



Scale effects in crop–fallow rotations

M. VAN NOORDWIJK

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

Key words: lateral interactions, model, neighborhood effects, roots, scaling, tree–soil–crop interactions

Abstract. Many aspects of ‘scaling up’ must be considered in the spectrum between promising results of new technologies in experimental plots and wide adoption by farmers. These aspects include extrapolating in time to optimize management decisions, extrapolating in space from small plots to large fields and to other farms and regions, and enlarging the range of (presumed) beneficiaries. Models can help in all these aspects to lay a biophysical foundation on which socioeconomic decisions can be built. We focus here on ‘improved fallow’ systems where trees are planted to restore soil fertility for subsequent food crops. The restoration of soil fertility – based on biomass production, litterfall, and build-up of dynamic soil organic matter pools – depends on total resource capture by the fallow vegetation. Where ‘lateral resource capture’ and ‘lateral resource flow’ play a substantive role in the performance of the fallow, the size (scale) of fallow and cropped plots may influence both the build-up and the decline of soil fertility during a cycle. On small farms, fallow systems should not be seen as pure sequential systems, but as mosaics of spatially interacting fallow and cropped plots. Border effects depend on the lateral spread of the root system of the fallow vegetation, as well as on rainfall and N supply. Scale effects in technology adoption include both positive and negative feedback effects, because the spread of a technology may both accelerate innovations as well as increase threats from pest and disease attack.

Introduction

Suppose that farmers or researchers identify tree or shrub species with superior properties in restoring soil fertility for subsequent food crops in a given location (Kwesiga et al., 1999), how would such a tree fallow best be used? Would it be used to obtain higher yields at the same fallow length, to reduce fallow duration at the same yield per cropping phase or by a combination of the two? Will yield improvement by such a fallow depend on the scale at which it is used? In this paper we will review and formulate simple models of how crop–fallow systems work to address these questions.

Sanchez (1995) and Rao et al. (1998) reviewed the scientific understanding of agroforestry and emphasized the essential difference between ‘sequential’ or rotation systems, in which tree and crop component are spatially separated, and ‘simultaneous’ systems, where competition between trees and crops is an important aspect. The ‘sequential’ versus ‘simultaneous’ dichotomy may be relevant on large farms, but in a smallholder context one should not ignore spatial interactions in sequential systems because fallow plots will interact with neighboring plots, which are currently cropped. In the analysis of the

soil fertility islands under savanna trees, the role of superficial nutrient scavenging by trees is now widely recognized (Belsky and Amundson, 1998). Can similar effects play a part in soil fertility improvement by woody fallow vegetation? The 'Trenbath model' (Van Noordwijk, 1999) describes crop-fallow rotations as a sequential system, but can spatial interactions be ignored?

Three stages can be recognized in field experimentation with agroforestry systems:

1. A period of blissful ignorance of lateral interactions (Figure 1.I – ignoring below-ground interactions). During this stage, the difference between crop yields in agroforestry and nearby 'control' plots is interpreted as yield effect of the agroforestry system.
2. Following recognition of the lateral extension of tree root systems, a period with strong emphasis on the need for trenches and barriers between experimental plots (Coe, 1994; Figure 1.II – blocking below-ground interactions). During this stage, the 'true' yield effect of agroforestry estimated in this way is assumed to be independent of the scale at which the system

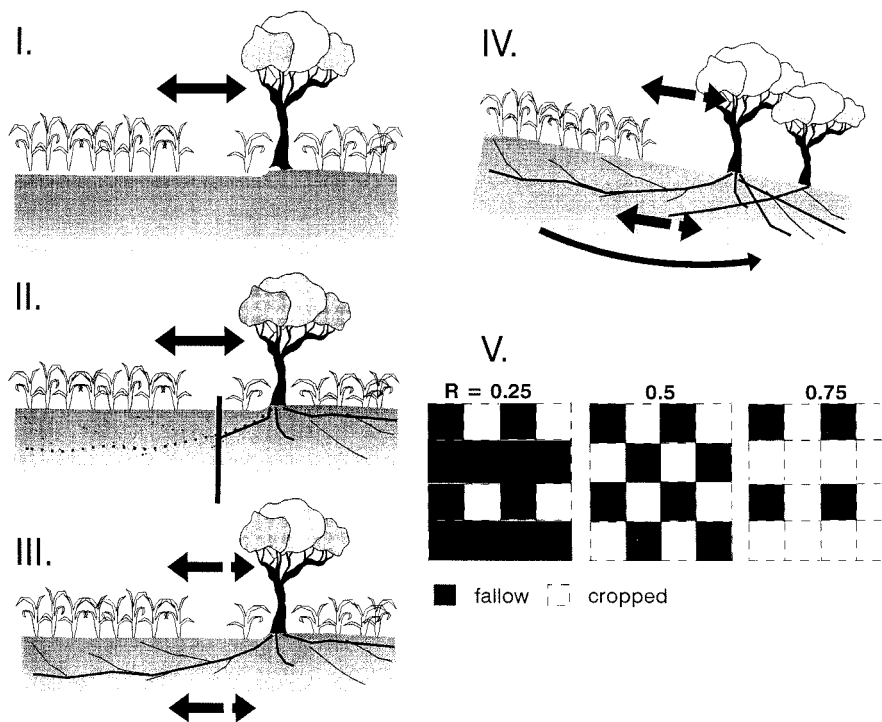


Figure 1. Stages in the way agroforestry experiments deal with lateral resource capture by tree roots: I. ignorance, II. prevention, III. recognition, and IV. recognition on sloping lands where lateral resource flows become an important interaction component that depends on the scale of the system. Part V shows that lateral interactions in cropped plots depend on the crop:fallow ratio as well as the specific configuration of fields.

is to be applied, and sampling methods are generally designed to ignore the 'border effects'.

3. Recognition of lateral resource flows and resource capture as an essential element of agroforestry systems on real world farms, making the overall yield effects dependent on the scale of application (Van Noordwijk and Ong, 1996; Figure 1.III and 1.IV). During this stage, below-ground resource capture and flow are recognized as part of the system under study.

We are at the verge of the third stage and just discovering the tools, which are needed to scale up from 'small plot' (0.001 ha) or 'big plot' (0.01 ha) experiments to small, medium, or large scale fields (0.1, 1, and 10 ha fields) on real farms. We must recognize that both the build-up and the depletion of soil fertility depend on local neighborhoods and thus on scale.

Spatially explicit models of tree-crop interactions are needed, especially for small farms, to evaluate the possible contribution of lateral tree roots to the replenishment of fertility in the fallow plots, as well as to the decline in productivity of nearby crop plots. Such lateral effects may be as important as the carry-over effects of tree roots on a subsequent crop (Torquebiau and Kwesiga, 1996). Here we will use the WaNuLCAS (water, nutrient and light capture in agroforestry systems) model (Van Noordwijk and Lusiana, 1998) to explore how spatial scale may affect the way fallow systems work for a given size of tree root systems. The fraction of a cropped plot that is potentially affected by roots of fallow vegetation depends on the crop:fallow ratio (Figure 1.V) and on the size of the individual plots (Figure 2).

Further complications in spatial scaling may arise if part of the restoration of soil fertility by the fallow is based on lateral flows of water and nutrients in a landscape, but this issue is left for a later discussion, as key insights in the quantities of resources involved are lacking. As a last element in the discussion of spatio-temporal scales, we will briefly explore scale effects at the landscape scale, based on changes in the pest and disease complex, and how such effects may influence results of technology dissemination. We will thus focus on how simplified models of fallow performance can be used to evaluate (i) management options of fallow systems with a range of fertility build-up and depletion characteristics, (ii) spatial interactions in fallow rotation systems at different scales, and (iii) scale effects in technology adoption.

Spatial extrapolation: neighborhood effects in fallow rotations

The results of the Trenbath model (Van Noordwijk, 1999) are expressed per unit area, as if the scale of application does not matter. In practice, however, the outer rows of trees in a fallow plot will often be bigger than the trees in the center of the plot (Figure 3) and thus biomass production of a fallow plot depends on the fraction of border trees in the plot as a whole. Because it is not directly obvious that the resources used for this additional tree growth

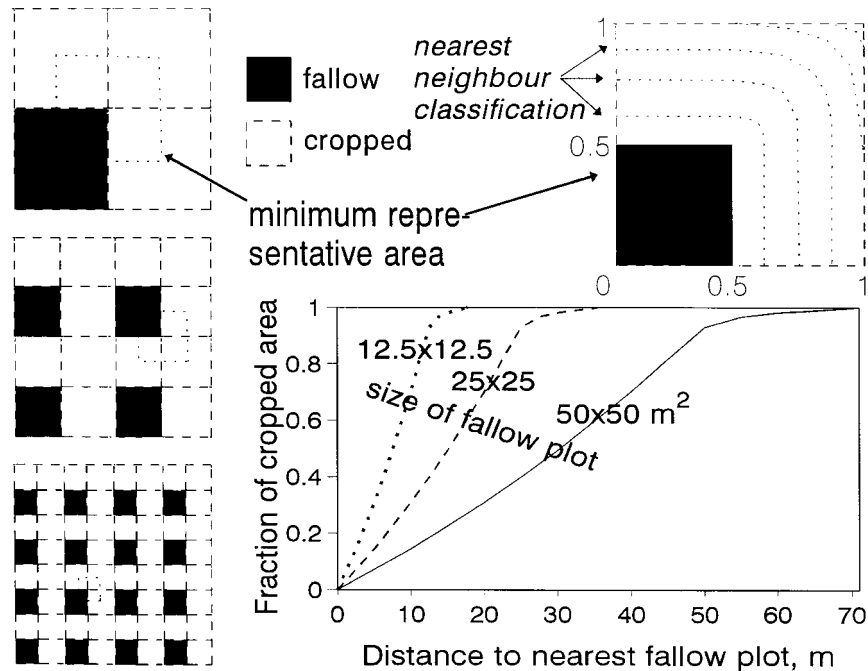


Figure 2. Fraction of a square crop field surrounded by fallow plots (such as in a crop:fallow ratio of 1:4, compare to Figure 1.V) that is not affected by below-ground edge effects – as a function of plot size and radius of tree root system.

would not otherwise have been available to the crop (Cannell et al., 1996), we must be careful in regarding this effect as a positive contribution of agroforestry. In small-scale applications this effect may not be negligible. Lateral resource capture (and the gradient in tree growth with distance from the edge of a plot) may increase in importance with increased fallow duration and increased water stress (RJ Buresh, personal communication)

The resources that sustain this additional growth of the border rows of trees will come from the neighboring plot, which may be currently cropped. Below-ground resource capture by the trees may extend over at least 10 m from the edge of the fallow, but in older tree fallows it may go beyond such a distance (Van Noordwijk et al., 1996).

The WaNuLCAS model (Van Noordwijk and Lusiana, 1998) describes biophysical tree–soil–crop interactions in spatially zoned agroforestry systems. We used an initial version of the model to investigate lateral resource capture by tree roots in fallow plots from nearby cropped fields as element in the scaling rules of fallow results. Key elements of the model are:

1. Four spatial zones, with trees growing in zone 1 and crops in zones 2, 3, and 4 with different intensities of above- and below-ground interaction per zone.

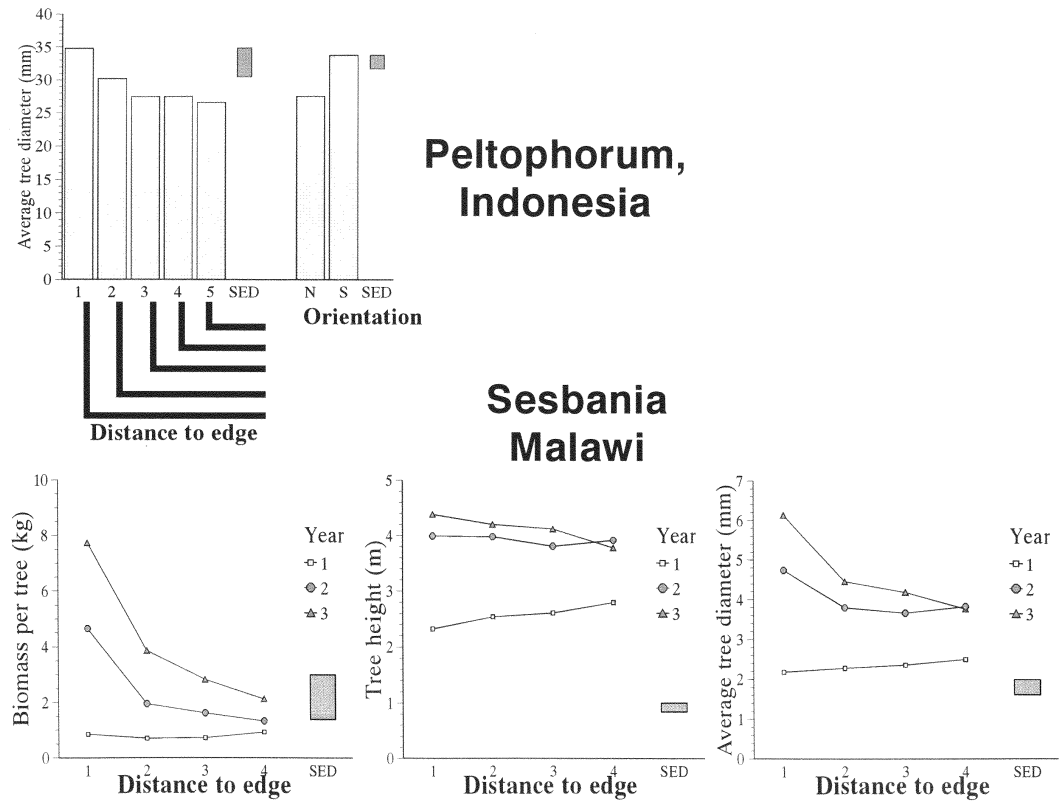


Figure 3. Examples of 'edge effects' in the size of trees by tree row in fallow plots, neighboring crop fields or other fallow types: *Peltophorum dasyrachis* in an experiment in Lampung, Indonesia (Hairiah et al., 1996) and *Sesbania sesban* in an experiment in Malawi (data courtesy of F. R. Kwesiga); N = North, S = South.

2. A four-layered soil system with a 'tipping bucket' model for water infiltration as a basis for N leaching. (A random rainfall generator or actual daily records can be used.)
3. Explicit description of competition for water and N on the basis of root length density and above-ground demand. (Roots of trees in zone 1 can extend into the other zones.)
4. Daily calculation of growth limitation of all components by the minimum of light, water, and N supply.
5. After canopy growth of the trees reaches a maximum value, litterfall is induced. The model does not yet account for drought-induced litterfall and may thus overestimate tree biomass production and indirectly overestimate litter inputs to the soil.
6. A three-pool soil organic matter model, similar to the Century model (Parton et al., 1994).
7. An option for scheduling cropping periods and fertilizer use.

To explore the possible effects of fallow plots of different sizes on crop production in neighboring plots, we started by using a 10-m-wide tree plot (zone 1) next to three crop zones (2, 3, and 4) of 2-, 3-, and 5-m width, respectively. Shading was restricted to zone 2, while tree roots extended into zones 2 to 4 to different degrees. After the first two years of the simulation, the fallow plot was cleared and cropped while the previously cropped plot returned to fallow. This switch was simulated by using the soil parameters at the end of a two-year fallow to re-initialize soil zones 2 to 4 in a subsequent run, while the parameters of the depleted zones 2 to 4 were used to re-initialize zone 1. This smoothed out the heterogeneity in soil conditions within this new fallow zone. Rainfall with an annual total of 2326 mm (repeating the same sequence for every year of simulation) and soil data from the Biological Management of Soil Fertility (BMSF) research site in Lampung (Sumatra, Indonesia) were used (Van Noordwijk et al., 1992, 1998; Hairiah et al., 1996).

During the first cycle, crop growth in zone 4 (Figure 4) is similar to that in a crop-only control without fertilizer. Tree canopy biomass (ignoring the woody stems) rapidly reaches a maximum value after which further growth is accompanied by equivalent litter fall. The second cycle, on land fallowed during phase 1 is similar to the first, suggesting that with a 1:1 ratio of fallowing and cropping yields can be maintained from one cycle to the other, for the conditions of the simulation. The soil organic matter pools (data not shown) are increased during a fallow period (in the model mainly by litterfall, which is supposed to be mixed through the upper soil layer by abundant faunal activity) and depleted during cropping. The model predicts that there will be substantial 'border effects' of the fallow on neighboring crop land, not only caused by shading (zone 2) but also by root competition (zone 3).

Model results (Figure 4) confirm that a build-up of fertility via organic matter pools and subsequent exponential decrease of crop yields can be generated on the basis of the principles included in the model. When the

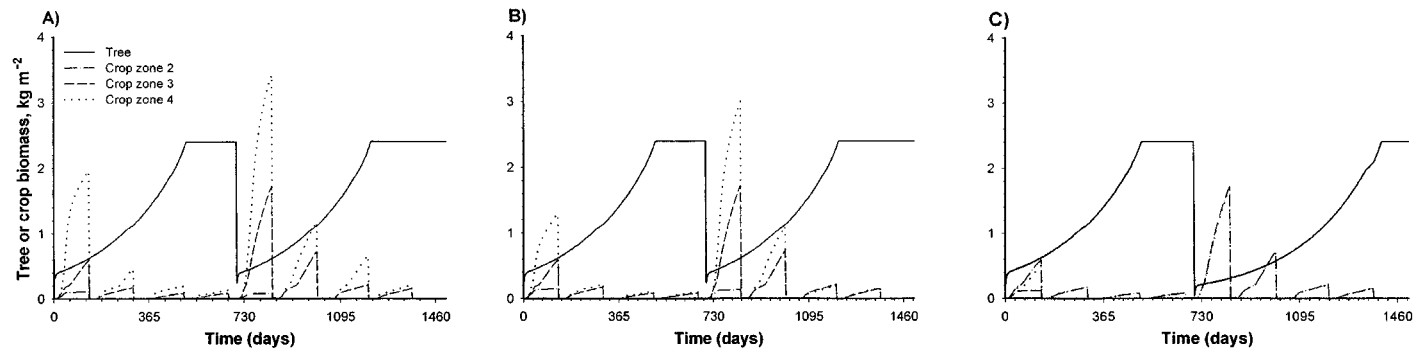


Figure 4. WaNuLCAS simulation of the development of tree–fallow vegetation and the simultaneous yield of crops with increasing distance to this fallow plot, over two cycles of a two-year fallow and two-year cropping (four crops cycle⁻¹). Part A illustrates the case of no tree roots outside of the fallow plot, and shading in zone 2 is the only border effect (crop biomass in zone 3 equals that in zone 4). Part B illustrates the case when tree root length density (cm cm⁻³) decreases by a factor 0.6 from zone 1 to zone 2, decreases by a factor 0.6 from zone 2 to zone 3, and no tree roots are in zone 4. Part C illustrates the case when tree root length density in zones 2 and 3 is equal to that in zone 1, but there are no tree roots in zone 4 (for details of parameters see Van Noordwijk and Lusiana, 1998).

fraction of tree roots penetrating under the crop zone is modified, this has effect on both the growth of the fallow vegetation and that of the neighboring crops (compare Figure 4 A, B, and C). The more roots penetrate under the crop zone, the faster the build-up of fertility under the fallow as a result of reduced water and N limitations to the growth of the fallow vegetation. We thus expect a smaller fertility recovery half-life time (K_f value in the Trenbath model; see Van Noordwijk, 1999) if results are derived from small plots with substantial border effects. However, the crops that follow on to this fallow will have to compete with the roots of the neighboring vegetation, and their yield may actually be less than that obtained on a poorer plot with less competition.

The WaNuLCAS calculations we made show little effect on the fertility decrease factor (D in the Trenbath model; see Van Noordwijk, 1999), but give a smaller conversion factor between soil fertility and crop yield (c in the Trenbath model; see Van Noordwijk, 1999) in the presence of tree roots. The magnitude of these neighborhood and scale effects depends on climate, soil, tree, and crop properties, but for any combination of these we can now explore the likely biophysical returns to scale of a crop–fallow system. The scale effects in crop–fallow rotations depend on the architecture of the tree root system, but also on site factors – such as soil fertility, soil depth, and rainfall – and on the dependence of the fallow vegetation on soil N rather than biological N_2 fixation and on phenology and maximum growth rate of fallow vegetation. Competition between crop and tree is further influenced by crop root pattern, time pattern of N mineralization, and crop N demand (‘synchrony’).

These effects are familiar in the literature on alley cropping, where trees can indeed maintain soil fertility, but at the same time prevent crops from benefiting from this fertility (Sanchez, 1995). In crop–fallow mosaics we will find a milder form of such interactions, but we can not ignore them.

The WaNuLCAS model may offer the first opportunity to consider crop–fallow mosaics as a coherent system, instead of only regarding the sequential effects on plots that are supposed to be spatially isolated. The models may stimulate a renewed research attention on border effects in crop–fallow experiments, as no published data exist on the topic. Substantial border effects of teak (*Tectona*) stands in Java (Indonesia) were described in the 1930s (publications of Coster, reviewed in Van Noordwijk et al., 1996), and these were larger than what WaNuLCAS predicted for the parameters in Figure 4. Unfortunately, no tree root length densities are known for these (or similar) teak stands. Border effects in crop–fallow mosaics make that the overall effect will depend on the scale (absolute plot size) and not only on the crop:fallow ratio.

Scale effects in technology adoption

Whereas a small-scale experiment can determine the value a tree can have in a given management system, this value is probably not independent of the scale at which the tree is used or the technology is adopted. A number of positive and negative feedback loops may modify the value per unit tree during the process of technology adoption.

The value of a tree used for new technologies may depend on the scale of its application in a number of ways:

1. With increased scale of adoption more farmers will use their skills to improve the efficiency of tree management and this will likely reduce the production costs per tree and/or increase the physical production, thus increasing the profitability per tree, leading to a *positive* feedback.
2. Domestication, or the genetic selection, either based on seeds or on vegetative multiplication of 'superior' trees may increase the profitability of trees for a specific set of functions, leading to a *positive* feedback.
3. With increased scale of adoption the likelihood of spread of effective symbionts (effective *Rhizobium* strains and mycorrhizal partners) may increase, leading to a *positive* feedback.
4. With increased scale of adoption the likelihood of attack by pests and diseases will increase as the trees become easier to find for specialized organisms of the second trophic level, leading to a *negative* feedback. This decrease may slow down when natural enemies (third trophic level) increase and/or the technical skills of the farmer in pest and disease control improve. The *Leucaena*-psyllid (*Heterospsylla cubana* Crawford) interaction has provided a classical example (Bray, 1994; Geiger et al., 1995).

Two additional factors affect trees with globally marketable products:

5. The value may increase initially on adoption as the markets develop on the basis of increased efficiency of processing and 'marketing', leading to a *positive* feedback.
6. Increasing rates of adoption will lead to market saturation, depending on the 'elasticity' of demand for this product, and thus profitability per tree decreases, leading to a *negative* feedback loop.

Through the combined effects of positive and negative feedback loops, the overall profitability function for trees with a local 'service function' (indirect value, such as soil fertility improvement) may show an upward trend 'a' followed by a plateau 'b' and a downward trend in profitability 'c', which will lead to a maximum adoption rate 'd', followed by a decline phase 'e' (Figure 5A). The effects of pest and disease attack may decrease with decreased abundance of the tree species in the landscape, but generally a 'hysteresis' effect may be expected. Depending on the time delays involved in the interaction between farmer decisions on adoption and the pest-predator complex, a stabilization at some point 'e1' may be achieved or decline may

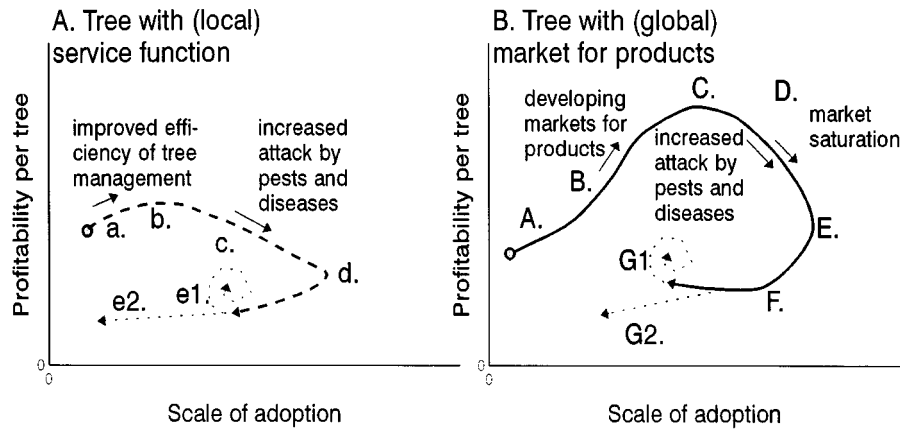


Figure 5. Hypothetical trajectories of trees undergoing a 'domestication' and wide-scale adoption process for trees with a 'local' service function or indirect value such as soil fertility improvement (part A) and for trees with a 'global' market for their products (part B).

continue 'e2' until a small residual population is left, which may be less than the initial scale of adoption.

The overall pattern for marketable trees may contain four phases: initial technology improvement and domestication 'A', market development 'B', plateau 'C', and decline 'D' due to market saturation as well as pest and disease attack (Figure 5B). The pest and disease attack is likely to increase production costs and may have a bigger impact on profitability if product prices come down. A maximum adoption rate 'E' may be achieved at a profitability per tree that is equal to or less than that at the start of the process. The 'decline in adoption' phase 'F' may be at least as prominent as for trees with only a 'service function' as the positive marketing and processing advantages at higher adoption rates become lost. A stabilization at some point 'G1' may occur, or a continued decline 'G2' may bring the tree into oblivion (until some new turn in world economical events leads to a new cycle).

These phases can be recognized in most tree crops and service trees. While attention for a certain 'promising' or 'miracle' tree by research, extension, and information services is likely to accelerate the upward initial trend and rate of adoption, it will also accelerate the following downfall. It is typical of the 'good news' focus of research and development that the 'downfall' of the various ex-miracle trees is much less documented. Similar phenomena are found for annual crops as well, but there the flexibility of farmers' response to changing markets and pest and disease pressure will be larger than for trees with a longer life cycle. Longer life cycles imply both lower genetic adaptation rates and longer time lags in the farmers' response.

Predictions of the final outcome of the domestication and increased adoption process will only be possible if both the economic responses of the markets (including their likely elasticity) are predictable, as well as the likely

response of the pest–predator complex and farmer decision-making processes and risk evaluation. Although ‘development agents’ working in phase ‘a’ and ‘A’ of this process will see their promotion of the trees as valuable beyond discussion, the final position of the tree in the adoption–profitability playing field is likely to be somewhere in the lower left quadrant. This makes ‘domestication’ an on-going process, with new ‘miracle trees’ appearing on the scene to make up for the unfulfilled promises of the previous ones.

Unfortunately, ecological theory and models of pest epidemiology and dynamics are not yet sufficiently advanced to predict how long it will take before pest outbreaks occur if a specific tree is grown on a larger scale. It is very likely that this will happen within 30 years, it may take only 10 years, but it is also possible within two to four years. These three scenarios, however, have different implications for whether it is advisable to promote a specific tree. If it takes 10 to 30 years for a crash to occur, promotion may help a large number of farms through an important transition. Whereas if it takes less than five years, the institutions and persons initiating the adoption will still be remembered and will be seen as irresponsible in taking risks. Where risks are based on rainfall variability rather than biotic interactions, risk reduction by not putting all eggs in one basket can be quantified and an ‘optimum diversity’ can be defined (Van Noordwijk et al., 1994; Van Noordwijk and Ong, 1999).

Concluding remarks

Extrapolating in space and time on the basis of promising ‘pilot’ experiments is still a difficult task. A farmer or researcher who identifies a tree or shrub with superior properties may benefit from some of the models and concepts presented here. The models address various aspects of ‘scaling up’: extrapolating in time to optimize the system on a given plot, extrapolation from a small experimental plot to a farm, extrapolation to other farms and regions, and enlarging the range of presumed beneficiaries of the new technology by including environmental aspects.

Spatial extrapolation of the productivity benefits is complex, because of the spatial variability in factors determining the main function of a fallow and because fallow vegetation may perform in different ways depending on its local neighborhood. A simplified view on the ‘system’ as in the Trenbath model (Van Noordwijk, 1999) can help to go beyond the experimental data – where comparisons are usually made after equal length of fallow period, rather than under a fallow duration that is optimized for the fallow’s growth rate – and suggest how farmers can best utilize an ‘improved’ technology, depending on their circumstances. Small-farm applications of a fallow technology should be viewed as spatially integrated mosaics, rather than as pure ‘sequential’ agroforestry systems. Edge effects of woody fallows should not be ignored for small farm sizes.

Acknowledgements

Thanks are due to F. R. Kwesiga for allowing the use of sesbania data for Figure 3 and to Mrs. Betha Lusiana for calculations underlying Figure 4.

References

- Belsky AJ and Amundson RG (1998) Influence of savannah trees and shrubs on understorey grasses and soils: new directions in research. In: Bergstrom L and Kirchman H (eds) Carbon and Nutrient Dynamics in Natural and Agricultural Tropical Ecosystems, pp 153–171. CAB International, Wallingford, UK
- Bray RA (1994) The Leucaena psyllid. In: Gutteridge RC and Shelton GHM (eds) Forage Tree Legumes in Tropical Agriculture, pp 283–291. CAB International, Wallingford, UK
- Cannell MGR, van Noordwijk M and Ong CK (1996) The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. *Agroforestry Systems* 33: 1–5
- Coe R (1994) Through the looking glass: ten common problems in alley-cropping research. *Agroforestry Today* 6(1): 9–11
- Geiger CA, Napompeth B and Van Den Beldt R (1995) An update on the status of the Leucaena psyllid in Southeast Asia. In: Shelton HM, Piggitt CM and Brewbaker JL (eds) Leucaena – Opportunities and Limitations, pp 125–128. ACIAR Proceedings No. 57. Australian Centre for International Agricultural Research, Canberra, Australia
- Hairiah K, Kasniari DN, Van Noordwijk M and De Foresta H and Syekhfani MS (1996) Soil properties, litterfall, above-and belowground biomass during a *Chromolaena odorata* fallow. *AGRIVITA* 19: 184–192
- Kwesiga FR, Franzel S, Place F, Phiri D and Simwanza CP (1999) Sesbania sesban improved fallows in eastern Zambia: Their inception, development and farmer enthusiasm. *Agroforestry Systems* (this issue)
- Parton WJ, Ojima DS, Cole CV and Schimel DS (1994) A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Quantitative Modeling of Soil Forming Processes, pp 147–167. Special Publication 39, Soil Science Society of America, Madison WI, USA
- Rao MR, Nair PKR and Ong CK (1998) Biophysical interactions in tropical agroforestry systems. *Agroforestry Systems* 38: 3–50
- Sanchez PA (1995) Science in agroforestry. *Agroforestry Systems* 30: 5–55
- Torquebiau EF and Kwesiga F (1996) Root development in a *Sesbania sesban* fallow–maize system in Eastern Zambia. *Agroforestry Systems* 34: 193–211
- Van Noordwijk M (1999) Productivity of intensified crop–fallow rotations in the Trenbath model. *Agroforestry Systems* (this issue)
- Van Noordwijk M, Dijksterhuis G and Van Keulen H (1994) Risk management in crop production and fertilizer use with uncertain rainfall: how many eggs in which baskets. *Netherlands Journal of Agricultural Science* 42: 249–269
- Van Noordwijk M, Hairiah K, Lusiana B and Cadisch G (1998) Tree–soil–crop interactions in sequential and simultaneous agroforestry systems. In: Bergstrom L and Kirchman H (eds) Carbon and Nutrient Dynamics in Natural and Agricultural Tropical Ecosystems, pp 173–190. CAB International, Wallingford, UK
- Van Noordwijk M, Lawson G, Groot JJR and Hairiah K (1996) Root distribution in relation to nutrients and competition. In: Ong CK and Huxley PA (eds). *Tree–Crop Interactions – a Physiological Approach*, pp 319–364. CAB International, Wallingford, UK
- Van Noordwijk M and Lusiana B (1998) WaNuLCAS 1.1, Backgrounds of a model of water

- nutrient and light capture in agroforestry systems. Working Document, International Centre for Research in Agroforestry (ICRAF), Bogor, Indonesia, 102 pp
- Van Noordwijk M and Ong CK (1996) Lateral resource flow and capture – the key to scaling up agroforestry results. *Agroforestry Forum* 7(3): 29–31
- Van Noordwijk M and Ong CK (1999) Can the ecosystem mimic hypotheses be applied to farms in African savannahs? *Agroforestry Systems* 45: 131–158
- Van Noordwijk M, Widiyanto, Sitompul SM, Hairiah K and Guritno B (1992) Nitrogen management under high rainfall conditions for shallow rooted crops: principles and hypotheses. *AGRIVITA* 15: 10–18