DATA 609 - Final Project

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Contents

0.1   Textbook Part III:

0.1.1   The problem

The digestive processes of sheep can highlight the nutrionaly value in varied feeding schedules or varied food prepation. This is esspecially important when raising sheep for commercial purposes.

0.1.2   The digestive process

Sheep are a cud-chewing animal which means that unchewed food goes through a series of storage stomachs called the rumen and the reticulum. The process is illustrated below:
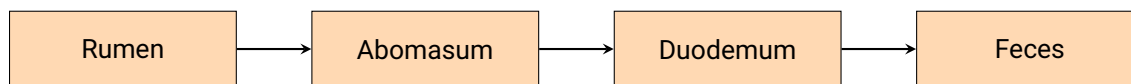
0.1.3   The experiment

The digestive process is most observable at the beginning and at the end, we can observer and control what goes in and what comes out.

0.1.4   The model

Suppose that at $t = 0$ a sheep is fed an amount R of food which goes immediately into its rumen. This food will pass gradually from the rumen through the abomasum into the duodenum. At any later time t we shall define:

$r(t)$ = the amount of food still in the rumen; $a(t)$ = the amount in the abomasum; $d(t)$ = the amount which by then has arrived in the duodenum.

So $r(0) = R$, $a(0)$ = $d(0)$ = 0, and, for all t>0, (1) $r(t) + a(t) + d(t) = R$.

0.1.5 The assumptions

Two assumptions are made: (A) Food moves out of the rumen at a rate proportional to the amount of food in the rumen. Mathematically this says:

(2) $r'(t) = -k_1 r(t)$

where k_1 is a positive proportionality constant.

(B) Food moves out of the abomasum at a rate proportional to the amout of food in the abomasum. Since at the same time food is moving into the abomasum at the rate given by Equation (2), the assumption says

(3) $a'(t) = k_1 r(t) - k_2 a(t)$

where k_2 is another positive proprtionality constant.

0.1.6 The solutions of the equations

0.1.6.1 Solving for $r(t)$

It is straightforward to solve Equation (2) for $r(t)$. We just divide through by $r(t)$ and then integrate from 0 to t:

$\int_0^t \frac{r'(t)}{r(t)} dt = - \int_0^t k_1 dt$

$ln(\frac{r(t)}{R}) = -k_1 t$, since r(0) = R, and finally (4) $r(t) = Re^{-k_1 t}$

0.1.6.2 Solving for $a(t)$

Finding $a(t)$ is a bit more tricky. Applying Equations (4) to Equation (3) we get:

(5) $a'(t) = k_1 Re^{-k_1 t} - k_2 a(t)$

Equation (5) probably looks quite different from any you have seen before. Let us try to make a shrew quess what kind of solution it has. It says that the derivative of $a(t)$ is the sum of two terms, $k_1 Re^{-k_1 t}$ and $-k_2 a(t)$. With luck, this might remind us of the product rule:

(6) if $a(t) = u(t) \bullet v(t)$ then $a'(t) = u(t) \bullet v'(t) + v(t) \bullet u'(t)$

Can we pick $u(t)$ and $v(t)$ so the terms in Equation (6) match up with the terms in Equation (5)? In other words, can we pick $u(t)$ and $v(t)$ so that

(7) $u(t) \bullet v'(t) = k_1 Re^{-k_1^t}$

and

(8) $v(t) \bullet u'(t) = -k_2 a(t)$?

Since $a(t) = u(t) \bullet v(t)$, Equation (8) can rewritten $v(t) \bullet u'(t) = -k_2 u(t)v(t)$, we are in business! The $v(t)$ factors cancel out, leaving us with

$$u'(t) = -k_2 u(t)$$

which looks very much like Equation (2) and can be solved in the same way.

$\int_0^t \frac{u'(t)}{u(t)} dt = - \int_0^t k_2 dt$

Writing K = u(0):

$ln(\frac{u(t)}{K}) = -k_2 t$
$u(t) = Ke^{-k_2 t}$.

Putting this into Equation (7) gives

$Ke^{-k_2 t} v'(t) = k_1 Re^{-k_1 t}$
$v'(t) = \frac{k_1 R}{K} e(k_2 - k_1)^t$.

If $k_1 = k_2$ we feel confident you can complete this solution yourself (Exercise 1).

1 TODO Complete this exercise

Exercise 1. Find $a(t)$ if $k_1 = k_2$.

The derivative of $a(t)$ is the sum of two terms, $k_1 Re^{-k_1 t}$ and $-k_2 a(t)$. If $a'(t) = u(t) \bullet v'(t) + v(t) \bullet u'(t)$

$a'(t) = k_1 Re^{-k_1 t} - k_2 a(t)$

$a'(t) = u(t) \bullet \frac{k_1 R}{K} e(k_2 - k_1)^t + v(t) \bullet -k_2 u(t)$

$a(t) = k_1 Rte^{-k_2 t}$

If $k_1 \neq k_2$, then $k_2 - k_1 \neq 0$ and so we can write

$$v(t) = \frac{k_1 R}{K(k_2 - k_1)} e^{(k_2 - k_1)^t} + c$$

Where C is the constant of integration. Then

$$a(t) = u(t) \bullet v(t) = \frac{k_1 R}{k_2 - k_1} e^{-k_1 t} + CKe^{-k_2 t}$$

Using the fact that $a(0) = 0$, we get

$$0 = \frac{k_1 R}{k_2 - k_1} + CK$$

$$CK = -\frac{k_1 R}{k_2 - k_1}$$

(9) $a(t) = \frac{k_1 R}{k_2 - k_1} (e^{-k_1 t} - e^{-k_2 t})$

2 TODO complete this exercise

Exercise 2.

(a) Find the time t at which $a(t)$ is maximum.

answer: (a) $t = \frac{ln k_1 - ln k_2}{k_1 - k_2}$

(b) Find the maximum value of $a(t)$.

answer: $\frac{k_1 R}{k_2 - k_1}\left[\left(\frac{k_1}{k_2}\right)^{-\frac{k_1}{k_1 - k_2}} - \left(\frac{k_1}{k_2}\right)^{-\frac{k_2}{k_1 - k_2}}\right]$

3 TODO complete this exercise

Exercise 3. If k_1 = 2 and k_2 = 1, how much food must the abomasum be able to hold if a meal of amount R is fed at time t = 0?

answer: $\frac{1/2}{R}$

4 4. Comparison of the Model's Predictions with Experimental Data

Equations (4) and (9) are purly theoretical and are based on assumptions. To confirm their accuracy we will see if they agree with experimental data. Since the data concern is fecal excretion as a function of time, we must first translate our results into results on fecal excretion.

4.1 4.1 Solving for $d(t)$

Starting with Equation (1), and using Equations (4) and (9) (still assuming $k_1 \neq k_2$):

$d(t) = R - r(t) - a(t)$
$= R - Re^{-k_1 t} - \frac{k_1 R}{k_2 - k_1}(e^{-k_1 t} - e - k_2 t)$
$= R - \frac{R}{k_2 - k_1}(k_2 e^{-k_1 t} - k_1 e^{-k_2 t})$

4.2 4.2 The Formula for the Amount of Feces

Recall that $d(t)4 is the total amount of food which has entered the duodenum by time t, including food already excreted. Since excretion is not a continuous process, we cannot hope to represent it by an equation involving derivatives. Instead, we simply note that all food arriving in the duodenum is excreted after a certain time delay. Let us suppose that the average time delay is T hours. In other words, the amount of feces produced by any time t > T is, on the average, the amount of food which had already entered the duodenum T hours earlier, at time t - T. If f(t) denotes the amount of feces produced by time t, this says:

$f(t) = d(t - T) for all t > T$

(10) $f(t) = R - \frac{R}{k_2 - k_1}(k_2 e^{-k_1(t-T)} - k_1 e^{-k_2(t-T)})$

for all t > T.

5 TODO Complete Exercise 4.

(a) Determine the values of t for which r'(t) is, respectively, positive, negative, and zero.
(b) Determine the values of t for which r''(t) is, respectively, positive, negative, and zero.
(c) Determine $\lim_{t \to \infty} r(t)$