Agroforestry Systems **40**: 199–206, 1998.

Maximizing crop yield in alley crops

J. VANDERMEER
Department of Ecological Agriculture, Wageningen Agricultural University, Haarweg 333, NL-6709 RZ Wageningen, The Netherlands (Address for correspondence: Department of Biology, University of Michigan, Ann Arbor, MI 48109, USA; E-mail: jvander@umich.edu)

Key words: competition, facilitation, prunings

Abstract. A simple graphical model is presented illustrating the balance between facilitation and competition necessary for maximizing crop yield in alley cropping systems. Three functions are composed into the decision function: (1) the percent increase in crop yield from facilitation resulting from prunings, (2) the amount of prunings resulting from different tree densities, and (3) the percent reduction in crop yield from competition from trees. The resulting function illustrates how the balance between facilitation and competition may provide a window of opportunity for the beneficial use of alley crops.

In a recent influential paper (Sanchez, 1995) it has been suggested that previous enthusiasm for alley cropping is unwarranted, based on analysis of numerous experiences throughout the tropics. While Sanchez presents his case cautiously and in the spirit of a call for further and more careful research on the topic, his analysis has caused what might be considered something of a backlash amongst the very people who have been studying this system. Conversations with at least three agroforestry experts (Ong, pers. comm.; van Noordwijk, pers. comm.; Wessel, pers. comm., also see Ong, 1994) have given me the impression that Sanchez's analysis implies that alley cropping simply will not work and perhaps should be abandoned as part of any agroecosystem development strategy. But do we risk throwing out the baby with the bath water?

Using the analytical formulation of Ong (1994), Sanchez presented data collected by Ong and van Noordwijk on eight alley cropping experiments in which the facilitative effect (F) of prunings was separated experimentally from the competitive effect (C) of the trees. In five of the cases the net effect ($I = F - C$) favored competition and the specific form of the alley cropping system tested was judged to be a failure. It is worth noting that in all but one case the facilitative effect was relatively large, the problem being that the competitive effect was also very large.

There is an obvious problem with this data set. All of the experiments were designed without prior information on densities and their relationship to competition or facilitation to try to optimize the planting pattern. The designs of all of the systems were therefore *ad hoc*. The question then arises, would a different design have created a different result? The data set is useful for answering the question 'have we found any alley crops that perform well yet?'

but not for the question 'will alley crops perform well?' Even if the first hundred attempts to fly were failures, this did not allow us to conclude that flying was inherently impossible, only that the proper design of an aircraft had not yet been found. The problem here is a classical one (Vandermeer, 1980, 1989) of understanding the balance between facilitative and competitive effects in an ecological interaction.

In this note I present a very simple graphical model designed to (1) heuristically demonstrate the underlying problem with designing alley cropping systems, and (2) provide a systematic framework for how to gather the proper data to permit an informed decision about whether or not a particular system will be productive and if so, what would be the optimal planting design. In another study aimed at this same objective, van Noordwijk (1996) provides a more comprehensive yet far more complicated approach. This strength of the present model is its simplicity and easily interpretable graphical format.

The problem revolves around three fundamental transformations: (1) the increase in crop production resulting from a given quantity of prunings (Figure 1a), (2) the amount of prunings provided by a given density of trees (in this paper I represent the quantity of trees as the number of rows of trees – extensions to other measures of density are obvious) (Figure 1b), and (3) the decrease in crop production resulting from competition from a given density of trees (Figure 1c). The first and second transformation together (Figure 1a and b) constitute the F of Ong's equation. The functional relationships in Figure 1 are not necessarily fixed and can be modified considerably without changing the basic message of this note, as I think will become obvious. For example, the S-shaped nature of the facilitation function (Figure 1a) could just as well be a monotonic 'diminishing returns' curve without changing the qualitative nature of the conclusions.

Two compositions (taking a function of another function) are required. First note that the number of rows of trees determines the amount of prunings that the system will provide, and in turn the amount of prunings determines the increase in facilitation (i.e. the fertilization and/or mulching effect of the prunings) – making it directly possible to express the quantity of prunings as a function of the number of rows of trees. Second, the reverse composition is also possible (given that the functions are invertible, most likely the case for the current situation – see Appendix). That is, we can begin with a certain amount of facilitation and back calculate the number of rows of trees there must have been to produce that amount. If we proceed with this second composition, and proceed to compose the process of translating the number of tree rows into the amount of competition, we can express the amount of competition as a function of the amount of facilitation.

This basic compositional process is illustrated in Figure 2. Here the three graphs of Figure 1 are arranged so as to be related to one another. The quadrat labelled 'a' for example, is the same as the graph in Figure 1a, rotated 90 degrees to the left. The quadrat labelled 'c' is the graph in Figure 1c, rotated 90 degrees to the right. With this presentation we can see the relationship

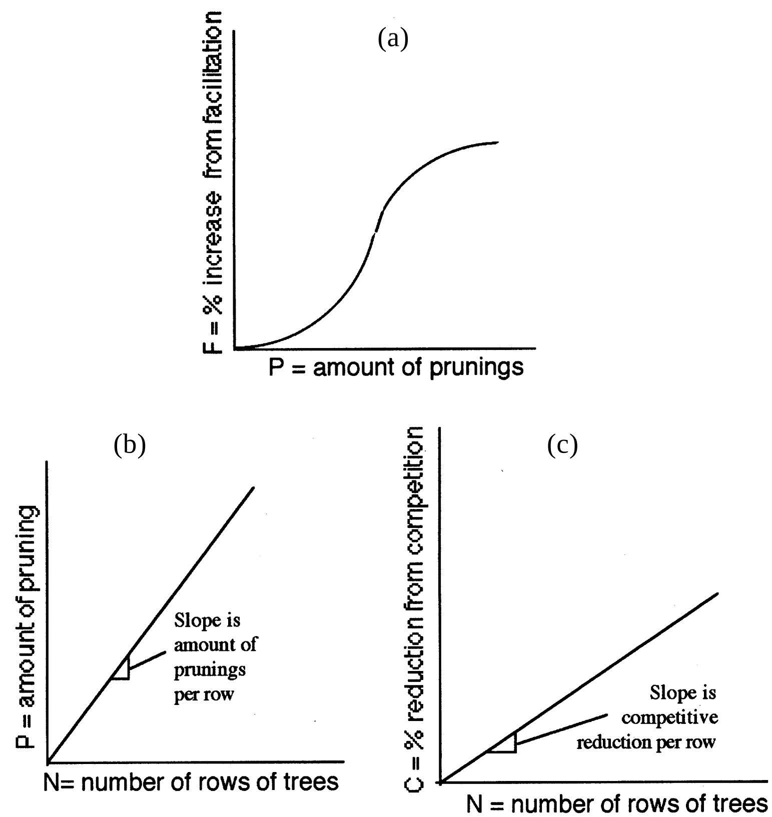

Figure 1. The three basic transformations of the model of ecological interactions in alley crops showing the relationship between facilitative and competitive effects.

among the three transformations, and also visualize how to construct the composed function that gives us competition as a function of facilitation, as shown in the quadrant labelled ‘d’. Begin with any point on the axis labelled ‘*F* = % increase from facilitation’ and project upward to the function (which is the inverse of the function as presented in Figure 1a). From that function project to the right to intersect the appropriate value on the axis labelled “*P* = amount of prunings’. From that axis project to the right again to the function (which is the inverse of the function as presented in Figure 1b), and then downward to the axis labelled ‘*N* = number of rows of trees’. From that axis project downward to the function, and then to the right to the axis labelled ‘*C* = % reduction from competition’. The intersection of that axis is then projected to the original point on the ‘*F* = % increase from facilitation’ axis to make a point on the function that relates competition as a function of facilitation. Repeat this process for all the points on the *F* axis, and the function is complete, as illustrated in the quadrant labelled ‘d’ in Figure 2. The diagonal

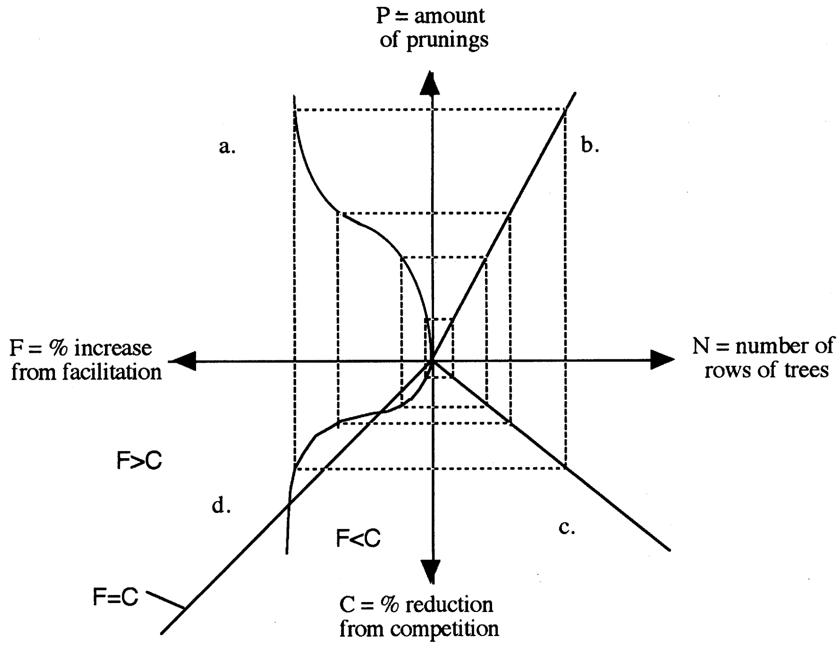

Figure 2. Graphical composition of the three basic transformations. Quadrant 'a' corresponds to the top graph of Figure 1 and relates the amount of prunings to the percent increase from facilitation. Quadrant 'b' corresponds to the middle graph of Figure 1 and relates the number of rows of trees to the amount of prunings. Quadrant 'c' corresponds to the bottom graph of Figure 1 and relates the number of rows of trees to the percent reduction of crop yield resulting from competition from the trees. Quadrant 'd' then shows the composed function, which expresses the percent competition as a function of the percent facilitation.

in quadrant 'd' represents $F = C$, the locus of points for which facilitation exactly equals competition.

The composed function (the function representing competition as a function of facilitation) is shown in a more conventional form in Figure 3 (that is, its construction in Figure 2 has it upside down and reflected to the left, to create Figure 3 from quadrat 'd' of Figure 2, flip the latter once vertically and once horizontally). Here we see the obvious conclusion that, given appropriate relationships between facilitation and competition, there are some regions in which facilitation clearly outweighs competition (the hatched area), which defines the boundaries within which the alley cropping system will be advantageous (labelled the 'window' of alley crop advantage). Also there is an optimum alley crop for which the difference between facilitation and competition is greatest (assuming the facilitative effect is greater than the competitive effect). This occurs where the slope of the function is 1.0, and the function itself lies below the 45 degree line.

The window of alley crop advantage and the optimal alley crop can then be related to the number of tree rows (the variable with which we can plan

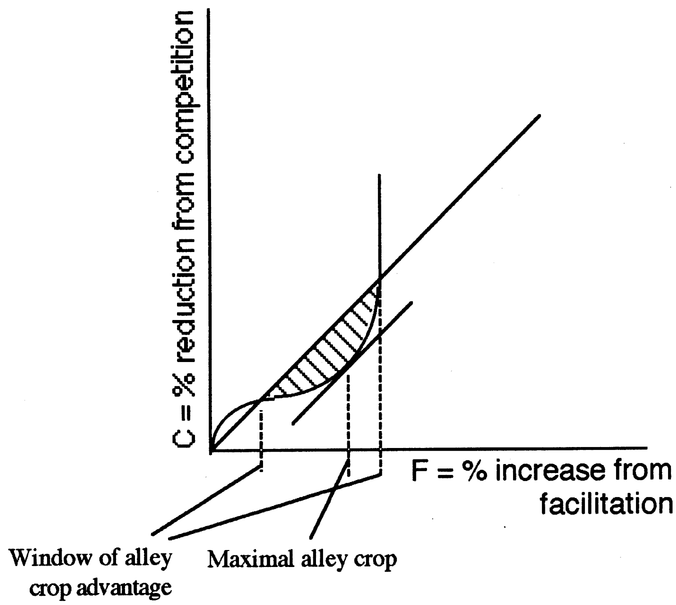

Figure 3. The basic decision function. The same graph as in quadrant 'd' of Figure 2, rotated once horizontally and once vertically. Hatched area indicates the region of facilitation and competition reduction in which the alley crop will be advantageous, and the tangent point on the function indicates the maximal alley crop yield.

the ecosystem), by reverting to part of the graph of Figure 2, specifically quadrants 'd' and 'c'. Presenting these two quadrants in Figure 4, we see the elementary process of projecting from the facilitation axis (in the quadrant on the right of Figure 4) to the 'number of rows' axis, for both the design window and the optimal alley crop.

It is, of course, not guaranteed that the composed function will have a section that falls below the 45 degree line, which is necessary to have a net advantage for the alley crop. It is possible to imagine three basic forms for the function, as illustrated in Figure 5. Form I represents the situation in which there is no possible design of the system that will yield an advantage for the alley cropping system, while Form III illustrates a clear region in which the system will be advantageous. Form II shows an intermediate case in which there is a possibility of an alley crop system advantage, but the design window is so small that investing in the basic research to find it may not be worthwhile, and the possibility that the environment will change to make it disappear entirely in the future is so great that the search is not worth bothering about. Obviously these are not three fixed types, but rather points on a continuum.

It is also worth noting that the planting design of the crop is not a design variable. Future research may reveal this to be a prejudicial assumption, but for now it greatly simplifies the analysis.

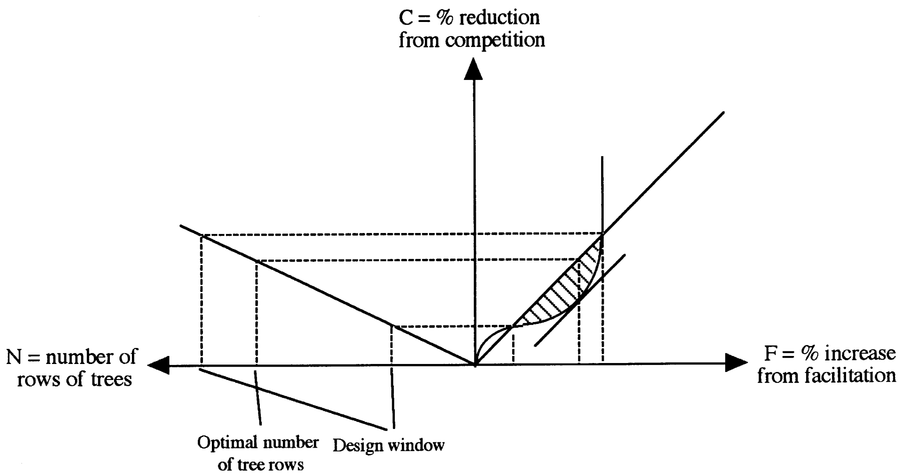

Figure 4. Illustration of how to determine the range of values of 'number of rows of trees' that correspond to the design window (as labelled 'window of alley crop advantage' in Figure 3) and the optimal number of tree rows (corresponding to the 'optimal alley crop' of Figure 3). By choosing a point on the axis of *F* (percent increase from facilitation), reflect that point back to the function that determines the relationship between *N* (number of rows of trees) to the competitive reduction. That reflection on the *N* axis gives the number of rows of trees that result in the maximal (or other desired quantity) alley cropping system.

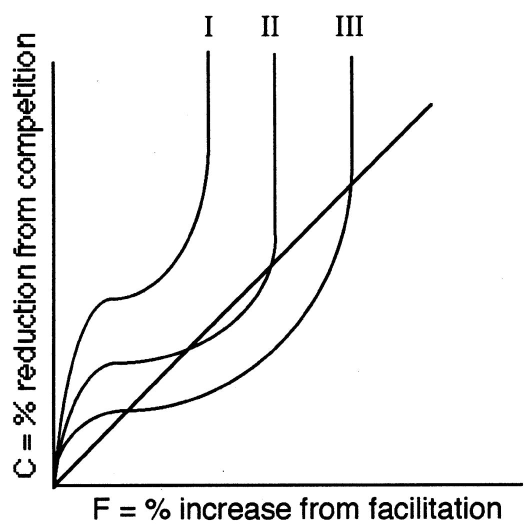

Figure 5. The three qualitatively distinct forms of the composed function. Form I represents the situation in which there is no possible design that will yield an advantage for the alley cropping system. Form III illustrates a clear region in which the system will be advantageous. Form II shows an intermediate case in which there is a possibility for an alley crop system advantage, but the design window is so small that investing in the basic research to find it may not be worthwhile.

In conclusion, while recent summaries of alley cropping systems generate some skepticism about the technique, its wholesale abandonment is not yet warranted. A complete study must include investigation of all three factors: (1) amount of competition as a function of density of trees; (2) amount of prunings as a function of density of trees; and (3) amount of facilitation as a function of amount of prunings, as already noted in previous work (Cannell et al., 1996; Ong et al., 1996; van Noordwijk, 1996). All three of these functions are easily estimable experimentally, but so far the examples we have are representative of only single points on the graph. Deciding whether type I, II, or III (see Figure 5) is the truth is not possible for any system with our current state of knowledge. We can indeed say that for at least three of the systems presented by Sanchez (with *Senna siamea* at Machacos, Kenya, with *Leucaena leucocephala* in Chipata, Zambia, and with *Peltophorun dasyrachis* in North Lampung, Indonesia, all grown with maize) type I is impossible (since in all three cases facilitative effect is greater than the competitive effect, meaning there is at least one point below the 45 degree line). The evidence from all of the other cases is incomplete since they may represent particular points outside the design window of a type III curve, and some other design might indeed fall below the 45 degree line.

All of the above presentation is presented in a simplified graphical form. For the interested reader, the same analysis is presented in an analytical form in the Appendix. It should also be noted that this analysis refers to only the ‘agronomic’ component of the alley cropping system and ignores the obviously important social and economic components, such as labor and input costs, that are ultimately important to the practical farmer. When evaluating actual systems, these other factors must be taken into account. The methods outlined here are thus limited in their intention.

Mathematical appendix

Let the % increase in production due to facilitation = F, the % decrease in production due to competition = C, and the amount of pruning produced by the trees = P. Let N = the number of rows of trees in the system.

Presuming that the amount of pruning will be a function of the number of rows of trees, that the facilitation will be a function of the amount of pruning and the competition will be a function of the number of tree rows, we have:

$$F = g(P)$$

$$P = f(N)$$

and

$$C = h(N)$$

Note that both P and C are constrained by resource capture per unit biomass produced and thus cannot be freely changed. Both are dependent on hedgerow biomass. Furthermore, F will depend on crop and initial site fertility.

We presume that f and g have inverses, so that,

$$N = f^{-1}(P)$$

and

$$N = g^{-1}(C).$$

We can thus compose the functions as follows:

$$C = h(f^{-1}(g^{-1}(F))) = A(F)$$

where A is a new function (the 'Alley cropping function'), which is the composition. Note that,

$$\frac{\partial C}{\partial F} = \frac{\partial C(F)}{\partial F} = \frac{\partial h}{\partial N}\frac{\partial f^{-1}}{\partial P}\frac{\partial g^{-1}}{\partial F}$$

and the maximum yield occurs when,

$$\frac{\partial C}{\partial F} = 1.0 \quad \text{and} \quad \frac{\partial^2 C}{\partial F^2} > 0.$$

Optimal includes $F > C$ iff $F^* > C^*$ where F^* and C^* are the values of F and C evaluated at the optimal.

References

Cannell MGR, van Noordwik M and Ong CK (1996) The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agrofor Syst 34: 27–31

Ong CK (1994) Alley cropping, ecological pie in the sky? Agrofor Today 6: 8–10

Ong CK, Black CR, Marshall FM and Corlett JE (1996) Principles of resource capture and utilization of light and water. In: Ong CK and Huxley P (eds) Tree-Crop Interactions: A Physiological Approach, CAB International, Walligford, UK

Sanchez PA (1995) Science in agroforestry. Agrofor Syst 30: 5–55

Vandermeer JH (1980) Indirect mutualism: variations on a theme by Stephen Levine. Amer Nat 116: 441–448

Vandermeer JH (1989) The Ecology of Intercropping Systems. Cambridge University Press, 237 pp

van Noordwijk M (1996) Mulch and shade model for optimum alley-cropping design depending on soil fertility. In Ong CK and Huxley P (eds) Tree-Crop Interactions: A Physiological Approach. CAB International, Walligford, UK