Discriminative power of acoustic features for jaw movement classification in cattle and sheep

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Measuring foraging behaviour and pasture intake of ruminants is useful but difficult. Acoustic monitoring is one of the most promising methods for this task. In this work, we test its potential to classify jaw movements (JM) according to type (bite, chew, chew-bite), activity (grazing or rumination), and forage species being consumed. Experiments with cows and sheep grazing and ruminating several forages were conducted. First, each JM was manually identified, classified and described by two sets of sound features: i) one containing energy bands of the spectrum (EB), and ii) one containing four complementary (or global) variables (C_V). Two models were evaluated, one with EB alone and the other one combining EB and C_V. Jaw movements were correctly classified by type with 73.0% and 78.5% average accuracy. Accuracy was better for cows than sheep (85 vs 66%). Simultaneous identification of type of JM and plant species was about 78%. Classification accuracy of activity based on chews averaged 68.5% and 77.0% for rumination and grazing. Models including global variables performed better than using only the spectrum. Acoustic monitoring is a very promising method for further development, particularly to study diet selection.

Keywords: acoustic variables, jaw movements, grazing behaviour, precision livestock farming.

I. INTRODUCTION

Accurate monitoring of livestock grazing behaviour is useful to determine and supply living and food environments conducive to ruminant health and welfare. Detailed knowledge about ingestion and rumination of pasture is essential to understand and improve ruminant production systems because of the paramount role of chewing in exposing fibre to digestion and maintaining a properly buffered rumen environment (Jiang *et al.*, 2017). Relevant information includes number and type of jaw movements, duration of grazing and rumination bouts and dry matter intake. This type of information is used in precision livestock farming, which was developed to address challenges production and environmental challenges.

Behavioural studies in ruminants require measurement of rate and duration of activities such grazing and rumination (Baumont *et al.*, 2006). Direct visual observation needs frequent sampling (2-to-15-minute interval), which is very laborious and difficult to perform for extended periods and especially at night. Therefore, much effort has been devoted to developing automated systems based on mechanical and electronic sen-

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sors. Masticatory activity is measured through jaw motion detectors. Rumination and grazing are distinguished by head position (Stobbs and Cowper, 1972), head movement (Chambers *et al.*, 1981), rhythmic patterns of breaks between sets of jaw movements (Matsui and Okubo, 1991) or signal shape (Rutter *et al.*, 1997). All these methods tend to overestimate grazing time and number of bites because they include false positives caused by movements associated with grooming and scratching. The advantages and disadvantages of these methods are highly dependent on the goals and the conditions of each case. In general, their limitations lie in the difficulties in obtaining continuous records for long periods of time without affecting the normal animal behaviour. Methods must also be accurate and have low cost for recording and decoding.

Acoustic biotelemetry was proposed to address some of these constraints. Alkon *et al.* (1989) presented an acoustic method to determine the nocturnal feeding behaviour in porcupines. The use of sound in studies of herbivores was later applied in grazing ruminants (Delagarde *et al.*, 1999; Klein *et al.*, 1994). Moreover, some studies demonstrated that the signal quality obtained by placing a microphone on the forehead of the animal enabled experts to very precisely differentiate the sounds associated with diverse jaw movements during grazing (Ginnett and Demment, 1995; Laca *et al.*, 1994, 1992; Ungar *et al.*, 2006; Ungar and Rutter, 2006) and rumination (Cangiano *et al.*, 2006). Observers were able to recognise three different events by listening to recording of grazing animals: bites are characterized by the ripping sound caused the severing of pasture, chews or mastications produce a crunching sound that is richer in lower frequencies and chew-bites produce a crunching sound followed within a fraction of a second by a ripping sound produced by the severing of herbage associated with the same jaw movement (Laca *et al.*, 1994; Ungar and Rutter, 2006).

The principles of acoustics are important for the acquisition of sounds during ruminant feeding. Feeding sounds propagate through the skull by bone conduction of vibrations. This phenomenon has been extensively studied in humans for the development of hearing applications (Hood, 1962; Håkansson *et al.*, 1996). In animals, these vibrations can be sensed using a unidirectional microphone placed on the forehead, in a noninvasive manner, which does not interfere with their natural behaviour (Fig. 1).

Several studies have used acoustic analysis for ruminant foraging behaviour (Chelotti *et al.*, 2016; Clapham *et al.*, 2011; Galli *et al.*, 2006; Milone *et al.*, 2012; Navon *et al.*, 2013). Laca *et al.* (2000) reported that it was possible to accurately discriminate between bites and chews by differences in the 0-8 kHz spectrum and other acoustic variables (sound duration, energy flux density, average intensity and peak pressure). Milone *et al.* (2012) developed an algorithm that expanded upon previous Hidden Markov Models and achieved up to 85.0% correct classification rate for chews, bites and chew-bites in grazing cattle. Chelotti *et al.* (2016) presented an low computational cost algorithm to detect and classify ruminant jaw movements based on a simple set of heuristic rules derived from expert knowledge. Using only temporal features, the algorithm achieved rates of correct detection and classification of up to 84.0%.

However, to the best of our knowledge, no work has yet tested the performance of automated acoustic methods to detect and correctly classify grazing event across contrasting species of animals and forages, and including discrimination of forage selected and interspersed rumination activity.

The purpose of this study is to analyse temporal and spectral domains of acoustic signals derived from ruminants for classification of jaw movements. The analysis is carried out varying the animal species, the pasture ingested and the feeding activity. This information is crucial to evaluate the potential of acoustic method to: (1) achieve better discrimination of jaw movements in different grazing animals and forage species, (2) determine the diet selection, (3) discriminate between ingestion and rumination activities, (4) improve automation methods and 5) obtain an estimate of the dry matter intake.

II. MATERIALS AND METHODS

Three experiments were conducted during March-August (2009).

FIG. 1. A cow grazing artificial alfalfa microswards. The microphone (placed on the forehead) and the transmitter (placed on the neck) can be seen.

A. Experimental protocol

1. Experiment 1:

Each session was filmed with a digital video camera (Sony DCR-PC100) and the sounds produced by the ingestion of pasture were recorded with the same camera at 22,050 Hz. A wireless unidirectional microphone (151 Nady VR, Nady Systems, Oakland, CA, USA) was used, which has good frequency response (25-20000 Hz $\pm$ 3 dB) and dynamic range (120 dB) features. The microphone was capped and isolated with a rubber capsule, placed on the forehead of the animal and fixed to the halter. The microphone transmitter was attached to the halter over the back of the animal's neck (Fig. 1). Very docile animals, accustomed to the sampling routine, were used. Four adult Holstein dairy cows (liveweight= 608 $\pm$ 24.9 kg) and three adult crossbred sheep (liveweight= 85 $\pm$ 6.0 kg) grazing artificial alfalfa microsward (*Medicago sativa*) in vegetative state were used in Experiment 1. Microswards consisted of sets of 4-6 litre pots that were adjacent and firmly attached to the ground, and were offered to the animals inside a barn. Average plant height was 23.4 $\pm$ 2.1 cm for cows and 28.1 $\pm$ 1.12 cm for sheep. For each grazing session, an animal controlled with a rope and a halter was led to the plants and allowed to graze 30 bites from the upper horizon to avoid depletion effects.

2. Experiment 2:

Artificial microswards were again used in Experiment 2, but four pasture species (one at a time) were offered to the animals in this experiment: two legumes (alfalfa and white clover-*Trifolium repens*-) and two grasses (oats -*Avena sativa*- and tall fescue -*Festuca arundinacea*-), all of them in vegetative state. Average plant heights were 24.6 $\pm$ 2.6 cm, 17 $\pm$ 4.2 cm, 30 $\pm$ 5.9 cm and 39.6 $\pm$ 3.8 cm in alfalfa, white clover, oats and tall fescue, respectively. Plants were offered inside a barn in groups of 24 pots. Four adult Holstein dairy cows (liveweight = 620 $\pm$ 18.3 kg) were used. For each grazing session, an animal controlled with a rope and a halter was led to the plants and allowed to graze for 30 bites. The video camera, wireless microphones and transmitters used were the same as in Experiment 1, but sounds were recorded with an analogue sound recorder (Pioneer CT-F500).

3. Experiment 3:

In Experiment 3, four adult Holstein dairy cows (liveweight= 596 $\pm$ 26.2 kg) grazed legume (alfalfa) or grass (annual ryegrass -*Lolium multiflorum*-), both in vegetative state. Average plant heights were 26.1 $\pm$ 2.2 cm in alfalfa and 33.2 $\pm$ 7.5 cm in annual ryegrass. Sounds were acquired using the same microphone and transmitter of the previous experiments, but the sessions were outdoors with natural pastures and the video and sound were recorded with an analogue video camera (Sony CCD-TR517). For each grazing session the cows were controlled with a rope and a halter (as in experiment 1 and 2) and allowed to graze in the specific pasture for 5-10 minutes. Before each grazing session, cows were fasted for at least 1 hour. After grazing sessions the an-

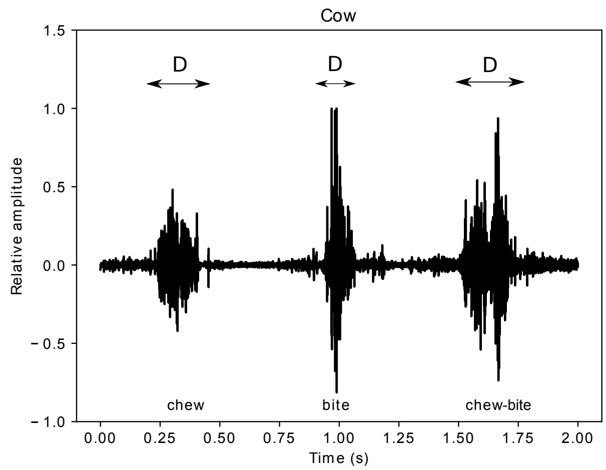

FIG. 2. Sound signal examples of the three types of jaw movements in a cow and the duration (D) of each one. Similar patterns were observed for sheep.

imals were taken into a yard without food until they started a rumination cycle. At least 10 minutes of rumination activity were recorded. To ensure that the animals were ruminating forage from the same pasture they grazed, the cows used in the experiment were grazed in the same type of pasture for at least one week before grazing and rumination were recorded.

B. Signal processing and description of jaw movements

The benchmark classification was performed by an expert in foraging behaviour of ruminants, who watched the videotape while listening the audio signal. Expert segmentation and classification were done using audio editing software[1]. The software was used simply to visually inspect the time-domain signal, mark beginning and end of events and label them with the correct class. Sounds that were distorted or hard to classify were discarded. Events were classified as bite (B), chew (C) and chew-bite (CB) (Fig. 2). In each treatment, 60 events (jaw movements) of each type were selected at random from each treatment. After each event was marked and classified the mean of each jaw movement (i.e. the average value of the sound signal) was subtracted, the autocorrelation was calculated and the energy was normalised.

Each jaw movement was described by the following acoustic variables:

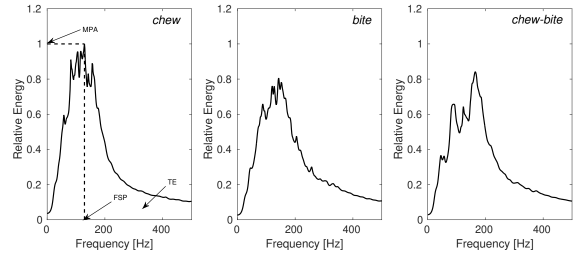

FIG. 3. Spectrum examples showing the three jaw movements in cows grazing alfalfa indicating the maximum spectral peak amplitude (MPA), the frequency where MPA occurs (FSP) and the total sound energy of each jaw movement (TE).

1. Band energy (Eb_i) or spectrum: the spectral energy distribution of the whole jaw movement (sampling frequency of 22,050 Hz) was computed. To approximate the envelope of this spectrum, a linear autoregressive model of order 2^{10} was used. The linear prediction coefficients were calculated using the Levinson-Durbin algorithm (Proakis, 2001) and a spectrum of 2^{13} points was resynthesised through the impulse response of the model. Frequencies in the range 0-2317 Hz (bandwidths hypothesised to have discriminatory information) were retained, obtaining a spectrum of 862 points. Thus, a spectral resolution of 2.7 Hz by point was obtained.

2. Univariate features of jaw movements termed "complementary variables" because they were considered to potentially improve over the use of spectrum alone (C_V):
   (a) Total energy (TE, Fig. 3): $TE = \sum_i Eb_i$.
   (b) Maximum spectral peak amplitude (MPA, Fig. 3): $MPA = max_i Eb_i$
   (c) Frequency band where the maximum spectral peak occurs (FSP, Fig. 3).
   (d) Duration (D, Fig. 2).

C. Classification of jaw movements

Two sets of acoustic variables were considered for each of the experiments: 1) EB, based on the band energy using only the Eb_i, and 2) EB with C_V, based on the band energy and

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the complementary variables. The two groups of variables were used to develop specific models (in all experiments) and general models (only in experiments 2 and 3). Specific models were obtained by grouping data according to the objectives of each analysis. For example, in part of Experiment 2, specific models were developed and tested for classification of jaw movements within each pasture species. In a similar way, specific models were developed and tested in order to identify the pasture species for a given jaw movement. Also, a general model was obtained to identify simultaneously both jaw movement and pasture species.

To identify and select the most discriminatory predictors for each group of acoustic variables the stepwise linear discriminant analysis was used[2]. The best models with up to seven variables were selected(Hocking, 1976). This number of variables was fixed to keep it from exceeding the square root of the number of observations that are used to obtain the model ($\sqrt{50} \approx 7$), in order to avoid overfitting.

Once the best acoustic variables for each group were defined, jaw movements were classified by linear discriminant analysis (LDA) (Johnson and Wichern, 2004). The number and percentage of correctly classified jaw movements were determined using a k-fold cross validation procedure by dividing the 60 jaw movements per treatment into k=6 partitions with 50/10 jaw movements for training/testing. A model was obtained for each partition and then the individual results were averaged to produce a single estimation. To compare the jaw movements using complementary variables, the analysis of variance was applied and when evidence of F was significant, the differences between averages were analysed by the Tukey-Kramer HSD test (Sokhal and Rohlf, 1969). A qualitative analysis of the discriminative power of the complementary variables is detailed in the supplementary material.

Discriminant functions were developed to classify jaw movements as follows:

- Experiment 1a: identify type of jaw movement (B, C, CB) for each animal species separately (2 models, one per animal species);
- Experiment 2a: identify type of jaw movement for each of the four pasture species grazed by cows (4 models, one per forage species);
- Experiment 2b: identify pasture species (alfalfa, fescue, avena and white clover) using each type of jaw movement separately (3 models, 1 per type of jaw movement);
- Experiment 2c: simultaneously identify jaw movements and pasture species (12 classes resulting from crossing 3 types of jaw movement and 4 forage species, 1 model);
- Experiment 3a: identify type of activity (rumination or grazing) based on characteristics of chewing jaw movements only for alfalfa or annual ryegrass pastures (2 models, 1 per pasture species);
- Experiment 3b: identify pasture species (alfalfa, ryegrass) based on the chewing sounds produced during rumination (1 model);
- Experiment 3c: identify pasture species being grazed (alfalfa, ryegrass) using each of the three types of jaw movements separately (3 models, one per type of jaw movement);
- Experiment 3d: identify type of jaw movement (C, B, CB) during grazing for each of the two pasture species grazed by cows (2 models, one per pasture species).

Accuracy (Acc) was the metric used to compare models along the study, which was defined as

$$Acc = \frac{TP + TN}{TP + TN + FP + FN}$$

where TP are true positives, TN are true negatives, FP are false positives and FN are false negatives.

III. RESULTS

A. Experiment 1: Classification of jaw movements within cows and sheep

Experiment 1a). Overall correct classification rates using one model with EB and C_V for each ruminant species were 85.0% for cows and 66.0% for sheep (Table I). In general, models with both EB with C_V variables performed significantly better than with EB alone. Correct classification rates of EB with C_V models were

20.0% and 30.0% higher than with EB alone for sheep and cows, respectively. Accuracy for sheep ranged from 54.0% for C to 75.0% for CB. Variation in accuracy among types of jaw movements was smaller for cows than for sheep, with correct rates ranging from 83.0% for C and CB to 90.0% for B. The type of jaw movement with the worst correct classification rate differed between ruminant species. In sheep, 33.0% of C's were misclassified as B's, and in cows 15.0% of observed CB's were classified as B's.

B. Experiment 2: Classification of jaw movements using different pasture species grazed by cows

Experiment 2a). The percentage of jaw movements classified as the correct type (C, B or CB) using independent models for alfalfa, tall fescue, oats and white clover (N = 240) was highest in alfalfa (82.0%), falling 2.0% in tall fescue, 5.0% in oats and 12.0% in white clover (Table II). Considered over all pasture species, the model with EB and C_V was better than with EB only in 23.0% of the cases. Correct classification rates (Table II) ranged from 65.0% (C for oats) to 90.0% (B for alfalfa). On average across all species, CB had the highest correct classification rate, whereas C had the lowest.

Experiment 2b). Discrimination between pasture species was relatively poor for all types of jaw movements, but promising. Using the model with EB and C_V predictors, 33.5% of B, 45.0% of C and 43.0% of CB were classified as the correct forage species being consumed (Table III). Correct classification rates ranged from 17% for C in oats up to 72% for C in white clover, which was the species that was least confused with others. Overall, alfalfa was indistinguishable from clover, oats from alfalfa and tall fescue from oats. Bites of white clover were frequently confused with those of oats, and C and CB of white clover were confused with those of alfalfa.

Experiment 2c). All the data from Experiment 2 (N = 480) were used to generate a single model to classify each jaw movement into one of the 12 possible classes that arise from combining type of jaw movement (B, C and CB) with forage species (alfalfa, oats, fescue and white clover). An average classification accuracy of 78.5% was obtained for all pastures, with 77.0% correct classification for alfalfa, 84.0% for oats, 82.0% for tall fescue and 71.0% for white clover. These rates are all better than when using separate models, except for alfalfa (Experiment 2a). This is a very promising result for the automated assessment of diet selection when several species are available in discrete patches.

C. Experiment 3: Classification of jaw movements within and between grazing and rumination.

Experiment 3a). Discrimination between grazing and rumination activities using chewing sounds (N = 120) did not improve by adding the complementary variables to the models. An average classification accuracy of 67.0% was obtained for each species (Table IV), with correct classification rates ranging from 47.0% for ingestive chewing in annual ryegrass, up to 85.0% for rumination in annual ryegrass.

Experiment 3b). A similar analysis was conducted for chewing during rumination between pasture species (Table V). An average accuracy of 68.5% was obtained for both pastures.

Experiment 3c). On average, the ability to discriminate the pasture species grazed based on features of different types of jaw movements was 50.0% for B, 64.0% for C and 57.0% for CB over test data (Table VI). For CB, the model with EB and C_V variables achieved a lower correct classification rate than with EB only (64.0%). The confusion matrix shows that B events in annual ryegrass were very difficult to classify.

Experiment 3d). Correct classification rates of jaw movements using specific models for each pasture (N = 120) averaged 77.0%. That was the result of a 79.0% in annual ryegrass and 75.0% in alfalfa (Table VII). On average, the model with EB and C_V obtained an improvement of 23.0% over the EB alone. For each jaw movement, correct classification ranged from 69.0% (CB in annual ryegrass) up to 88.0% (B in annual ryegrass) (Table VII).

IV. DISCUSSION

This work tests the potential to automate classification of ruminant jaw movements into types of jaw movement (i.e. C, B and CB) and forage being consumed by analysing the sounds produced while grazing and ruminating. Correct classification rates varied widely, but in several cases they were very high and suitable for research and management purposes. The specific jaw movements used for the analyses were randomly selected from the whole database, but only those events having clear, clean signals that were unambiguously identified by a trained observer were considered. Therefore, the classification rates obtained represent a best-case scenario and may not be carelessly extrapolated to conditions in which jaw movements are not filtered by quality.

A. Discrimination of jaw movements during grazing

The results obtained in all experiments demonstrated that the analysis of sound signals can be used to discriminate between bites (B), chews (C) and chew-bites (CB) in different ruminant species (cows and sheep), for a wide range of pasture species including legumes (alfalfa and white clover) and grasses (tall fescue, oats and annual ryegrass) in vegetative state. Although the results for cows were better than for sheep, the correct classification rates obtained with sheep in alfalfa are promising and justify further work to verify whether these differences between ruminants persist across varying experimental conditions.

Models using a multivariate representation of the sound spectrum plus additional univariate descriptors of the sound signal performed significantly better at discriminating types of jaw movements than those that used spectrum alone. Laca and WallisDevries (2000) were able to discriminate between bites and chews with a 94.0% accuracy using spectral analysis (eight bands of 1 kHz,each between 0 and 8 kHz) and other variables similar to those used in this study (duration, total energy, intensity and average peak pressure of each signal), which was higher than the 86.0% obtained in this work (Experiment 1 with cows). However, they did not include a chew-bite class, therefore, the results are not directly comparable. Laca and WallisDevries used Hereford steers (weight: 604-710 kg) grazing a very homogeneous grass (*Setaria lutescens*) in vegetative state. Our experiments 2 and 3 showed that grasses yield better classification rates for jaw movements than legumes. In agreement with Laca and WallisDevries, the present study found that D was the most important feature for classification (details are in the supplementary material). The present work used a much smaller range of the spectrum (0-2 kHz vs. 0-8 kHz) with a much greater frequency resolution (862 vs. 8), which allowed for a more detailed analysis. Unlike Laca *et al.* (2000), we found no significant levels of energy in bands above 2 kHz to justify their inclusion, given that much of TE concentrated between 0 and 500 Hz.

Across the three present experiments, chew-bite events exhibited characteristics that are not the simple addition of the characteristics of the component events. For example, total energy (TE) and duration (D) were larger for CB than for B or C, but CB duration was not equal to the sum of B and C durations. Values of MPAs and FSPs for CB were different from the corresponding values for B and C.

Because of the differences between sounds produced by sheep and cows (Experiment 1), it is clear that, in such cases, independent models for each animal species must be developed. The reason for this is that the spectrum of the same type of jaw movements differs between cows and sheep. Moreover, the effect of predictors in the C_V group on the discrimination function depend on the ruminant species. Cows produced sounds that were louder and had more TE than those from sheep, yet, their bites were not significantly longer than those by sheep. This difference in volume and TE of jaw movements between animal species is probably caused by the larger size and grinding surface of cow's teeth, which allow a greater amount of material to be comminuted in a single chew or severed in a single head motion. The lack of difference in duration is probably related to the fact that although cows bite more material, they use a much greater force to sever it (Laca *et al.*, 1994). Such mechanisms of plant-animal interface may also explain why bites are shorter than chews in cows but not in sheep.

B. Diet selection

If jaw movements from different forage species could be discriminated by their sound, acoustic telemetry could be used to estimate diet composition. However, it is likely that this method would be restricted to pastures with simple botanical composition, where species are not interspersed at the bite level. Regardless, this first test of the idea yielded promising results that warrant further investigation.

Acoustic analysis has been applied to humans to describe and explain the sounds produced when biting and chewing different types of food (Drake, 1963; Lee, 1988; VICKERS, 1991), where food with different textures can be distinguished by their particular sound as more or less crunchy (Dacremont, 1995). Galli *et al.* (2006) suggested that similar mechanisms may explain the differences found in steers eating fresh or dry pastures of legume (alfalfa) or grass (fresh orchard grass and oat hay). Fresh pastures produced sounds shorter and more intense than dry pastures, but there were no significant differences between legumes and grasses. Even though in the present work cows consuming legumes produced jaw movements with higher TE values (experiments 2 and 3) and shorter D than grasses (Experiment 2), these differences were not large enough to achieve good classification rates for any of the three types of jaw movements among pasture species. The discrimination techniques used in the present study have limited value for determining diets in mixed pastures in vegetative state. Therefore, other classification techniques should be tested.

C. Discrimination between grazing and rumination.

If it were possible to discriminate between rumination and grazing by the sound analysis, continuous monitoring of the time spent on each activity would be possible at a low cost. The present results show that discrimination was 74.0% accurate in alfalfa and 67.0% accurate in annual ryegrass, and that the differences are located in the spectrum energy of each band. This fact explains why the models not only do not improve when C_V predictors are included in the models.

For the method to be effective, these values should be improved and the sequence of jaw movements should be analysed considering that, during ingestion, bite sounds occurs and jaw movements are irregular due to short breaks between the bite-and-chew sequence. On the other hand, different cycle-to-cycle variations (i.e. alternation between activity bouts) between ingestive events can be studied to allow differentiation between grazing and rumination. The chewing cycles during rumination could also be recognised through the identification of sounds produced by swallowing and regurgitating the cud (Cangiano *et al.*, 2006). Thus, the recognition of jaw movements provide information in order to identify the activity (i.e. grazing or rumination) or the feeding behaviour. In this sense, this information could be processed in a real-time system. On the contrary, the sound signal could be post-processed, searching additional information (rumination pauses) in a big-picture. Even so, the classification of jaw movements provides important information that could be used for intake estimation (Galli *et al.*, 2018).

Contrary to initial expectations, Experiment 3 showed that using chewing sounds it is possible to discriminate whether animals are chewing alfalfa or ryegrass, both for chewing during rumination and during grazing (68.0% vs. 64.0% accuracy, respectively). Ruminants process pasture by first chewing it during ingestion and then regurgitating the cud for further chewing during rumination. Before the ingested forage is regurgitated and re-chewed during rumination, it is processed in the rumen where it become saturated with rumen fluids. The high liquid content of regurgitated cud partly explains why chews during grazing and rumination sound different.

V. CONCLUSIONS

While it is still necessary to conduct further studies to evaluate and expand the potential of the acoustic method, the analysis of grazing sounds discriminated jaw movements within different species of ruminants and within various pasture species. Moreover, the linear discriminant analysis allowed discrimination between grazing activities but not among pasture species, at least for the species used in the present work. These experiments present new evidence on the usefulness of the acoustic method for recording and analysing foraging behaviour of grazing ruminants.

In general, the models based not only on the spectrum but also on additional characteristics of the sound wave achieved more accurate classification than models using only the spectral characteristics of the sounds in all experiments. This indicates that the spectral information is not enough to achieve the highest correct classification rates. One of the most important complementary variables was event duration (D). In this sense, recent studies have demonstrated the existence of discriminative information in simple temporal features of grazing sounds (Chelotti *et al.*, 2016; Clapham *et al.*, 2011; Navon *et al.*, 2013). The lower computational cost of these methods is a clear advantage for real-time analysis of sounds. A more exhaustive study of the combined use of frequency and temporal features will be the object of future studies.

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TABLES

TABLE I. Confusion matrix for classification of bites (B), chews (C) and chew-bites (CB) using separate models for sheep and cows that included EB with C_V predictors (Experiment 1a). Values are averages of classification percentages for test data. Average correct classification rates obtained on test data are in boldface.

Observed/Predicted	Sheep			Cows		
	B	C	CB	B	C	CB
B	**70**	15	15	**90**	7	3
C	33	**54**	13	7	**83**	10
CB	17	8	**75**	15	2	**83**

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TABLE II. Confusion matrix for classification of bites (B), chews (C) and chew-bites (CB) using separate models for alfalfa, tall fescue, oats and white clover that included EB and C_V predictors (Experiment 2a). Values are averages of classification percentages for test data. Average correct classification rates obtained on test data are in boldface.

Observed/Predicted	Alfalfa			Fescue			Oats			Clover		
	B	C	CB	B	C	CB	B	C	CB	B	C	CB
B	**90**	7	3	**77**	7	16	**80**	17	3	**68**	17	15
C	12	**75**	13	17	**75**	8	25	**65**	10	28	**69**	3
CB	10	10	**80**	8	3	**89**	3	10	**87**	13	15	**72**

TABLE IV. Confusion matrix for classification of chews (C) as grazing or rumination using separate models for alfalfa and annual ryegrass that included EB and C_V predictors (Experiment 3a). Values are averages of classification percentages for test data. Average correct classification rates obtained on test data are in boldface.

Observed/Predicted	Alfalfa		Anual Ryegrass	
	Grazing	Rumination	Grazing	Rumination
Grazing	**62**	38	**47**	53
Rumination	27	**73**	15	**85**

TABLE III. Confusion matrix for classification of pasture using separate models for bites (B), chews (C) and chew-bites (CB) that included EB and C_V predictors (Experiment 2b). Values are averages of classification percentages for test data. Average correct classification rates obtained on test data are in boldface.

Observed/Predicted	B				C				CB			
	Alfalfa	Oats	Fescue	Clover	Alfalfa	Oats	Fescue	Clover	Alfalfa	Oats	Fescue	Clover
Alfalfa	**45**	18	15	22	**32**	23	12	33	**22**	20	20	38
Oats	40	**23**	17	20	32	**17**	38	13	20	**52**	20	8
Fescue	24	20	**24**	32	10	30	**60**	0	17	33	**28**	22
Clover	28	22	8	**42**	20	3	5	**72**	20	5	10	**70**

TABLE V. Confusion matrix for classification of rumination chews as alfalfa or annual ryegrass with a model that included EB and C_V predictors (Experiment 3b). Values are averages of classification percentages for test data. Average correct classification rates obtained on test data are in boldface.

Observed/Predicted	Alfalfa	Ryegrass
Alfalfa	**57**	43
Ryegrass	20	**80**

TABLE VI. Confusion matrix for classification of jaw movement as coming from alfalfa or annual ryegrass pastures using separate models for bites (B), chews (C) and chew-bites (CB) that included EB and C_V predictors (Experiment 3c). Values are averages of classification percentages for test data. Average correct classification rates obtained on test data are in boldface.

Observed/Predicted	B		C		CB	
	Alfalfa	Ryegrass	Alfalfa	Ryegrass	Alfalfa	Ryegrass
Alfalfa	**52**	48	**68**	32	**52**	48
Ryegrass	52	**48**	40	**60**	37	**63**

TABLE VII. Confusion matrix for classification of grazing jaw movements using separate models for alfalfa and annual ryegrass that included EB and C_V predictors (Experiment 3d). Values are averages of classification percentages for test data. Average correct classification rates obtained on test data are in boldface.

Observed/Predicted	Alfalfa			Anual Ryegrass		
	B	C	CB	B	C	CB
B	**78**	13	9	**88**	9	3
C	18	**74**	8	8	**80**	12
CB	12	15	**73**	13	18	**69**

Supplementary material: Complementary variables analysis

For each experiment, a qualitative analysis of the influence of complementary variables was conducted.

1. Experiment 1

a. Identification of type of jaw movement (B, C, CB) for each animal species separately (2 models, one per animal species)

The CB sound had a longer D than other types of jaw movement in both ruminant species ($P \leq 0.001$). Whereas duration of B and C did not differ significantly for sheep, in cows B events were shorter than C events (Table A1). In all jaw movements the FSP where the peak occurs was similar in cows ($P = 0.123$), but in sheep the peak of C was detected in a frequency band significantly higher ($P \leq 0.001$) than B and CB. The C events presented the lowest TE values in sheep ($P \leq 0.001$), whereas the opposite was observed in cows, where C showed the highest values ($P \leq 0.001$). While in cows C showed the highest MPA, in sheep there were no significant differences ($P = 0.06$) between three types of jaw movements. In both sheep and cows, D was the only variable selected in all the partitions for discriminant analysis using EB with C_V model. The MPA was important in cows, participating in all cases, but was not the same in sheep. The FSP was selected in half of the sheep partitions but never in cows. The TE was never selected as a meaningful variable.

2. Experiment 2

a. Comparison of types of jaw movements within plant species

Except for alfalfa, B events were the shortest and CB the longest ($P \leq 0.001$, Table A2). Bites produced the peak energy at a lower FSP frequency ($P = 0.023$) than C and CB. There were no significant differences in TE ($P = 0.137$) within species. Chews produced the highest MPA peak in all pasture species ($P \leq 0.001$). Event duration D was the main and only complementary variable selected to identify type of jaw movement, except for alfalfa, where MPA was also selected.

b. Comparison of each type of jaw movements across plant species

Bites were longest in alfalfa and shortest in oats ($P \leq 0.001$). Chew-bite events were longest ($P \leq 0.001$) in oats and shortest in white clover and alfalfa. There were no significant differences in the FSP among the pastures considered for any type of jaw movement. All types of jaw movement were significantly different in TE among plant species. White clover produced the highest MPA for all jaw movements ($P \leq 0.001$). Discriminant analysis selected D and TE as the main complementary variables for models considering all covariates. MPA was also included in the discrimination of B and FSP in the discrimination of CB.

c. Simultaneous identification of jaw movements and pasture species

Event duration (D) was the most important variable in the discrimination of the 12 classes (3 jaw movement types x 4 plant species). Peak amplitude (MPA) was also included in the discrimination function.

3. Experiment 3

a. Comparison of chewing during rumination or grazing within pasture species

Chewing during grazing was significantly shorter ($P = 0.022$) than during rumination for alfalfa (Table A3), but differences were not significant in annual ryegrass ($P = 0.412$). Chewing during rumination in alfalfa produced a peak of energy in a lower FSP ($P \leq 0.001$) than during grazing, but the difference was not significant in annual ryegrass ($P = 133$). TE was lowest in annual ryegrass grazing ($P \leq 0.001$), and it was the only complementary variable selected for discrimination from the C_V group.

b. Comparison of types of jaw movements in two pasture species

Bites were the shortest (Table A4), CB were the longest events ($P \leq 0.001$). Bites had power peaks at lower FSP frequency ($P = 0.001$) than C and CB. Within each species, all jaw movements had similar TE ($P = 0.452$), but all B, C and CB in alfalfa had higher TE than in annual ryegrass ($P \leq 0.001$). Chewing events produced the highest MPA energy in both pasture species

($P \leq 0.001$), and for each type of jaw movement, MPA was higher in alfalfa than in annual ryegrass ($P \leq 0.001$). Although it did not improve the classification, TE was selected to discriminate CB; for the other types of jaw movements models with EB only or EB with C_V achieved the same accuracy.

Appendices Tables

TABLE A1. Test of differences among types of jaw movements and grazing animal species cows and sheep (Experiment 1). D is event duration, FSP is frequency of peak power, TE is total energy and MPA is amplitude of peak power. Lack of common letters between any two cells within variables denotes a significant difference between the means (Tukey-Kramer HSD, P<0.05). Values are ranked from highest (a) to lowest (d).

Variable		B	C	CB
D(ms)	Cows	c	b	**a**
	Sheep	c	c	b
FSP(Hz)	Cows	b	bc	b
	Sheep	d	**a**	cd
TE	Cows	b	**a**	b
	Sheep	c	d	c
MPA	Cows	b	**a**	b
	Sheep	b	b	b

TABLE A2. Test of differences among types of jaw movements and forage species (Experiment 2). D is event duration, FSP is frequency of peak power, TE is total energy and MPA is amplitude of peak power. Lack of common letters between any two cells within variables denotes a significant difference between the means (Tukey-Kramer HSD, P<0.05). Values are ranked from highest (a) to lowest (d).

Variable		B	C	CB
D(ms)	Alfalfa	b	ef	c
	Fescue	fg	cd	b
	Oats	g	de	**a**
	Clover	fg	gh	c
FSP(Hz)	Alfalfa	b	a	**a**
	Fescue	b	a	**a**
	Oats	b	a	**a**
	Clover	b	a	**a**
TE	Alfalfa	b	b	b
	Fescue	d	d	d
	Oats	c	c	c
	Clover	**a**	**a**	**a**
MPA	Alfalfa	e	ab	de
	Fescue	cde	bcd	e
	Oats	de	bcd	e
	Clover	ab	**a**	bc

TABLE A3. Test of differences between grazing and rumination chews in different pasture species (Experiment 3). D is event duration, FSP is frequency of peak power, TE is total energy and MPA is amplitude of peak power. Lack of common letters between any two cells within variables denotes a significant difference between the means (Tukey-Kramer HSD, P<0.05). Values are ranked from highest (a) to lowest (d).

Variable		Grazing	Rumination
D(ms)	Alfalfa	c	**a**
	Ryegrass	bc	b
FSP(Hz)	Alfalfa	**a**	b
	Ryegrass	**a**	**a**
TE	Alfalfa	**a**	**a**
	Ryegrass	b	**a**
MPA	Alfalfa	**a**	**a**
	Ryegrass	b	b

TABLE A4. Test of differences among types of jaw movements and forage species (Experiment 3). D is event duration, FSP is frequency of peak power, TE is total energy and MPA is amplitude of peak power. Lack of common letters between any two cells within variables denotes a significant difference between the means (Tukey-Kramer HSD, P<0.05). Values are ranked from highest (a) to lowest (d).

Variable		B	C	CB
D(ms)	Alfalfa	c	b	**a**
	Ryegrass	c	b	**a**
FSP(Hz)	Alfalfa	c	b	ab
	Ryegrass	c	b	ab
TE	Alfalfa	**a**	**a**	**a**
	Ryegrass	b	b	b
MPA	Alfalfa	b	**a**	b
	Ryegrass	c	b	c