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Productivity of intensified crop–fallow rotations in the Trenbath model

M. VAN NOORDWIJK
ICRAF-S.E. Asia, P.O. Box 161, Bogor 16001, Indonesia; E-mail: m.van-noordwijk@cgiar.org

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Abstract. Management of crop–fallow rotations should strike a balance between exploitation, during cropping, and restoration of soil fertility during the fallow period. The 'Trenbath' model describes build-up of soil fertility during a fallow period by two parameters (a maximum level and a half-recovery time) and decline during cropping as a simple proportion. The model can be used to predict potential crop production for a large number of management options consisting of length of cropping period and duration of fallow. In solving the equations, the model can be restricted to 'sustainable' systems, where fallow length is sufficient to restore soil fertility to its value at the start of the previous cropping period. The model outcome suggests that the highest yields per unit of land can be obtained by starting a new cropping period after soil fertility has recovered to 50–60% of its maximum value. This prediction is virtually independent of the growth rate of the fallow vegetation. The nature of the fallow vegetation (natural regrowth, planted trees, or cover crops) mainly influences the crop yield by modifying the required duration of fallow periods. Intensification of land use by shortening fallow periods will initially increase returns per unit land at the likely costs of returns per unit labor. When fallows no longer restore soil fertility to 50% of the maximum, overall productivity will decline both per unit land and per unit labor, unless external inputs replace the soil fertility restoring functions of a fallow.

Introduction

Fallows can be defined as land that is not currently cropped, but will be cropped in the future. Such a definition emphasizes annual food crops as the main output of land use. In practice, however, non-cropped land is rarely idle. It can be used, for example, as grazing land and for producing firewood, honey, and thatching material. The first step in farmer management of fallow lands is usually the retention or promotion of certain plant species, which appear spontaneously either from native vegetation or as neophytes in the fallow and are considered to be of value for one of the several functions of a fallow. During further intensification, however, choices among the multiple functions may be necessary. Figure 1 indicates three pathways for intensification of undifferentiated, multi-purpose fallows: one leading to systems where the value is increasingly derived from tree products, one where it is based on fodder value, and one leading to increased cropping intensity.

The classical agronomic view on intensification of upland cropping systems (Ruthenberg, 1976) is that a higher cumulative output per ha, and therefore a higher human 'carrying capacity', can be obtained by increasing the cropping

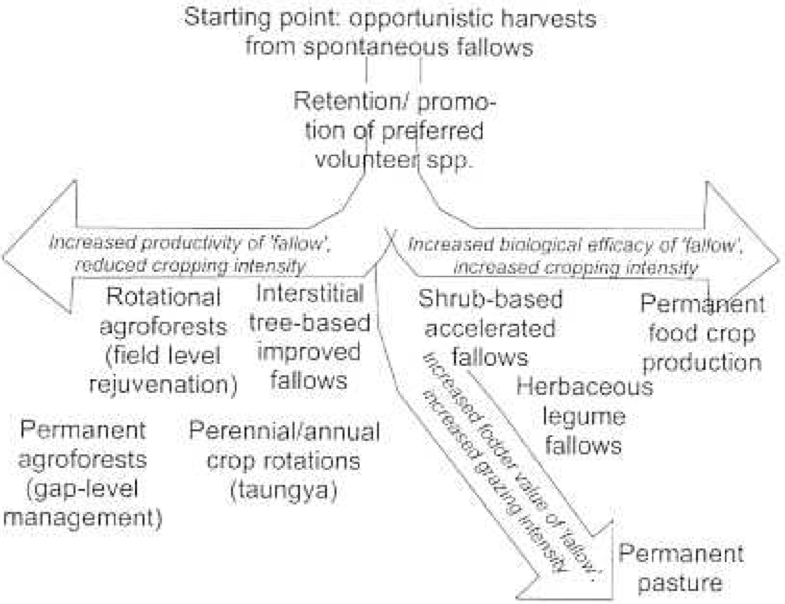


Figure 1. Indigenous approaches to modifying 'fallow' vegetation that emphasize the tree, fodder, or subsequent crop production as main functions (modified from Cairns and Garrity, 1999).

intensity (Figure 2, the upward sloping diagonal). An increase in productivity per unit land may be accompanied by a reduction in productivity per unit labor, unless (1) mechanization replaces the labor needs of managing increased weed pressure, reduced soil structure, and increased pest pressures that are the consequence of a loss of fallow functions and (2) fertilizers replace the soil fertility restoration function. Fallow rotation systems, in the definition of Ruthenberg (1976), are an intermediate stage between 'shifting cultivation' or 'long-rotation fallow systems' where land is cropped for less than one-third of the time ($R < 0.33$) and 'continuous cropping' where land is cropped more than two-thirds of the time ($R > 0.67$). The R value of Ruthenberg (1976) is the fraction of time (or land area) used for annual food crops as part of the total cropping cycle (area). The equivalence of time and area only applies in 'steady state' conditions of land-use intensity.

More intensive land use (higher R values) requires that the soil-restoring functions of a fallow must be obtained in less time, by a so-called improved (more effective) fallow, or that these soil-restoring functions must be fully integrated into the cropping system. In practice there is a danger of 'over-intensification' leading to degradation (Trenbath, 1989; Van Noordwijk et al., 1997). Imperata [*Imperata cylindrica* (L.) Raeuschel] fallows may on one hand prevent complete soil degradation, but they are not productive, do little to restore soil fertility, and may lead to land abandonment (Figure 2, trend towards lower left corner).

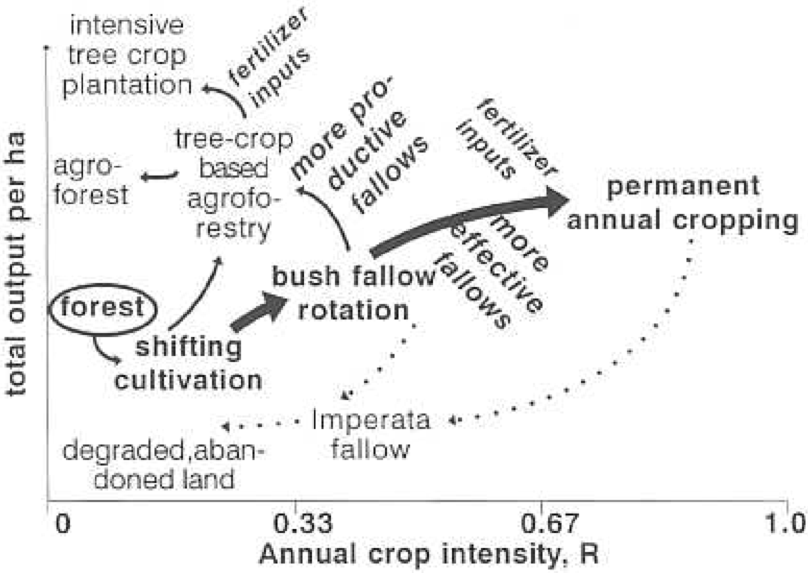


Figure 2. Pathways for intensification of shifting cultivation and fallow rotation systems as related to annual crop intensity R (fraction of the time land is used for annual crops) and total output per ha. Whereas shifting cultivation systems can be initially intensified by increasing both the value of the fallow and the frequency of cropping, at some point a choice must be made between an annual, food-crop-based pathway and one leading to agroforests and tree-crop plantations (Van Noordwijk et al., 1996a).

When management of a fallow aims to increase its direct production value, such as tree products and herbaceous legume fodders, the fallow is referred to as 'enriched' (more productive). Fallows that start from very low management intensities can be both 'improved' and 'enriched', but conflicts will arise at a certain intensity of land use because improved fallows will be of rather short duration and many of the elements of enriched fallows require longer maturation periods. As shown in Figure 2, it is necessary to choose between more effective fallows with food-crop based production systems (trend towards the upper right) or more productive fallows with a reduced importance of food crops (trend to the upper left). Land-use systems such as the rubber agroforests of Sumatra (Gouyon et al., 1993) have evolved from 'enriched' fallows into land-use systems where the tree fallow dominates and the food-crop period has become a minor element in the total land-use system. This paper will only focus on models of 'improved' fallows, emphasizing effects of fallows on subsequent crop production.

The usual connotation of a fallow is that of restoring the productive potential of a soil, and one generally expects higher crop production per season after a fallow than it would have been under continuous cropping. There are many reasons why crop productivity declines during continuous cropping in a particular site, and there are therefore many potential functions of fallows and potential parameters to be used as yardsticks of success (Van Noordwijk et al., 1996b). Fallows can only be 'improved' for a given location if the improvements address the critical problem for that location. A site-specific diagnosis is thus needed of the decline in crop productivity to evaluate the biophysical effectiveness of fallows and thus predict the limits of extrapolating results of fallow experiments (Table 1). A site-specific diagnosis is also needed to choose the technical alternatives to which fallows can be compared in an evaluation of their financial attractiveness to smallholders.

The R value of Ruthenberg (1976) suggests that the ratio of fallow length and cropping period, rather than the absolute length of both, is important. This would be true if both the decline of productivity during cropping periods and the restoration during a fallow are linear processes, independent of the current fertility status of the soil. In practice, however, the decline of productivity is exponential rather than linear. Literature reviewed by Ruthenberg (1976) illustrated that a linear model of productivity decline easily leads to negative yields, whereas real data show an asymptotic approach of zero yield. The restoration of productivity will not continue indefinitely, but may follow some form of saturation curve (Nye and Greenland, 1960). Models of organic matter dynamics in relation to land use, such as Century (Parton et al., 1992) and Rotate (Robertson, 1994; Mobbs and Cannell, 1995) predict non-linear dynamics. This means that the absolute duration of both fallow and cropping periods remain important at given land-use intensity, and that the R value only gives a first indication.

Models of fallow rotations at different temporal and spatial scales should potentially address the wide range of fallow functions listed in Table 1. Yet, the major part of specific research efforts (empirical and modeling) has focussed on the decline and build-up of soil organic matter during cropping and fallow periods and its role in the N supply of subsequent crops, with secondary attention to P and other nutrients.

Trenbath (1984; 1989) formulated a simple model of restoration and depletion of 'soil fertility' during fallow and cropping periods, respectively. 'Soil fertility' is here taken to be a complex of effective nutrient supply and biological factors (diseases, weeds) affecting crop yield. In the following pages, I will explore the consequences of a 'sustainability' constraint on this model and use it to explore how key management choices can best be made by farmers, depending on whether they want to maximize productivity per unit land or per unit labor.

Trenbath model of fallow rotations

Yields and decline of soil fertility during cropping

Crop yield in the model of Trenbath (1984; 1989) is assumed to be directly proportional to an (unspecified) 'soil fertility' complex. During a cropping

Table 1. Determinants of biophysical limits to improved fallows, depending on the key constraint to crop yields under the given soil and climate conditions; the technical alternatives should be included in an economic evaluation of the fallow's effectiveness.

Constraint to crop yield	Functions of the fallow	Determinants of biophysical limits to 'fallow functions'	Technical alternatives
N supply	a) N_2 fixation b) Recover N leached into subsoil during cropping period c) Capture of N from subsurface lateral flow	a) Occurrence of effective *Rhizobium* strains b) Soil depth, rainfall, hydrology, nitrification, apparent adsorption constant c) As 'b' and slope	a–c) N fertilizer
P supply	a) Increase soil organic P – based on P capture by fallow species from occluded soil P sources b) Decrease P sorption during crop phase – due to organic acids from fallow residues c) Release of organically bound P during fire used for clearing of fallow vegetation d) Facilitate mycorrhiza development	a) P capture strategy (root exudates, mycorrhiza) of fallow vegetation, presence of occluded soil P fractions, soil mineralogy b) Soil P sorption characteristics c) Changes in organic P pools, fire temperatures d) Occurrence of effective mycorrhizal infection in crop	a–c) P fertilizer d) vesicular–arbuscular mycorrhiza inoculation
Cation supply and acidity	a) Recycle cations from soil depth b) Reduce acidity – based on interactions of organic acid from fallow residues on soil Al	a) Recharge of subsoil cation content, leaching, lateral flow b) Chemical composition of fallow residues interacting with Al	Lime, dolomite, K fertilizer
Nematodes and other soil-borne pests	a) 'Fool' propagules to reduce their infection potential b) Stimulation of antagonists	a) Specific biological properties of soil and fallow species	Nematicides, crop rotations
Weeds including parasites	a) 'Fool' propagules into germination (e.g., *Striga* seeds) b) Reduce vigor of propagules (e.g., *Imperata* rhizomes)	a) Effectiveness of root exudates from fallow vegetation b) Shade duration and intensity	Herbicides
Soil structure affecting infiltration	a) Create old tree root channels b) Facilitate soil biota – through inputs of organic materials	a) Rooting pattern and fine root turnover of fallow vegetation b) Specific effects of fallow litterfall on soil fauna	Use of crop residues, soil tillage

Modified from Van Noordwijk et al. (1996b).

period, soil fertility declines with a fraction D per crop. Soil fertility during the cropping period is (Figure 3A):

$$F_t = F_{c0}\,(1 - D)^{n(t-1)} \tag{1}$$

where:
F_t = soil fertility at time t (years);
F_{c0} = soil fertility at start of cropping period;
n = number of crops per year during cropping period;
D = reduction factor of soil fertility per crop.

Cumulative yield for a cropping cycle is:

$$Y_{\mathrm{cum}} = c\,F_{c0} \sum_{i=1}^{nt_c} (1 - D)^{i-1} \tag{2}$$

where:
c = conversion efficiency of soil fertility to crop yield;
t_c = length of cropping period in years.

Restoring soil fertility during fallow periods

During a fallow period soil fertility (or more correctly, the ability to support future crop yields) can be restored (re-created) with an asymptotic approach to a maximum value (Figure 3C).

$$F = \frac{F_{\max}\,t_f}{K_f + t_f} \tag{3}$$

where:
F = soil fertility at end of fallow period, assuming a value of zero at the start of the fallow;
K_f = 'half-recovery time' or time needed to halve the difference between current and maximum soil fertility;
$F_{\max}$ = maximum fertility, reached after an infinitely long fallow period;
t_f = length of fallow period in years.

The shape of this curve is similar to a Michaelis-Menten equation. The increment in soil fertility during one year of fallow depends on the initial soil fertility, F_i, which can be expressed as an 'apparent fallow time', t_i:

$$F = \frac{K_f\,F_i}{F_{\max} - t_i} \tag{4}$$

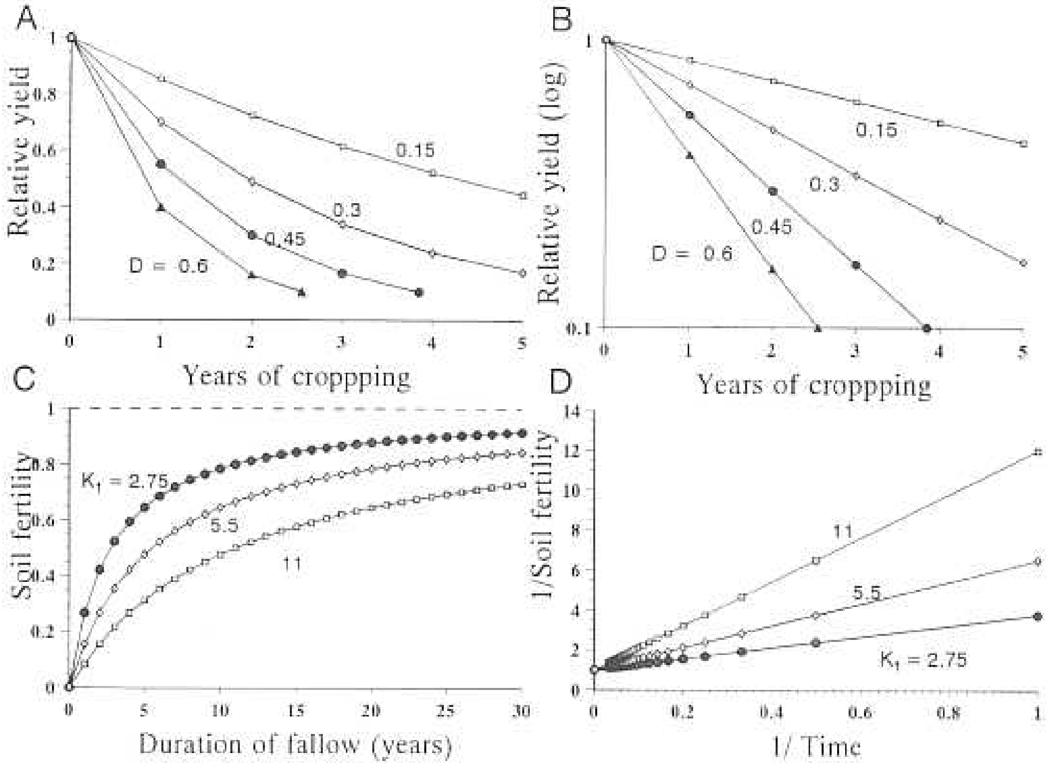


Figure 3. Basic assumptions of the simple fallow model of Trenbath (1989). Crop yields in subsequent years are governed by the reduction factor of soil fertility per crop (*D*) (part A), and a log scale for the *Y*-axis linearizes the relations and can be used for parameter estimation (part B). Part C shows recovery of soil fertility during a fallow, where K_t if the time required to halve the difference between current and maximum soil fertility, and part *D* illustrates a linearized plot of *1/x* against *1/y* that can be used to estimate parameters.

Soil fertility recovery during an interval from i to $i + 1$ equals:

$$F_{i+1} - F_i = F_{\max}\left[\frac{t_i + 1}{K_f + t_i + 1} - \frac{t_i}{K_f + t_i}\right] = \frac{(F_{\max} - F_i)^2}{F_{\max}(1 + K_f) - F_i} \tag{5}$$

The equation shows that soil fertility returns directly to its maximum value if $K_f = 0$. The length of the fallow period (t_f) depends on the 'cropping intensity' factor R based on Ruthenberg (1976):

$$t_f = \frac{t_c\,(1 - R)}{R} \tag{6}$$

where:

$R = t_c/(t_c + t_f) =$ relative length of the cropping period (or relative area cropped at any time in a steady-state situation).

Deriving model parameters from experimental data

The model thus contains two parameters that depend on soil, climate, and fallow vegetation ($F_{\max}$ depends on soil type, K_f depends on fallow vegetation and climatic conditions) and two that depend on the cropping practice (D depends for example on soil tillage, c depends on crop genotype and crop management). These four parameters determine the response domain within which the farmer operates. Farmer management choices are then the number of years of cropping (t_c), the number of crops per year (n), and the cropping intensity (R).

Results of experiments or of more detailed models can be used to obtain the two key parameters, D and K_f, as follows. To estimate D, a time course of crop yields under continuous cropping is needed, for a given soil and climate, as equation (1) leads to:

$$\begin{aligned} \log F_t &= [\log F_{c0} - n \log (1 - D)] + t\, n \log (1 - D) \\ &= (a - b) + b\, t \end{aligned} \tag{7}$$

If the parameters a and b are derived by a regression of $\log F_t$ on t (Figure 3B), we can derive:

$$F_{c0} = \exp(a) \tag{8}$$

and

$$D = 1 - \exp(b/n) \tag{9}$$

The fallow recovery parameter K_f can be obtained from a linear regression of $1/F$ against $1/t$ for fallows of different length (Figure 3D), as:

$$\frac{1}{F} = \frac{1}{F_{\max}} + \frac{1}{t}\left(\frac{K_f}{F_{\max}}\right) \tag{10}$$

F can not normally be measured directly during a fallow growth and a time series of F must be obtained by growing crops after fallows of different duration. Because crop yields are used as indirect measures of F, it is preferable to use data from fallows established at different points in time and cropped in the same growing season.

Adding a sustainability constraint

We can take the model of Trenbath a step further, by constraining solutions to a subset that is 'sustainable', in the sense that there is no change in yields between subsequent fallow–crop cycles. The relative change of soil fertility over one crop + fallow cycle is defined as S:

$$S = 100\,\frac{F'_{c0} - F_{c0}}{F_{c0}} \tag{11}$$

or

$$= -100\left[1 - \frac{F_{\max}\,(t_f + t'_f)}{F_{c0}\,(K_f + t_f + t'_f)}\right] \tag{12}$$

with

$$t'_f = \frac{K_f\,F_{c0}\,(1 - D)^{nt_c}}{F_{\max} - F_{c0}\,(1 - D)^{nt_c}} \tag{13}$$

The required length of fallow (T_{fe}) for an equilibrium situation ($S = 0$) can then be calculated from:

$$T_{fe} = \frac{K_f\,[1 - (1 - D)^{nt_c}]}{(1 - f)\,[1 - f\,(1 - D)^{nt_c}]} \tag{14}$$

where $f = F_{c0}/F_{\max}$ indicates the relative fertility at which the fallow vegetation is replaced by the first crop. The required fallow length is directly proportional to K_f, and thus inversely proportional to the efficiency of the fallow in recreating soil fertility.

Maximizing yield per unit land

Average yield over the cropping years (Y_{cum}/t_c) follows directly from equation (2) and is proportional to F_{c0} and thus to f. Average crop yield over the whole fallow + cropping cycle, under the restriction of a non-degrading system, can be obtained by combining equations (2) and (14):

$$y_t = \frac{Y_{cum}/Y_{max}}{T_c + T_{fe}} = \frac{f\,(1-f)\,\sum_{i=1}^{nt_c} (1-D)^{i-1}}{T_c\,(1-f) + K_f\,M} \tag{15}$$

with

$$M = \frac{1-(1-D)^{nt_c}}{1-f\,(1-D)^{nt_f}} \tag{16}$$

the term M may be close to 1 for realistic parameter values, and with this simplification we can derive the value f_{opt} that will give the highest relative yield per unit land by equating the derivative dy_t/df to zero:

$$f_{opt} = \mathrm{B} - \sqrt{B^2 - B}, \quad \text{with} \quad B = 1 + \frac{K_f}{t_c} \tag{17}$$

Results and discussion

Equation (17) suggests that not the K_f or t_c values themselves, but only their ratio is important in determining the optimum time for slashing the fallow vegetation. For $K_f = 0$ we obtain $f_{opt} = 1$, but such instantaneous fertility recovery is only possible by using external nutrient inputs (organic or inorganic) and not by on-site fallow vegetation. For even the best 'improved fallow', the K_f/t_c ratio will be at least 0.5, and this leads to $f_{opt} = 0.63$ as a likely upper limit of initial fertility for maximizing yields. The lower limit is $f_{opt} = 0.5$, which is asymptotically approached for high K_f/t_c ratios (Figure 4).

Without the approximation used in deriving equation (17), numerical results also show a maximum yield, averaged over the whole crop + fallow cycle, for relative fertility f (at the start of a cropping cycle) just above 0.5 (Figure 5D). Halving the K_f value causes a slight shift to higher f_{opt} value (Figure 5B versus 5D), and shorter cropping cycles (smaller t_c) will shift f_{opt} to slightly lower values (Figure 5B and 5D).

If labor is the main limitation, yields should be expressed per cropping period and then clearly the higher the initial fertility the higher the yields. The required fallow length may be about 100 years, however. Depending on the labor costs in a second, third, or subsequent year compared to that for clearing the initial plot, the lower average yields for longer cropping cycles can still

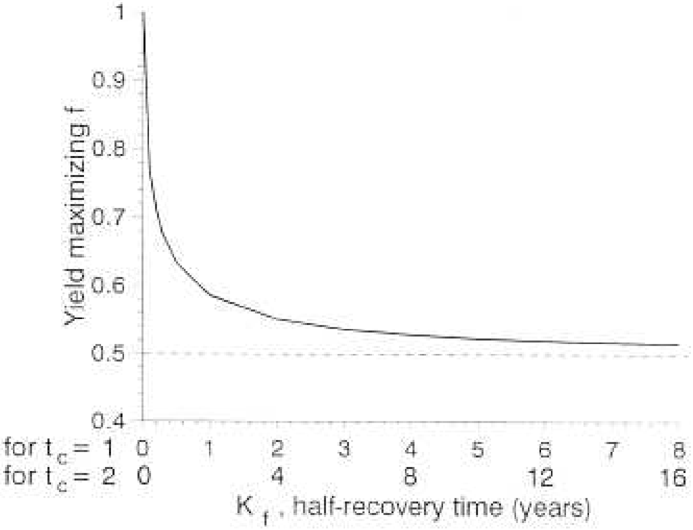
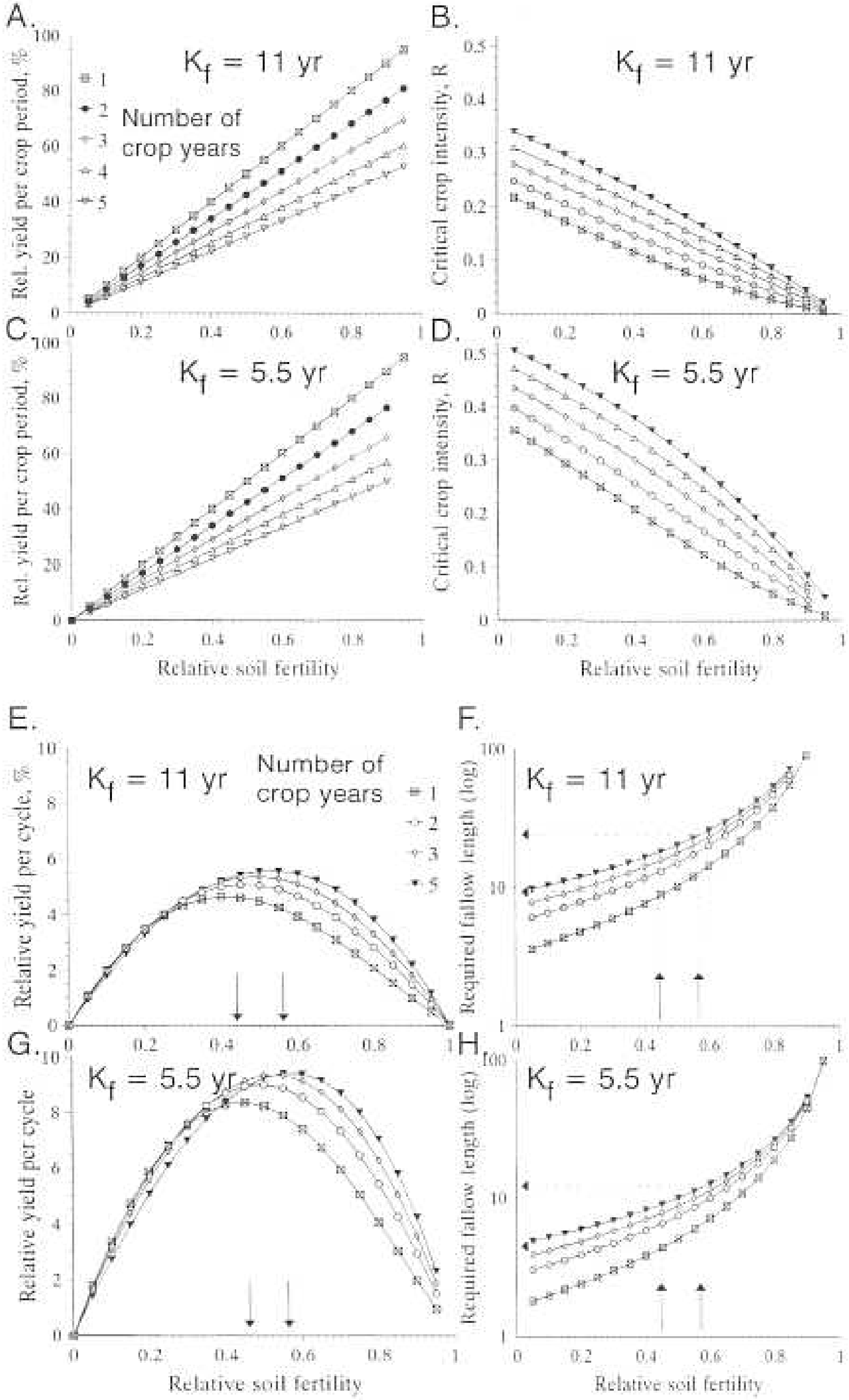


Figure 4. The choice of initial fertility (f_{opt}) upon opening a fallow for cropping that maximizes yield per unit land for crop + fallow cycle, as a function of fallow half-recovery time (K_f) and length of cropping period (t_c).

be acceptable. The cropping intensity *R* can be less than 0.1, and in Ruthenberg's definition these are true shifting cultivation systems.

If land is the main limitation, however, yields should be expressed per total amount of land under the fallow rotation system and then the best yields are apparently obtained where the soil fertility is allowed to recover up to about 50% of the maximum value. Longer cropping periods only give a moderate increase in total yield per unit area up to t_c of three years and hardly anything beyond this value. Typical cropping intensities *R* for t_c of one to three years are 0.1–0.2 for a K_f value of 11 years (Trenbath, 1989), or 0.2–0.3 for a K_f of 5.5 years. This latter value brings the system just on the edge of 'fallow rotation' systems in Ruthenberg's classification. A fallow half-recovery time of < 5 years is required to allow cropping intensities of more than 0.3 without degrading the soil.

If the cropping intensity is increased beyond this critical value, the total yields will drop. This has been described as the 'crashing' of the system, as the 'normal' farmer response of opening fallows at a lower initial fertility level suddenly becomes counter-productive – whereas it was an effective way of increasing yield per unit area up to f_{opt}. Declining yields may not allow the required fallow length to be maintained. Within the assumptions of this simple model, 'sustainability' in the sense of no long-term degradation does not require that fallows restore soil fertility up to the level of the original forest or long-term fallow. Up to about half of that fertility, fallow rotations can be sustainable and reasonably productive. Yields per unit labor (if we assume


A.
Kf = 11 yr
Rel. yield per crop period, %
1
2
3
4
5
Number of crop years
B.
Kf = 11 yr
Critical crop intensity, R
C.
Kf = 5.5 yr
Rel. yield per crop period, %
D.
Kf = 5.5 yr
Critical crop intensity, R
Relative soil fertility
Relative soil fertility
E.
Kf = 11 yr
Number of crop years
1
2
3
5
Relative yield per cycle, %
F.
Kf = 11 yr
Required fallow length (log)
G.
Kf = 5.5 yr
Relative yield per cycle
H.
Kf = 5.5 yr
Required fallow length (log)
Relative soil fertility
Relative soil fertility

labor to be directly linked to the cropping period only) will reduce by about 50%, however, if total yield per unit area is maximized. Where both land and labor restrictions are felt, the optimum solutions will operate at a relative fertility at the start of cropping of 0.6 to 0.9 times the maximum fertility. This choice hardly depends on the efficiency of the fallow vegetation in restoring soil fertility, as reflected in K_f. The yields obtainable per unit area (though not per unit labor), however, do increase with smaller K_f values (more effective fallows).

The highest crop yields obtainable in sustainable versions of fallow rotations are only 5–9% of the maximum yields per unit area, which could be obtained if the maximum fertility of a long-term fallow could be permanently maintained without fallowing. Inputs from outside the plot may be needed to sustain higher production levels.

As Trenbath (1989) remarked, the most critical assumption of this simple model may be the shape of the function describing restoration of soil fertility. In reality the regrowth of a fallow vegetation may be impeded if cropping has reduced soil fertility too far. If the fertility restoration curve is sigmoidal rather than hyperbolic, yields obtainable for high cropping intensities – operating at low initial soil fertility levels – will be further reduced. With the hyperbolic fallow recreation function, the model suggested, however, that solutions operating at f values of less than 0.5 or t_c values of more than three were likely to be sub-optimal anyway.

So far 'soil fertility' was treated as a purely empirical term – the ability of a soil to support a good crop development and yield. Decline as well as restoration (recreation) of fertility may be based on a range of factors, including the supply of N, P, and other nutrients and the prevalence of specific soil-borne diseases. Two categories of situations can be distinguished: one where the decrease of fertility is a side-effect of growing crops – but not a necessary condition, and one where growth of the crop is directly linked to the decrease of soil fertility (e.g., by mineralization of organic matter). Examples of the first category may be the build-up of populations of soil-borne diseases or the role of organic matter in detoxifying Al or occupying P sorption sites and thus making soil P reserves more easily available. This is in fact what the Trenbath model describes in its current form. For the second category, the factor D indicates the 'rate of consumption' of the limiting soil resource, and we may link yield to $D*F$ rather than to F. This introduces D^2

◆ *Figure 5.* Crop yield per crop period (parts A and C) and per crop + fallow cycle (parts E and G), crop intensity R (parts B and D), and required fallow length (parts F and H) for sustainable fallow rotations (without soil degradation from cycle to cycle) as a function of the soil fertility at the start of a cropping period – relative to the maximum soil fertility after an infinitely long fallow period. Results are given for two values of the fallow half-recovery time (K_f), for five cropping period (t_c), for a reduction factor of soil fertility per crop (D) of 0.3, and for one crop per year ($n = 1$). The K_f value of 11 years approximates a 'natural' fallow, and the value of 5.5 years could reflect an 'improved' fallow.

rather than D in equation (1). Increasing D (e.g., by soil tillage speeding up mineralization of soil organic matter) will in this case increase yields on the short term, but speed up soil degradation and increase the duration of restoration fallow periods. With D^2 rather than D in the equations, the yields per unit area become indeed relatively insensitive to D, as shown in Figure 6. The

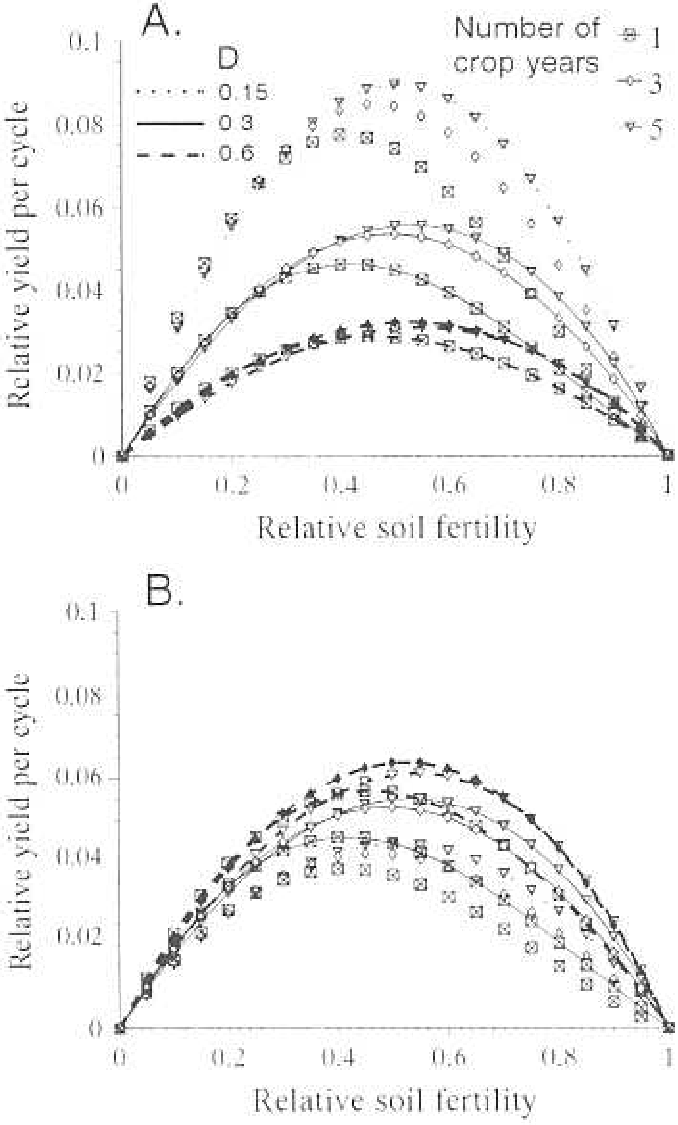


Figure 6. Influence of a reduction factor of soil fertility per crop (D) and cropping period (t_c) on yield per unit area. Lines of $D = 0.3$ in part A are the same as in Figure 5E, and part B presents a modified model in which crop yield is proportional to decline in fertility (e.g., by mineralization of soil organic matter) during a crop season.

gains in short-term productivity are balanced by the longer fallow periods required at more rapid depletion of soil fertility.

Conclusions

The Trenbath model suggests that 'improved fallows' with a reduced 'half recovery time' can indeed lead to increased cumulative crop yield per unit land area because fallow periods can be shortened. The improved fallows can also be used to obtain higher yields in cropping years, if the fallow period is not reduced. The options for benefiting by both higher yields per unit land (cumulative yield) as well as per unit labor (yield in cropping years) are, however, limited.

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