What We've Learned from Cows:
A Tale of Two Decades of Management Research at Miner

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Introduction

Earlier this year, Larry Chase asked me to prepare a paper called "*What I've Learned from Cows*" that would summarize three decades of dairy cattle research. I have switched the "I" to "we" and will present my perspectives on management research conducted by our Miner Institute team in the past 20 years and what the cows have taught us!

The research began with understanding behavioral time budgets and defining the concept of "cow comfort economics." An essential insight was that we *must accommodate the dairy cow's natural behaviors* – eating, resting, and ruminating – within an optimized management environment to enhance productivity, well-being, and herd profitability. Nutrition models improve rapidly as new biology is incorporated; attendees at the Cornell Nutrition Conference hear the latest advancements in the Cornell Net Carbohydrate and Protein System (CNCPS) every year. But the cow tells us that poor management impedes her ability to respond to the diet. Work by Bach et al. (2008) quantitated the overriding impact of non-dietary factors, such as feed availability and stall stocking density, on farm-to-farm variability in milk production relative to nutritional factors. Consequently, a long-term goal of Miner research has been to incorporate cow management into nutrition models.

An accurate statement of what we've learned from cows can be summarized as: *cows that aren't rushed while eating, have the freedom to lie down and ruminate, and can strike the correct balance between eating and recumbent rumination, will have optimal rumen conditions for fiber digestion, microbial growth, and healthy production of more milk components.* Explaining how I arrived at this statement is the objective of this paper.

Time Budgets and Cow Comfort Economics

We routinely monitor time budget behaviors to assess the quality of herd management. But what is commonplace today was not in the 1970s and earlier, and we can thank Jack Albright of Purdue University for his pioneering insight into the value of studying cow behavior to improve performance and well-being. In the June 2023 issue of the Miner Institute Farm Report (Grant, 2023), I explained how Albright and his team in 1975 recorded the daily behavior of the first cow to break 22,676 kg of milk/yr (i.e., 50,000 lb/yr), Beecher Arlinda Ellen. This record-setting cow spent approximately 6 h/d eating and nearly 14 h/d lying down. Her daily dry matter intake (DMI) approached an enormous 7% of bodyweight. She spent 7.5 h/d ruminating with about 93% of that rumination occurring while lying down (i.e., while sternally recumbent). Albright suggested that sternal recumbency, with a slight left-side laterality, allowed the cow to remain comfortable and for the rumen to function optimally. Given Ellen's prodigious productivity it is unsurprising that recently published research has reported a positive relationship between recumbent rumination and feed intake, milk fat, and milk protein percentage (McWilliams et al., 2022). More on this relationship later.

Conversations with Albright in the mid- to late 1990s led to an active interest in assessing cow behavior on commercial dairy farms. Baseline behavioral data collected by Bill Matzke (2003) as part of his MS research at the University of Nebraska on commercial dairy farms helped develop realistic and useful time budgets for lactating cows. Insights from this early work on time budgeting were: 1) excessive time outside the pen has a profound negative impact on resting behavior; 2) cows locked in headlocks beyond 1 h stop eating, and although 30 to 40% begin to ruminate while standing, they are essentially wasting their time; 3) the highest milk-producing cows in a pen spend up to 14 h/d resting (as did Beecher Arlinda Ellen); and 4) cows forced by poor management to spend more time on non-eating activities borrow that time from another one – most often resting. This early work highlighted the natural relationship between eating and resting, and how this interplay profoundly affects production and health.

Research at Miner Institute in the early 2000s cemented the idea that eating, resting, and ruminating are linked biologically – forming the foundation of cow comfort and what we called cow comfort economics (Grant, 2003; 2004; 2015). In many ways, we rediscovered previously reported information on the connection between eating and resting, and the priority that cows place on resting over eating behavior. Time outside the pen was crucial, given its impact on time available for eating, resting and other behaviors, and was viewed as the most vital component of dairy cow well-being in a competitive free-stall environment. Time outside the pen literally sets the limit on what is possible behaviorally within the pen. An Excel spreadsheet (Time Budget Evaluator, version 3. www.whminer.org; described by Grant, 2004) was developed to assess the time budget behaviors of cows and the potential for lost production in competitive environments.

Stocking Density and Overcrowding from the Cow's Perspective

Twenty years ago, it was already clear that overcrowding was becoming a significant management challenge in the dairy industry. When a pen of cows is overstocked, availability of resting and feeding space, area per cow, and access to water are all restricted. Studies conducted in the past 20 years have amply demonstrated that overcrowding, especially beyond 120% of stalls, hampers lying time, boosts lameness, reduces milk yield, encourages undesirable feeding behaviors (such as slug feeding and sorting), and elevates somatic cells (reviewed by Grant 2007; 2015). Early on, we compared alternative models for studying stocking density and concluded that simply denying resting and feeding space to simulate overcrowded 4-row housing was bioequivalent to more complicated research models (Krawczel et al, 2012b).

Defining the differential effect of overcrowding in a 4- or 6-row barn has not been rigorously examined with controlled research, yet we can safely infer that any specific stall stocking density will have potentially greater negative effects in a 6- versus a 4-row barn. Importantly, we have proposed that *time outside the pen interacts with stocking density*. Even at 100% stall stocking in a 4-row barn, time outside the pen of 6 versus 3 h/d reduced resting time by 2.6 h/d for multiparous cows and 4.2 h/d for primiparous cows in commingled pens (Matzke, 2003). It is difficult to name many factors that would affect resting so substantially.

Parity and Lameness Affect Response to Overcrowding

Soon after my arrival at Miner Institute, Chris Hill began a series of studies aimed at defining the short-term effects of overcrowding on behavior, performance, and how the response differed by parity and lameness. Hill et al. (2006; 2009) homed in on how stocking density affected primi- versus multiparous cows. As stall and headlock stocking density in 2-row pens increased from 100 to 142%, the difference in milk yield between multi- and primiparous cows increased from 2.8 kg/d at 100% up to 9.6 kg/d for 130% stocking density. At 142% stocking density, the difference dropped to 6.8 kg/d reflecting a negative effect on the dominant, multiparous cows as well as the subordinate, primiparous cows at this elevated level. Similarly, the difference in milk yield between sound and lame cows increased by 11.9 kg/d as stocking density of stalls and headlocks increased. Reinforcing the importance of resting rumination, these reductions in milk yield tracked with losses in both lying and ruminating, particularly for the lame cows.

What Stocking Density Does the Cow Actually Experience?

In this early work, we observed that sometimes daily rumination time was affected by stocking density, but not always (Hill, 2006; Krawczel et al., 2012a). But in all our studies rumination while lying down decreased at higher stocking densities. Furthermore, one study noted that subordinate cows lying in stalls preferred by dominant cows spent 40% less time ruminating while lying in the stall (Krawczel, 2007, unpublished). Given the recently recognized importance of recumbent rumination on DMI and milk components, this reduction in resting rumination with higher stocking density looms large as an economically important management challenge. An overarching management question must be: *what stocking density does an individual cow experience relative to the measured value (i.e., cows/stall)?* Beyond the number of cows per stall, it seems likely that subordinate cows faced with using stalls preferred by dominant cows must experience a functionally higher stocking density than the calculated one.

Currently we are evaluating the importance of location preference within a pen, whether free stalls, alley, or feed bunk. If individual cows, or types of cows, prefer to eat or rest only in certain areas of a pen then that would also affect their perceived level of competition for the resource and the optimal management practice to ensure adequate access for all cows in the pen. For example, Hefter et al. (2023) reported that lame cows preferred to use the free stalls nearest the pen exit. Cows, regardless of lameness status, also exhibited a strong preference for eating at feed bunk sections closest to the exit gate between ~6:00 am and 9:00 pm, but not at night, presumably in relation to milking and feed availability. We plan future research on this topic.

De Vries et al. (2016) published a model that predicts changes in performance and profit per stall with variable stall stocking densities. A central relationship in this model of a loss of 0.50 kg/d of milk per 10% greater stall stocking density is based on Grant (2011), Fregonesi et al. (2007), and Bach et al. (2008). This useful model is available on the University of Florida web site: https://edis.ifas.ufl.edu/publication/AN346.

Assessing Cow Comfort in Overcrowded Pens

Increasing stocking density beyond 100 to 113% with our research model clearly increases the proportion of cows standing in alleys and compromises their ability to access free stalls when motivation to lie down is greatest. Pete Krawczel led research demonstrating that assessing cow comfort on a pen level is best done using the stall use index which is calculated as the number of cows in a pen lying down divided by the total number of cows minus those actively eating (Krawczel et al., 2008). In other words, the denominator includes cows that are essentially wasting their time, idling and mainly waiting to use a stall. The commonly used cow comfort index and stall standing index, calculated using only the cows lying or standing in a stall, remain relatively unchanged at higher stocking densities. For indices routinely measured and monitored on-farm, the stall use index and the rumination index (% of cows ruminating that are lying in stalls) top our list of priority indices. Campbell (2017) found that the commonly used rumination index is related to 24-h rumination time. Plus, the rumination index allows us to monitor recumbent rumination specifically.

Feed and Feeding Environment: Focus on Rumen pH

Overcrowding as a Subclinical Stressor

Given the wide array of negative behavioral, health, and performance consequences of overcrowding measured in research studies, the diversity of herd responses to overcrowding seems puzzling. Some herds seem to be immune to the negative consequences of overcrowding whereas others experience severe effects at low stall stocking density, and everything in between. One possible explanation would be to consider overcrowding a subclinical stressor. Moberg (2000) defined a subclinical stressor as one that depletes biological resources of an animal without creating detectable change in function such as milk yield, reproduction, or health. However, it leaves the animal unable to successfully respond to additional stressors. Using this model, one can imagine an overcrowded pen of dairy cattle that appears to be meeting most or even all of the commonly used industry performance benchmarks, but at some point, secondary stressor(s) will cause a measurable change in function. We propose that the extent to which the biological reserves are expended by the subclinical stress of overcrowding in any specific herd is a function of the quality of the housing and management routines.

Mac Campbell embraced this model and asked the question of what occurs with chronically overcrowded dairy cows when the secondary stressor is inadequate ration fiber and feed availability (Campbell and Grant, 2016). As a ruminant, little is as important to dairy cattle well-being and productivity as a healthy rumen environment, particularly pH. When comparing stall and headlock stocking density of 100 versus 142% with physically effective neutral detergent fiber (peNDF) of 19 or 21% (8.5 and 9.7% undegraded NDF at 240 h of in vitro fermentation; uNDF240), Campbell and Grant (2016) reported that the extent of subacute rumen acidosis (time that pH <5.8) was up to 2 h/d greater for the main effect of overstocking versus fiber. Furthermore, when cows were fed the same total mixed ration (TMR), cows overstocked at 142% and also experiencing a 5-h feed restriction prior to delivery of the morning ration had up to 9 h/d greater subacute rumen acidosis than those at 100% stocking density with unrestricted feed access. The bottom line was that stocking density and feed restriction had a greater negative impact on rumen pH than dietary fiber characteristics. In fact, this work suggests that the ideal recipe to lower rumen pH would be to: 1) feed a highly fermentable diet, 2) overcrowd the feed bunk and stalls, and 3) feed to an empty bunk.

We have joked that this research does not give the nutritionist a "get out of jail free card," but it clearly recasts the relative importance of ration formulation and feed-bunk management. *Ration formulation, especially carbohydrates, is critical to maintaining healthy rumen pH conditions, but we now know that how the ration is fed is paramount*.

Overcrowding resulted in lower rumen pH in Campbell's work, but it did not have great effects on feeding or ruminating time. Like previous research, lying time was significantly reduced, and notably recumbent rumination was depressed at higher stocking density. With overcrowded environments, Campbell (2017) observed a negative relationship between the fraction of rumination that occurs in the free stall (x) and hours that rumen pH is below 5.8 ($y = -20.7x + 21.1$; $r = 0.66$). This result had not been expected but raised interesting questions regarding the potential importance of rumination in stalls to maintaining desirable rumen pH conditions. For the first time, *there was evidence that posture during rumination (i.e., standing or lying) affected rumen pH*. This makes sense given what we know about the relative rates of saliva secretion when the cow is eating, ruminating, or resting, and how sternal recumbency aids the rumination process (reviewed by Grant and Cotanch, 2023).

Management and Milk Components

Based on the positive relationship between rumen pH and greater milk de novo fatty acids and total fat production (Fukumori et al., 2021), de novo fatty acid content of milk fat should serve as a useful barometer of rumen pH conditions conducive to fiber digestion and microbial growth. Barbano has published extensively on the positive relationship between milk de novo fatty acids and output of milk fat and true protein (Barbano et al., 2018) and suggested as much. Published literature demonstrates the positive relationship between higher rumen pH and greater de novo fatty acids, milk fat, and true protein percentage (Allen, 1997; Fukumori et al., 2021; Stone, 2004).

At roughly the same time that Campbell was conducting his work, Melissa Woolpert reported on factors affecting milk de novo fatty acid production for 79 commercial herds in VT and NY (Woolpert et al., 2016; 2017). Higher de novo fatty acid herds produced 17% more milk fat and 14% more true protein than lower de novo herds. Across these herds, the top-five factors that characterized high de novo, high component herds were: 1) dietary fat ≤3.5% of ration DM; 2) dietary peNDF ≥21% of ration DM; 3) lower feed bunk and stall stocking density; and 5) greater feeding frequency of TMR. High de novo herds were 10x more likely than low de novo herds to have feed bunk space ≥45 cm/cow and stall stocking density ≤110%. High de novo herds were 5x more likely to feed TMR twice daily rather than once. Importantly, 65% of the variation in milk de novo fatty acid content among herds was explained by feed bunk space alone. This relates well to earlier work that found greater feed bunk space to be correlated with increased milk yield and milk fat percentage (Sova et al., 2013). We cannot overstate the negative effect that overcrowding may have on milk component production. *Overcrowded cows cannot respond maximally in milk components to the formulated ration.*

Considering Campbell's demonstration that greater rumination in the stalls is associated with higher rumen pH, then cows in competitive feeding environments who are able to achieve more recumbent rumination should have better rumen conditions for fiber digestion and potential for greater de novo fatty acids, milk fat and protein output. In fact, McWilliams et al. (2022) observed that cows with greater ruminating time while lying down had greater DMI and produced milk with more fat and true protein content. To follow up on this work, we conducted a student research project in spring 2023 using Holstein cows that ranged from 3.2 to 6.4% milk fat. Similar to McWilliams et al. (2022) we found a significant positive correlation ($R = 0.34$; $P = 0.03$) between minutes of rumination while lying down and milk fat percentage. This relationship was significantly stronger than for ruminating, resting, or eating time. *Recumbent rumination, and not simply total rumination time, is critical to a healthy, productive, and profitable herd*.

Forage Quality and the Balance Between Eating and Recumbent Rumination

Eating time between 3 and 5 h/d is typically associated with desirable feeding behavior as reviewed by Grant and Albright (2001). In a cow's ideal environment, she will achieve over 80% of daily rumination while lying down. Hence, the cost of excessive time at the bunk, beyond 5 h/d, is considerable since it directly reduces time available for resting and ruminating. In fact, Jiang et al. (2017) observed an exact daily balance between total chewing time, driven by eating, and resting time. As dietary forage content increased beyond 50% of ration DM, eating time increased markedly, with little impact on rumination. The extra time needed for eating was carved minute-for-minute from resting time, and inescapably from resting rumination. *We propose that maintaining a proper balance between eating time (3 to 5 h/d) and optimal resting (11 to 14 h/d) and ruminating time (8 to 9 h/d) is central to cow productivity and well-being*.

Understanding the fundamental importance of maintaining the balance between eating and recumbent rumination was paradigm shifting. And it begged the question of how forage quality influences the cow's ability to keep eating and resting/ruminating in balance. Fiber plays a major role in stimulating chewing, both eating and ruminating. Dietary fiber content, source of fiber, particle size, digestibility, and fragility all contribute to the effect of fiber on chewing. Grant and Cotanch (2023) reviewed recent research showing that the primary effect of forage particle size is on eating rather than ruminating in many feeding scenarios. Cows chew to a relatively uniform particle size endpoint prior to swallowing while eating. Consequently, the rumen is populated with a forage particle size distribution that is smaller and more uniform than the TMR. In fact, for many of our commonly fed corn silage-based diets the particles retained on the 8-mm sieve of the Penn State Particle Separator are essentially the same size as the swallowed bolus while eating.

Particle size reduction that occurs during eating requires more chews per gram of feed DM and takes longer for diets that are coarser, higher in forage NDF, and less digestible. We have measured up to a 6-fold reduction in the longest TMR particles prior to ingestive swallowing when we fed cows coarse diets with high uNDF240 (Grant et al., 2018; Smith, 2019). The published literature shows that eating time can be increased by up to an hour when forage NDF is greater, less digestible, or chopped coarser (Grant and Ferraretto, 2018; Grant and Cotanch, 2023). Details are provided in the review by Grant and Cotanch (2023), but the main point is that a system has been proposed that allows theoretical length of cut to be adjusted based on forage maturity, moisture content, and digestibility or fragility to optimize the balance between eating and recumbent rumination. Additionally, an optimal TMR particle size distribution has been proposed to balance eating, ruminating, and resting.

In our approach to particle size, *eating time at the feed bunk is a crucial and overlooked component of forage quality*. Lower quality forage is less digestible and takes longer to eat unless particle size is reduced. Likewise, higher quality forage benefits from longer chop length in most cases. Understanding the fundamental importance of this relationship will be most critical in competitive feeding environments – which characterize many of our commercial herds. We view this as a holistic approach to optimizing the two fundamental components of a profitable dairy farm: forage quality and cow comfort.

Modeling Management: The Holy Grail?

Publications by Grant and Tylutki (2010; 2011) for the first time proposed that time budget analysis should become a routine and important part of DMI prediction and ration formulation. The feeding environment is comprised of both physical and social components that modulate feeding behavior and feed intake in dairy cattle. Currently, key components of the physical environment such as temperature, humidity, wind speed, and so forth are inputted into the model during ration formulation. But, effectively incorporating social and management factors such as time budgets, stocking density, and feed availability has proven challenging. Nonetheless, nutrition models need to incorporate management inputs. Feeding behavior and intake are dramatically affected by time available to eat, forage NDF characteristics, notably particle size, and stocking density to name a few.

To date, the best effort has been the management model created as part of Michael Miller's Ph.D. dissertation (Miller et al. 2020; detailed equations provided by Miller, 2020). The model remains a work-in-progress, but initial field experience suggests that it has usefulness. It has been implemented in AMTS version 4.18 as a recipe tool called the "management model."

The model was designed to allow input of commonly measured farm variables such as stocking density and milking time to assess the effect of management decisions on DMI, milk production, and behavior. The model is divided into five sections: 1) behavioral time budget adapted from the original model by Grant and Tylutki (2011); 2) stocking density calculation; 3) eating time prediction; 4) DMI prediction; and 5) physically effective uNDF240 (peuNDF240) adjustment to DMI. The time budget analysis provides time available for eating plus resting, and eating time is predicted from NDF, peNDF, body weight, milk yield, and feeding frequency. Once time available for rest has been calculated, it is adjusted based on stocking density of stalls or manger, depending on whether the barn uses headlocks or post-and-rail. Then, we use a relationship between resting time and milk yield, based on a review of published data to predict fat-corrected milk production. The fat-corrected milk value, together with body weight and week of lactation, is used to predict DMI using NRC (2001) equation. Although this approach backs into a DMI prediction, it seems to be the best approach for now since no reported relationship between stocking density and short-term DMI has been reported.

Three main limitations remain: 1) rigorous model validation; 2) adjustments for parity effects; and 3) incorporation of feed availability. Although we know that parity and feed availability are important, a lack of data hampers further model development. The model is most sensitive to milking time and stocking density which makes sense given how important they are on farm. As part of model development, Miller (2020) reviewed the published literature and updated equations relating stocking density with lying time and lying time with milk yield. Although not a main part of the model, an intake adjustment based on the relationship between peuNDF240 and DMI was also incorporated to take advantage of the database we have built comparing uNDF240 and peuNDF240 and their relationship with DMI and energy-corrected milk (Grant et al., 2018; Miller et al., 2020; Farricker et al., 2022). It is conceivable that this component in the future could also incorporate the interaction between rumen fermentable starch and peuNDF240 (Smith et al., 2020). Stay tuned.

We Need to Push Forward!

The amount of cattle management research conducted over the past twenty years is mind boggling. When reviewing the many management factors affecting cow performance and health, few are surprising. *What is surprising is the sheer magnitude of the cow responses to an improvement in comfort*. Furthermore, it is amazing how a few factors rise repeatedly to the top as essential for a low-stress management environment: 1) time available for eating, resting, and ruminating; 2) managing stocking density and overcrowding; 3) ensuring feed availability 24/7; and 4) resting area comfort (e.g., deep bedding). Regardless of the management system – free-stall and parlor, automated milking system, tie stall, pasture, or whatever evolves – we need to understand how to accommodate natural cow behavior. Any sustainable dairy system will consider environmental, welfare, and societal concerns. And from a profitability perspective, there is little doubt that cow comfort economics will remain compelling!

Research needs to continue that builds on our new understanding of forage quality and cow well-being. How forage characteristics, housing, and management environment affect each cow's ability to balance eating with recumbent rumination needs to be a focus going forward. As advances in nutrition models occur, we need to implement a functional model incorporating physical and social components of the cow's environment. Time budgeting should become a routine part of ration formulation.

As behavior research moves toward answering much-needed questions that cross-cut society, such as cow-calf separation, we cannot forsake research aimed at enhancing the productivity and well-being of cows in commercial management systems. So, we return to the original assertion of this paper that I believe captures the essential importance of our work at Miner: "*cows that aren't rushed while eating, have the freedom to lie down and ruminate, and can strike the correct balance between eating and recumbent rumination, will have optimal rumen conditions for fiber digestion, microbial growth, and healthy production of more milk components."*

Our management research at Miner reaches back to Jack Albright's pioneering work in cattle behavior; his recognition that the need to accommodate natural cow behavior would become an essential component of successful herd management. After briefly reviewing two decades of management research at Miner Institute and looking to the future, I conclude that applied dairy management research must continue with the goal of "unleashing every cow's inner Ellen!"

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