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Monitoring Foraging Behavior in Ruminants in a Diverse Pasture

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Abstract

The foraging behavior of grazing ruminants plays an important role in their production as well as in maintaining plant diversity. The effects of plant species richness on animal production, health, and welfare occur only after animals have foraged on the relevant plant species. Thus, monitoring foraging behavior is a key tool for understanding the underlying relationships between plant species richness and animal production, health, and welfare. Efforts to monitor foraging behavior have, however, been confronted with methodological difficulty due to the complex and labor-intensive nature of the monitoring process. This difficulty increases when ruminants encounter more heterogeneous and diverse feeding environments, such as semi-natural or forest pastures, because they choose and ingest various plant species that have different structures and morphologies. Recent developments in information and communication technology will drastically change this situation. Compact and wearable devices, such as acceleration sensors, can detect complex and fine animal movements precisely over a relatively long period. In this review, we first summarize the foraging process in grazing ruminants to provide general knowledge for monitoring foraging behavior. Second, we briefly review previous findings from studies that have monitored foraging behavior using automatic sensors and consider the foraging behavior of animals when they ingest plants whose forms are different from those of typical short grasses. Third, recent findings on foraging behavior in diverse feeding environments that were revealed using a new technique are presented. Finally, the remaining issues regarding monitoring and assessing the foraging behavior of ruminants in diverse feeding environments are discussed.

1. Introduction

The foraging behavior of grazing ruminants plays an important role in their production, health and welfare states as well as in grassland management, including its productivity, sustainability and diversity. In homogeneous grasslands such as sown pastures, animal performance as a corollary of foraging behavior is almost predictable because we can estimate the nutritional composition of what the animals eat relatively easily. However, as stated in Ogura *et al*. (2017) on this issue, when animals graze on heterogeneous or species-rich grasslands, they have an opportunity to choose and ingest a variety of plant species that have different nutrient compositions. This situation leads to a hypothesis that the wider range of diet choice will provide animals with balanced nutrients. In fact, recent studies have suggested that great richness of plant species improved the intake of energy, protein (Wang *et al*. 2010) , minerals and amino acids (Yoshihara *et al*. 2013; Ogura *et al*. 2017) and may influence ruminal fermentation and digestion via changes in the microbial flora (Nakano and Ogura 2017). These changes are expected to have positive effects on animal production, health, and welfare. However, it should be emphasized that all of these results occur only after animals have foraged on the relevant plant species. Thus, monitoring foraging behavior is a key tool for understanding the underlying relationships between plant species richness and animal production, health, and welfare.

Efforts to monitor foraging behavior have, however, been confronted with methodological difficulties. The direct observation of foraging behavior is laborious, time-consuming and often implemented under unpleasant conditions (Penning and Rutter 2004). In general, a foraging bout lasts for about one to two hours, and the total daily grazing time ranges from 6 to 12 hours. This leads to a decrease in the concentration of observers and an increase differences in the interpretation of foraging activities among individuals. Another difficulty is that foraging behavior is composed of continuous and fine-scale jaw movements, and animals choose and eat one plant species after another. The processes of choice and ingestion via fine jaw movements occur within seconds. Thus, direct observation may be impossible for some foraging parameters (Penning and Rutter 2004).

These difficulties have promoted the development of many automatic monitoring devices and classification algorithms over recent decades. These efforts have successfully allowed the monitoring of foraging behavior and have advanced the understanding of fine foraging processes in animals in homogenous feeding environments (e.g., Laca *et al*. 1992a; Laca and Wallis De Vries 2000; Galli *et al*. 2011). However, the difficulty increases when ruminants graze in more heterogeneous and diverse feeding environments such as semi-natural or forest pastures because they choose and ingest various plant species that have different sizes, structures and morphologies. This complex situation causes observers to have to detect and identify the fine jaw movements used for various plant species instantaneously.

Recent developments in information and communication technology (ICT) will drastically change this situation. Compact and wearable devices such as acceleration sensors, action cameras and miniature data loggers can detect and record complex and fine animal movements precisely over a relatively long period. On the other hand, direct observation still has advantages in terms of flexibility and adaptability (Penning and Rutter, 2004; Bonnet *et al*. 2016). Therefore, combining direct observation and automatic devices is a feasible technique for monitoring and analyzing the foraging behavior of grazing ruminants in diverse pastures.

In this review, we first summarize the foraging process of grazing ruminants to provide general knowledge for monitoring foraging behavior. Second, we briefly review previous findings from studies that have used automatic sensors to monitor foraging behavior and consider the foraging behavior of animals when they ingest plants whose forms are different from those of typical short grasses. Third, recent findings on foraging behavior in diverse feeding environments that were revealed using a new technique are presented. Finally, the remaining issues regarding monitoring and assessing the foraging behavior of ruminants under diverse feeding environments are discussed.

2. Foraging process of grazing ruminants

Conceptually, the foraging behavior of ruminants has a temporally and spatially hierarchical structure (Senft *et al*. 1987; Bailey *et al*. 1996). The basic component of foraging or grazing behavior is a bite. The bite involves prehending and cutting a bunch of forage from a grassland (Ungar 1996). Ruminants bite some plants or plant parts at a feeding station, which is defined an array of plants available to an herbivore without moving their front feet (Novellie 1978; Ruyle and Dwyer 1985); they then move to a new feeding station. A cluster of feeding stations is called a patch. A patch is also identified by a break in the foraging sequence. In the same manner, a cluster of patches is defined as a feeding site. At a feeding site, animals continuously graze plants during a foraging bout. A set of feeding sites is called a camp, where animals drink and rest between foraging bouts. The top of the foraging hierarchy is the home range, which is defined by fences, barriers, the extent of migration, or transhumance (Bailey *et al.* 1996). When monitoring the foraging behavior of ruminants, the grazing process at a feeding station is critical because it falls on the very bottom of the foraging hierarchy.

At a feeding station, animals search for plants or plant parts according to their characteristics, such as quantity, quality, architecture and morphology. They then bite the forage—prehend a bunch of forage using the tongue, gums and lower jaw—and cut the herbage with a sudden movement of the lower jaw and the whole head (Ungar 1996; Andriamandroso *et al*. 2016). The ingested forage is ground using the molar teeth. This process is called chewing or mastication. Interestingly, some ruminants, such as cattle, sheep and goats, perform these two processes—biting and chewing—simultaneously (Laca and Wallis De

Vries., 2000; Milone *et al*. 2009; Navon *et al*. 2013). This ingestive behavior is defined as chew-bites (Laca and Wallis De Vries. 2000). Finally, they swallow the forage into the esophagus. All these processes are not mutually exclusive (Ungar 1996) (Fig. 1).

The bite can be divided into further components (Fig. 1). When animals prehend and remove a bunch of forage in one bite, the total volume of the forage is defined as the bite volume (Laca *et al*. 1992a; Ungar 1996). The bite volume is the product of the bite area and bite depth. The bite area is the harvested area taken by an animal in one bite, and the bite depth is the difference between the initial and residual height of the same plant(s) before and after grazing (Laca *et al*. 1992a; Ungar 1996). The bite mass (or bite weight) is the product of the bite volume and the weight of forage per unit volume in that space (Allen *et al*. 2011).

Plant characteristics such as size and architecture affect the bite dimensions: bite area, bite depth, and bite volume (Laca *et al*. 1992b; Ungar 1996; Searle and Shipley 2008). These bite dimensions determine the bite mass. Similarly, plant characteristics influence the cropping time, and this cropping time and the chew rate are involved in the rate of bites (bite rate) (Ungar 1996). The bite mass and bite rate are the factors that determine the intake rate, and the product of the intake rate and grazing time is the daily intake (Penning and Rutter 2004; Carvalho 2013). Daily intake directly relates to animal performance and health on one hand, and the daily intake linked with the movement patterns of animals affects the spatial heterogeneity of the landscape and grassland diversity (Searle and Shipley 2008). Considering this hierarchical foraging process (Fig. 2), bite mass and bite rate are the relevant properties in monitoring ruminant foraging behavior.

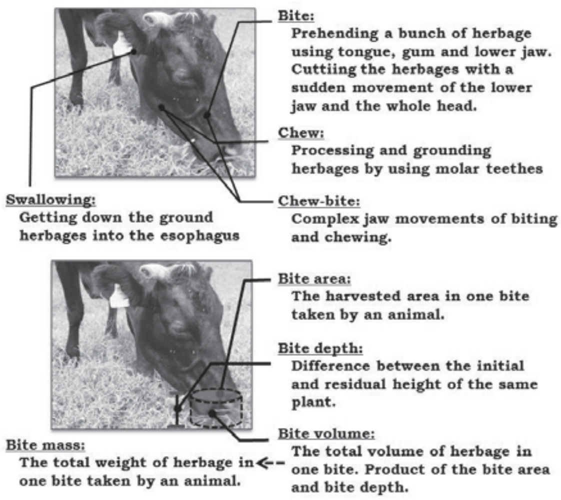

Fig. 1. Grazing jaw movements and bite dimensions of ruminants at a feeding station. (Terminologies are defined by Laca et al. (1992a), Ungar (1996) and Allen *et al*. (2011).)

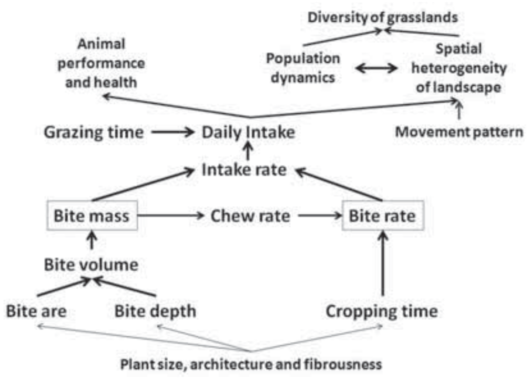

Fig. 2. Hierarchical relationships between plant characteristics, foraging behavior, daily intake, animal performance and the grassland ecosystem (adapted from Ungar (1996), Sealr and shipley (2008), and Carvalho (2013)).

3.Monitoring foraging behavior of grazing ruminants using automatic sensors

The problem is how we assess these fine jaw movements over the course of a day or, at least, a foraging bout. During the last five decades, many researchers have developed monitoring techniques for foraging jaw movements using mechanical and electrical sensors. There have been several excellent reviews on this topic (Penning and Rutter 2004; Navon *et al*. 2013; Andriamandroso *et al*. 2016); thus, only a brief summary is presented here.

The techniques are roughly divided into 6 categories based on the sensor: pneumatic sensors, transducers, electromyograms, pressure sensors, microphones and acceleration sensors. All of these sensors are attached to the head or the neck of the animal and record the jaw and/or head movements during eating and ruminating. Although what the sensors record slightly differs among the sensors, they principally convert the signals of physical jaw or head movements to waveforms. For example, an acceleration sensor detects static acceleration due to gravity, the low-frequency component of the acceleration and the dynamic acceleration due to movements by an animal (Brown *et al*. 2013). The sensor transforms physical acceleration from motion or gravity into waveforms. Each distinctive pattern in the waveforms shows the occurrence of grazing jaw movements. Thus, we can detect and identify the differences in waveforms among fine jaw movements and determine when and how many of each jaw movement occurred during observation. Some researchers have developed algorithms that can automatically identify types of jaw movements such as bite, chew, and chew-bite (Clapham *et al*. 2011; Milone *et al.* 2012; Chelotti *et al*. 2016).

Many previous studies using these sensors have successfully monitored grazing jaw movements in homogeneous feeding environments, mainly monocultures of short grass swards (e.g., Laca *et al*. 1992a; Rutter *et al*. 1997; Laca and Wallis De Vries. 2000). Although the determination of bite mass by the sensors has been a challenging problem, combining these sensors with a micro-sward technique or other methods has revealed functional relationships among intake rate, bite rate, bite mass and bite dimensions in homogenous swards (Laca *et al*. 1992b, 1994; Ungar 1996; Galli *et al*. 2011).

4.Foraging behavior for different plant forms

There are many plant species that have different sizes, architectures and morphologies. Different plant forms necessitate different motor patterns for their harvest (Flores *et al*. 1989). For example, when lambs graze grasses, they mainly show a typical prehension pattern: gripping grass tillers with their incisors and the upper dental pad while jerking the head forward or backward. However, when lambs graze shrubs, they show more complex prehension patterns that are composed of plucking individual leaves, breaking twigs and stripping leaves off branches (Flores *et al*. 1989).

Hirata *et al*. (2011) assessed the foraging behavior of cattle grazing tall grasses over 1 m in height with full-sized or half-sized leaves. They observed that cattle initially grazed leaves at the lower levels and progressively shifted to leaves at the upper levels of a tall grass. They also found that cattle sometimes ingested one leaf before completely consuming a previously detached leaf (Hirata *et al.* 2011). When cattle ate a half-sized leaf, they prehended the mid or distal part of the leaf. They then ate a leaf by chewing and swallowing part of the leaf while the reminder was attached to the stem. Contrastingly, cattle usually prehended the proximal or mid part of a full-sized leaf and severed the leaf from the stem with a movement of the head. Their results suggested that cattle show different motor patterns when foraging tall grasses and can control the allocation of jaw movements corresponding to vertical and horizontal leaf arrangements.

Moreover, Yayota *et al*. (2015) examined the foraging behavior of cattle when they encounter plants of different sizes and morphologies. They used four test plants: bahiagrass (*Paspalum notatum* Flügge; a short grass), Sudangrass (*Sorghum* × *drummondii*; a typical tall grass) and two growth forms of a dwarf bamboo (*Sasa senanensis*; a semi-woody plant): a naturally growing form (approximately 2 m tall) and a form that is under grazing (<0.8 m tall). The grazing jaw movements were assessed using a one-axis acceleration sensor and a micro-sward technique. Their results show that the total number of jaw movements is relatively the same among the plants (approximately 70 times per minute); however, the components of the grazing jaw movements are different. For example, the cattle used small numbers of bite or chew-bite jaw movements and frequently used chewing jaw movements when they ate dwarf bamboos. In contrast, the cattle frequently used bite and chew-bite movements when they ate the short grass (bahiagrass). Accordingly, the cattle showed a greater bite mass and slower bite rate when they ate the taller dwarf bamboo, whereas they showed a smaller bite mass and faster bite rate when they ate the short grass. These results suggested that the cattle were able to control their ingestive jaw movements depending on the plant characteristics, such as height, the spatial arrangement of the leaves and leaf morphology.

In brief summary, ruminants have the ability to control their ingestive behavior and/or jaw movements depending on the plant size, architecture and leaf morphology. Bite mass and bite rate vary with such ingestive behavior. These results likely suggest that biting style—how forage is prehended and severed—corresponding to plant morphology is the key factor that produces different bite masses and bite rates.

5. Monitoring foraging behavior in diverse pastures

Free-ranging animals continuously choose and ingest different species and types of plants in diverse pastures. In this context, the functional relationships among intake rate, bite rate, bite mass and bite dimension obtained in a homogenous pasture are not applicable because animals continuously change their grazing jaw movements based on the different plant species or types. Thus, we have to monitor the selection of plant species or type and bite style, including bite rate and bite mass, by grazing animals in a different way.

One of the recent promising techniques is the creation of a "bite-coding grid". Fundamental to this technique is the definition of several bite categories depending on the structural differences in the forages. Each bite category is illustrated as a symbolic image, and these categories are grouped by general botanical group and assumed bite mass. The bite-coding grid was originally developed by Agreil and Muret (2004) for small ruminants grazing on shrubby rangelands. Later, some researchers including themselves adapted it to several diverse pastures (Agreil and Muret 2008; Bonnet *et al*. 2011: Gonzalez-Pech *et al*. 2014). Bonnet *et al*. (2015) presented the detailed protocol for making bite-coding grids and introduced an application of the method for grazing animals on a diverse pasture in the Brazilian Pampa. They emphasize the importance of direct observation when making a bite-coding grid and conducting bite monitoring of grazing animals and highlight the problems with video recording: the lack of a three-dimensional perspective and several senses such as color, texture, touch and smell in the environmental context of the local plant community.

However, the direct observation of grazing animals is a time-consuming and labor-intensive process, and we sometimes do not capture foraging behavior using this method due to the fine and rapid movements involved, even if we use trained and tamed animals. We believe that techniques using video recording to design bite-coding grids and monitor foraging behavior are a viable alternative. Thus, we have attempted to develop a bite monitoring technique using a handheld video camera and a wearable camera.

We conducted a study on a semi-natural pasture that used to be an abandoned field for years, at Minokamo City in Gifu, Japan. Sixteen goats were set stocked from mid-May to early November from 2013. The pasture was dominated by graminoids, forbs, and woody plants, including shrub-like bamboos, during the years of the study (Tamiya *et al.* 2016). We identified more than 60 plant species in 2015 and approximately 80 plant species in 2016.

In the first stage, we defined bite categories and designed a bite-coding grid for the goats using a handheld camera (GZ-MG 575, JVC KENWOOD Co. Ltd., Kanagawa, Japan). The foraging behavior of six goats was recorded for at least 30 minutes. All visual assessments were conducted using video editing software (Power- Director Express 13; CyberLink Inc., Tokyo, Japan).

The resulting bite-coding grid in the semi-natural pasture is shown in Fig. 3. According to the similarities in plant structure, leaf morphology and assumed bite mass, 26 bite categories were defined by the video assessments. For example, one of the bite code groups is for graminoids, including Poaceae and Cyperaceae. This group was divided into five bite categories according to the bite depth. Forbs that have erect stems, such as Canadian goldenrod (*Solidago canadensis*) and *Erigeron annuus*, were also divided into five bite categories according to the assumed bite mass. One of unique plants in this pasture was a bamboo (*Phyllostachys edulis* (Carrière) Houz.). Generally, a bamboo is a giant, timber-like plant and reaches approximately 15 m tall, but it maintains semi-woody forms under heavy grazing conditions. Therefore, we decided to make independent bite categories for the bamboo.

According to this bite-coding grid, we assessed the frequency of appearance of each bite category. For this objective, we attached a wearable camera (HX-A500, Panasonic Co. Ltd., Osaka, Japan; MPEG-4 AVC, 1280×720 pixel, flame rates 30p) to the heads of the goats using a halter. The foraging behavior of five goats was recorded for 15 minutes. Of the 26 bite categories in this pasture, we can identify 24 bite types for the goats (Fig. 4). The frequency of appearance of each bite category differed among the individual goats (Fig. 4). This result was mainly caused by the locations where the goats foraged in the pasture because the plants classified into the different bite categories were unevenly distributed in the pasture. In this preliminary study, only three to five goats were analyzed using this technique. If more animals are analyzed, more bite categories will be required to monitor the foraging behavior of the goats.

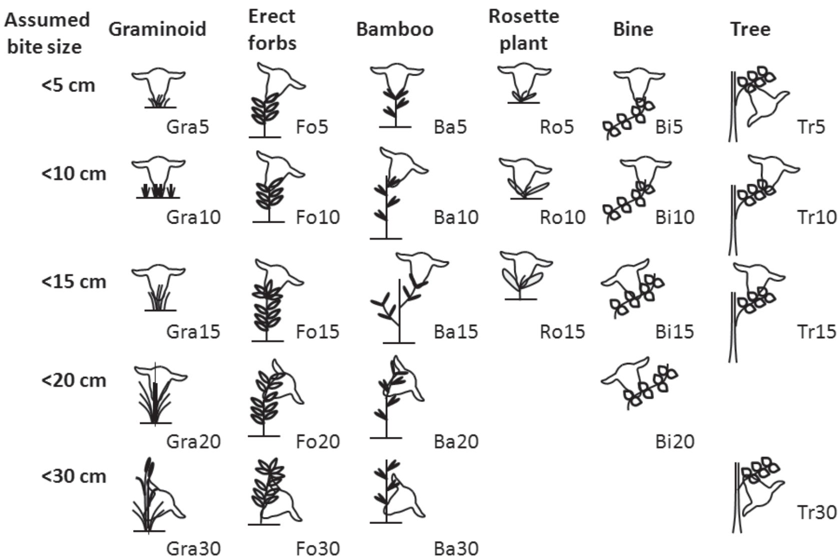

Fig. 3. Bite-coding grid for goats in a semi-natural pasture in Japan. Each pictogram illustrates the typical bite for each bite category. Bite categories are arranged according to plant structural characteristics and assumed bite size.

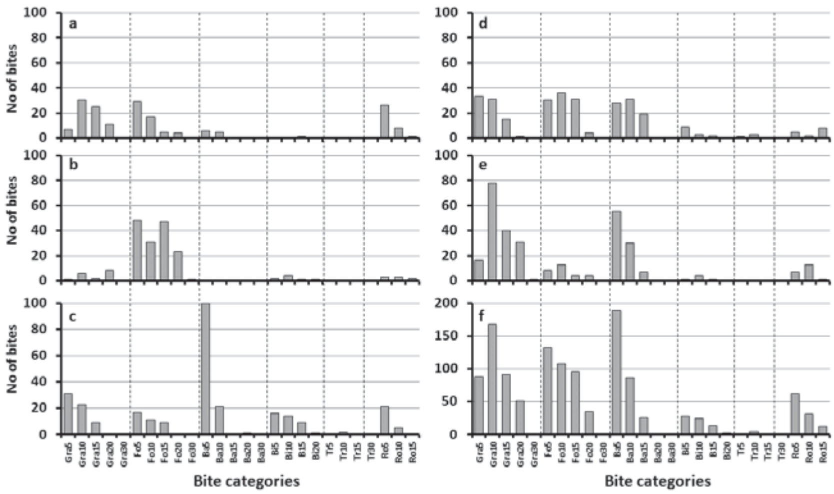

Fig. 4. Frequencies of the observed bite categories during the observation: a–e show the results from individual goats and f shows the total result from the observation. Counts and identification of the frequencies of each bite category were carried out using visual images from a wearable camera. See Fig. 3 for details of the bite categories.

6. Concluding remarks

Overall, we can design a bite-coding grid in a diverse feeding environment using a video recording technique. The use of a wearable camera with a bite-coding grid was successful in monitoring the foraging behavior of a small ruminant. Repeat playback, slow-motion replay and still images are favorable aspects when video recording devices are used; however, the direct assessment of plant species and their structure and the direct observation of animal foraging behavior are important considerations before the use of video recording techniques.

Even if we can successfully monitor the foraging behavior of grazing animals using a bite-coding grid, some issues still remain. One issue is the determination of bite mass in each bite category. As shown in Carvalho *et al*. (2013), some bite categories have a wide range in bite mass. This variation causes the over- or underestimation of bite mass, the short-term intake rate and the resulting daily intake. Another issue is the automatic identification of bite categories. The use of a wearable camera may reduce laborious work in the field; however, the visual assessment of video footage is also a time-consuming process. Currently, multi-axis acceleration sensors, such as six- and nine-axis acceleration sensors, are easily obtained, and the combination of such sensors and machine learning, such as decision forests and neural networks, may allow the characteristic features of each bite category to be detected.

In conclusion, although several challenging problems still remain, by using new wearable sensors and supplementary direct techniques, we can monitor the foraging behavior of grazing animals more precisely. This leads to the measurement of temporal changes in diet selection and nutrient intake in free-ranging animals in diverse feeding environments. The development of these techniques and technologies will be helpful in improving the production, health, welfare, and behavioral enrichment of grazing animals. Furthermore, by knowing when, where, how many, and what types of plant species are ingested by grazing animals, we can understand herbivore-plant interactions more precisely. This will contribute to the development of the multi-function of plant species for animal production, appropriate grassland management and conservation.

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