Hancock (1953) and later by Freer, Arnold, and colleagues in Australia brought careful field measurements to bear on these questions. These workers employed direct observation methods, trained observers quietly following individual animals and counting jaw movements or discrete biting actions and began to describe how bite rate varied with sward height and density. The general finding was that bite rate tended to decrease as sward height increased, because cattle needed more time per bite to sever longer forage stems and manipulate larger quantities of herbage in the mouth. Conversely, on very short swards, bite rate could increase but bite mass became so small that overall intake per unit time fell, creating the concept of a critical sward height below which intake became severely limited.

## 1.4 The Sward Structure Era: Canopy Architecture and Bite Rate (1960s–1980s)

From the mid-1960s through the 1980s, research on cattle bite rate became increasingly intertwined with the emerging discipline of sward structural analysis. Scientists recognized that it was not simply the height of a pasture that determined how cattle grazed it, but the entire three-dimensional architecture of the plant canopy: leaf area index, stem density, the proportion of stem versus leaf material at different horizons, and the spatial distribution of digestible versus less digestible components.

Work by Stobbs (1973, 1974) in tropical pastures was particularly influential. Stobbs demonstrated that cattle grazing tropical grasses such as Setaria and Pangola grass had markedly lower bite masses than those grazing temperate species like perennial ryegrass at comparable herbage allowances. He attributed this to differences in sward architecture; tropical grasses tended to present a more vertically distributed, stemmy structure that made it harder for cattle to harvest large mouthfuls. Crucially, Stobbs (1973, 1974) showed that cattle partially compensated by increasing bite rate on difficult swards, but this compensation was incomplete, leading to lower overall intakes on structurally challenging pastures.

During the same era, researchers in New Zealand, particularly at Massey University and the Ruakura Agricultural Research Centre, conducted extensive studies on dairy cow grazing behavior under rotational and continuous grazing systems, most notably C.P. McMeekan's seminal Ruakura work on rotational versus continuous grazing management (McMeekan & Walshe, 1963). These studies confirmed the inverse relationship between sward height and bite rate (Figure 1.1) and began to articulate optimal sward surface heights for dairy production, a concept that would eventually influence the development of New Zealand's highly influential farm systems research tradition.

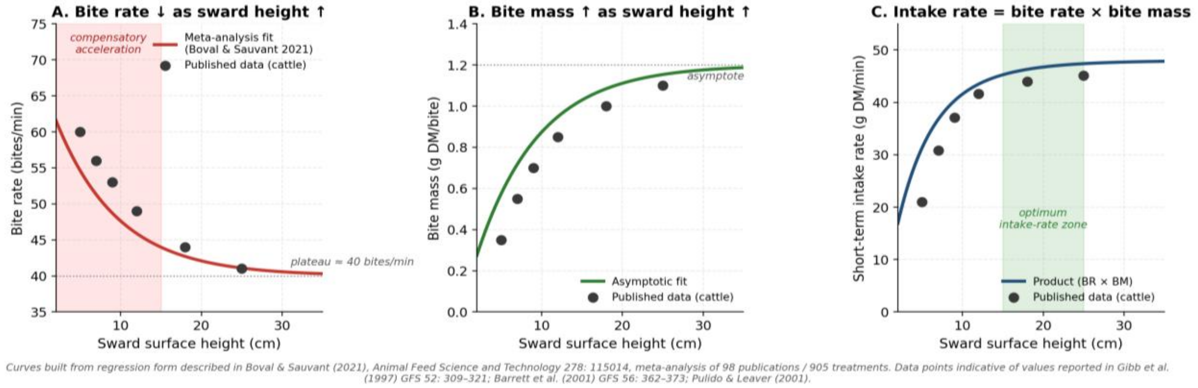
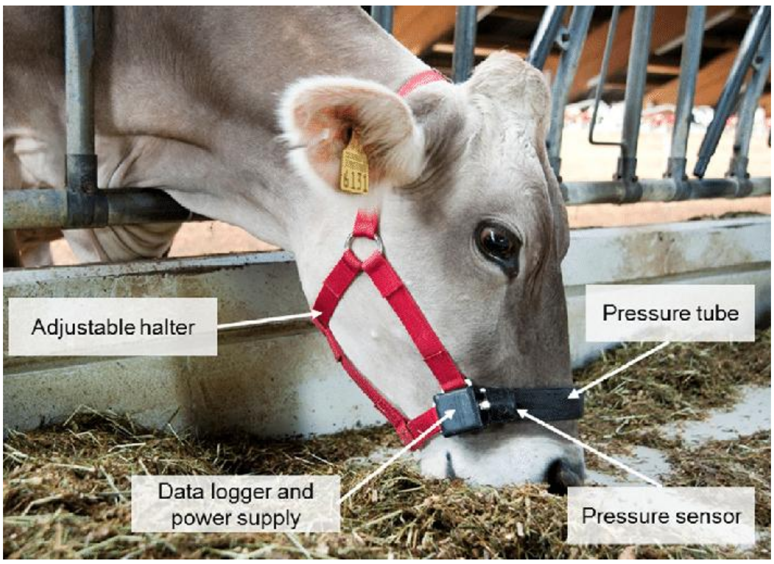



Figure 1.1: Interaction of bite rate and sward height in grazing cattle, adapted from McKeekan & Walshe (1963), Gibb et al (1997), Barrett et al (2001)

Methodologically, this era was still largely reliant on direct observation, though some researchers began experimenting with early electronic aids. Simple event recorders attached to head collars or jaw halters could detect the rhythmic lateral and vertical movements of the mandible associated with prehension biting, and early versions of what would become the "jaw movement recorder" were developed in several laboratories. These devices allowed researchers to record grazing events over longer periods without the exhausting demand of continuous human observation.

## 1.5 Electronic Revolution: Jaw Movement Recorders and Behavioural Differentiation (1980s–1990s)

The 1980s marked a turning point in the precision with which bite rate could be studied. The development and commercial refinement of electronic jaw movement recorders (JMRs) devices fitted to a halter around the muzzle that detected the electrical or mechanical signal of jaw closure during biting enabled continuous, automated recording of grazing activity over periods of many hours or days. This represented a qualitative leap beyond what was possible direct observation.




Picture 1.2 (RumiWatch noseband sensor)

Crucially, JMRs allowed researchers to distinguish between the two main jaw movement types in a grazing animal: prehension bites (the forward, cropping motion by which cattle sever herbage) and mastication chews (the lateral grinding movements used to process the bolus before swallowing and during rumination).

Distinguishing these two behaviours was essential because only prehension bites constitute "bite rate" in the intake sense, yet they are intertwined with chewing sequences during active grazing. Early algorithms to automatically classify jaw movement sequences from JMR data were developed by Penning (1983) at Hurley and by Rutter and colleagues in subsequent years, laying the groundwork for what became a cottage industry of behavioural classification research.

With JMRs came the ability to study diurnal patterns of bite rate and how grazing intensity varied across the day. Research consistently showed that cattle exhibited distinct peaks of grazing activity around dawn and dusk, with lower and more variable activity during midday hours, particularly in warm conditions. Bite rate within active grazing bouts was found to be relatively stable within an individual animal grazing a given sward, but varied considerably between animals and between sward conditions, reinforcing the importance of individual animal variation as a research consideration.

The same decade also saw increasing theoretical development. Ungar and Noy-Meir (1988) and later Laca and colleagues developed mechanistic models of bite rate and intake rate that attempted to describe, from first principles, how the physical process of harvesting herbage determined the rate at which an animal could acquire energy from a given sward (Figure 1.3). These models treated the bite as a physical process governed by the depth of the grazing horizon, the bulk density of the canopy, the resistance of stems to shearing, and the geometry of the animal's dental arcade; bringing a biophysical rigor to what had previously been a largely descriptive enterprise.

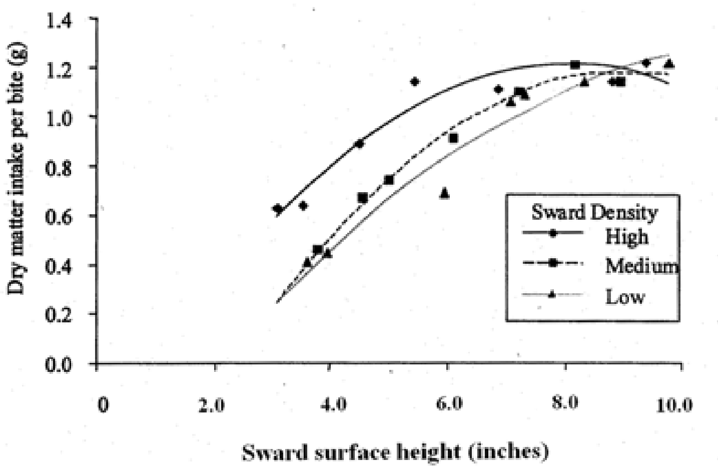



Figure 1.3: Effect of sward hight on bite weight
From: Effect of Sward Height and density on bite dimensions of cattle (E. Laca 1992)

This era brought formal mathematical modelling on bite research, predicted bite rate by analysis of the sward.

## 1.6 Laca and the Acoustic Approach to Bite Detection

Among Emilio Laca's most distinctive contributions to the study of cattle bite rate was his development and application of acoustic sensing techniques. His paper "Acoustic measurement of intake and grazing cattle behaviour" is the paper most referred to by other colleagues in this topic. The core insight was straightforward but powerful: the act of a cow biting through herbage produces a characteristic sound, a brief acoustic event generated by the shearing of plant tissue between the incisors and dental pad that is distinct from the sounds of chewing, swallowing, or movement. If that sound could be reliably detected and counted, it would offer a non-invasive, continuous, and potentially highly accurate record of bite rate without the need for physical attachment of jaw movement sensors or the labour demands of direct observation.

Laca and colleagues at the University of California, working through the 1990s and into the 2000s, explored the use of small microphones mounted close to the animal's head typically attached to a halter near the muzzle or jaw to capture these ingestive sounds. The recorded signals were then subjected to acoustic analysis, including frequency spectrum decomposition and amplitude thresholding, to identify and count discrete bite events (Figure 1.4). Early validation work demonstrated that acoustic bite detection could achieve good agreement with simultaneously recorded jaw movement data and with visual observation under controlled conditions, particularly when animals grazed relatively uniform swards where the acoustic signature of biting was consistent.

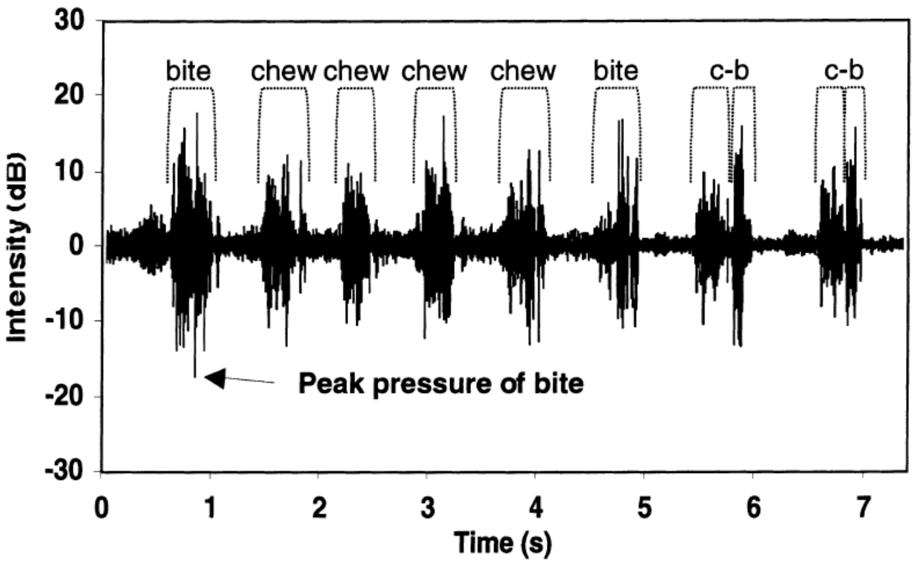



Figure 1.4: Example sound wave from a series of chews, bites and chew-bites

From: Acoustic measurement of intake and grazing behaviour in cattle (E. Laca 1999)

One of the most scientifically significant findings to emerge from this acoustic work was the relationship between the acoustic properties of individual bites and the characteristics of the forage being harvested. Laca's group showed that the duration, amplitude, and frequency content of the bite sound varied systematically with sward structure. Bites taken from tall, leafy, relatively easy-to-sever herbage produced shorter, sharper acoustic events, while bites from stemmy or fibrous material produced longer, more complex signals reflecting the greater mechanical work required to sever tougher plant tissue. This opened a remarkable possibility: that acoustic analysis of bite sounds could provide not only a count of bites per unit time, but also real-time information about the structural quality of the forage being consumed. Effectively, a continuous readout of what type of material the animal was eating and how much resistance it was encountering.

Further work by Laca and colleagues (Laca et al., 2000) examined the relationship between acoustic bite parameters and bite mass. Using a combination of acoustic recording and careful measurement of herbage removed per bite achieved by cropping techniques or by difference weighing of vegetation before and after known grazing periods, Laca's group demonstrated statistically significant correlations between certain acoustic features and bite mass. Longer, louder bites with more energy in the lower frequency bands tended to correspond to larger bite masses, consistent with the physical interpretation that more tissue being severed generates a more prolonged and powerful acoustic signal. While the correlations were not strong enough to allow precise prediction of bite mass from acoustic data alone, they were sufficient to suggest that acoustic methods could serve as a useful proxy or supplement to other measurement approaches in studies of intake estimation.

The acoustic approach also offered important advantages for studying bite rate in difficult field environments. Traditional jaw movement recorders and halter-mounted mechanical sensors required relatively close physical management of animals and were prone to signal drift and mechanical failure under prolonged field use. A well-mounted microphone with robust signal processing, by contrast, could in principle operate over extended periods with minimal disturbance to the animal. Laca's group explored configurations that allowed wireless transmission of acoustic data to a base station, anticipating by a decade the kind of remote behavioural monitoring systems that would become standard in precision livestock farming research.

The limitations of the acoustic approach were also candidly documented. Background noise wind, rain, the sounds of other animals, hoofbeats, and ambient farm noise posed persistent challenges for automated bite detection algorithms, particularly in outdoor grazing environments. Signal processing techniques including bandpass filtering, adaptive thresholding, and template matching were applied with varying degrees of success to discriminate true bite events from noise, but robust performance across a wide range of weather and sward conditions proved difficult to achieve with the computational tools available at the time. Later researchers revisiting acoustic bite detection with modern machine learning classifiers have achieved considerably better results, and Laca's foundational work is widely credited with establishing the feasibility and theoretical basis for this line of inquiry.

Beyond the acoustic work, Laca's broader program of research on bite mechanics contributed substantially to understanding the physical determinants of bite rate. His detailed analysis of how cattle position themselves relative to a sward horizon, how the incisor arcade sweeps through the canopy during a prehension bite, and how the geometry of tongue manipulation and lip movement affects the quantity of herbage captured, provided a mechanistic foundation for predicting bite rate and bite mass from measurable sward properties. This biophysical approach, integrating plant science, biomechanics, and animal behavior, helped move the field beyond purely empirical descriptions toward a more predictive, model-based science of grazing.

## 1.7 Integrating Nutrition and Behavior: Bite Rate, Selectivity, and Diet Quality (1990s–2000s)

By the 1990s, research on bite rate had expanded well beyond its original focus on total dry matter intake to encompass questions of diet quality and selective grazing. It became clear that cattle were not simply vacuum cleaners hoovering up whatever herbage was in front of them; rather, they were active selectors, preferentially targeting high-quality leaf material and avoiding stemmy or senescent plant parts when sward structure permitted. The rate at which cattle bit, and the spatial patterns of their movement through a paddock, were closely linked to this selectivity behavior.

Research by Prache, Gordon, and others demonstrated that when sward conditions forced cattle onto structurally complex or heterogeneous pastures, bite rate changed in response to the spatial patchiness of high-quality forage. Animals increased movement rates and shortened biting sequences when foraging in poor patches, while settling into longer, higher-rate biting sequences in rich patches. This research integrated bite rate into the broader framework of optimal foraging theory, which predicts that animals should allocate time and effort in ways that maximize energy or nutrient gain per unit time.

The relationship between bite rate and rumen fill also received growing attention during this period. Earlier work had established that cattle reduce grazing activity as the rumen fills, eventually stopping to ruminate when physical distension reaches a threshold. Researchers now examined how bite rate itself might change as the rumen filled during a grazing bout a phenomenon sometimes called "within-meal deceleration" and found subtle but measurable reductions in bite rate toward the end of prolonged grazing bouts, suggesting a feedback mechanism linking gut fill to ingestive behavior.

## 1.8 Precision Livestock Farming: Sensors, Algorithms, and Real-Time Monitoring (2000s–2020s)

The first two decades of the twenty-first century brought a dramatic expansion of technological tools available for studying cattle bite rate, coinciding with the broader emergence of precision livestock farming as a discipline. GPS collars, tri-axial accelerometers, acoustic sensors, and machine-learning classifiers transformed what had been a painstaking research methodology into a potentially scalable monitoring technology.

Accelerometers fitted to the jaw, ear, or neck of cattle could detect the characteristic motion signatures of grazing bites, and researchers developed increasingly sophisticated algorithms to distinguish biting from chewing, grazing from ruminating, and active foraging from walking or resting. Early work by Ungar and colleagues and by Gibb and others at Scottish Agricultural College demonstrated that accelerometer-based systems could achieve agreement levels of 85–95% with manually observed jaw movements under favourable conditions, though performance varied with sward type, animal breed, and sensor placement.

The integration of GPS with behavioural sensors enabled a new generation of spatially explicit studies. Researchers could now map not only when cattle were biting, but precisely where in a paddock biting occurred, at what rate, and in relation to sward measurements taken across the same landscape. Studies in Ireland, New Zealand, and France used these combined systems to show how cattle distributed bite rate across heterogeneous swards, confirming and extending earlier theoretical predictions from optimal foraging models.

At the same time, research attention shifted toward the genetic basis of grazing behavior. A meta-analysis of cattle behaviour traits found heritability estimates ranging from 0.01 to 0.44 (Alam et al., 2019), and more targeted work on feeding-pattern phenotypes in lactating Holstein cows has begun to quantify heritable variation in feeding behaviour and its genetic correlation with feed efficiency (Cavani et al., 2024), though direct heritability estimates for pasture bite rate specifically remain limited. The possibility of selecting for more efficient grazing animals with high bite mass and moderate bite rate, capable of achieving adequate intake on challenging swards opened a new frontier connecting behavioural research with genomic selection programs.

Machine learning brought further advances. Deep learning models trained on large datasets of jaw movement recordings could classify behavioural states with accuracy approaching that of expert human observers and could generalize across animal breeds and sward types more effectively than the rule-based algorithms that had dominated the field since the jaw movement recorders era. Commercial products incorporating these technologies have brought bite rate estimation capabilities to commercial farms for the first time, primarily for health and welfare monitoring rather than nutritional management, but with clear potential for the latter.

## 1.9 The MINDY Model

Pablo Gregorini from Lincoln university published a paper in 2013 based on an empirical modelling software, he developed (MINDY) that essentially is a virtual cow, to simulate mathematically real grazing conditions where bite rate was not only affect by sward architecture, but also by diurnal patterns of ingestive and digestive behaviours, hunger, rumen fill, satiety, animal genetics and heterogenous swards.

The key mechanisms encoded are:

- **Diurnal grazing patterns**
  Cattle show bi-modal grazing behaviour with peaks of activity at dawn and dusk, that is influenced by circadian cycle, hormones (ghrelin, insulin and glucose) and management (break allocation).
  Gregorini's work demonstrated that timing of herbage allocation alters grazing, rumination, and idling patterns, and that afternoon allocation leads to longer and more intense grazing bouts when herbage has greater quality, which improves cattle performance.

- **Diet selection**
  This module captures the well-documented phenomenon where animals with low rumen fill graze relatively non-selectively, accepting lower quality material, while animals approaching satiety become increasingly selective, slowing their bite rate but seeking higher quality patches.
  The implication for bite rate studies is that the relationship between sward state and bite rate is not constant across the grazing bout, it changes as a function of rumen fill in ways that the diet selection module can simulate but that are difficult to account for without some measure of fill state.

- **Hunger**

Rumen fill exerts short-term control over feeding motivation through mechanoreceptors in the rumen wall that respond to physical distension

In this experimental foundation by manipulating rumen fill directly to rumen-cannulated cows and observing the resulting changes in bite mechanics, Gregorini established the quantitative relationships that MINDY encodes. The finding that bite rate, bite mass, and jaw movement patterns slowed down at the termination of the grazing bout. Furthermore, he found that the "rate of rumen fill" is more important that the absolute level.

It also means rumen state is detectable in the ingestive behaviour signal (bite rate decrease), not just in the intake outcome.

- **MINDY's ingestion-digestion dynamics**

  This module demonstrates that the physical characteristics of each bite (particle size distribution, moisture content, chew number per bolus) vary systematically with sward structure, and that these variations have downstream consequences for digestion rate and therefore the timing of satiety signals. On short, depleted swards, the reduced bite mass and altered particle size distribution slow the accumulation of rumen fill per unit of grazing time, which in turn prolongs grazing bouts and elevates bite rate relative to what would be predicted from sward height alone. This finding reinforces the interpretation of bite rate as a complex integrative signal rather than a simple linear function of pasture availability.

## Key Findings and Enduring Principles

Across more than a century of research, certain findings about cattle bite rate have proven robust and are now regarded as established principles of grazing science.

Bite rate under typical grazing conditions on temperate pastures falls in the range of 40 to 70 bites per minute, with most studies of dairy cows on ryegrass-based swards reporting means in the 50–65 bites per minute range. Beef cattle tend to have slightly lower bite rates than dairy cows on equivalent swards, reflecting differences in muzzle width and incisor arcade geometry.

Sward height exerts a strong and consistent negative effect on bite rate. As sward height decreases below approximately 5–8 cm in temperate ryegrass pastures, cattle increase bite rate but with diminishing returns, because bite mass declines even faster than bite rate increases. This trade-off defines the characteristic intake curve that underlies much of modern rotational grazing management theory.

Bite rate and bite mass are inversely related across most naturally occurring variations in sward structure, meaning that animals on structurally challenging swards must invest more time per unit of dry matter harvested. This fundamental trade-off sets a physiological ceiling on intake that cannot be overcome by behavioural adjustments alone, placing real limits on the ability of cattle to compensate for poor pasture quality or structure through increased grazing effort.

Individual animal variation in bite rate is substantial and partly heritable, suggesting that genetic selection could modify grazing efficiency, though the full implications of such selection for long-term productivity and welfare remain an active area of investigation.

# Literature review. Part 2

## Cow-wearable tech

Cow-wearable technology has been around for more than 20 years. It started with pedometers to measure cow activity and through the mentioned jaw movement halters, evolved to the current devices. Adoption has grown significantly in New Zealand, from 3% of farmers in 2018 to 18% in 2023, covering more than 820,000 dairy cows (DairyNZ, 2023), with industry estimates now putting uptake at around a third of all herds.

There are a few types of devices, most popularly collars, boluses and ear tags. Despite the differences of placement all of them have tri-axial accelerometers which measure acceleration (kinetic movement) in three different directions to distinguish position and movement. Head position is very important as it changes for different behaviors like grazing, ruminating and moving.

They basically mimic the inner ear's vestibular system that sets the equilibrium and understanding of where is up.

The sensors inside are called micro-electro-mechanical systems (MEMS) devises, made of tiny silicon structures with a suspended mass that deflects under acceleration (including gravity). They are cheap to mass produce and use very little power.

The main use is for heat detection shown in devices as increases in activity with lowering rumination time, but as the data collected evolves, these devices are being tuned to identify differences in behaviors (rumination, eating, and activity) with applications for nutrition and for the detection of animal health issues.

Most devices have nuances that differentiate them in the market like detection of water intake, temperature, standing time, GIS location and virtual fencing. They all do the basics, but no device does everything.

As meta-data is being analyzed the uses of this information expand into pasture management. Prediction of pre- and post-grazing pasture mass using automated methods has the potential to improve farm system profitability. Improved and near real-time decision-making that optimizes pasture production and utilization (Stumpe et al., 2024)

## 2.1 On-animal sensors may predict paddock level pasture mass in rotationally grazed dairy systems (Paul Edwards and col.)

In Paul Edwards study, they had the objective to investigate whether a relationship could be established between behaviour classifications from on-animal sensors and pasture parameters to provide objective data on herd-level feed allocation.

Five different devices were used simultaneously on dairy cows at Ashley Dene Farm (Canterbury, New Zealand). The results suggest that this is feasible, but the accuracy may limit its usefulness.

Rumination time was the most predictive behaviour of the five sensor-derived behaviours tested. This matters because rumination is already one of the most widely reported metrics on commercial wearables, so if it also carries a usable pasture-mass signal, farmers may be able to get grazing management insight from data their devices are already producing, without needing new hardware or new behavioural channels.

Unexpectedly the result from comparing the relationship of rumination with different pasture management indicators, shows stronger correlation of pasture mass per ha rather than intake per cow (Figure 2.1). And furthermore, post-grazing residuals are predicted with higher statistical significance ($R^2 = 0.55$).

On top of the accuracy issues, with rumination being a mostly nocturnal behaviour, the pasture mass predictions require at least a 24-hour period which limits it potential use.

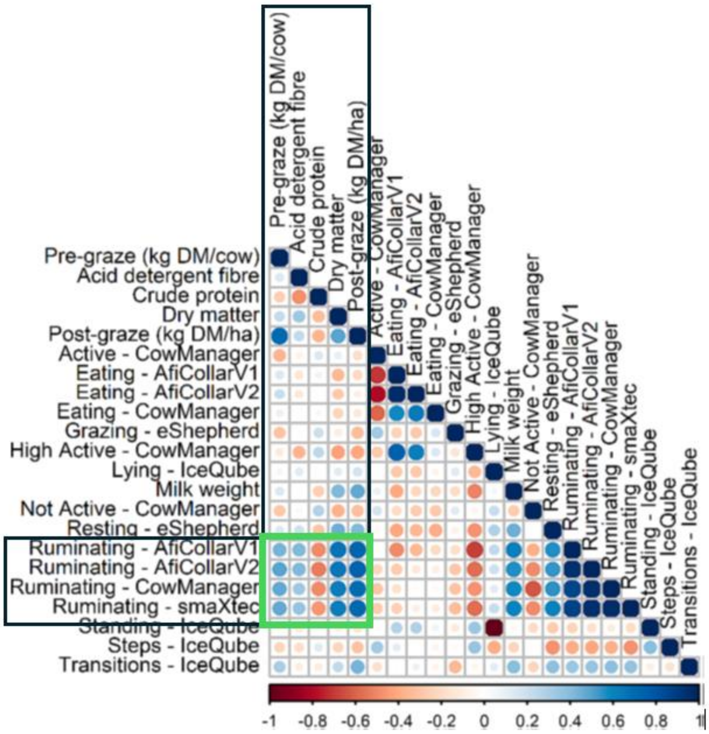



Figure 2.1: Correlation of pasture allocation and sensor recorded behaviours (Edwards et al., 2024)

## 2.2 Relationships between paddock-level pasture mass and cow data derived from GPS and behaviour-monitoring animal-sensors (S. Hendriks)

In this DairyNZ research, Hendrik follows from the previous paper and adds GPS location data (travelled distance and distance to other grazing mates). She then hypothesised that data derived from wearables and location, would be associated with feed availability in four different mobs with different feeding levels (see figure 2.2).

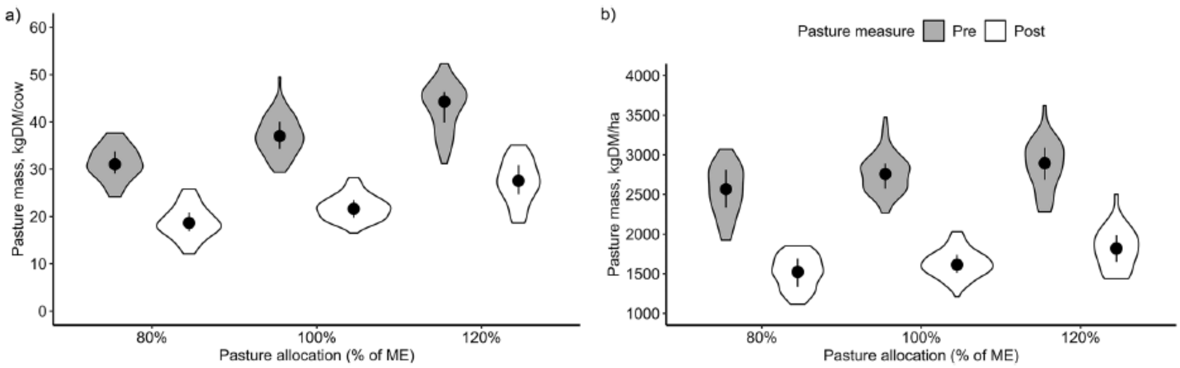



Figure 2.2. Distribution of pasture mass values recorded across four groups of dairy cows

The study explained in part the variation in pasture mass but could not reach the required level of accuracy for predictive models.

Despite the above the main takeaway is that combining and stacking behaviors improved the $R^2$ of the predictive models.

The paper also suggests that by incorporating other animal or paddock level behaviors may further improve modeling.

## 2.3 Assessing the validity of sensor-based predictions of post-grazing residuals in dairy systems

Further to the previous papers, Waynne Hofmann and col decided to test the findings of predicting pasture mass from derived animal-sensor data in an uncontrolled environment. The study was carried in a commercial farm and at NARF (Northland Agri Research Farm) which carries three different farmlets: alternative pastures, current farm system and low emissions (see figure 2.3).

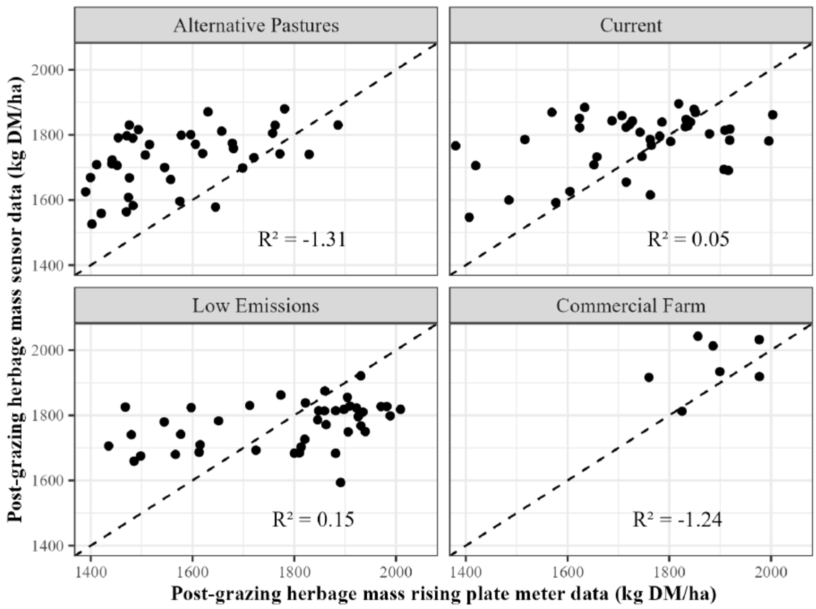



Figure 2.3: Comparison of the post-grazing mass estimate against the sensor predictive model

There was some alignment between the predicted post-grazing residuals from the sensor-based model and rising plate meter data. However, the model's explanatory ability was poor, with $R^2$ values calculated as the coefficient of determination ranging from -1.31 to 0.15 between farms.

While previous studies have demonstrated the potential of predicting pasture residuals from animal sensors, this study identified some challenges that would need to be overcome for broader application, including accounting for variations in on-farm management practices (e.g., supplement usage, frequency of pasture allocation) and pasture species diversity.

# Literature review. Part 3

## Pasture management

Optimal pasture management, including accurate estimation of herbage yield, plays a crucial role in the production of milk solids and the overall profitability of dairy farms. Pasture growth follows a seasonal pattern in temperate regions like New Zealand, making it the primary source of feed for dairy cattle (Holmes et al. 2002; Neal and Roche 2019) and providing the New Zealand dairy industry a competitive edge on the global stage due to its low-cost nature (Neal 2021). However, pasture growth is highly variable within and between years due to factors such as pests, species mix, rainfall, temperature, soil nutrient status and management (Keller et al. 2021). Such fluctuations in inter-annual variability in pasture herbage accumulation introduce significant complexity to grazing management strategies (Chapman et al. 2013).

While the topic has been extensively researched, I will focus on what's relevant to this study.

### 3.1 Post-grazing residuals

For dairy farmers utilising rotational grazing, knowledge of post-grazing residuals, which reflect the animals' feeding status, is vital. This knowledge, in conjunction with other farm data (e.g., average pasture cover and feed wedge), helps inform farm decisions such as adjusting feed supply (e.g., daily pasture allowance and supplement usage) to prioritise the utilisation of low-cost, high-quality pasture, leading to cost savings and environmental sustainability (Rotz et al. 2020; Palma-Molina et al. 2023). Such strategies aim to maximise pasture utilisation, provide a constant feed allocation to maintain milk production, decrease dependence on imported feeds, and uphold farm profitability by optimising animal and pasture performance (Holmes et al. 2002; Fulkerson et al. 2005).

Maintaining post-grazing residuals at the appropriate level for ryegrass and white clover pastures, which Barenbrug (2024) described as 5 cm or 1500 kg DM/ ha in dairy systems

- Adequate post-grazing residual level is desirable for several reasons, including maximising pasture utilisation, retaining pasture quality for subsequent grazings, and maintaining pasture in an actively growing state (Chapman et al. 2012; Roche et al. 2017).
- A lower post-grazing residual will decrease subsequent pasture regrowth and total pasture production and may reduce pasture persistence,

- while a higher residual will reduce pasture utilisation and subsequent pasture quality, lowering animal performance (McCarthy et al. 2014; Leddin et al. 2023; Barenbrug 2024).

*Therefore, consistently achieving post-grazing residual targets is at the heart of good daily pasture management.*

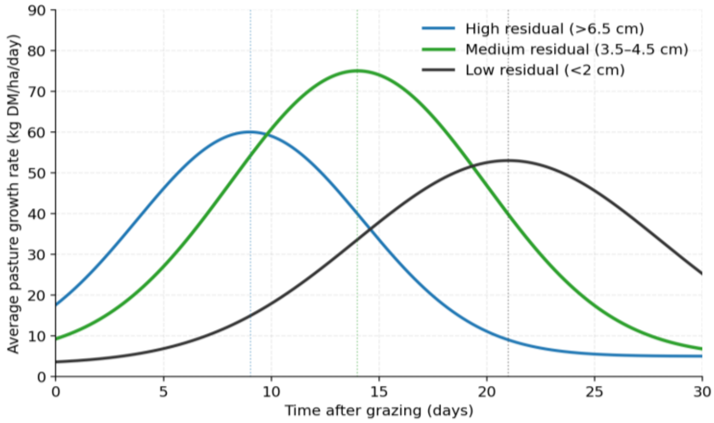



Figure 3.1: Effect of post-grazing residuals height on subsequent regrowth rate. Recreated from Parsons et al (1988)

Many farmers do not estimate pre or post-grazing pasture mass due to the inconvenience and the time required to measure pasture mass using currently available methods such as the rising plate meter (RPM) (Anderson and McNaughton 2018). Additionally, the perceived inaccuracy of the RPM due to the number of calibration equations available (e.g., variations by season, region and pasture species) to convert the RPM readings into a measure of herbage mass further discourages its use (Lile et al. 2001). Previous studies have found visual estimation of herbage mass by trained observers to be more accurate than using a RPM (L'Huillier and Thomson 1988; O'Donovan et al. 2002). Due to these disadvantages of the RPM, many farmers rely on subjective measures (e.g., visual assessment), intuition, and experience from previous seasons to make farm grazing and feeding decisions (Leddin et al. 2023), making daily pasture management observations an art as much of a science (see figure 3.2).

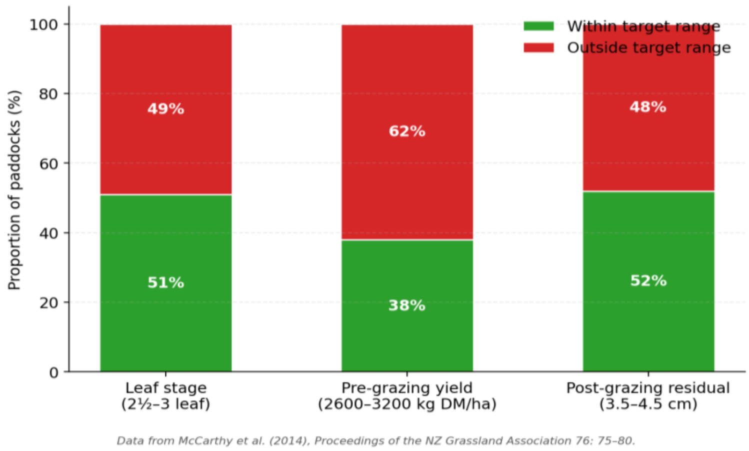



Figure 3.2: Proportion of paddocks meeting grazing management targets as per trial run by DairyNZ on monitor farms (2012-2013)

Incorporating measured pre- and post-grazing data regularly (e.g., weekly) in such decisions with other farm data can facilitate maintaining optimal animal feeding levels, pasture utilisation, and pasture quality by enabling early detection of under or overfeeding situations and pasture surpluses or deficits, therefore allowing for timely management interventions.

## Conclusions from literature review

Research into cattle bite rate has travelled a long road from the stopwatch-equipped observers of early agricultural stations to the machine-learning-enabled sensor systems of the modern precision farming era. Throughout this journey, the core scientific questions have remained remarkably stable: how fast do cattle eat, what determines that rate, and how can understanding it help us feed animals more efficiently while managing pastures more sustainably?

From the learnings from these papers, very important foundations were set for optimal pasture and grazing management. The most relevant for New Zealand are pasture density, sward length and the post-grazing residuals.

Looking forward, several frontiers appear particularly promising. The integration of high-resolution bite rate data with real-time pasture biomass models, could allow dynamic grazing management decisions to be informed by continuous animal behavior data.

The application of genomic tools to identify the molecular basis of heritable variation in bite rate could open pathways to selective breeding for grazing efficiency. And the deployment of bite rate monitoring at commercial scale, if validation challenges can be overcome, could give farmers an unprecedented window into the nutritional status of their herds at pasture.

The translation of few-animal mechanistic predictions to herd-scale empirical measurement using commercially available wearable platforms represents the next frontier in this research area. Whole-herd instrumentation, combined with spatially resolved pasture measurement and careful accounting for the confounding variables, offers a tractable pathway to the development of real-time, estimation from animal behaviour, a tool with significant practical value for the management of New Zealand's pastoral based dairy systems.

# Method- Field trials

## 4.1 First research question:

**Can we estimate bite rate using existing cow-wearable technology?**

### Bite Detection from in-ear sensor Accelerometer Data Analysis

**Materials and method**

- Two steers (2501 and 2502) wearing in-ear sensors (ProTag), grazing a heterogeneous pasture with rough patches of poor quality grass, some rushes, swales, and fresher patches of grass.
- Video recording period 09:00am to17:00pm on 11$^{th}$ of May 2026. For visual count of bites and observation of grazing behaviour
- Data per animal: triaxial accelerometer at 12.5 Hz (X, Y, Z)
- ProTag's 4-class behaviour classifier at ~12-second resolution.
- The file was exported to compare the videography with the accelerometer data.
- Data analysed using AI tool (Claude)

**Behaviour classifier**

The in-sensor classifier emits one label per 12-second window with 4 classes: grazing; rumination, walking/active and resting / inactive (Table 4.1.1).

Table 4.1.1: Totals for the two animals during the 8 hours period were:

| Class | 2501 (min) | 2502 (min) | Comment |
|---|---|---|---|
| Grazing | 276 | 277 | within 1 minute of each other |
| **Rumination** | **83** | **94** | **2502 ruminated 11 min more**<br>**13% difference maintained 85% of the time (14 days)** |
| Walking | 21 | 16 | similar |
| Resting | 98 | 92 | similar |

**Analysis of accelerometer data**

The data collected from the accelerometer takes 12.5 samples per second for each of the three-axis measured (135,000 data points per hour) (Table 4.1.2):

- Y axis: vertical movement (up and down)
- Z axis: nodding (forward-backwards movement)
- X axis: lateral movement (side to side)

Table 4.1.2 sample of raw data exported from a tri-axial accelerometer

| milliseconds | x | y | z |
|---|---|---|---|
| 1.77845E+12 | 1535 | 1479 | 208 |
| 1.77845E+12 | 1505 | 1520 | 75 |
| 1.77845E+12 | 1437 | 1487 | 115 |

Here is also a graph showing what the raw accelerometer data looks like for information collected during one minute (Figure 4.1.1), in the graph you'll see three lines, one for each axis measured.

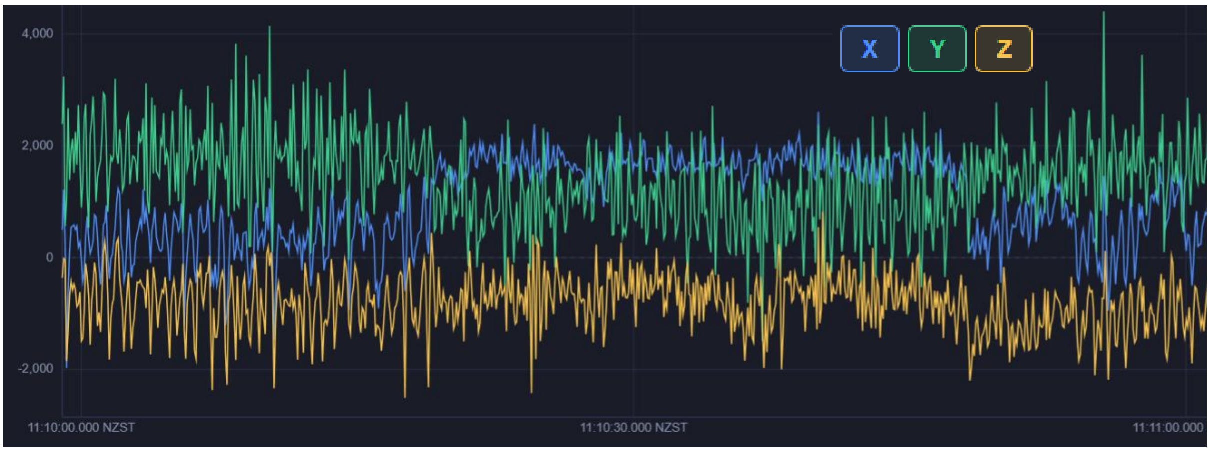



Figure 4.1.1: Sample accelerometer data in a line graph

The data pictured is somewhat like the audio waves in the E. Laca and E. Ungar acoustic studies. Perhaps we can extract information about sward from the derived data.

From the raw data extracted from the accelerometer throughout this study, these are the main indicators looked at for each axis with its sample graphs:

- Local maxima: number of peaks in the axis (see figure 4.1.2)
- Local minima: number of troughs in the axis
- Magnitude: $\sqrt{(Y^2+Z^2)}$ combines nodding and vertical movement of Y&Z (bite movements) (see Figure 4.1.3)
- Mean (see table 4.1.3)

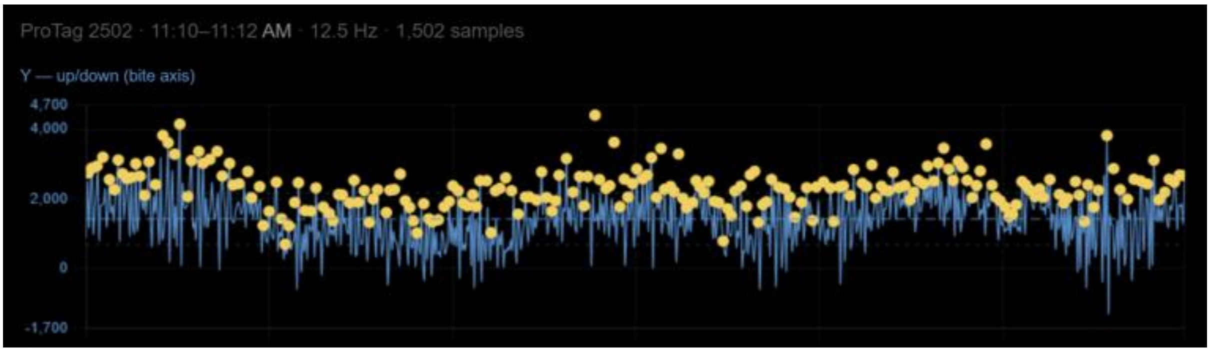



Figure 4.1.2: Y axis local máxima

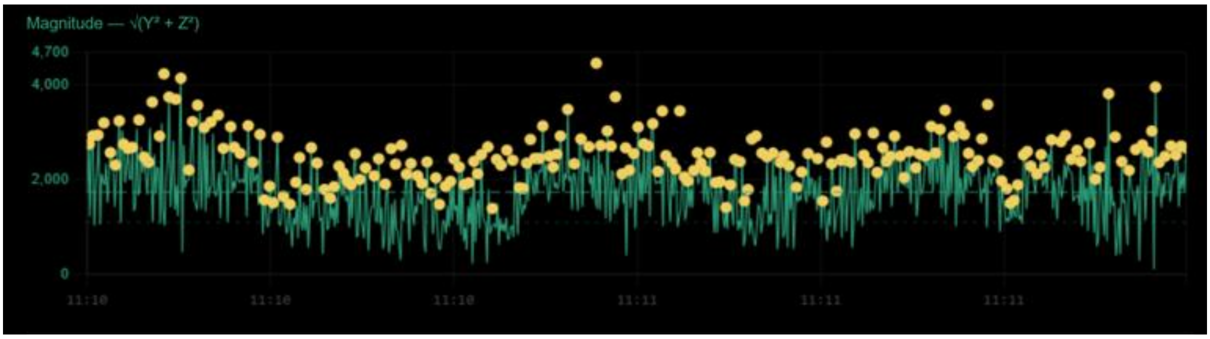



Figure 4.1.3: Combined Y+Z axis into Magnitude √(Y²+Z²)

Table 4.1.3: Mean and other metrics reviewed

— Y — Z — X — Mag ● Local maxima ---- Mean ±1 SD

| | | | | | |
|---|---|---|---|---|---|
| Y mean 1,428 | Y SD 743 | Y peaks 215 | Z mean -726 | Z SD 540 | Z peaks 210 |
| X mean 1,065 | X SD 681 | X peaks 206 | Mag mean 1,733 | Mag SD 638 | Mag peaks 214 |

**Bite detection algorithm creation – A journey of iterations**

After aligning the timestamp of the accelerometer data and video, by identifying a spike event, I provided AI with the hand bite count to compare against the data for the same period. After testing, the following pipeline produced bite counts within the hand-counted range (i.e. bites manually counted by eye from the video footage, used as the ground-truth benchmark) without over-counting on non-grazing minutes. First attempt:

1. Gate on classifier output: only run detection on samples within class-0 windows
2. Compute Magnitude signal: $M = \sqrt{Y^2 + Z^2}$. Using magnitude rather than a single axis collapses the ~240 ms phase lag between Y peaks and Z troughs into a single event per bite.
3. Detect peaks in Magnitude with minimum spacing 10 samples (0.8 s, the physiological ceiling for bite cadence (75 bites/min)) and
4. Minimum prominence 900, to filter ripples and small movements not related to bites

Raw peaks shown in accelerometer data shown 210 and 202 peak counts (see figure 4.1.4), overcounting bites roughly 4-fold during active grazing (the sensor motion produces ~4 ripples per bite). The minimum-spacing rule collapses these clusters; the prominence rule excludes lower-amplitude motions characteristic of chews or other "noise".

On the validation minute (11:10–11:11 for steer 2502) the detector returned 47 bites against the hand count of 50 bites/min.

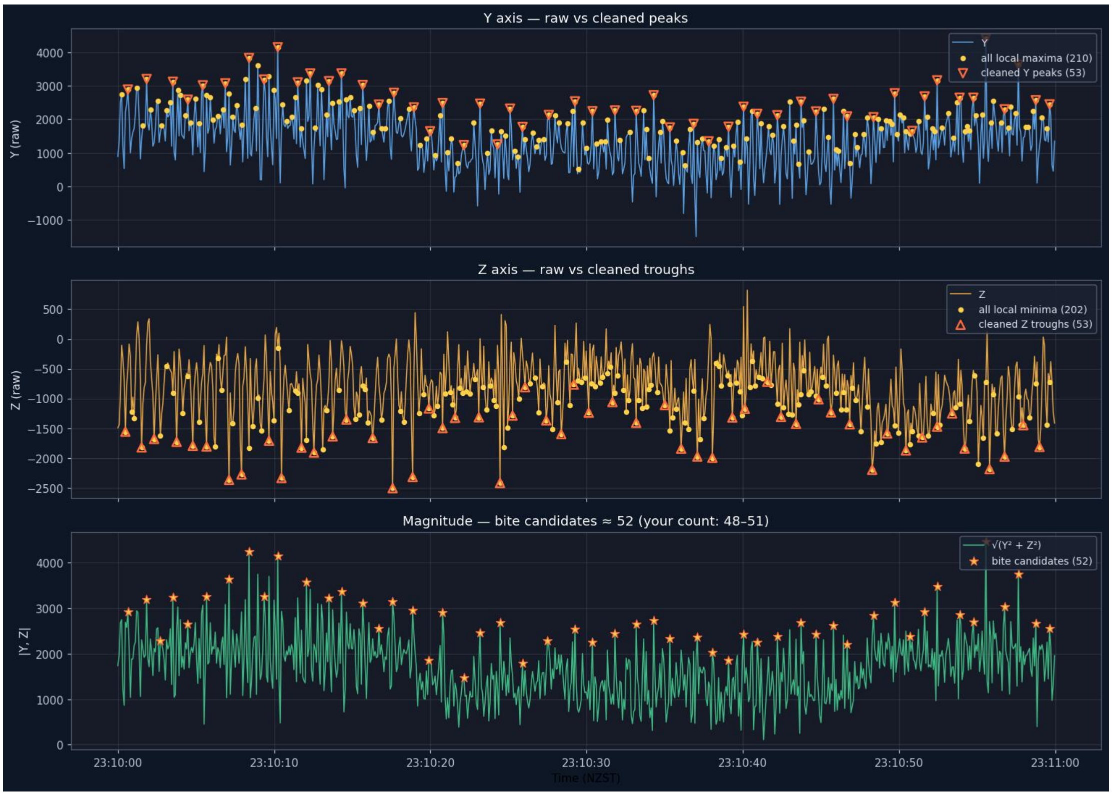



Figure 4.1.4: Identification of bite candidates (magnitude), from Y & Z axis

Once bite detection algorithm was developed a threshold of Prominence (minimum hight of accelerometer data) was used to classify as bites and then run the algorithm on the rest of the grazing data for the day.

**Estimated bite rate from the whole grazing bout**

From the algorithm developed we then proceeded to analyse the prediction for the whole grazing day.

The findings from the whole day analysis shown some promising patterns where grazing bouts get shorter towards the end of the day, and there are reductions identified in predicted bite rate with rumen fill, in line with literature from Pablo Gregorini's MINDY work.

*However, a red flag arose in the range within Bite Rate,*
*as all predictions were below 60 bites/min which confronts with literature*
*and paddock observations.*

**Testing the algorithm prediction against a different visual bite count**

I then looked at videos again but this time from a lush patch of more homogenous sward, shorter grass (circa 2,600 kgDM/ha) and pasture of visually better quality. I counted the bites manually for a 40 second period of clear footage and compared with the predictions from the algorithm.

The visual count yielded 66 bites/min. This is a good test as the validation windows have very different rates. But while the hand count was 66 bites/min, predictions were 48 bites/min (27% miscount).

Why the algorithm may have under-detected:

- **High bite rate compresses bite spacing.** 66 bites/min = one bite every 909 ms. The minimum-distance rule is 800 ms. That leaves only 109 ms of safety margin, bites fall closer and get merged into one detected event. The detector physically cannot count them as separate.
- **Lush, easy bites may have lower prominence.** On easy feed, the cow shears cleanly without much head-pull, so the bite signatures are smaller missing the magnitude threshold.
- **The 12.5 Hz sample rate is the underlying constraint.** At 80 ms per sample, distinguishing two bites 700 ms apart from one bite with a long tail is genuinely hard.

*What is genuinely true is: the algorithm as currently configured is unsophisticated and not suitable for absolute bite-rate reporting across a range of conditions. In retrospect, that agreement to the original sample was partly a calibration artefact. The algorithm and my eye were tuned to agree. Showing the limitations of AI tools and their lack of discerning ability.*

**Per-bite features beyond count**

Some interesting observations were captured during the first video, where steer 2502 displayed some larger jerks of the head (backwards-pull motion) that were easy to identify in the data log's "Z" axis as deeper troughs (see figure 4.1.5).

My hypothesis is that a lower quality sward would require more effort to shear and proposed another question: Does the data (prominence of Z axis' peaks) have potential to be used as a proxy to pasture quality?

For each detected bite, I then analysed as recommended by Claude two further features:

- **Prominence**: how much the peak rises above its local neighbourhood. Proxy for kinetic work per bite.

- **Width at half-prominence**: how long the magnitude excursion lasts. Proxy for whether the bite is a fast clean shear or a slow tough pull.

Figure 4.1.5: Visual identification of large head pull matched with a short delay in the data

But when comparing with the second video, results were inconclusive as the depth of the troughs in the Z axis (magnitude of prominence) where very similar in both samples, refuting the hypothesis of effort being related to quality. My logic to explain this behaviour is that cows are uber-efficient and apply the same effort during grazing, but that force can be either allocated to a smaller bite of a hard sward or to a larger bite of better quality grass.

However, there was other findings in the data that differentiated between the rough and lush patches:

- The directional motion of the bite pull does discriminate, the lush grass patch produced a much smaller median Z signal, and Z:Y ratio (see table 4.1.4 below). Vertical pull amplitude rather than total bite energy appears to be the candidate for kinetic correlation of sward characteristics.

Table 4.1.4: difference in accelerometer derived date from two different quality grazing patches

| Metric | 11:10 window (rough patch) | 15:11 window (lush patch) | Difference |
|---|---|---|---|
| **Hand-counted bite rate** | 50/min | 66/min | +32% |
| **Median Z/Y ratio at bite peak** (directional motion of pull) | **0.33** | **0.14** | **lush ≈ ⅓ of rough** |
| **Head pitch (median X – Z)** | **1973** | **996** | **lush ≈ ½ of rough** |
| **Z local Maxima** | 203 | 176 | Less vertical wobble on the lush patch |
| **Z range (max – min)** | 3328 | 4887 | more variable on lush |
| **Median peak width** | 128 ms | 186 ms | +45% on lush |

This two are strongly associated, and inversely related with Bite Rate

This improves the picture from the earlier in-bite analysis: head-pose extremity (X−Z) and per-bite Z amplitude both shifted between the two swards, while overall bite-event prominence stayed similar. The Z axis is genuinely telling the story of how she is engaging the sward.

However on further observation, I questioned how differences in tag placement, ear shape and slope would affect head pitch and Z axis measures

**Sensor mounting and the importance of a baseline**

A finding that came out of re-analysing the data is that the two sensors were not mounted in identical orientations. Using only rumination and resting periods as the reference (the most reliable static state, since the animal is still and the sensor records only gravity), the head pitch differs between the two tags by about 13° and the roll by about 8°. (Table 4.1.5)

Table 4.1.5: sensor mounting baseline calibration

| | Static X | Static Y | Static Z | Static head pitch | Static roll |
|---|---|---|---|---|---|
| **2501** | +125 | +2,022 | −234 | +6.3° | +3.4° |
| **2502** | +419 | +1,933 | +270 | −7.4° | +11.5° |
| **Difference** | | | **504** | **13.7°** | **8.1°** |

This matters because comparisons of raw Z values across animals are partly comparing mounting angles, not behaviour. Each animal needs its own baseline before any meaningful cross-animal feature comparison can be made.

When the whole grazing day Z is expressed as a deviation from each animal's static baseline, the picture changes (Table 4.1.6):

Table 4.1.6: deviation correction from static baseline

| | Static baseline Z | Median Z while grazing | Behavioural shift |
|---|---|---|---|
| 2501 | −234 | −1,139 | **−905** |
| 2502 | +270 | −577 | **−847** |

Both animals pitch their heads down by approximately 850–900 units when transitioning from static to grazing. The behavioural response is essentially identical between the two animals once mounting is factored out. The earlier findings in Z values between rough and lush patches (Table 4.1.3) reflects mounting or terrain rather than behaviour.

**Slope and posture correction**

The cleanest fix is to subtract a 10-second rolling mean from Y and Z before computing per-bite metrics. Peak detection itself stays on the raw magnitude signal. What changes is the interpretation of each peak.

**The bog**

At this stage of the field trials, it was disappointing to see that any findings made were refuted by later exploration of potential caveats.

The bite rate predicted worked on the calibration window but didn't tolerate validation due to algorithm limitations and the sensor's sampling rate; the within bite findings did not differentiate between patches; and the Z axis story was due to terrain or sensor mounting.

So, I went back to the drawing board analysing the process and the algorithm, I got inquisitive about other statistical options to try and combine them to make the Bite Rate detecting algorithm better.

Seven different approaches were tested, see table 4.1.7 below

Table 4.1.7: Approaches testes for algorithm

| Detector | Rough (hand=50) | Lush (hand=66) |
|---|---|---|
| 1. M (original magnitude) | 47/min (−6%) | 51/min (−23%) |
| 2. M² (squared magnitude) | 55/min (+10%) | 55.5/min (−16%) |
| 3. M (AC, slope-corrected) | 49/min (−2%) | 46.5/min (−30%) |
| **4. Jerk \|dM/dt\|** | **67/min (+34%)** | **70.5/min (+7%)** |
| 5. Adaptive M (P90 threshold) | 39/min (−22%) | 36/min (−46%) |
| 6. Bandpass 0.4–1.5 Hz | 51/min (+2%) | 43.5/min (−34%) |
| 7. Combined Y∧Z peaks | 41/min (−18%) | 31.5/min (−52%) |

The only detector that provided a closer figure to the faster bite rate on the lush patch is the Jerk (a time derivative of magnitude, |dM/dt|) that returned 70.5/min on the lush window where hand count was 66/min. That is a +7% error compared to the original detector's −23%.

Why jerk works? A derivative captures the onset and offset of each bite as separate transient events, rather than the peak itself. Even when two consecutive bites at 70/min are close enough that their magnitude peaks merge into a single hump (the failure of the original algorithm), the rising edge of the first and the rising edge of the second still appear as distinct events in the derivative. The 12.5 Hz sampling rate ceiling is therefore not a hard limit on bite detection. It is a hard limit on magnitude-peak detection, if it move to a derivative based approach and the ceiling moves up.

The downside of pure jerk detection is that it overcounted on the rough window by +34%. As on harder feed the cow makes lots of small sharp head adjustments, head shakes against roughage, small repositioning, jaw resettling, all that movement produce high jerk without being bites. So, a pure jerk detector needs a drafting gate.

***The hybrid jerk + magnitude detector***

The detector that best balanced both windows uses jerk to find candidates and magnitude to validate them:

- Detect peaks in the jerk signal |dM/dt| with minimum prominence 80 (these are bite onsets and offsets).
- Detect peaks in the magnitude signal M with minimum prominence 800
- Keep only those jerk peaks that have a magnitude peak within ±3 samples (validation).
- Apply a 640 ms refractory period to avoid double-counting
- Gate by classifier output (only count peaks within grazing windows).

Calibrated this way via the detector lands at 55/min on the rough window (hand 50, +10%) and 63/min on the lush window (hand 66, −5%). Within ±10% variance, which is more balanced rather than perfect, not accurate as using a hand counted measuring device but good enough for proof of concept.

When extrapolating with the new hybrid algorithm, the bite rate prediction for the whole day, see figure 4.1.6 where different morning grazing bouts can be observed with a range of bites/min. We can see changes in bite rate as animals deal with heterogenous swards and distractions, but the average remain consistent within grazing bouts. Shorter bouts tend to be of slower bite rate. And the rest period between these bouts is shorter than 5 minutes.

Figure 4.1.6: Per-Bout Bite rate (morning grazing)

In the afternoon we can observe another two grazing bouts before an hour's rumination break. These bouts particularly (see figure 4.1.7), have a downwards trend in bite rate, as expected with increasing rumen fill.

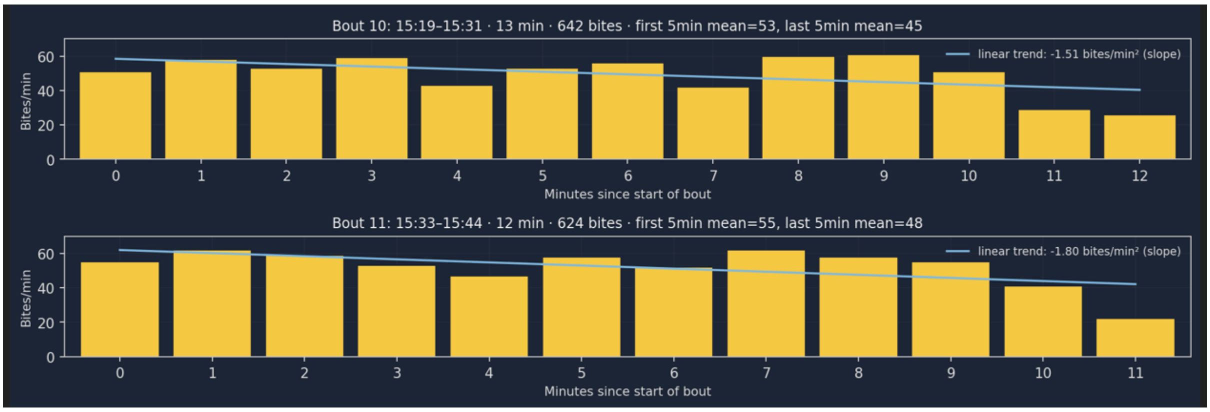


Figure 4.1.7: Per-bout bite rate (afternoon bouts before rumination)

When we look at the averages for the whole day (see table 4.1.8 below), the figures for both animals are very similar

Table 4.1.8: Full-day results with the hybrid detector

| Feature | 2501 | 2502 | Comment |
|---|---|---|---|
| **Bites detected (full day)** | 15,315 | 15,699 | ~25% more than original M-only detector |
| **Median bite rate** | 55/min | 57/min | squarely in the literature range |
| **Median magnitude at peak** | 2,972 | 2,798 | similar |
| **Median jerk at peak** | 247 | 248 | nearly identical |
| **Median peak width** | 167 ms | 151 ms | 2501 slightly slower bites |
| **Median inter-bite interval** | 965 ms | 960 ms | similar rhythm |
| **Median Z:Y ratio (AC)** | **0.63** | **0.59** | **within 7%** |
| **Median bite angle** | **32.2°** | **30.5°** | **5% difference** |
| **CV of inter-bite interval** | 0.40 | 0.39 | similar rhythm regularity |

The whole day bite rates are 55–57 bites/min which puts the result inside the band which Boval and Sauvant's (2021) meta-analysis predicts for cattle on temperate swards. The original 45/min was suspicious. The hybrid is now reporting numbers that match the literature, and the earlier worry about "all predictions below 60 bites/min" is resolved.

**Per-bite features beyond count, the multi-channel pipeline**

With 15,000+ bites per animal and slope-corrected features, four independent channels of information emerge from the same accelerometer signal that describes the Bite Strategy:

- Bite Rate: bite cadence, detected by hybrid algorithm.
- Angle of approach: Z amplitude, bite angle. How the cow is harvesting (forward shear vs more vertical lift).
- Waltzing: X-axis amplitude and lateral sway. Discussed below.
- Effort: jerk amplitude per bite, peak prominence, peak width. How hard each bite works.

All four are extractable from the same 12.5 Hz triaxial accelerometer that the ProTag sensor is already collecting. No additional hardware is needed to measure these parameters.

**A new metric: bite motion angle**

Computed as atan2(|Z_ac|, |Y_ac|) in degrees, the bite motion angle has a straightforward interpretation:

- 0° = pure forward shear (head moves in Y only, no vertical component)
- 45° = balanced motion in Y and Z
- 90° = pure vertical pull (head moves in Z only, no forward shear)

Across the whole day both animals sit around 31–32°. The cow's bite is mostly horizontal but with about 60% as much vertical motion as forward. This is the geometry of the prehension act in a single number, free of mounting and slope confounds.

**X-axis and the waltz (lateral sway motion)**

A late observation during the analysis was that when looking cows grazing, sometimes they do a lateral sway of the head while using their tongue to grab grass into the mouth, a different harvesting strategy from pure incisor shear, and that it should happen more on certain sward length conditions. The literature supports this idea, and the data does too with a useful nuance.

The clearest finding is in the power spectra. Comparing power in the "sway band" (0.2–0.5 Hz, slower than bite cadence) to the "bite band" (0.5–2 Hz):

Table 4.1.9: Sway/Bite ratio

| Axis | Sway/bite ratio (rough) | Sway/bite ratio (lush) |
|---|---|---|
| **X (lateral)** | **0.43** | **0.40** |
| **Y (forward)** | 0.09 | 0.04 |
| **Z (vertical)** | 0.19 | 0.10 |

X has 3–10 times more proportional power in the slow sway-frequency band than Y or Z (see table 4.1.9). That is the spectral signature of an oscillation slower than the bite cadence, the "waltz" rhythm. Y and Z spectra are dominated by the bite-frequency peak. X has a much flatter, more spread-out spectrum with substantial low-frequency content.

There are some differences here too between the steers in their grazing strategy, potentially related to sward or behaviour (see figure 4.1.8).

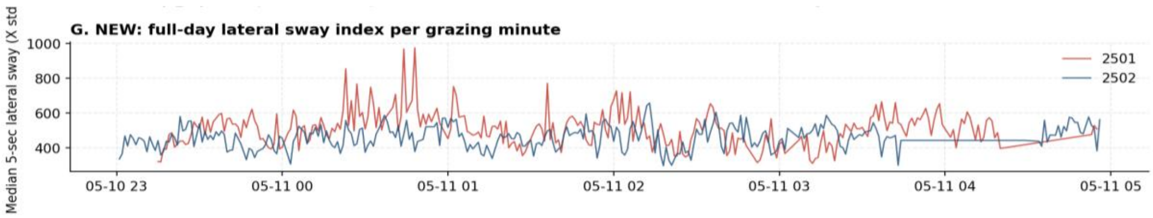



Figure 4.1.8: Full-day lateral sway index.

Per-bite lateral amplitude is different between rough and lush patches (see table 4.1.10):

Table 4.1.10: Later amplitude of X axis

| Metric | Rough | Lush | Lush vs rough |
|---|---|---|---|
| **Median \|X_ac\| at bite peak** | 274 | 362 | +32% |
| **Median X range in ±480 ms** | 958 | 1,291 | +35% |
| **Median X std-dev in ±480 ms** | 258 | 378 | +46% |
| **5-second sway index (background)** | 439 | 436 | essentially identical |

Lush conditions add bigger per-bite lateral excursions (about 30–45% larger). On rough patches the lateral excursions are smaller.

The mean that bite waveforms confirm this with lateral motion not synchronized to bites. The waltz happens on its own timescale, not in lockstep with each individual bite.

#### Rough vs lush, using the multi-channel pipeline

Pulling all four channels together, the comparison between the two windows for steer 2502 looks like this:

Table 4.1.11: Comparison of Multi-Channel Pipeline data for rough and lush patches of pasture

| Metric | Rough 11:10 | Lush 15:11 | Channel |
|---|---|---|---|
| **Hand-counted bite rate** | 50/min | 66/min | Rate |
| **Algorithm bite rate (hybrid)** | 55/min | 63/min | Rate |
| **Median peak width** | 128 ms | 173 ms | Effort |
| **Jerk at peak** | 254 | 285 | Effort |
| **Bite angle** | **21.0°** | **35.1°** | Approach |
| **AC Z amplitude per bite** | 450 | 758 | Approach |
| **Mean Z (DC) within window** | −811 | −377 | Posture |
| **Per-bite \|X\| lateral motion** | 274 | 362 | Lateral |
| **Per-bite X range in ±480 ms** | 958 | 1,291 | Lateral |

Bite angle (21° vs 35°) is the cleanest single number to summarise the difference. On the rough patch the cow shears nearly horizontally through the canopy (see table 4.1.11 above). On the lush patch she lifts and crops at a more vertical angle. Add the lateral motion finding to that and the picture becomes: on rough patches the cow takes deep, fast, horizontal shears with limited lateral motion. On lush patches she lifts, vary her bite angle, and incorporate more lateral motion plausibly tongue-wrapping on the easier-to-grasp leaves.

The discrimination of differences in bite rate, effort, approach and lateral sway when comparing two different sward characteristics, is perhaps the most important finding in this study. The multi-channel pipeline is yielding valuable information about how the cows engages with the sward.

#### Whole day cross animal comparison

The two animals are similar across every channel once mounting is properly accounted for. The differences 2501 presented lower rumination, more vertical angle of approach and more waltzing, in line with predictions of spending more time in lusher swards (see table 4.1.12 and figure 4.1.9).

Table 4.1.12: Whole day cross animal comparison

| Metric | 2501 | 2502 | Notes |
|---|---|---|---|
| **Grazing time** | 276 min | 277 min | virtually identical |
| Rumination time | **83 min** | **94 min** | **2502 ruminated 11 min more** |
| *Rumination was 40 min/day lower in 2502 (85% of the time during the following 14 days)* | | | |
| **Behavioural Z shift (grazing − static)** | −905 | −847 | **nearly identical once mounting is removed** |
| **Median bite rate (full day)** | 55/min | 57/min | nearly identical |
| Median bite angle | **32.2°** | **30.5°** | **similar bite mechanics** |
| **Median jerk per bite** | 247 | 248 | identical effort |
| Median lateral sway index | **504** | **464** | **2501 slightly more lateral motion** |

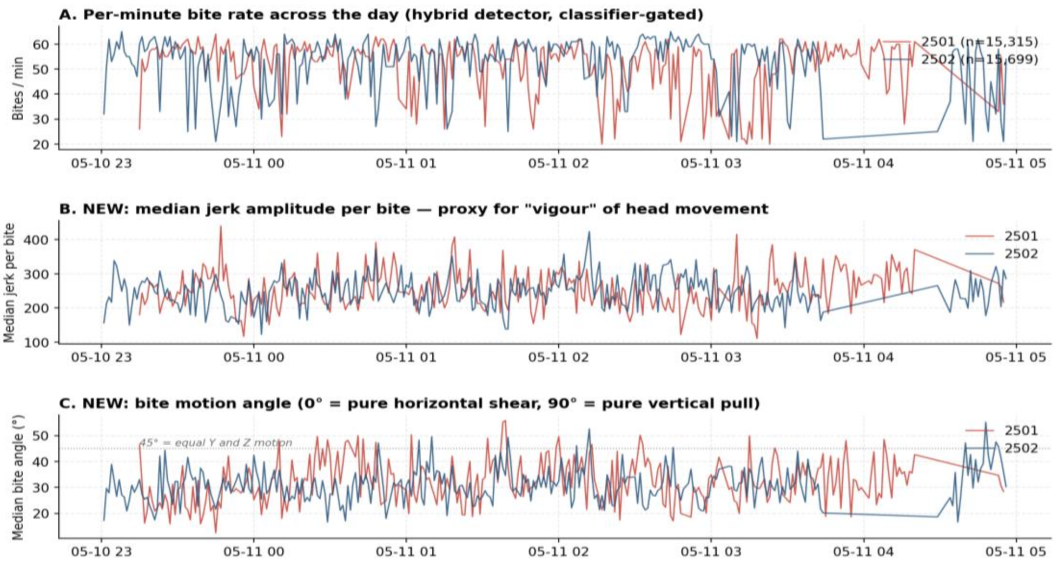



Figure 4.1.9: Full-day in-bite characteristics for 2501 and 2502 using the hybrid detector

**What this means for cow-wearable accelerometer**

Incisor-shearing bites and tongue-wrapping bites leave different signatures in the three-axial data. A pure shear bite is dominated by Y and Z motion (forward then back, with some vertical lift); a tongue-wrapping bite adds lateral X motion that does not appear in pure shear. If an accelerometer can distinguish the two on the basis of the X-axis signature, then the same wearable that measures bite count can also report on bite strategy. Bite strategy is itself a sward-state signal, since the strategy is associated with sward characteristics. This is the line of reasoning that motivates the X-axis analysis in Section 4.1, which finds that the lateral channel does indeed carry information that the bite-rate channel alone does not.

In retrospect, the original algorithm's under-counting was the most useful failure of the project. It forced a systematic investigation of alternative detection methods that returned not only a working algorithm but three additional behavioural channels in the same data. The revised analysis can be more confident: with the right algorithm and proper baseline correction, the predictions are feasible.

## 4.2 Second research question:

**Can we use bite rate as a proxy to post-razing residuals?**

**Materials and methods**

- I observed and measured bite rate using visual assessment and video recording at a commercial spring calving dairy farm in Southland on the 10th of May 2026.
- Two mobs of cows in milk were observed during morning grazing between 8am and 1pm.
    a. Young herd = 300 cows
    b. Mature herd = 580 cows
- Every hour recordings were taking for bite count and,
- Pasture covers were measured every hour by visual assessment. A calibration with plate meter was run beforehand.
- A journal was kept to record observations
- Cows were being offered 9 kgDM/cow of supplements (3kgDM/cow of silage and 6kg/cow of a PKE/DDG 80/20 blend in the cowshed)
- Estimated grass offered:
    a. Pre grazing cover 2,700 kgDM/ha
    b. Residual = 1700 kgDM/ha
    c. Area offered = 90 $m^2$/cow
    d. Estimated grass intake 9 kgDM/cow/day

**Mature herd findings**

The grazing period between end of milking (8:00 am) and the laying/rumination break had a range of Bite Rate between animals of 50-75 bites/min. It is worth noting that pasture mass doesn't drop evenly through the grazing bout and as result, the sward is visually heterogenous with patches of high untouched grass amongst areas grazed down to near residual levels. Cows grazed and selected different areas and pasture lengths, but more often a combination of both. See figure 4.2.1


Figure 4.2.1: Bite Rate examples from two random cows at 8am

Amongst the observations is worth noting that cows attitude seems eager to eat potentially due to lower rumen fill and eating patterns aligned with circadian cycle as described in Pablo Gregorini's MINDY work.

Between 9:00am and 10:00am cows took a laying/rumination break (see figure 4.2.2)

Figure 4.2.2: Cows starting to lay down at 9am

In the period that followed the laying break and until the afternoon milking (10:00am to 1:30pm) cows had a drink and spread to the grazed break from the previous day. The cows' attitude was characterised by a marked change in behaviour, being more restful, with short grazing bouts often interrupted by social interactions (see figure 4.2.4), the eagerness observed earlier wasn't there anymore. And the bite rate was slow (see figure 4.2.3).

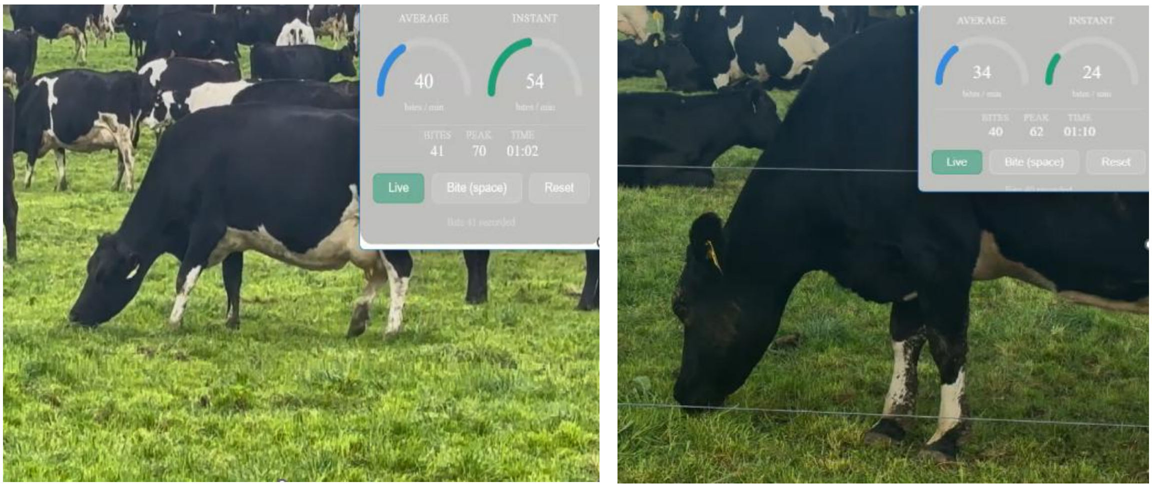



Figure 4.2.3: Reduced bite rate following laying/rumination break

Figure 4.2.4: Socal interactions after laying/rumination break

In the table 4.2.1 below we can see a summary of the observations recorded

Table 4.2.2 Evolution of covers and bite rate between milkings

| Time | Pasture cover | Bite Rate | Observations |
|---|---|---|---|
| **7:00** | 2700 | | Cows arriving to paddock |
| **8:00-9:30** | 2400-2100 | 52-57 | Cows already eaten visibly the top grazing horizon<br>Bite rate increases and decreases with heterogenous sward architecture |
| **9:30-10:30** | 2100 | | Cows laying and ruminating. Pasture is patchy |
| **10:30-13:00** | 2100-1800 | 34-44 | Cows Spread into previous grazing break, water drinking events<br>Attitude is more social and restful |

As per observations, bite rate is clearly influenced by rumen fill. Cows slowed down in bite rate regardless of pasture covers when closer to rumen fill and afterwards.

The period following the morning rumination break and until 13:30 (milking time), was dominated by slow bite rate with small grazing bouts interrupted by social activity and rest breaks.

**Younger herd:**

The data from the younger mob was of no use to bite rate, other than anecdotical, they had a larger pre-grazing cover of 3,400 kgDM/ha and similar feed available per cow but in a smaller area. They ate a lot in the dark before my arrival and bite rate was not recorded.

Worth noting, the density of the sward must have made the harvesting very efficient and the rate of fill was faster. Both herds had 3.5 hours grazing bout after milking, and similar pasture cover at the end of the bout, but the younger herd ate 1.5 kgDM/cow more (2.24 kgDM/cow vs 3.74 kgDM/cow). (see table 4.2.2)

Table 4.2.3; Differences in intake during the 3.5 hours following morning milking

| | Pre-grazing cover (kDM/ha) | Pasture cover at laying time (kgDM/cow) | Area offered (m2/cow) | Intake per cow (kgDM/cow) |
|---|---|---|---|---|
| **Mature herd** | 2700 | 2100 | 38 | **2.24** |
| **Young herd** | 3400 | 2100 | 29 | **3.74** |
| **Difference** | -700 | 0 | 9 | **-1.5** |

The observable difference was at resting time, while all of the mature cows were laying down, the younger herd was also inactive, but cows were split between laying or standing. This is a plausible behavioural signal of high intake rate and high satiety, perhaps by standing cows avoid increasing discomfort from abdominal pressure. Anecdotically, I have observed similar behaviour with pastures mowed before grazing which results in high harvesting efficiency.

### Caveats

During late Autumn when this field trial was conducted cows are expected to behave differently since:

- they don't have a high energy demand from milk production,
- they were supplemented half of their diet which would affect eating time,
- cows were in their last pregnancy trimester with expected foetus and membranes competing with the rumen for space in the abdomen.

### Other findings beyond Bite rate and Bite Strategy

The devise provides a wealth of information. We can potentially also look for:

- Locomotion scoring, could be derived from unevenness of movement in the Y and X axis while walking, helping the identification of lame cows
- Bolus chewing rate. While ruminating it is observable, how the chewing oscillation stops for the swallowing and regurgitation of a bolus. Counting chewing-seconds per bolus can be linked to:
    a. Feed indigestibility (high chewing per bolus).
    b. Acidosis (low chewing per bolus)
- Rumen fill identification, from the slowing trend of bite rate before rumination
- Heavy breathing frequency has been identified and would be of value when in risk of heat stress
- Energy expenditure proxy from effort vector magnitude
- Head shakes count for discomfort/welfare identification

## Conclusions

Following decades of research leading to precision livestock farming, we're at the cutting edge of science and technology, where we wish to fill the gap between data derived from cow-wearable technology and real-time pasture management decisions. This research project is at the right place and time, and while the hypothesis proposed in this study where at a plausible gap in the literature reviewed, the research questions that started this research project have been proved or challenged:

1- **Can we identify bite rate with existing cow wearable technology?**
   Yes, Bite Rate can be estimated from existing cow-wearable accelerometer data. The sensor signal yields at least four independent behavioural channels: bite rate, bite effort, engagement angle, and lateral motion. Each carries information that is not redundant with the others.

2- **Can bite rate serve as a proxy for post grazing residual on intensively grazed pastures?**
   Bite Rate is not a good predictor of post-grazing residuals as satiety influences bite rate negatively, at least in late lactation.

Finding bite rate not to be a good predictor of post-grazing residuals has challenged the initial hypothesis, however the Bite Strategy detected has potential to enhance other indicators in the building of predictive models with implications beyond post-grazing residuals.

Through the literature reviewed, Laca and Ungar were able to predict and model cows' bite rate and strategy from the knowledge of sward architecture cows were being offered. To the contrary, this study opens the possibility for Bite Strategy (derived from the in-ear sensor) to predict sward architecture.

*So, can Bite Rate bridge the gap between cow-wearable technology and real-time pasture management? The straight answer in no, but Bite Strategy might*

## Recommendations

The data derived from accelerometers is very rich and has information ripe for use and further investigation:

- Replicating this research with a validated bite counting method, during early lactation and with more animals, would provide a large enough dataset to allow for the refinement of the algorithm and machine learning.
- Further research on the utility of the Bite Strategy data derived from the multi-channel pipeline to test its capability as a proxy is also recommended.

We know stacking behaviours improves the reliability of pasture predictive models, if Bite Strategy though the multi-channel pipeline can be established as a behaviour, we would be getting closer to reliable indicators to help fine tune farm systems and identify animal efficiency traits.

Quoting Baden Parr (co-founder of ProTag) who so generously supported this project, *"This technology has the potential to give every cow a voice"*.

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*Consolidated reference list for all sources cited throughout this report (Parts 1, 2 and 3 of the literature review, and the field trial sections).*


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