

Microclimatic interactions in agroforestry systems¹

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ABSTRACT

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The interaction of the components of an agroforestry system with elements of microclimate is presented in terms of the interception by foliage of radiant energy and of rainfall; and of the temperature, humidity and windspeed of air surrounding the foliage. Most of the measurements reported are from a trial in which pearl millet was grown at ICRISAT, Hyderabad, between hedges of *Leucaena leucocephala* Lam. In terms of microclimate, the main advantage of the alley system was to intercept more light throughout the year and therefore to produce more biomass. Temperature and humidity within the alleys differed little from values in the open but windspeed was substantially less. The main disadvantage of the system in terms of pearl millet production was therefore competition below ground rather than above.

COMPETITION FOR RESOURCES

In all types of vegetation, the ability of an individual to grow and reproduce depends on its success in capturing resources from its environment, often in competition with neighbors. When there is only one species in a stand with a uniform genetic base, resources appear to be shared equitably except when overcrowding makes self-thinning unavoidable. In stands with more than one species, competition for limited resources is inevitable, both above and below ground. However, as in a free market economy, competition can increase production by the system as a whole or can help to stabilize outputs when the supply of resources is erratic.

The potential for manipulating competition by intercropping has been exploited by farmers in many parts of the world and is a conspicuous feature of

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low-input agriculture in the tropics where sunlight is often abundant, rainfall is strongly seasonal but unreliable within seasons, and nutrients are usually deficient. There is a close resemblance between intercropping and the type of agroforestry in which annual arable species are grown in close association with trees (often nitrogen-fixing legumes) which provide food, fodder and fuel, shade for labour and livestock and shelter from strong winds or sandstorms.

Hitherto, agroforestry systems, like intercrops, have been explored empirically through trials in which species, population, row geometry, pruning, etc., have been introduced as variables in the hope of establishing optimum designs. Progress has been slow because the interaction of variables is complex and because it is unsafe to generalise from experience at one site. For example, alley cropping systems based on *Leucaena leucocephala* which proved successful in the humid zone of Nigeria fail in semi-arid parts of India because the tree component competes too strongly for water (Singh et al., 1986).

At ICRISAT Center, we have therefore been exploring *mechanisms* of competition between perennial woody species and annual crops as a step towards the much more formidable objective of developing *models* which will help us to predict which combinations of species and cultivars are likely to yield best in a specified environment. This introductory paper describes some of the microclimatic aspects of this work, leaving the underground component to be dealt with in a complementary paper (Ong et al., 1991).

ICRISAT's agroforestry programme evolved from intercropping trials by Willey and his colleagues between 1977 and 1984 who discussed their analyses in terms of the complementarity of resource use in space and in time (Willey et al., 1987). No annual crop, grown alone, can intercept *all* the sunlight reaching its foliage or extract *all* the water and nutrients surrounding its root system. When these resources can be tapped by a second crop maturing at more or less the same time as the first, the system is said to demonstrate spatial complementarity. When the second crop matures later, the complementarity is partly temporal. Advantages from both types of complementarity can be obtained in agroforestry systems by the choice of season length for the annual species or of a pruning cycle for the trees.

The interaction of agroforestry components with the atmosphere will now be reviewed with respect to the following elements:

- (1) the interception of radiant energy by foliage which is a major determinant of biomass production;
- (2) the interception of rainfall by foliage, which determines how reserves of soil water are recharged;
- (3) saturation water vapour pressure deficit (VPD), which determines water loss by transpiration per unit of biomass produced;
- (4) temperature (often in association with daylength), which determines the rate of development and, if extreme, may also influence growth rate.

LIGHT INTERCEPTION

When the growth is not limited either by water or by nutrients, the amount of biomass produced by a stand of a single species is limited by the amount of radiant energy that its foliage can intercept. Many trials with arable crops – and a few with trees – have demonstrated that provided stress is minimal biomass production per unit of intercepted radiation (e) is a conservative quantity, usually between 1.0 and 1.5 g/MJ for C_3 species in a temperate climate (Monteith and Elston, 1983; Russell et al., 1988) and between 1.5 and 1.7 g/MJ for C_4 species in a tropical climate (Kiniry et al., 1989; Monteith, 1990). It is therefore possible to express the seasonal biomass production of a single species, growing alone or in an agroforestry system, as the time integral of the product $e f_i S$, where f_i is the fraction of incident radiation intercepted on a given day and S is the corresponding incident radiation (MJ m^{-2}). If the fraction of radiation intercepted by the whole system is also recorded, a value of e can be obtained for the whole system and its performance can be analysed in terms of (a) the efficiency of radiation capture, and (b) the efficiency with which captured radiation is used to produce biomass.

In agroforestry systems, there is little scope for *increasing* light interception unless the population in one or more of the sole stands is sub-optimal but there is a possibility of interception *decreasing* as a consequence of competition. The scope for increasing e is not large but this response has been detected, e.g., in groundnut grown between rows of millet or sorghum (Harris et al., 1987). The basis for the effect appears to be that in the sole groundnut used for the comparison, leaf photosynthesis was light-saturated for a significant fraction of the day so that part of the intercepted light was wasted. In the intercropped groundnut where the irradiance was smaller because of shading, fewer leaves were light-saturated for a shorter time and so e was larger.

We now illustrate these concepts by measurements from an agroforestry trial conducted by Corlett et al. (1987), to which we shall refer several times and in which pearl millet (*Pennisetum glaucum*, cv. BK560) was grown between hedges of *Leucaena leucocephala* on a shallow Alfisol at ICRISAT Center, Andhra Pradesh, India. The trial extended over the rainy seasons (June to September) of 1986 and 1987 and the intervening dry season. The treatments consisted of sole pearl millet (SM), sole *L. leucocephala* (SL) and a millet/*L. leucocephala* alley crop (LM). In all treatments, *L. leucocephala* hedge rows were spaced 3.4 m apart. The management of the *L. leucocephala* in the SL and LM treatments was the same except that the alleys in the sole *L. leucocephala* stand were kept fallow. The *L. leucocephala* was seeded directly in north-south rows during August, 1985. Five rows of millet were sown in the alleys on 27 June 1986, occupying 3/4 of the ground area.

At the start of the rainy season in 1986, the *L. leucocephala* was pruned three times to a height of 0.7 m before sowing millet, at 30 days after sowing

(DAS), and after harvest (85 DAS). At harvest, the millet and *L. leucocephala* were both about 1.5 m tall.

Tube solarimeters were placed at ground level in all three treatments to span one row in the sole millet and the full alley width in the SL and LM treatments. (In systems with dispersed trees we are now using fish-eye photographs to estimate interception by tree and crop components separately.)

Figure 1 (a) shows the interception of light in the sole stands over 11 months.

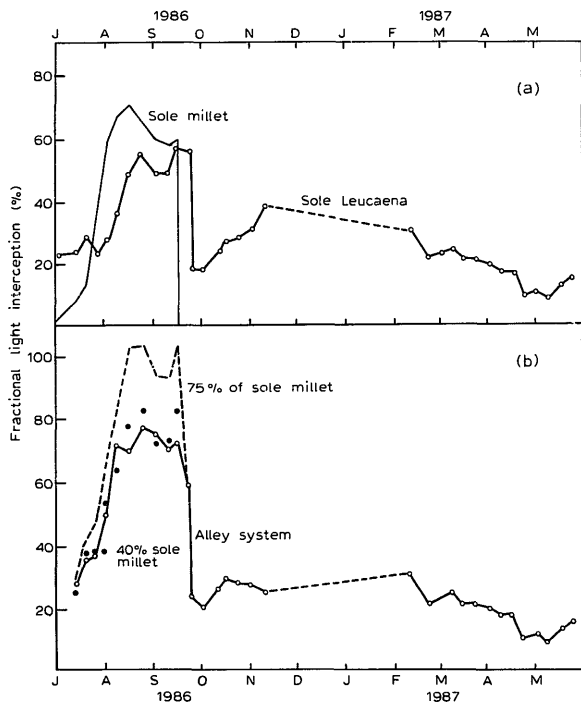


Fig. 1. (a) Fractional interception of radiation by sole stands of *L. leucocephala* (dashed line) and millet (thin line). (b) Fractional interception of alley system (full bold line) and estimate from components assuming that millet intercepted 75% (broken bold line) or 40% (points) of sole millet value (see text).

Maximum light interception in the *L. leucocephala* was only 0.6 compared with 0.7 for the millet; but because the *L. leucocephala* retained some of its foliage during the dry season, it intercepted about twice as much radiation as the sole millet over a whole year (Table 1). Figure 1(b) compares the total interception of light by the agroforestry system as measured and as predicted on the basis of interception in the sole crops. When interception by the millet component of the system was assumed to be 70% of interception by the sole millet (5 rows out of 7), the predicted interception was much larger than the observed. Better agreement [see points in Fig. 1(b)] was obtained assuming that the appropriate fraction was 40% implying that, as a consequence of competition, the millet in the alleys had less foliage than in the sole stand and intercepted about half the amount of light per plant.

Table 1 sets out the figures needed to calculate e for the two species grown apart and together. For millet, e is expected to be about 1.5 to 1.7 g MJ⁻¹ in the absence of stress. In the sole millet stand, e was only 0.81 g MJ⁻¹, presumably because plants growing on a shallow Alfisol were often short of water (the total rainfall for the growing season of the millet was 36% below normal). In the alley, e for millet was substantially larger, possibly because the light saturation of photosynthesis associated with drought occurred less often in partial shade.

The value of e for *L. leucocephala* in the rainy season was less than expected for a C₃ species in the absence of stress but comparisons with arable crops are unreliable because of unknown differences in root:shoot ratios. If these are larger for a perennial species than for an annual, e estimated for above ground biomass would be smaller. Much smaller values of e were recorded during the

TABLE 1

Values of intercepted (total) solar radiation, above-ground biomass and intercepted radiation per unit biomass

	Intercepted radiation (MJ m ⁻²)	Biomass (t ha ⁻¹)	e (g MJ ⁻¹)
Rainy season (Jul–Aug 1986)			
Sole millet	581	4.7	0.81
Alley millet	300	3.1	1.03
Sole <i>L. leucocephala</i>	520	4.0	0.77
Alley <i>L. leucocephala</i>	510	4.0	0.77
Total alley system	810	7.1	0.88
Dry season (Sep 1986–Jun 1987)			
Sole <i>L. leucocephala</i>	1270	1.5	0.12
Alley <i>L. leucocephala</i>	1160	1.7	0.15
Year (Jul 1986–Jun 1987)			
Total alley system	1970	8.8	0.45

almost rainless dry period when the *L. leucocephala* was severely short of water and foliage was shed.

Both for the rainy season and for the whole year, the agroforestry system is clearly more productive than either species grown alone. In terms of the present analysis, more biomass can be associated with the interception of more radiation but this implies access to more water in the root zones of the two species – a topic outside the scope of this review. In terms of grain production, it is significant that the reduced interception of light by millet in the alleys, a consequence of both defoliation and moisture competition, was not compensated by a larger value of e .

In the 1987 monsoon season which was drier during grain filling, this compensation did not operate. For sole millet, e was 0.98 compared with 0.60 g MJ⁻¹ in the alleys where only 0.9 t ha⁻¹ (1 tonne = 1 Mg = 10³ kg) of biomass was harvested, possibly because the *L. leucocephala* had developed an even more competitive root system. The figures discussed here should therefore be regarded as illustrative of an analytical technique rather than a definitive account of light interception and use in an alley system.

Crops growing within an alley are exposed to radiation in which the red:far-red ratio must be substantially less than in the open. We have found no reported measurements either of spectral quality or of processes of development, extension, or assimilate allocation which depend on quality.

RAINFALL INTERCEPTION

Raindrops, like light, are intercepted by all surfaces within a stand of vegetation and the consequent redistribution of water has several agronomic consequences.

First, a small amount of water is retained by leaves. Nearly all the rain in a very light shower may be trapped in this way but once rainfall exceeds about 5 mm, the amount held within a canopy covering the ground is often between 1 and 2 mm. Subsequent evaporation of this water reduces the amount lost by transpiration but occurs much more rapidly than transpiration because the diffusion resistance of stomata is not involved (Rutter, 1975).

Second, a large fraction of the water intercepted but not retained by leaves and other organs finds its way to the soil by running down a stem or trunk. Water in the soil is therefore recharged preferentially at the base of individual plants where stemflow can account for as much as 20% of incident rainfall.

Third, the kinetic energy of individual raindrops is dissipated at the time of interception, reducing the risk of soil erosion during heavy storms.

All three processes are relevant to agroforestry but have been little studied in this context. We concentrate on the second because we have collected some

experimental evidence from the trial already referred to, to explore the question: "Does the interception of water by the tree component in an alley system divert enough water from the annual component to reduce its production?"

With prevailing W to SW winds during the early months of the monsoon and from sowing to 40 DAS, rain-gauges sited close to the west side of the N-S *L. leucocephala* hedge recorded almost the same amount of rain (P) as a rain-gauge outside the plot (Fig. 2). By 80 DAS, the fraction of P recorded in this position had fallen to about 80%. In other positions, 70–90% of P was recorded throughout the life of the millet.

This approximate figure is consistent with measurements in a separate stand of pure *L. leucocephala*, set out in a systematic design and growing to a height of about 5 m. Interception ranged from about 10% at the smallest population of 400 trees/ha to over 40% at 10 000 trees/ha. Corresponding ratios for stem cross section per unit land area range from about 4 to 11×10^{-4} . The ratio in the alley crop was in the middle of this range and on this basis the *Leucaena* in the alley crop would be expected to intercept about 20% of incident rainfall, a figure which agrees well with the measurements already reported. If millet production were limited by available water, the corresponding loss of millet biomass would be approximately 1.2 t/ha assuming about 82 mm loss in water. With abundant rainfall, this adverse impact of agroforestry would

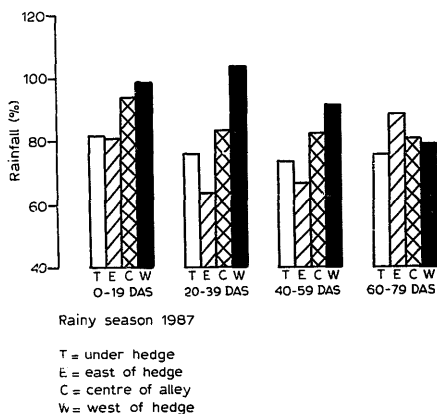


Fig. 2. Fractional interception of rain by *L. leucocephala* hedges over four periods during the rainy season, 1987, and at three locations within the alley (C = centre of alley, E = east, W = west of hedge).

be negligible; competition for light (or nutrients) would then come into play as discussed in the last section.

TEMPERATURE

For a given air temperature, the temperature of foliage increases as solar radiation increases, decreases as air becomes drier (specified by a saturation vapour pressure deficit or VPD) and usually decreases with increasing wind-speed. The relevant equations are well established (Monteith, 1981) but are difficult to apply in agroforestry systems because of horizontal and vertical gradients of all three variables. We therefore measured the temperature of the upper leaves of millet in the system already described, using fine wire thermocouples.

As expected, windspeed was substantially and systematically reduced within the alley (Fig. 3); less predictably, VPD was little affected by the presence of trees (Fig. 4) and a possible reason is discussed later; the radiation load was always less in the alleys. The net effect of differences in these variables changed during the season. Initially, the foliage of millet within alleys was about 1°C

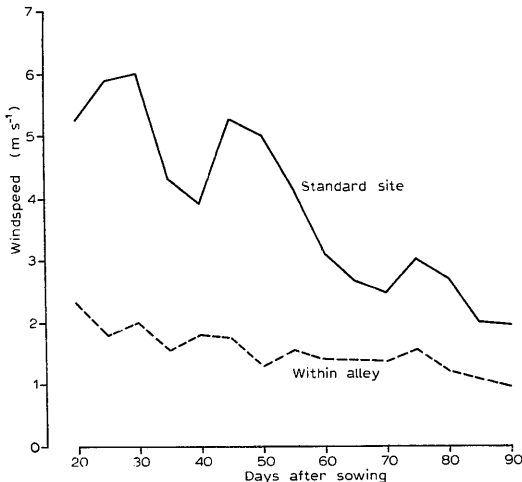


Fig. 3. Comparison of windspeed measured above the canopy of the alley crop and at 2 m outside the trial during the rainy season, 1986, ICRISAT Center.

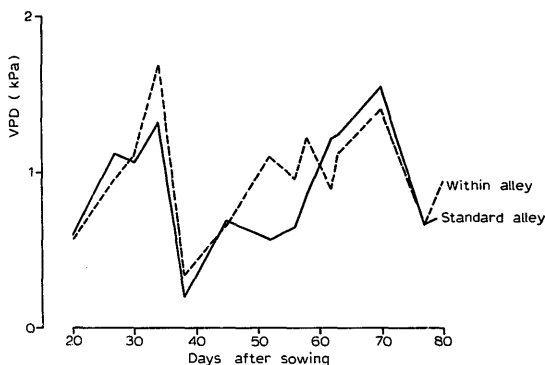


Fig. 4. Comparison of water vapour pressure deficit above the canopy of the alley crop and at 2 m outside the trial during the rainy season, 1986, ICRISAT Center.

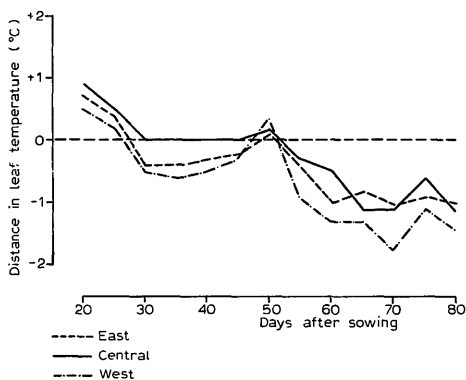


Fig. 5. Difference between mean leaf temperature of alley millet and sole millet during the rainy season, 1986 (C=centre of alley, E= east, W= west of hedge).

warmer than in a sole stand of millet (less wind) but by the end of the season it was 0.5 to 1°C cooler (less radiation), see Fig. 5.

Larger differences were observed in soil temperature (Fig. 6), probably because turbulent mixing of air close to the ground was more suppressed within

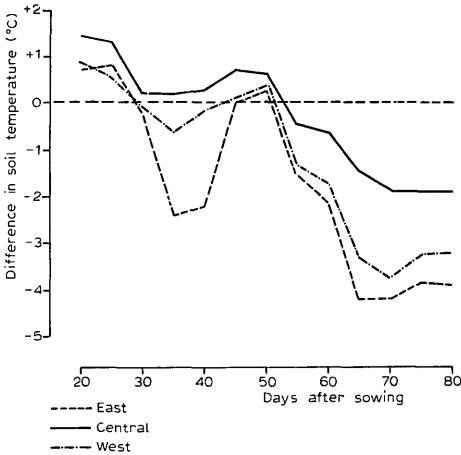


Fig. 6. Difference between mean soil temperature of alley millet and sole millet during the rainy season, 1986 (C = centre of alley, E = east, W = west of hedge).

the alleys than in the sole stand. Initially, the soil temperature in the alleys was about 1°C warmer, as for foliage, but this figure dropped to -2 to -4°C at the end of the millet season, the lowest figures being recorded close to the hedge where shading was heaviest.

On a much larger scale, Barradas and Fanjul (1986), working in Veracruz, Mexico, measured air temperature in plantations of coffee (*Coffea arabica*) that were unshaded or shaded by 14 m tall trees of *Inga jinicuil*, transmitting about 25% of incident radiation. Shade reduced mean maximum temperature by between 5 and 10°C in most months but there was little difference in monthly mean minimum temperature. As the absolute maximum air temperature was about 34°C , the main thermal effects of shade were probably to slow leaf expansion and to extend the period of reproductive growth with possible benefits for yield.

VAPOUR PRESSURE DEFICIT

In addition to its role in establishing the difference between foliage and air temperature, VPD is intimately related to the dry matter production:water use ratio of vegetation (more commonly but less correctly referred to as a 'water use efficiency').

The transpiration rate of a leaf is almost exactly proportional to the VPD at its surface and is *approximately* proportional to the VPD of ambient air. The photosynthetic rate of a leaf is approximately proportional to the decrease in CO₂ concentration across stomata. Stomata respond to the environment in a way which makes this difference approximately constant during the day in many circumstances. The amount of water transpired per unit of assimilated CO₂ is therefore expected to be approximately proportional to VPD and this prediction is supported by many field observations demonstrating that the dry matter production: water use ratio is *inversely* proportional to VPD (Mon-teith, 1990).

In an agroforestry system where trees provide shelter, it is intuitive that the sheltered area is likely to be more humid than the open area. However, the air may also be warmer, and because VPD depends on both temperature and saturation deficit, its value in a sheltered area can be either larger or smaller than in the open. In our *L. leucocephala*/millet system, differences in VPD were small and changed sign during the season (Fig. 4).

The small difference in VPD between the air sampled within the alleys and in the open implies that, at both sites, microclimate and macroclimate were tightly coupled as a result of efficient turbulent mixing. If VPD within the alleys had been measured just above the ground where the microclimate is expected to be effectively decoupled from the macroclimate, it is likely that much smaller values of VPD would have been recorded. The ecological implication is that millet growing in the alleys and exposed to almost the same VPD as a stand of sole millet would use the same amount of water for transpiration per unit of dry matter produced. However, a short-statured species would be exposed to a more humid environment and should therefore produce more dry matter per unit of water.

Turning to forests for measurements on a larger scale, Ghuman and Lal (1987) measured differences in microclimate 1 m above the ground below 50 m tall trees in a rainforest near Benin City, Nigeria, and in a 30 ha clearing within the forest. For the period from September to December 1984, the mean rate of evaporation in the forest was only 0.53 mm/day compared with 3.3 mm/day in the clearing. These figures imply a similar range of about 1 to 6 in VPD between forest and clearing and a corresponding range of 6 to 1 in the dry matter production: water use ratio. It is most unlikely that such large differences of VPD could exist in an agroforestry system; but even a 2 to 1 advantage could be responsible for a significant increase in crop yield and the effect deserves closer investigation.

IMPLICATIONS AND APPLICATIONS

Because of the very limited and unsystematic information available from elsewhere, our discussion has been mainly confined to experience with an alley cropping system based on *L. leucocephala* and to one site in the semi-

arid tropics (SAT). As more measurements emerge from hundreds of new agroforestry experiments throughout the world, it should be possible to generalise to other agroforestry systems appropriate to particular environments.

In the SAT of India, attention is now being focussed on improving systems with trees scattered among crops, a common feature of traditional agroforestry in the arid regions of the Sahel and northwestern India. Ecological interactions within such systems differ markedly from those in alley cropping systems. For example, in a dispersed system based on *Faidherbia albida* (formerly *Acacia albida*) spaced at 4 × 4 m, the canopy intercepted a maximum of 20% of the incident light compared to a maximum of 60% in the alley cropping system. The impact of the trees on the distribution of rainfall must be negligible since the leaves of this species are shed before the onset of rain and the next flush is produced late in the rainy season. The *F. albida* system therefore represents another extreme agroforestry system with virtually no ecological interaction for much of the cropping season.

Several important lessons can be drawn from the experience with alley cropping in the SAT. First, advantages in terms of the interception of radiation, windspeed, VPD and temperature are relatively unimportant compared with the adverse effects of interception of rainfall (which decreases the availability of water to roots) and below-ground interactions (Ong et al., 1991). Second, reduction in soil erosion under a tree canopy or leaf mulch is also of minor importance compared to the competition for water between well-established roots of trees and crops (Singh, 1989). Third, it is misleading to extrapolate to agroforestry the benefits of atmospheric interactions based on conventional agricultural or forestry systems. Striking contrasts between the positive ecological interactions of conventional intercropping and the negative interactions of alley cropping are good illustrations of the danger of such extrapolation (Ong, 1991). For example, a major benefit of intercropping groundnut/millet is the substantial increase in the partitioning of dry matter to reproductive organs in intercrop groundnut (Harris et al., 1987), but this interaction has not been reported in agroforestry. Nevertheless, the principles of complementarity in resource utilisation hold good for both intercropping and agroforestry systems, and should form the guidelines for the development of new agroforestry systems.

It is widely assumed that shading by overstorey species is undesirable and a major emphasis of agroforestry research is to develop pruning regimes to improve the light available to understorey crops. Furthermore, considerable effort is being spent to select for tree species with erect branches in order to minimise shading. Experiments in the SAT have shown that shading up to 50% has little impact on the yield of legumes and that competition between root systems is much more significant. Below-ground competition is beyond the scope of this paper but must be integrated with above-ground competition to establish sound guidelines for agroforestry systems.

At ICRISAT Center, our approach to resource utilisation by alley cropping systems is now being applied to the potential for using perennial pigeonpea (*Cajanus cajan*) as the woody component. Perennial pigeonpea agroforestry systems exhibit virtually all the advantages of conventional intercropping (e.g., sorghum/pigeonpea) as well as the benefits associated with multipurpose trees. Preliminary trials indicate that perennial pigeonpea resembles grain pigeonpea in terms of the complementarity of resource use in time, and has the additional benefit of deeper rooting so that fodder can be produced during the long dry season. Combined with recent advances in measuring transpiration, e.g. the heat balance technique, the resource utilisation approach is a powerful tool for exploring the mechanisms of competition in agroforestry systems.

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