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Category

Research Article

Abstract

This work examines a scaling approach to predict the amount of methane released from the daily activity of livestock on farms. The subject animals are ruminants, i.e. having rumen or a ruminant stomach, that generates methane through digestion processes via several microbial fermentation steps. The produced methane is mixed into their breathing and released into the atmosphere. Existing data on methane released from various kinds of ruminant livestock were correlated as a power function of an animal's weight, with an exponent near 0.92. This value is larger than a value of 0.75 which was related to the general metabolism rates for various animals. These differences may be explained by structure differences of the digestive organs or, more precisely, the difference in the relative length of the small intestine against animal size. Smaller animals have relatively longer small intestines, suggesting that the digestive activity in their stomachs is relatively less-active with less methane production as compared to larger animals. Validity of these structurally-dependent hypothesis was examined and a scaling law is proposed. The derived scaling law can then be used to estimate the release of global warming gas from various kinds of livestock and help to consider reduction strategies to decrease this emitted methane.

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Emission, Methane, Rumination, Livestock, Similarity in digestive organs

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A strategy to predict the global warming gas from stock farming
—Potential scaling law of the released methane from livestock—

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Abstract

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Keywords: Emission; Methane; Lamination; Livestock; Similarity in digestive organs

Introduction

For decades, global warming has been recognized as an environmental problem throughout the world. It is accepted as a consequence of the "industry revolution" in which drastic increases of dust and carbon dioxide (CO_2) were emitted into the atmosphere; global warming is often regarded as a negative aspect of technological development. To negate such impacts, much effort has been expended to reduce atmospheric emissions by introducing improvements in combustion efficiencies and utilize biomass fuels, nuclear reactors, and solar and wind power as substitutes of fossil fuels. Currently, the reduction of CO_2 emissions by technology improvement seems to be close to an upper limit unless carbon storage also becomes effective.

Apart from reducing CO_2 emissions, several options exist to help minimize global warming gas emissions. Table 1 shows the global warming potential (GWP) in an updated assessment report (AR) by the Intergovernmental Panel for Climate Change of the United Nations (IPCC). According to the table, it is obvious that reducing emissions of methane (CH_4), N_2O, fluorocarbons and sulfur hexafluoride (SF6) would also be impactful. Because fluorocarbons and SF6 are industrial products, some approach (maybe political) may successfully suppress them. However, N_2O is an important combustion product and its emission can be controlled by improving combustion technology. However, methane is different than the other gases; it is produced without any industrial activity. In fact, significant amounts of methane are released into the atmosphere by livestock during fermentation reactions associated with digestion processes of ruminant animals. According to a recent report [2], the amount of methane released from livestock corresponded to 7.38% of the total methane supplied into the atmosphere during 2006 and its portion will increase up to 30% in 2020. These data suggest that the elimination of livestock-generated methane would be a quite effective strategy against global warming gas emissions. One approach may be to "convert" animal methane to

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Table 1. Global warming potential (GWP) in the past assessment reports [1]

Substance	AR1 (1990)	AR2 (1995)	AR3 (2001)	AR4 (2007)	AR5 (2013)
Carbon dioxide, fossil (CO_2)	1	1	1	1	1
Methane, fossil (CH_4)	21	21	23	25	28
Methane, biogenic (CH_4)	18.25	18.25	20.25	22.25	25.25
Dinitrogen monoxide (N_2O)	290	310	296	298	265
HCFC-141b	440	-	700	725	782
HFC-134a	1200	1300	1300	1430	1300
HCFC-22	1500	-	1700	1810	1760
HCFC-142b	1600	-	2400	2310	1980
CFC-11	3500	-	4600	4750	4660
CFC-12	7300	-	10600	10900	10200
Sulfur hexafluoride	-	23900	22200	22800	23500

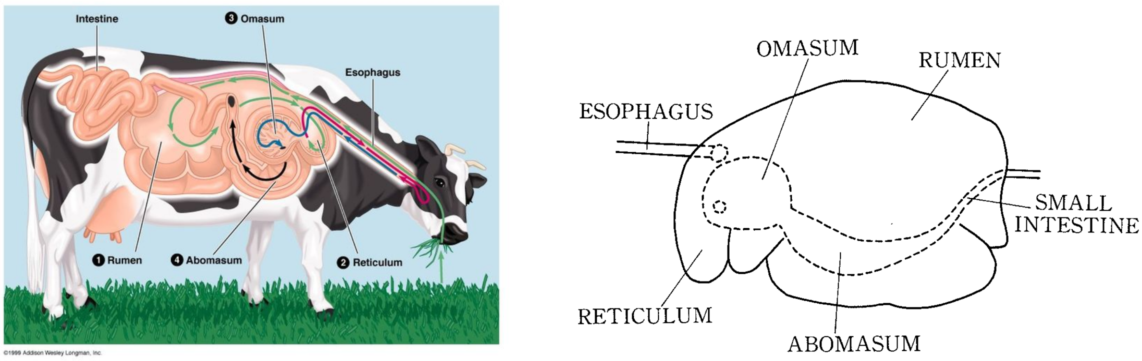

Fig. 1. (left) Schematics drawing of whole digestion process of ruminant animal (cattle) [3], (right) diagram of the ruminant stomach [4].

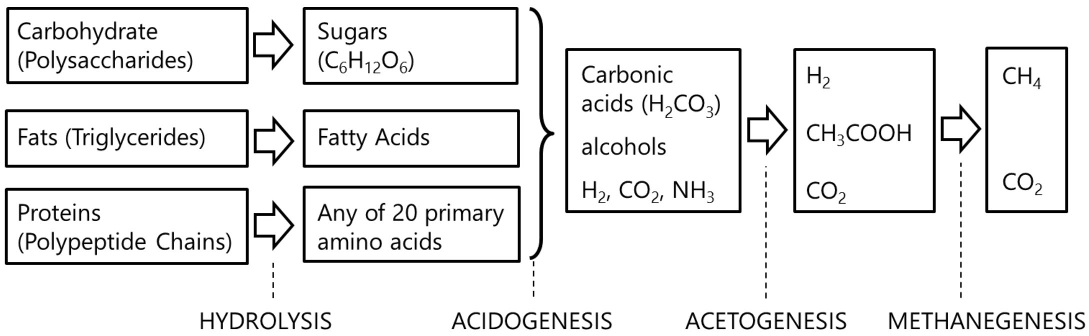

Fig. 2. Chemistry of digestion (modified from figure referred from [5]).

CO_2 by oxidation, e.g. by combustion. To consider how to do this, it is necessary to know or estimate: (1) how much methane; and (2) what kinds of major diluent compounds shall be considered in the treatable atmosphere. For instance, if the concentration is rich enough in methane, simple combustion would be available; if not, catalytic conversion would be preferred if harmful gases are not included.

In this study, a scaling modeling concept is used to predict the concentration of methane in emissions from animals on farms. A brief description of the methane production process in ruminant animals is reviewed, and then a potential scaling law is proposed. By using existing data, the prediction and the scaling law are evaluated and discussed.

Brief overview of methane production via digestion process of ruminant

Ruminant animals have four stomachs, as depicted in

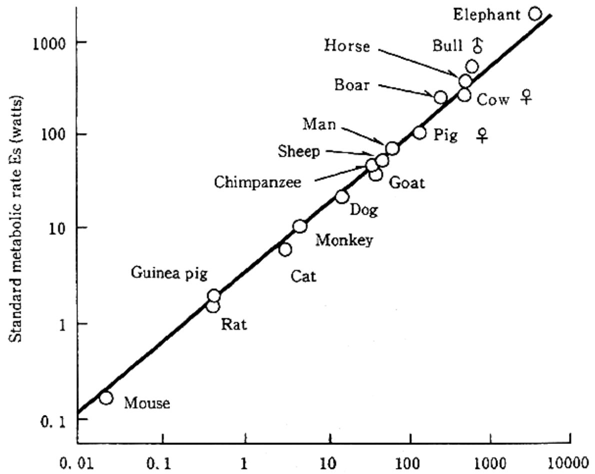

Fig. 3. Relationship between metabolic rate and body weight (mammals) [7].

Fig. 1, and include: (1) rumen, (2) reticulum, (3) omasum and (4) abomasum. The rumen, the first stomach, is the largest and occupies 80% of the total stomach volume. The three stomachs—rumen, reticulum and omasum—are responsible for the totality of rumination; the abomasum is considered the small intestine.

Rumination stands for the "looping" process involved in digesting of foods; the three stomachs break up or partially dissolve the cellulose sufficiently to form a product called the substrate without the use of oxygen. The substrate volume is considerably smaller than the original volume of food entering the first stomach, thereby its exposed surface area per unit volume is larger and enables the promotion of microbial fermentation. The microbial fermentation sequences are briefly summarized by Fig. 2. It clearly shows that methane is a product of fermentation at the end of digestion.

The microbial action involves anaerobic processes and forms volatile fatty acids (VFA) like, formic acid, acetic acid, propionic acid and butyric acid – these are considered direct energy inputs for livestock. Hydrogen is produced during metabolic activity but not all of it is consumed during rumination. Because residual hydrogen is deleterious to the activity of microbial fermentation, methane-producing bacteria also in the stomachs will reform the residual hydrogen with other small carbonic species (e.g. formic acid, carbon dioxide) and produce methane. Methane is not water-soluble and not acted upon by the bacteria; consequently, it is released from the stomach by eructation or belching.

Overall, methane is an unavoidable byproduct of microbial fermentation processes and its release during eructation events demonstrates the healthy state of ruminant animals. Recently, special artificial digestion processes have been developed to suppress the formation of methane during fermentation; although this may sound effective, it may also affect the health condition of the livestock and the quality of their meat.

Scaling law in metabolism

Kleiber's Law [6] states that the standard metabolic rate (E) correlates to the three-fourths power (3/4) of the body weight ($W^{0.75}$) for various animals, as shown in Fig. 3 [7]. This expression is slightly different from Bergmann's law that states metabolism is balanced with heat loss from body surfaces, and the metabolic rate would be a two-thirds power relationship of the body weight [8]; various opinions on which law accurately reflects metabolic activity have been expressed in the scientific literature [9, 10].

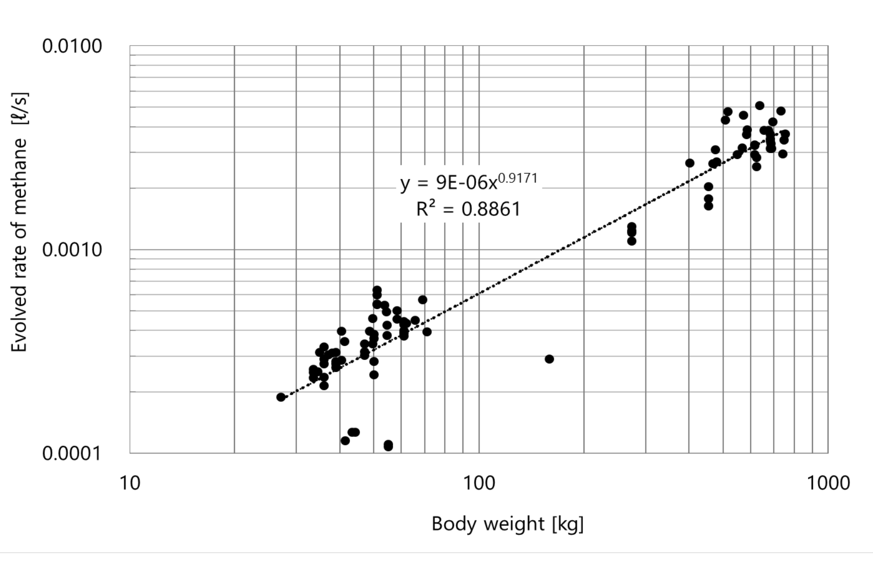

Fig. 4. Evolved methane rate vs. body weight for ruminant animals. All plots are selectively taken from the literature (23 of resources are listed in Appendix).

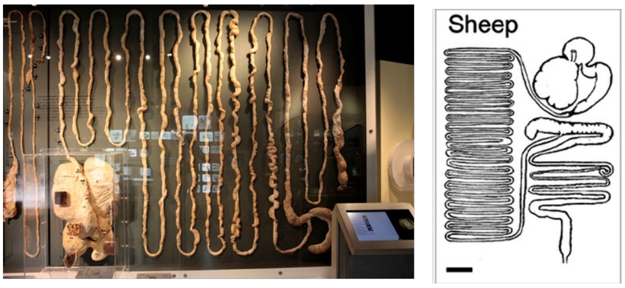

Fig. 5. Digestive organ for cattle (left) [12] and sheep (right) [13].

Table 2. Length of parts of the intestines [14].

Animal	Part of intestine	Relative length (%)	Average absolute length (m)	Ratio of body length to intestine length
Cattle	Small intestine	81	46,0	1 :20
	Cecum	2	0,9	
	Colon	17	10,2	
	Total:	100	57,1	
Sheep and goat	Small intestine	80	26,2	1 :27
	Cecum	1	0,4	
	Colon	19	6,2	
	Total:	100	32,8	

A clarification of whether a three-fourths or a two-thirds exponent is more accurate has yet to exist [11], but in this study it was first assumed to be 3/4. Because methane is emitted through eructation events, its emission frequency would be identical to that of ruminant animal breathing. If it assumed that the concentration of methane during breathing is constant, then the rate of methane also follows a form of $\sim W^{3/4}$.

Literature review

An extensive review of scientific literature was conducted to determine methane emission rates from three ruminant animals, including cattle, sheep and goats (see the appendix for a list of these articles); a summary of the data is given in Fig. 4. It clearly demonstrates that methane emission is represented by $\sim W^{0.92}$ but rather by $\sim W^{0.75}$. Although not widely different, this difference suggests the discussion in the previous section would not accurately depict methane emission from these three animals.

Potential correction in scaling law

Because the whole digestion process is complicated, the following assumptions were made to simplify how to handle the scaling: (1) all animals have their best efficiency in terms of nutrient absorption; and (2) the structure of the small intestines is identical irrespective of the kind of animal.

Fig. 5 compares the digestive organs for cattle and sheep. Although the sizes are different, trends exist between them; for example, the stomachs occupy a large amount of the digestive organ track but the small intestine is longer. Importantly, the ratio of the body length to the total intestine volume is not identical for cattle versus sheep or goats, but the relative lengths of the stomach versus the small intestines are identical. According to Table 2 [14], the scale of animal bodies has an inverse correlation to the relative length of the intestine, i.e. a lighter body weight animal (sheep and goats) has a longer intestine relative to their body length. This correlation also suggests that the smaller ruminants have a relatively less active stomach section and a longer intestine to compensate for incomplete nutrient absorption within the stomach. If so, ruminant action would be less active in smaller animals and the relative production rate of methane would be less as compared to the larger ruminant animals like cattle. This concept can be introduced as an approach to correct the scaling law $\sim W^{0.75}$. Let us test whether this concept enables an explanation of methane production having a dependence of $W^{0.92}$ versus $W^{0.75}$.

The curves from Kleiber's Law, i.e. $\sim W^{3/4}$, and after it has been corrected to $\sim W^{a}$ are presented in Fig. 6 (note that the curves are normalized for cattle data). Assuming that the activity of the stomach for emitting methane is inversely proportional to the length of intestine, the curves in Table 2 point to the emitted methane rate for sheep or goats would be estimated by a 74 % (= 20/27) correction (namely, 26% smaller than shown in Fig. 6). Then, the exponent, a, would be calculated from the following relations:

$$\mathrm{A}\cdot[500]^{3/4} = \mathrm{A}'\cdot[500]^{a} \tag{1}$$

$$0.74\cdot\mathrm{A}\cdot[50]^{3/4} = \mathrm{A}'\cdot[50]^{a} \tag{2}$$

Solving for a gives the following value:

$$a = \frac{3}{4} + \log_{10}\left[\frac{1}{0.74}\right] \sim 0.88 \tag{3}$$

The value of the exponent in Eq. (3) is very close to 0.92 which was proposed from the extensive literature review (Fig. 4). Hence, the difference in the ratio of body length to intestine length is anticipated to be a reasonable approach to adjust the scaling law that predicts emitted methane rates from ruminants.

Although the above-described approach is, admittedly, rough, it points to an important aspect of studying scaling laws: that is, it is imperative to examine the structure of models to ensure "similarity". Because relative length of each part of the intestine is identical in cattle versus sheep or goats, it is safe to state that their intestine structures are statistically similar. Hence, the basic function of the intestine is expected to be an exactly the same, whereas the ratio of stomach-to-intestine is not identical so the whole similarity may ultimately fail.

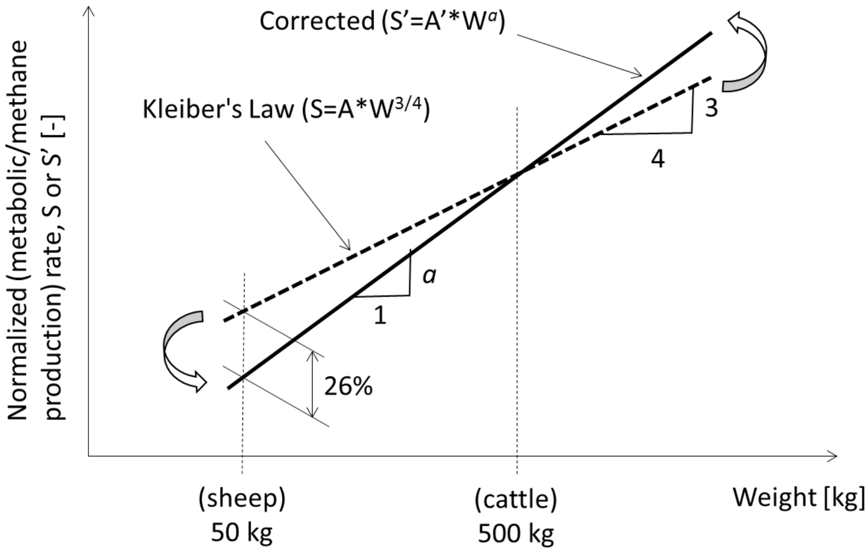

Fig. 6. How to correct to find the acceptable evolved rate of the methane.

Conclusions

The possibility of using a scaling approach to predict the emission rate of methane from the daily activity of livestock on farms was examined using ruminants, including cattle, sheep and goats. Existing data for emitted methane from these animals shows a power of 0.92 of body weights, a value larger than a power of 0.75 when considering metabolism rates for these animals. This difference has been ascribed to differences in the structure of the respective digestive organs as represented the relative length of the small intestine versus animal size. The validity of this structure-dependent correlation was examined and a scaling law was then proposed. From these discussions it was learned that it was imperative to consider structure within similarity while scaling laws are proposed. Overall, the foregoing scaling points to an approach to estimate the global warming effects of methane gas released from various kinds of livestock and then consider reduction strategies for decreasing its emission rate.

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Appendix

Here is the list of references (alphabetic order by first author) for literature review to summarize Fig. 4. It is included the methane evolved rate of cattle, sheep and goat. Because the number strongly depends on the environmental condition (e.g., air temperature) and so on, only picking up the comparable data to construct Fig. 4.

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