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Standardization of rotting rates by a linearizing transformation

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1 *Summary*
Linearization is a mathematical technique for inferring process rates from an observed response variable that, under constant conditions, does not change linearly with time. Experiments have shown that, under constant conditions, tensile strength of buried cotton cloth changes according to the relation:

$$y = y_0 / (1 + (CRR.t)^3)$$

where y_0 and y are initial and final tensile strength, t is time, and CRR is the cotton rotting rate. In soil insertion tests, the initial and final tensile strengths (TS) of cotton are known, so the loss (CTSL) can be calculated, and CRR yr^{-1} may be estimated from the formula:

$$CRR = \sqrt[3]{(CTSL/final\ TS)} \times 365 / t$$

where t is the duration of insertion in days. Thus, using CRR, degradation rates can be manipulated freely, eg to derive a mean annual value, time to 50% CTSL (also used for estimating retrieval time), or a temperature response coefficient Q_{10}.

2 *Introduction*
When a cotton strip is inserted in a particular soil, the reason commonly given is that the research worker aims to determine the potential for cellulose degradation under particular environmental conditions.

This vague answer requires elucidation. By 'potential' is meant the potential rate, which assumes that there is such a thing as a general rate of cellulose degradation. In one sense, a generalized rate is a meaningless hypothetical construct; much depends on how cellulose is presented to decomposer organisms in the soil. However, if, to a reasonable approximation, the rate for one type of substrate is a multiple of that for another, then results for the rate of degradation of a cotton strip could be generalized to materials such as leaves and rotten wood.

Underlying this idea is a multiplicative model (cf Swift *et al.* 1979, p259). In symbols:

$$R(T, M, Q,...) = const \times f(T) \times f(M) \times f(Q) \times ...$$

where R is the rate of the decomposition process, and T, M, Q, .. are variables such as temperature, moisture and substrate quality, which determine the value of R. The advantage of the cotton strip method for soil assay is that it fixes the value of f(Q), allowing the effects of the other variables to be determined more accurately.

3 *Need for linearization*
Unfortunately, the cotton strip assay does not lend itself naturally to the definition of a process rate, R, in contrast, for example, with respirometry, for which the rate of oxygen uptake defines a natural measure of the rate at which the process is occurring. The purpose of linearization is to convert an arbitrary response variable, which might be tensile strength loss, mass loss, FDA hydrolysis (Smith & Maw 1988), or some such factor, to a derived variable that changes linearly with time.

It is instructive to consider an analogous problem familiar to ecologists, namely how to define a process rate for the decay of organic matter in litter bags. Suppose that 100 g of litter are placed in a bag and that, after one year, 50 g remain. This phenomenon would very likely be described by saying that the decay rate:

$$k = \log_e (100/50) = 0.69 \text{ g yr}^{-1}$$

Underlying this description is a model of decay under constant conditions, namely that the proportional rate of loss is constant.

In symbols:

$$y = y_0 \exp(-kt)$$

where y is the measured response variable (mass remaining in the bag), and k is a constant for those environmental conditions, called the decay rate.

Now, it is well known that, under field conditions, the actual instantaneous rate of decay will vary in response to temperature, moisture, and other environmental influences. The decay rate, k, is thus not in reality a constant, but an estimate of the average rate of decay over the year. This average value can be treated as a constant feature of the site, because the between-year variation will usually be small compared to seasonal variation within a year.

To estimate k, we take logarithms:

$$k = \log_e (y_0/y)/t$$

Note that $\log_e$ is the inverse function of exp, ie if $y = \exp(x)$, then $x = \log_e(y)$. Thus, the process rate, k, is estimated by using the inverse function ($\log_e$) of the function (exp) which defines the change in y under constant conditions.

In order to perform a linearizing transformation of this kind, one essential condition must apply, namely that, under constant conditions,

$$y/y_0 = f(Rt)$$

where R is a rate parameter and f is some function. In other words, the shape of the curves describing variation in y over time must be independent of the experimental conditions, although the rate at which things happen (ie the parameter R) may vary. If the shape of the curve f(x) is known, then it is possible to estimate the rate parameter from the equation

$$R = f^{-1}(y/y_0) / t$$

where f^{-1} denotes the inverse function of f.

4 *Hueck–Toorn degradation curves*

Hueck and Toorn (1965) made a study of the form of the decay curve for loss of cotton tensile strength under constant conditions in soil burial beds at 28°C. They fitted curves of the form

$$y = y_0 / (1 + (t/t_{50})^b)$$

to results of 11 individual experiments. Their model has 3 parameters: y_0, the initial tensile strength; t_{50}, the time to 50% loss of tensile strength; and b, a parameter specifying the shape of the curves. For untreated cloth, they found mean parameter values

$$y_0 = 54 \text{ kg cm}^{-1} \text{ (53 kN m}^{-1}\text{)}$$
$$t_{50} = 3.1 \text{ days}$$
$$b = 3.0$$

It can be seen that the shape of the curves is not very sensitive to variations in the parameter b (Figure 1). However, if b varies, then so, by implication, does the shape of the decay curves, and linearization is not possible.

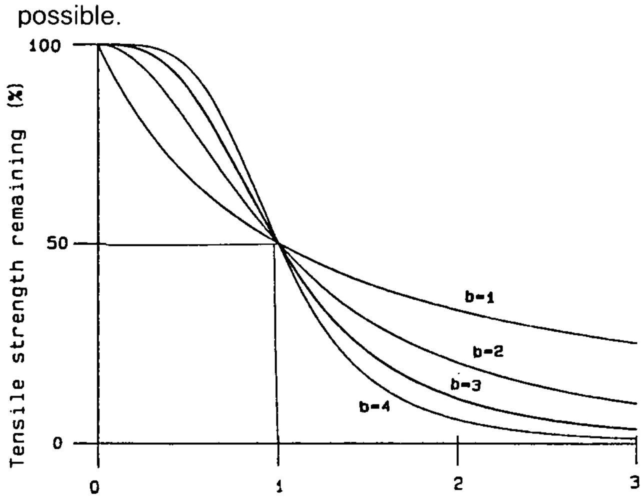

Figure 1. Curves of the Hueck–Toorn family, standardized to 50% loss of tensile strength at time t = 1. The curves have the formula TS = 100/(1 + t_b). The parameter b determines the shape of the curves

5 *An experiment to compare soils*

Following Hueck and Toorn's work, cotton strips were laid within trays of contrasting soils out of doors at the Institute of Terrestrial Ecology's Merlewood Research Station, in Cumbria. Detailed results have been published elsewhere (Hill *et al.* 1985). The aim was to answer 2 questions: did the curves defining the rate of loss of tensile strength have approximately the same shape, and, if the shape was approximately similar, how could it be parameterized?

The experiment was not conducted under controlled conditions. For cotton buried in raised-bog peat, it was necessary to wait more than 2 years before the degradation process was complete. It was, thus, necessary to make allowance for a reduced rate of rotting during the winter, one-third of the summer rate, and the results for 5 soils (Figure 2) then agreed well with those of Hueck and Toorn (1965). Furthermore, it was possible to confirm that the value b = 3.0 fitted our data as well as those of Hueck and Toorn.

On this basis, it is possible to describe the change in tensile strength over time by an equation of the right functional form for linearization, namely:

$$y/y_0 = \text{proportion of tensile strength remaining}$$
$$= (1 + (CRR.t)^3)^{-1}$$

where CRR is a single parameter defining the process rate, and is, by definition, $CRR = CT50^{-1}$, with CT50 = time to 50% CTSL.

Values of CRR range from 1.0 yr^{-1} (CT50 = 365 days) to 40 yr^{-1} (CT50 = 9.1 days) (Ineson *et al.* 1988), with antarctic peat soils giving the lowest values and a tropical swamp the highest.

6 *The linearizing transformation*

The behaviour of tensile strength over time has now been described by a parametric relation of the form:

$$y/y_0 = f(CRR.t)$$

where $f(x) = 1/(1 + x^3)$.

To estimate the process rate, CRR, we need to know the inverse function of f. This is given by:

$$f^{-1}(y) = \sqrt[3]{((1-y)/y)}$$

Let CR (cotton rottenness) be defined by:

$$CR = f^{-1}(y/y_0)$$
$$= \sqrt[3]{((y_0-y)/y)}$$
$$= \sqrt[3]{(CTSL/\text{final TS})}$$

where CTSL = initial (or field control) TS − final TS. Then, the process rate CRR = CR/t.

Provided that the extreme values (unrotted or totally

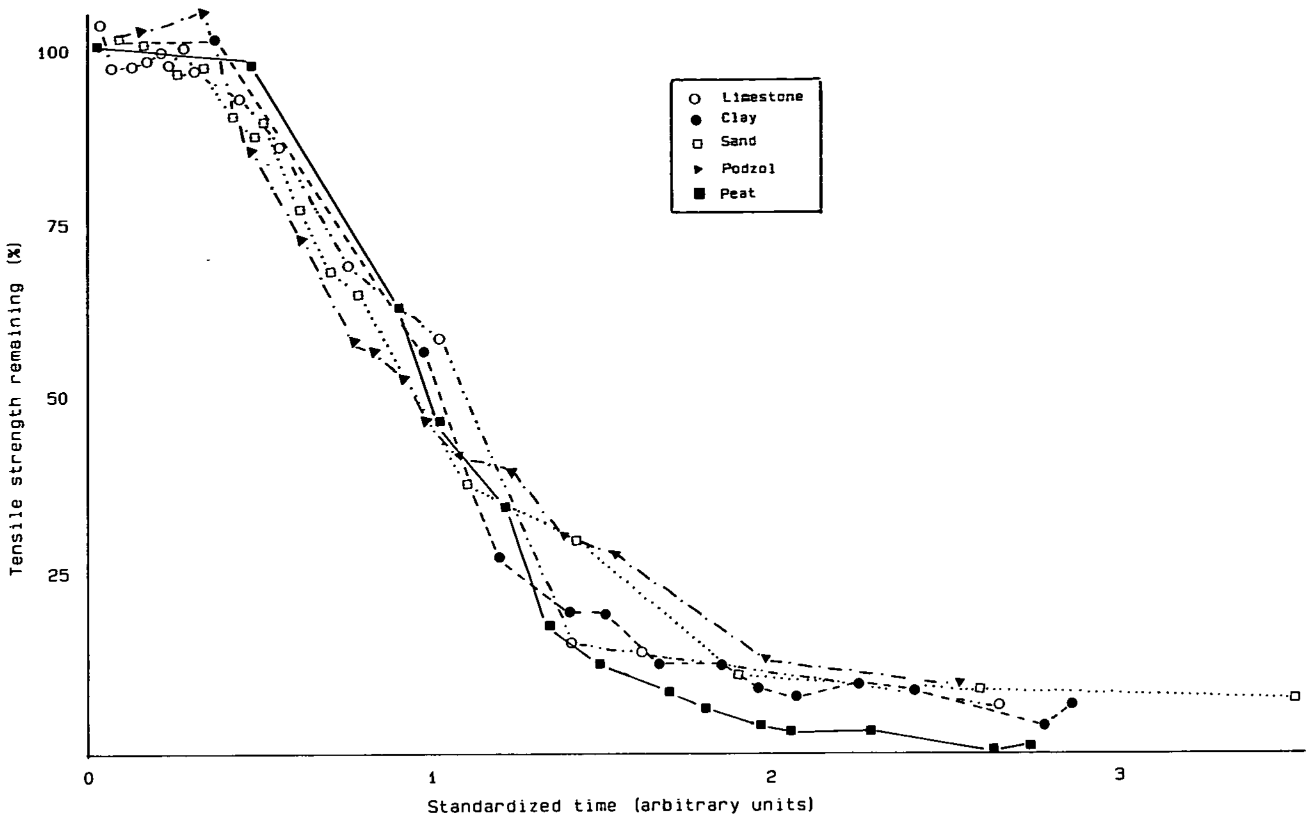

Figure 2. Loss of tensile strength in relation to time in trays of soil at ITE's Merlewood Research Station. The curve for each type of soil has been standardized by adjusting the timescale, so that, as far as possible, the curves lie on top of one another. Allowance has also been made for a reduced rate of rotting in winter (cf Hill et al. *1985)*

rotted) of y/y_0 were avoided, independent estimates of CRR were consistent for each soil, with a coefficient of variation of 11%. However, for values of y/y_0 outside the range 0.1–0.9, estimates of CRR were much less reliable, as also discussed by Walton (1988). As a test of the linearizing transformation, CR was estimated from CTSL after differing periods of burial (Figure 3).

It is now recommended that CRR should be expressed in annual units, even if CT50 is as low as 3 days, which is the sort of value obtained from soil burial beds at 30°C. If CT50 = 3 days, then CRR = 365/CT50 = 122 yr^{-1}. This value may be compared directly with the slower rate of 21 yr^{-1} obtained out of doors at 14°C, suggesting that Q_{10} for the process rate is about 3.0.

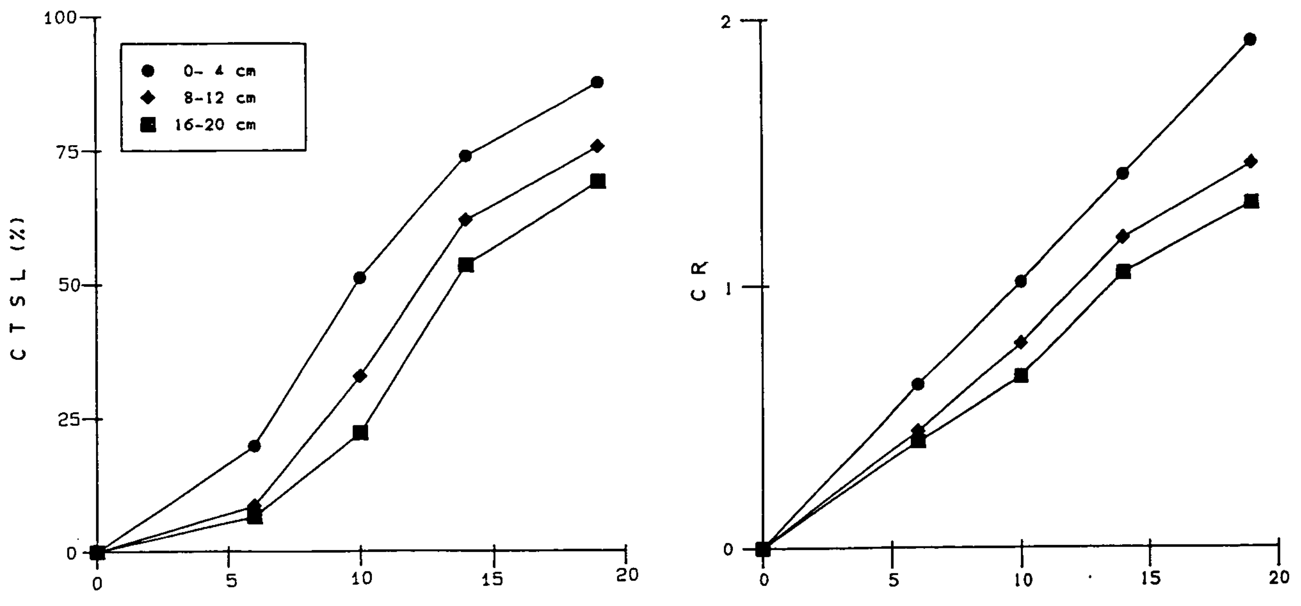

Figure 3. Loss in tensile strength in relation to time in soil in a field experiment at Gisburn Forest, Lancashire (Brown & Howson 1988). Combined data for 4 monoculture plots are presented as unlinearized (CTSL %) and linearized (CR) according to formula in text

7 *Applications*

Given the linearizing transformation, attention can be focused on the results of cotton strip assays, and their interpretation. In particular, it is possible to estimate an annual rate of rotting for a site, based on a number of individual observations. Suppose that strips are buried at 4-monthly intervals, say on 1 January, 1 May and 1 September, and recovered after 6 weeks. If the seasonal rates of rotting, CRR, are 3 yr^{-1} for January, 5 yr^{-1} May and 8 yr^{-1} September, then an estimate of the mean annual value is $(3 + 5 + 8)/3 = 5.3\ yr^{-1}$. The meaning of this value is that, if each strip were left in place until it had reached 50% CTSL, and then withdrawn and replaced by a fresh one, 53 strips would be decomposed in 10 years. This annual value allows a direct comparison with arctic sites, where it is possible to leave a single set of strips buried for a whole year before recovery.

A mean result can also be calculated for a sequential sampling series, where strips are inserted at one time but removed at several time intervals (provided that the means for any one removal date are within the range 10–90% CTSL).

The optimum retrieval time of approximately 50% loss is easily estimated using a CT50 calculated for a set of test control samples at a certain time t, where:

$$\text{days to 50\% CTSL} = \frac{\text{days at time t}}{\text{CR at time t}}$$

Using the linearized process rate, CRR, it is also possible to define a temperature response Q_{10} for decomposition. If observations are available from tests at differing temperatures, and if the soils are not too different, then the decomposition rate may be expected to show a roughly exponential temperature response:

$$\text{CRR} = \text{constant} \times Q_{10}^{(T/10)}$$

ie $\log_e \text{CRR} = \text{constant} + \log_e \text{CRR} = \text{constant} + \log_e (Q_{10})/10 \times T$.

In other words, if the slope of the regression of $\log_e$ CRR on temperature is b, then:

$$Q_{10} = \exp(10 \times b)$$

8 *References*

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