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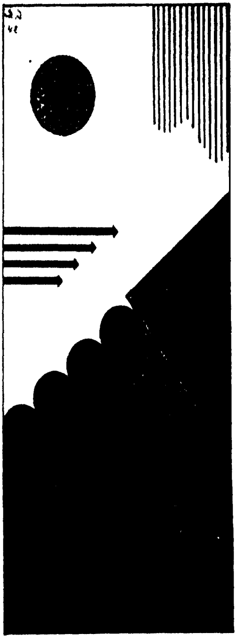

METEOROLOGY
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Crop simulation models and some implications for agroforestry systems

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Abstract

ICRISAT's work on modeling sorghum, pearl millet, and groundnut is summarized, and the implications for agroforestry systems are examined. Trees can improve water infiltration rate and utilize deeper profile water not accessible to conventional crops. In this paper we have studied how the introduction of tree species in crop systems would affect overall water use and productivity. We have analyzed climatic data of five selected locations in arid and semi-arid India in terms of the distribution and dependability of rainfall and the trend in seasonal rainfall pattern in the recent years.

Probabilities of available soil water are simulated for these locations. Available water holding capacity of the soils are assumed as 25, 50, 100, and 150 mm at each of the selected locations to account soils for ranging from very shallow to medium deep. Grain yields and total dry matter are simulated for these agroclimatic conditions to outline the environments where agroforestry is feasible.

Grain yields and total dry matter of the crops at various levels of shading by the tree-component are simulated. These results are expected to give some insight as to how the tree-management will affect the microclimate and productivity of the crop. Effects of changes in microclimate such as canopy temperature and radiation intercepted (by manipulating row width, plant density, canopy growth) on productivity based on information from intercropping and forestry studies are discussed. Simulation results are compared with the experimental data from ICRISAT and elsewhere on appropriate cropping systems under various agroclimatic conditions.

Minimum data sets that need to be collected from specific experiments designed for agroforestry studies are identified.

Introduction

Crop simulation models are useful tools to examine the feasibility of agricultural management systems and can be used to examine the effect of trees within cropping systems. Trees can utilize water in deep layers of the soil profile not accessible to the roots of conventional crops. In this presentation an attempt is made to study how the introduction of tree species into cropping systems is likely to affect the overall use of environmental resources.

This paper has been divided into three parts:

a comparison of the performance of the two crops, sorghum *Sorghum bicolor* (L.) Moench and pigeonpea *Cajanus cajan* (L.) Millsp., in sole and intercrop systems and relating their performance to agroforestry systems;

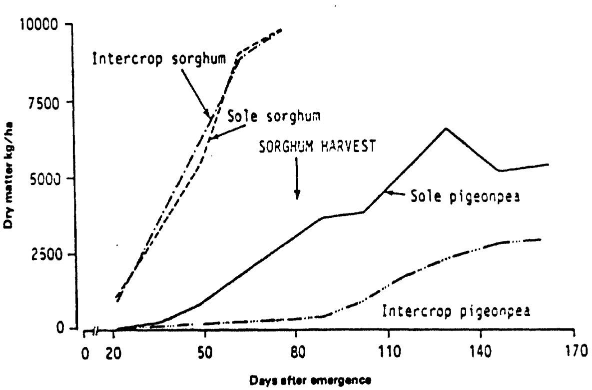
- an analysis of the climatic and soil water data for five selected locations in India to examine where agroforestry systems may be feasible; and
- a simulation using a sorghum crop model and the implications for agroforestry systems.

Intercropping

Many investigations (e.g., Kassam and Stockinger 1973; Willey and Lakhani 1976; Natarajan and Willey 1981; Rao and Morgado 1984; Natarajan and Willey 1985), have shown that intercropping can give rise to substantial increases in yield because the component crops complement each other and make better use of environmental resources than when grown separately. We have used the performance of two crops sorghum and pigeonpea in sole and intercrop systems as a simple model of an agroforestry system.

Figure 1 illustrates the cumulative dry matter per unit area of a sorghum/pigeonpea intercrop during the growing season (Natarajan and Willey 1981). In intercropping, sorghum was the dominant component, and grew at a rate comparable to that of sole sorghum. In contrast, pigeonpea in the intercrop experienced severe competition from sorghum plants which formed a canopy very rapidly.

Figure 1 Dry matter accumulation in sole sorghum and pigeonpea and in sorghum/pigeonpea intercrop on Vertisols in 1977 at ICRISAT Center (after Natarajan and Willey 1981).



At only 30 days after emergence, sorghum intercepted more than 70% of the incident radiation and by about 55 days the peak interception of 84% was achieved (Figure 2). Canopy development in sole pigeonpea was much slower: at 30 days, this crop was intercepting only 10% of the incident light; and at 60-65 days, it had reached a near maximum value of 70% which was more or less maintained until about 110 days.

Figure 3 illustrates the efficiency with which the intercepted energy was converted into dry matter throughout the growing period. Comparing the sole crops, the fitted regression lines show that the sorghum (1.5 g MJ^{-1}) was more efficient than the pigeonpea (0.6 g MJ^{-1}). The intercrop converted the intercepted light energy before sorghum harvest at a rate of 1.7 g MJ^{-1}, which was more efficient than sole sorghum. After the sorghum harvest, the efficiency of conversion of the intercrop pigeonpea reverted to a value virtually identical to that of sole pigeonpea.

Natarajan and Willey (1981) reported that intercropping altered the ratio of transpiration to evaporation from the soil surface. Thus the yield advantages of intercropping were achieved simply by channeling a greater proportion of the water through the crop. These data on sorghum/pigeonpea intercropping were collected from one location (ICRISAT Center, Patancheru). Analysis of agroclimatic data from other locations is a necessary first step to identify areas where the reported success of double cropping is likely to occur.

Figure 2 Light interception by sole sorghum and pigeonpea and sorghum/pigeonpea intercrop on Vertisols in 1977 at ICRISAT Center (after Natarajan and Willey 1981).

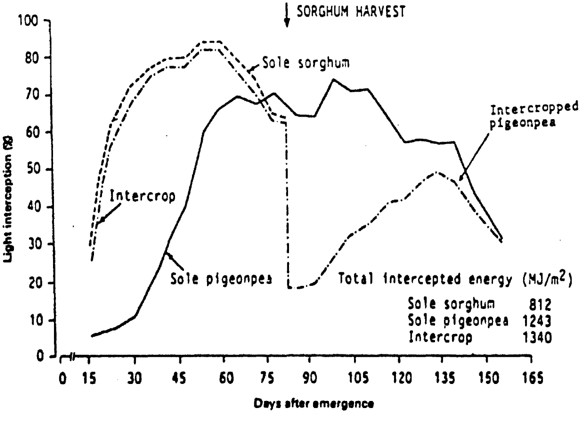
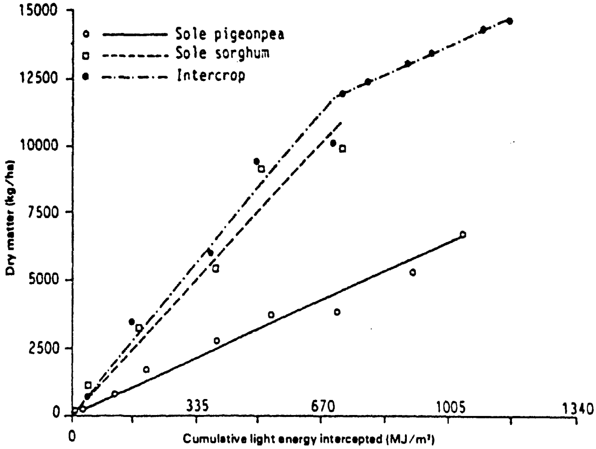


Figure 3 Efficiency of conversion of intercepted light energy into dry matter on Vertisols in 1977 at ICRISAT Center (after Natarajan and Willey 1981).



Climate and soil water

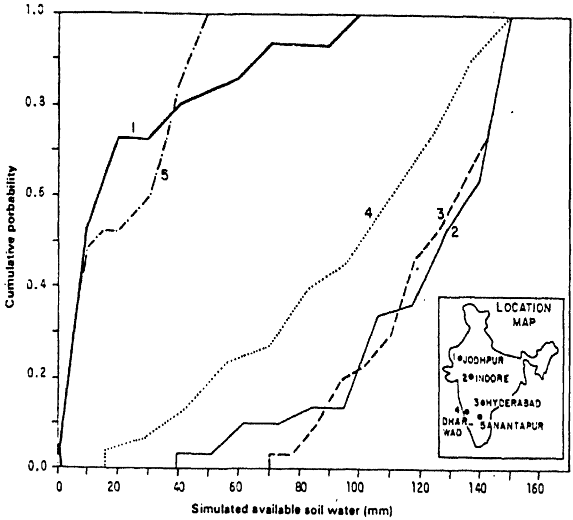
We analyzed climatic data of five selected locations in arid and semi- arid India in terms of the distribution and dependability of rainfall and the trend in seasonal rainfall pattern. Annual rainfall of five locations (Jodhpur, Anantapur, Hyderabad, Dharwad, and Indore) in India, based on data from 1941-70, ranged from 382 mm (Jodhpur) to 1001 mm (Indore); and the coefficients of variation ranged from 20% (Hyderabad) to 42% (Jodhpur).

We examined the mean weekly rainfall distribution and the probability of receiving at least 10 and 20 mm rainfall in each week for these five locations. The number of weeks receiving at least 20 mm rainfall was 11 in Jodhpur, 10 in Anantapur, 16 in Hyderabad, 22 in Dharwad, and 16 in Indore. The continuity of rainfall is important for determining length of growing season. The consecutive weeks receiving at least 20 mm rainfall were 11 in Jodhpur, 5 in Anantapur; 15 in Hyderabad; 15 in Dharwad; and 16 in Indore.

Probabilities of available soil water (ASW) stored in the profile at the beginning of post-rainy seasons were simulated using the Ritchie (1972) soil water model to indicate the possibility of growing a second crop after rainy season cropping.

Soil water was simulated assuming a sorghum crop in the rainy season and using climatic data from 1941 to 1970 (Figure 4). Available water-holding capacities (AWHC) of soils for Anantapur, and Jodhpur were 50 and 100 mm, respectively. For

Figure 4 Probability of (less than a given amount) simulated available soil water at the beginning of postrainy seasons after a rainy season sorghum at five locations in India. Data base is 1941 to 1970.



the other locations, AWHC was 150 mm each. In 70% of the years, the simulated ASW was less than 20 mm in Jodhpur, 35 mm in Anantapur, 120 mm in Dharwad, 140 mm each in Hyderabad and Indore.

Simulation results show that another crop can be grown in the post-rainy season in 70% of the years under residual soil water conditions in Indore, Dharwad, and Hyderabad where 50-75% of the soil profile was charged with available soil water at the beginning of postrainy season. For Jodhpur and Anantapur, the soil was left with a negligible amount of available water at the end of the rainy season crop, and thus growing two crops in a year without irrigation involves high risk. The reasons are not only the amount and distribution of rainfall, but also the poor water-holding capacity of the soils.

Simulation models based on soil, crop, and weather factors are useful to characterize environments quantitatively in terms of production potential and can be used as tools for planning alternate strategies for cropping and land use. No models are yet available for simulating the performance of intercropping and agroforestry systems. However, we have used in this study a sorghum simulation model developed at Texas A&M University and modified at ICRISAT for use in the semi-arid tropics.

Modeling

The sorghum simulation model, SORGF, developed by Arkin et al. (1976) and modified by Huda (1987) was used in this study. The SORGF model requires daily rainfall, maximum and minimum air temperatures, and solar radiation as weather input data, and latitude of the location. The plant and soil information needed includes date of sowing, depth of sowing, row spacing, plant density, potential number of leaves and their maximum size, water-holding capacity of the soils and available soil water at sowing.

The model calculates the daily growth and development of a standard-grain sorghum plant under adequate management, sufficient plant protection, and recommended doses of nutrients in a field stand. It accounts for the physical and physiological processes such as phenology, leaf area development, light interception, and water use which are independently computed and used as sub-models. The potential dry matter is calculated from radiation intercepted and the net dry matter is calculated accounting for water and temperature stress. Partitioning of dry matter into different plant parts is based upon the stage of development of the plant. The final biomass and grain yield per unit area are calculated by multiplying plant density with the biomass and grain weight per plant at physiological maturity, respectively.

Because our analysis deals with soil water availability and the feasibility studies of agroforestry systems, it is pertinent to describe briefly the soil water balance sub-routine of the SORGF model. Daily soil water is simulated in the model using the data on rainfall and irrigation, initial water content in the soil profile, and the available water-holding capacity of the soil, following the approach of Ritchie (1972; 1973). Evaporation and transpiration are calculated separately to obtain evapotranspiration. Evaporation is primarily dependent upon the potential evapotranspiration (PET) and the number of days since the last significant rainfall/irrigation event. Potential evaporation below a plant canopy (EOS) is calculated after simulating the potential evaporation from bare soil (EO) and relating it to the leaf area index (LAI) values. EO is calculated in the model using net radiation as input data. Net radiation is calculated from albedo, maximum solar radiation reaching the soil surface, and sky emissivity. Ritchie (1973) reported that transpiration is dependent upon PET and the relative soil water level, RSW, defined as the ratio of available water on any day to the maximum available water holding capacity of the rooted profile. Arkin et al. (1976) defined the water-stress coefficient as 1.0 (suggesting no drought-stress) if RSW is above 0.4, the coefficient decreasing linearly from there to 0 when RSW is 0.

The SORGF model was used to simulate total biomass production of sorghum at ICRISAT Center. Climatic data from 1974 to 1986 were used. Simulations were made for three soil types.

Available water-holding capacity of these soils was taken as 50 mm (Shallow Alfisols), 150 mm (Vertic Inceptisols), and 250 mm (Vertisols). Simulations were made for three periods in a year (June to September, October to January, and February to May). June to September is the rainy season; October to January is the post-rainy season, and February to May is the summer season. Because of insufficient available water in the soil profile, it was difficult to support a second crop on the Alfisol in all the years and a third crop on all the soils in almost all the years except during 1983/84. However we assumed an established stand (trees) in the beginning of the second (for Alfisol) and third seasons (for all soils).

Huda (1987) used a simple relationship of 3.0 g of dry matter accumulation for each megajoule (MJ) of radiation interception. This coefficient was derived from an irrigated sorghum grown during post-rainy season. The coefficients for dry matter accumulation efficiency used in the simulation study were 25% higher for the rainy season, when saturation vapour pressure deficit is usually less than 1 kPa; and 25% lower in the summer season, when saturation vapour pressure deficit is usually greater than 2 kPa (Monteith 1986), as compared to the values used for the post-rainy season. The introduction of separate light use efficiency coefficients in the SORGF model for rainy, post-rainy and summer seasons needs further investigations.

Figure 5 shows available soil water simulated for three soil types at the beginning of each crop season for three periods at ICRISAT Center. It is apparent that in Shallow Alfisols there is very little soil water available for crop use over extended drought periods. In Vertic Inceptisols and in Vertisols, there is fairly good degree of storage for a longer time. Results show that in 70% of the years simulated soil water at the beginning of postrainy (after rainy season sorghum) was nearly full in all three soils. At the beginning of summer season the simulated soil water was zero in the shallow Alfisol in all years and was less than 15 mm in Vertic Inceptisol and less than 95 mm in Vertisol in 70% of the years, respectively.

Figure 5 Probability of (less than a given amount) simulated available soil water at the beginning of each of three periods in three soils having different available water holding capacity (AWHC) at ICRISAT Center. Climatic data from 1974 to 1986 were used.

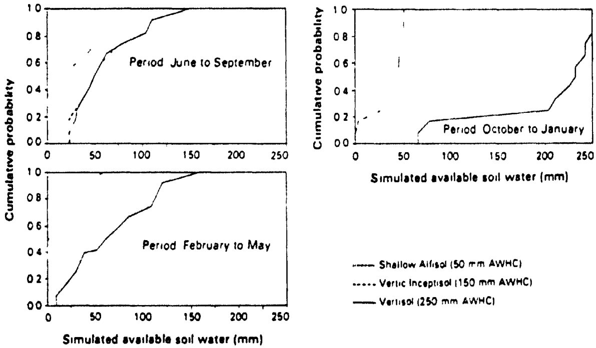
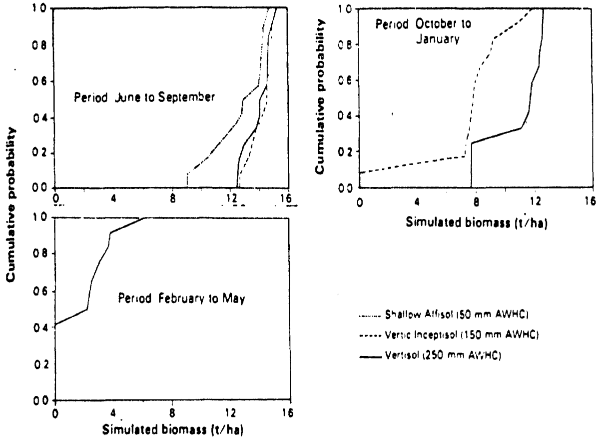


Figure 6 shows the simulated biomass of sorghum in three periods in three soils at ICRISAT Center. The range and variability in biomass across three seasons and three soils are noticeable. In Vertisols, for example, simulated biomass production decreased from the rainy to the post-rainy season; and in the summer season simulated biomass was zero in 42% of the years. In the rainy season there was no difference between

Vertisol and Vertic Inceptisol, but in Vertic Inceptisol simulated sorghum biomass was considerably lower in the postrainy season and zero in the summer season. Simulated sorghum biomass in the Alfisol was lower and more variable than in the other two soils in the rainy season and was zero in the postrainy and summer seasons. Zero biomass simulation of sorghum resulted from an extended period of drought when simulated available soil water in the profile was virtually zero for more than 15 days and the model assumed the complete senescence of thé crop.

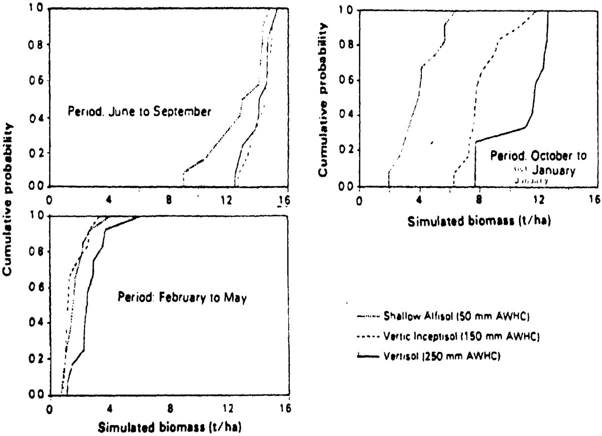
Figure 6 Probability of (less than a given amount) simulated biomass using a sorghum simulation model, SORGF for three periods in three soils having different available water holding capapcity (AWHC) at ICRISAT Center. Climatic data from 1974 to 1986 were used.



Considering an established stand (tree) in an Alfisol during the post-rainy and the summer seasons, and in a Vertic Inceptisol during the summer season, we report the corresponding simulated biomass of sorghum in Figure 7. These were simulated biomass values of sorghum at the time when the soil in the crop root zone became completely dry. Complete senescence of sorghum occurred when zero soil water continued for more than 15 days. Under such circumstances we made assumptions that the model allowed sorghum crop to senesce but permitted trees to use water from deeper layers in the soil profile for their sustenance. We made these assumptions based on our experience with sorghum. However, further research is needed to understand how a tree species behaves in a situation when zero soil water continues in crop rooting zone for a number of days. The mean biomass (tree) in a Shallow Alfisol was 13, 4, and 2 t ha^{-1} in rainy, postrainy, and summer seasons, respectively. Mean biomass in a

Vertic Inceptisol was 14, 8, and 2 t ha^{-1} in rainy, post-rainy, and summer seasons, respectively (Fig. 7). Mean biomass in a Vertisol was 14, 11, and 3 t ha^{-1} in rainy, post-rainy, and summer seasons, respectively. Thus, trees could provide some biomass during the summer season which could be used as fuel and fodder, unlike sorghum which stopped growing.

Figure 7 Probability of (less than a given amount) simulated biomass of tree using a sorghum simulation model, SORGF for three periods in three soils having different available water holding capacity (AWHC) at ICRISAT Center. Climatic data from 1974 to 1986 were used.



Simulation results using a sorghum model showed some promise to generate first hand approximation information about the alternate land use systems for three soil types in one location. Such studies need to be extended to other locations. However, validation of the simulation results in respect to agroforestry systems is an essential step for extending this work further.

Validation

The validity of this simulation will be examined by comparing actual values being collected on *Leucaena* based systems at ICRISAT. Important values to be considered are the depth of water uptake by trees, the competition for moisture between trees and crops, the rate of canopy formation of trees following pruning and the efficiency in which intercepted energy is converted into biomass.

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