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An analysis of the literature indicates that polyculture, growing two or more useful plants simultaneously in the same area, is generally beneficial. The choice of crops and other environmental variables will determine to a large extent whether the practice is advantageous in any given situation. In terms of wind and of nutrients from the soil, [illegible] of the nitrogen status of the soil-plant system when one of the crops is a legume, and greater stability of yields over time, the benefits of polyculture are clear. [illegible] to use of heavy farm other mechanized operations, polyculture often [illegible] but recent research [illegible] removing these difficulties has been [illegible] successful. Certain species and combinations of species appear to perform more successfully in polyculture than do others. Associations of cereals, grain-legumes, and tree-legume combinations are commonly used and it is the price relationships of these combinations, rather than the cropping systems themselves, which appear to be the determining factors. The effects of climatic change on polyculture have been well documented primarily with respect to wet and dry seasons in the tropics rather than year to year variability in the same cropping season. The fact that nutritional requirements and phynology of varieties within a single species may vary more than those of different species has been described in the literature on polyculture. Suggestions for futher research are summarized in the bulletin.


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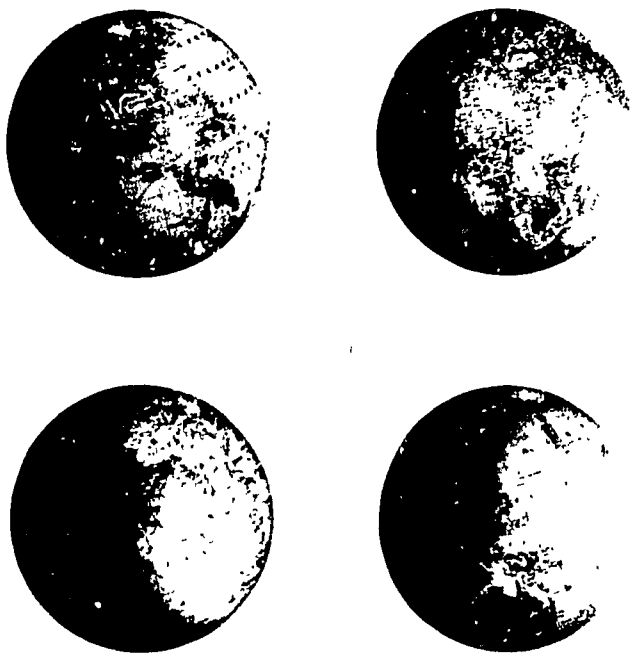

# POLYCULTURE CROPPING SYSTEMS:
## Review and Analysis

Donald C. L. Kass

NEW YORK STATE COLLEGE OF AGRICULTURE AND LIFE SCIENCES
A STATUTORY COLLEGE OF THE STATE UNIVERSITY AT
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February 1978

# Polyculture Cropping Systems: Review and Analysis*

Donald C. L. Kass†

## *Introduction*

Although agricultural systems in which two or more useful plants are grown simultaneously on the same area have been receiving increasing attention in recent years, the practice has long been recognized as a way in which farmers in the tropics and subtropics with limited land resources can produce food and cash crops (King, 1911, Nicol, 1935, Aiyer, 1949, Donald 1963, Miracle, 1967, Ruthenberg, 1971). Associations of cereal crops and legume-maize mixtures were common in the temperate zone until the advent of mechanization and heavy fertilization made them less practical (Warburton, 1914, Zavitz, 1927, Thatcher, 1925, Hackleman, Sears, and Burlison, 1929, Prine, F 50, FAO, 1966). Many studies of the benefits and disadvantages of these mixtures were published prior to 1940 (Pilz, 1911, Lipman, 1912, Warburton, 1915, Etheridge and Helm, 1924, Morrish, 1934). Legume-maize mixtures were the subject of several reviews (Fred, Baldwin, and McCoy, 1932, Nicol, 1934, 1936, Brown, 1935; Wilson, 1940) during the period in which they were considered practical. Mix-

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tures of cereals still occupied 2.5 million hectares in the temperate zone in 1973 (FAO, 1974) and have received sporadic attention up to the present (Jensen, 1952; de Wit, 1960, 1961; Baeumer and de Wit, 1968)

While modern practices have probably largely eliminated the benefits of crop mixtures in the temperate zone, crop mixtures still offer considerable advantages in the tropical zone, where use of mechanization and agricultural chemicals remain low. The widespread use of crop mixtures in nonmechanized agriculture was noted by earlier authors but critical investigation of whether their use was beneficial only began after World War II (Aiyer, 1949, Evans, 1960, Anthony and Willimott, 1957, Pillai et al., 1957, Iso, 1954)

With establishment of international institutes of agricultural research in the 1960s, there has been widespread recognition that the ability to expand world food supplies would depend on increasing food production by small farmers in the tropics, most of whom were growing crop mixtures (Miracle, 1967, IRRI, 1973, 1974, 1975; Francis, Flor, and Temple, 1976). As a result, the number of investigations on the subject has greatly increased during the past decade (American Society of Agronomy, 1976) and an analysis and summary of the findings seemed worthwhile at this time. It is my hope that a review might establish some generalizations about crop mixtures as well as serve as a guide to those planning to study the topic further

**Definition of terms**

Before considering the literature, it will be necessary to define some terms used by various authors since their use is by no means consistent. The practice of growing two or more useful plants simultaneously on the same area is variously described as multiple cropping, intercropping, interplanting, and interculture. However, these terms have been defined specifically by certain authors (Harwood, 1975, Ruthenberg, 1971; Dalrymple, 1971; Andrews and Kassam, 1976) as described below

***Multiple cropping*** — Growing more than one crop on the same land in one year (Dalrymple, 1971; Harwood, 1975, Andrews and Kassam, 1976).

***Maximum cropping*** — Attainment of the highest possible production per unit area per unit time without regard to cost or net return (Harwood, 1975).

***Mixed cropping*** — Two or more crops grown simultaneously and intermingled with no row arrangement (Ruthenberg, 1971, Harwood, 1975)

***Intercropping*** — Two or more crops grown simultaneously in alternate rows in the same area (Ruthenberg, 1971). A more general definition is "growing two or more crops simultaneously on the same field in a year" (Andrews and Kassam, 1976).

***Relay planting*** — The maturing annual crop interplanted with seedlings or seeds of the following crop (Ruthenberg, 1971). According to Harwood (1975), if the flowering period

| | |
|---|---|
| | of one crop overlaps that of the second crop in the field the combination becomes intercropping or, in the phrase of Andrews and Kassam (1976), relay intercropping |
| ***Interplanting*** | Long-term annual or biennial crops interplanted with short-term annual crops during early stages of plant development (Ruthenberg, 1971) |
| ***Interculture*** | Arable crops grown under perennial crops (Ruthenberg, 1971) |

Unfortunately, very few investigators have adhered to these definitions. Thus, one may encounter a paper entitled "The agronomic significance of mixed cropping. I. Maize interplanted with cowpeas" (Hazel, 1974), which concerns intercropping as defined above. Furthermore, none of the definitions listed here contains a general term for situations in which "two or more useful plants are grown simultaneously in the same area" (Ruthenberg, 1971). For the general case, which would include ***mixed cropping*** or ***mixed intercropping***, ***intercropping***, and ***interculture*** as well as those phases of ***interplanting*** and ***relay planting*** where more than one crop is growing, this author proposes the term, polyculture. Already used by some researchers, it distinguishes all of these situations from monoculture and indicates that an area is being used for more than one crop at a time. The term *policultivos* has been used in Spanish to contrast with *monocultivos*, crops grown in pure stands (Sorra et al., 1975). In earlier American literature, one encounters the terms ***crop mixtures*** (Warburton, 1915, Morrish, 1934, Klages, 1935) and ***crop associations*** (Lipman, 1912, Elliott, Hills, and Harris, 1915, Nicol, 1934). While somewhat lacking in precision, such terms are probably less awkward and more readily understood than their counterparts. I will seek to use more specific terms here as they were defined above, and reserve either polyculture, crop mixtures, or crop associations for the general case.

The primary focus of this study will be on polyculture of annual crops; the literature on perennial and pasture crops will be drawn upon only when necessary to provide evidence not available in articles on polyculture. There are several reasons for this limitation. First, the extensive literature on pastures has been reviewed adequately in recent years (Donald, 1963). Second, principles obtained from the study of perennial or pasture species are probably not applicable to annual crops, which are often biologically completely dissimilar. Finally, primary emphasis is being placed on food and cash crops raised by smallholders, which are almost exclusively annuals.

## Occurrence of Polyculture

While most investigators and casual observers can testify to the ubiquity of polyculture in the tropics (Miracle, 1967, Webster and Wilson, 1966), actual measurements of its extent and importance in relation to monoculture are hard to find. Estimates for various countries are included in Volume 5 of the World

Census of Agriculture (FAO, 1973) and are also presented in table 1. Acreage measurements for each crop given in the Brazilian agricultural census for 1950 are summarized for certain crops in table 2. It can be shown from the Brazilian data that polyculture is, or at least was in 1950, much more common in the northern and northeastern parts of the country where farms tend to be small and nonmechanized than in the southern and southeastern parts where larger mechanized farms predominate.[1] This author was unable to determine whether similar surveys were taken since 1950.

Other census data are given by FAO (1966, 1974) for cereal mixtures. Three million hectares of mixed grains were planted each year from 1948-52, with the number decreasing to 2.5 million hectares in 1973 (FAO, 1974). Two-thirds of this area was in Europe, two-ninths in Canada, and one-ninth in Turkey.

The only other modern measurement of the extent of polyculture over a large area is given by Chih-Kung (1975) who states that in 1970 sweet potatoes were relayed into rice on 46,038 hectares in Taiwan, or about 5 percent of the cropland, but this number dropped to 27,890 hectares by 1973.

Some measurements of the extent of soybean-maize mixtures were taken in the United States prior to 1930. Thatcher (1925) reported that 57 percent of the soybean acreage in Ohio was grown in mixtures with maize in 1923, but only 40 percent in 1924. Hackleman et al. (1928) gave figures showing that nearly 60 percent of the 673,998 acres of soybeans in Illinois (1923-1926 average) consisted of soybean-maize mixtures.

Other measurements of polyculture are probably little more than educated guesses or are based on surveys taken over a very limited area. Francis et al. (1976) state that 98 percent of cowpeas in Africa and more than 60 percent of maize and beans in Latin America are in crop mixtures. A survey of 300 farms in five zones of Colombia indicates that 60 percent of the farms and 70 percent of the area are in monoculture manioc. Surveys reported by Baker and Norman (1975) show that 93 percent of the Sokoto area (353.1 ha surveyed), 83 percent of the Zaria area (360.5 ha surveyed), and 53 percent of the Omu-Aran area (84.3 ha surveyed) in northern Nigeria are planted to crop mixtures. A survey of 220 hectares in the groundnut growing area of Senegal showed that one-third of the area was planted to crop mixtures (Schilling, 1965).

Where actual measurements have been taken it would appear that polyculture is probably less significant than indicated in general estimates. Usually, mono-

[1]Data calculated from 1970 Brazilian agricultural census (IBGE, 1974).

| Region | Number of farms with tractors | Percent of farms with tractors | Mean area (ha) per farm in annual crops |
|---|---|---|---|
| North | 735 | 0.3 | 2.34 |
| Northeast | 4,158 | 0.4 | 3.26 |
| Southeast | 55,055 | 5.9 | 10.11 |
| South | 42,654 | 3.3 | 8.38 |
| Central west | 7,455 | 2.9 | 10.38 |

culture systems are more productive since they are often mechanized and less reliant on human labor. Hence, in most countries the larger part of total production of most crops probably comes from pure stands. Although most small farmers, who generally represent the greater part of the farming population in developing countries, probably practice polyculture, their total production and cultivated acreage may represent only a small part of a country's overall totals.

*Table 1.* **Extent of polyculture in selected countries as derived from 1960 World Census of Agriculture (FAO, 1973)***

| Country | Observation made by FAO about polyculture |
|---|---|
| Dominican Republic | 40% or more maize grown with other crops |
| El Salvador | Maize and beans; maize and sorghum; maize and other crops in mixtures |
| Jamaica | 50% of maize mixed with other crops |
| Mexico | 20% of maize mixed with other crops |
| Brazil | 6–11% of rice and maize mixed with other crops |
| Paraguay | 33% of beans; 10% of sweet potatoes; 10% of maize mixed with other crops |
| Venezuela | 16% of rice; 35% of maize; 20% of beans; 20% of cassava; 50% of cotton mixed with other crops |
| India | 5–6% of rice and 70–80% of other crops grown in mixtures |
| Indonesia | Maize and rice grown in mixtures |
| Pakistan | Wheat, barley, cotton, and oil seeds frequently grown in mixture |
| Central African Republic | 25% of cotton; 33% of coffee; 20% of cassava grown in mixtures |
| Libya | Considerable part of area in maize and beans grown in mixtures |
| Senegal | 25% of area in groundnuts and millet grown in mixtures |
| Southern Rhodesia | 50% of area planted in mixed crops |

* These are the only countries about which such observations were made by FAO.

*Table 2.* **Extent of polyculture of selected Brazilian crops**

| Crop | Production | | | |
|---|---|---|---|---|
| | Country as a whole | | Northeast | |
| | Monoculture | Polyculture | Monoculture | Polyculture |
| | percent | | | |
| Cotton | 81 | 19 | 64 | 36 |
| Peanuts | 90 | 10 | 77 | 23 |
| Rice | 82 | 18 | 32 | 68 |
| Beans | 40 | 60 | 12 | 88 |
| Manioc | 81 | 19 | 66 | 34 |
| Maize | 64 | 36 | 10 | 90 |

Source: 1950 Agricultural Census of Brazil.

The 1950 Brazilian data illustrate this point. For the country as a whole only 18 percent of the rice, 19 percent of the manioc, and 36 percent of the maize came from areas in polyculture. Yet in the Bragantina region of the Brazilian Amazon, an area of small subsistence farms, the same census showed that 99 percent of the maize and rice and 97 percent of the manioc came from mixed stands (Penteado, 1967).

## Concepts and Methodology of Polyculture Research

Research with polyculture had focused primarily on whether the practice is more profitable or beneficial than growing crops as monocultures. But such inquiry is complicated by the fact that the crops involved rarely are of equivalent value to the farmer and the consumer, and some more appropriate method must be devised for comparing the two systems. Secondly, population, spacing, and arrangement of crops may have considerable effect on the results obtained. Most researchers have addressed themselves to these problems and have come up with a considerable number of approaches, which we will attempt to summarize here.

### Comparing monoculture and polyculture

***Methods of comparing crop yields.*** Let us begin with an example. On a hectare of land, one can produce either 1000 kg of crop A in pure stand, or 500 kg of crop B in pure stand, or, in a mixture, 700 kg of crop A and 500 kg of crop B. Which is preferable? The simplest method is to take the means of the pure-stand yields and compare them to the total yield of the mixture (Donald, 1963), yet it will be immediately objected that the average of 1000 kg maize and 500 kg beans is a completely meaningless concept. The mean might have some validity where two crops are similar and can be used in the same way — for example, a mixture of small grains used for feed. The mean of pure-stand yields is commonly used for evaluating polyculture in pasture (Donald, 1963) and in mixed cereal production (Zavitz, 1927, Bussell, 1937, Jensen, 1952).

However, the inadequacy of this method was recognized by the earliest researchers (Pilz, 1911, Lipman, 1912). They suggested that the yield-per-unit-area of two crops in a mixture be compared with the production of each crop if it were planted in pure stands covering half the area. Thus, in our example, the 700 kg of crop A in the mixture should be compared with 500 kg, the production of a half-hectare of a pure stand of crop A, and the 300 kg of crop B in the mixture to 250 kg, the production of a half-hectare of a pure stand of crop B. This method was recommended by Evans (1960) who criticized investigators who did not plant pure stands of both crops and make the evaluation. Frequently, investigators planted pure stands of only one of the crops because they were only interested in its particular yield. This was the case with research on maize–soybean mixtures (McClelland, 1928; Hackleman et al., 1928, Wiggans, 1935) and on combinations in which only one crop was grown for cash (Anthony and Willimott,

1957; Divekar, 1960, Grimes, 1962). Despite criticisms by Morrish (1934) and Willey and Osiru (1972) that there is no reason to assume that two crops in a mixture are planted in equal amounts, polyculture was most frequently evaluated by comparing it with the yields of half-hectare pure stands (Andrews, 1972). This began to change in 1973 with the advent of new methods (IRRI, 1974, 1975, Hazel, 1974, Pinchinat and Oelsligle, 1974).

In contrast to the above procedure, Morrish (1934) suggested taking the yield of each crop in the mixture, dividing it by the pure-stand yield, and summing the two fractions. The total yield of the mixture is then divided by this sum, which gives the yield that would result from one hectare if the two crops were grown separately and then combined in the same proportion as in the mixture. The total yield is then divided by this quantity to obtain the percentage benefit due to the mixture. Going back to our example, the mixture was 0.7 crop A and 0.3 crop B. Dividing the yields in the mixture by pure-stand yields, we obtain 0.7 for crop A and 0.6 for crop B. The sum is 1.3. Dividing the total yield of the mixture, 1000 kg, by this number, we obtain 769.2, which, Morrish asserts, would be the yield from one hectare if the crops were grown separately and combined in the same proportion as the mixture. Polyculture, then, would give a 30 percent increase in yields. This procedure does not differ much, as we shall see, from calculating the Land Equivalent Ratio except that Morrish unnecessarily divides the total yield of the mixture by 1.3, a step that already assumes polyculture was responsible for a 30 percent benefit. Morrish is, however, considering the situation where the farmer might blend two species grown separately in order to get a mixture of the same nutritional value.

Willey and Osiru (1972) raise the same objection as Morrish but proceed differently. They say it would take 0.7 ha to produce 700 kg of crop A in pure stand and 0.6 ha to produce 300 kg of crop B. Thus the mixture is comparable to a hectare planted 54 percent ($\frac{0.7}{1.3}$) to crop A or 46 percent ($\frac{0.6}{1.3}$) to crop B. The pure-stand production of a hectare so divided would be 540 kg of crop A and 230 kg of crop B, decidedly inferior to the mixture. The author was unable to find any investigators besides Morrish (1934) and Willey and Osiru (1972) using these methods.

A somewhat less cumbersome procedure was used by Niqueux (1959), formulated by van den Bergh (1968), and then reintroduced by IRRI (1974). Commonly used by many investigators since then (Sorta et al., 1975, Francis et al., 1976, Sastrawinata, 1976, Crookston, 1976), it consists of dividing the yield of each crop in the mixture by its yield in pure stand to obtain what van den Bergh called the relative yield. These can then be summed to obtain the Relative Yield Total (RYT), which is also the amount of land needed to produce the same quantity of the two crops obtained in the mixture through the use of pure stands (Niqueux). It can be seen that when this figure is greater than 1, polyculture can be said to be beneficial. The Relative Yield Total was called the Land Equivalent Ratio (LER) by IRRI (1974) or, in Spanish, Uso Equivalente de Tierra (UET) (Sorta et al., 1975). Now the most frequently encountered term in the literature, the LER has the advantage of being adaptable for mixtures of more than two crops. However, neither this nor the other methods give any measure of factors such as

the economic returns, which might be the basis for deciding whether to grow a monoculture or a polyculture.

***Crop competitive methods.*** Other methods of determining whether polyculture is beneficial have been derived from studies of plant competition. De Wit (1960) based his model on the assumption that two competing species would divide a constant environment, which he called *space* for the sake of convenience. Thus if $A_1$ is the space available for species 1, and $A_2$ is the space available for species 2; and $Z_1$ and $Z_2$ are the number of seeds sown of species 1 and 2, respectively; these quantities will be related by two coefficients $b_1$ and $b_2$ as follows:

$$A_1 : A_2 = b_1 Z_1 : b_2 Z_2 \quad \text{or} \quad \frac{A_1}{A_2} = \frac{b_1 Z_1}{b_2 Z_2} \quad . \tag{I}$$

Since environment is constant,

$$A_1 + A_2 = 1 \quad ; \tag{II}$$

and since only species 1 and 2 are sown,

$$\frac{Z_1}{Z_1 + Z_2} + \frac{Z_2}{Z_1 + Z_2} = 1 \quad . \tag{III}$$

The quantities $\frac{Z_1}{Z_1 + Z_2}$ and $\frac{Z_2}{Z_1 + Z_2}$ are called the relative seed frequencies $z_1$ and $z_2$ of species 1 and 2 and $z_1 + z_2 = 1$. DeWit terms the quality $\frac{b_1}{b_2}$ the relative crowding coefficient $k_{12}$ of species 1 with respect to species 2. Similarly, $\frac{b_2}{b_1}$ or $k_{21}$ is the relative crowding coefficient of species 2 with respect to species 1.

The monoculture yields $M_1$ and $M_2$ and the polyculture yields $O_1$ and $O_2$ of species 1 and 2 are related by the following equations:

$$O_1 = b_1 Z_1 \, [b_1 Z_1 + b_2 Z_2]^{-1} M_1 ;$$
$$O_2 = b_2 Z_2 \, [b_1 Z_1 + b_2 Z_2]^{-1} M_2 ,$$

or, using $z_1$, $z_2$, and $k_{12}$,

$$O_1 = \frac{k_{12} z_1}{k_{12} z_1 + z_2} \text{ and } O_2 = \frac{z_2 M_2}{k_{12} z_1 + z_2} \quad . \tag{V}$$

Another quantity defined by deWit (1960) was the relative reproduction rate, $\alpha$, of the two species defined as:

$$\alpha = \frac{\text{The ratio of the proportion of species 1 in the harvested mixture to the proportion of species 1 in the sown mixture}}{\text{The ratio of the proportion of species 2 in the harvested mixture to the proportion of species 2 in the sown mixture}} \quad ;$$

or using the terms defined above,

$$\alpha = \frac{O_1 Z_1^{1}}{O_2 Z_2} = k_{12} \frac{M_1}{M_2} \qquad (11)$$

From these equations, it was possible to show that since the highest yield of each species is proportional to the relative space it occupies, each species maximum yield would occur in pure stand when it had the entire space available to it. De Wit stated that in certain cases, with oat and barley mixtures, polyculture would be beneficial. These were:

1. The thousand kernel weight of oats was greater when intercropped with barley because the earlier maturing barley provided less competition to the oats at later stages of development.
2. Oats reduced lodging in barley.
3. In a field of variable pH, sowing a mixture would ensure that barley and oats would be located in areas of high and low pH, respectively, where each was better adapted.
4. If one species were eliminated by disease, the second species would have a proportionately larger share of the environment than expected from its share of the seeds sown.

In the latter case, de Wit stated that the effect would be to increase the relative crowding coefficient of the resistant species. It has been pointed out that de Wit's model does not hold when the space shared by the two crops in polyculture is not the same as that available to monocultures, a reason frequently cited for the increased production often obtained with polyculture. Kasyer (1911), Aiyer (1949), Mitchandi and Mishra (1957), Andrews (1972), Willey and Osiru (1972), Shelton and Humphreys (1975) and Harris (1970) have stated that polyculture offers advantages if the product of the relative crowding coefficients is greater than unity.

De Wit (1960, 1961) expanded his model to account for the cases where it did not hold. He recognized three situations:

1. The relative reproduction rate, $\alpha = 1$, and the proportion of species harvested is the same as that seeded. In this case, the log of the ratio of the species in the harvested mixture is plotted against that of the species in the seeded mixture and a straight line of slope +1 passing through the origin will be obtained.
2. $\alpha \neq 1$ because one species has a competitive advantage over the other although they are still competing for the same space. In this case, the plot of the ratios of the harvested against the seeded mixtures is a straight line, not passing through the origin. This situation would occur with two species, with different growth curves, growing simultaneously.
3. $\alpha \neq 1$ because the species together exploit a larger or smaller share of the environment than either species grown alone. If one species profits by the presence of the other (for example, in a legume–cereal association) or if the growth curves are nonsynchronous, so that the two species are not competing for the same space, the plot of the ratios of the harvested and seeded mixtures will have a slope of less than +1 and will not pass through the origin. If one

species has a harmful effect on the other, the slope of the ratios will be greater than one and not pass through the origin. In both cases, the curves tend to be S-shaped rather than straight lines.

Donald (1963) attempted to identify situations where polyculture was beneficial by comparing the behavior of individual plants in mixtures with pure stands. He proposed a "competition index" (CI) developed by C. A. MacIntyre and defined as

$$\frac{(N'_A - N_A)\,(N'_B - N_B)}{N_A \cdot N_B} \quad .$$

where $N_A$ plants of species A compete with $N_B$ plants of species B on a unit area. The yield per plant of species A in the mixture equals the yield per plant of $N'_A$ plants grown in pure stand and the yield per plant of species B in the mixture equals the yield per plant of $N'_B$ plants grown in pure stand. A competition index of less than unity would indicate a beneficial association while an index of more than unity would indicate a harmful one. To determine $N'_A$ and $N'_B$ it would be necessary to grow both species at a range of plant populations to construct a curve relating density to yield per plant (Donald, 1963). In spite of the difficulty that such a procedure entails and of the fact that it was designed for use with pasture species where the relationship of yield to plant density is less complex, the competition index has been calculated by several authors (Willey and Osiru, 1972, Osiru and Willey, 1972, Reddy and Chatterjee, 1973, Hazel, 1974) for mixtures of annual crops. However, these authors do not appear to have constructed density-yield curves over a great number of plant populations. Furthermore, they obtain competition index values of less than unity where polyculture did not appear to be beneficial by other determinations, casting some doubt on their use of the calculation and on the application of the method to mixtures of annual crops. However, the competition index does emphasize the importance of having comparable populations in pure and mixed stands when determining the benefits of polyculture.

***Use of common parameters.*** A way of avoiding the difficulties involved in comparing the yields of two inherently different crops is to measure the production of a parameter common to the two species, such as dry matter, total digestible nutrients, nitrogen, crude protein, kilocalories, or other particular constituents. Another method of obtaining comparable quantities is to convert the production to cash value or calculate returns per unit of labor. Such methods are common in the literature prior to 1940 when investigators were primarily concerned with production of TDN and crude protein or total nitrogen recovery of mixtures and pure stands (Noble and Richter, 1902, Lipman, 1912, Etheridge and Helm, 1924; Thatcher, 1925; Hackleman et al, 1928). While such methods avoid comparison of noncomparable quantities, the parameter chosen will depend on use of the production. Thus a cash farmer may have little interest in the dry matter or protein production of two different cropping systems. A problem with the determination of cash values is that they tend to vary and a cropping system that may be profitable under one set of prices may no longer be so if prices change.

***Production per unit time.*** The two or more crops involved in polyculture rarely occupy an area for the same length of time. Thus, a comparison of beans and manioc in pure and mixed stands would involve a comparison of a three-month monoculture, a ten-month monoculture, and a ten-month polyculture. One solution to this problem is to express yields per unit area, per unit time, as has been done by some authors (Pillai et al., 1957; Andrews, 1972; Dalal, 1971). However, such a comparison generally favors the short-cycle crops, which are generally grown when conditions are most favorable; their production levels would probably be less if they were grown at a different time of the year. Thus, cropping systems should be compared over the same time period so that they are all subjected to the same conditions. Such an approach has been taken recently by several investigators (IRRI, 1973, 1974, 1975; Sorta et al., 1975; Sastrawinata, 1976) and gives a more realistic assessment of alternative land uses.

### Crop arrangement

When polyculture is practiced by small-scale cultivators without animal or mechanical power, crops are usually planted in a relatively random fashion (Miracle, 1967; Webster and Wilson, 1966; Ruthenberg, 1971; Igbozurike, 1971), although more regular patterns are sometimes encountered. Largely because it is impossible to imitate the random patterns[2] used in nonmechanized farming, selecting a planting pattern to use in experiments with polyculture presents a considerable problem, although this has been attempted in some experiments (Norman, Bunyet, and Goddard, 1970). While more regular planting patterns ease many cultural operations (Syarifuddin, Soeharsono, and MacIntosh, 1975) and perhaps would sometimes enable mechanization (Andrews, 1972; Willey and Osiru, 1972), polyculture in a regular pattern may be completely irrelevant to the small farmer's situation and may entail a loss of benefits, such as prevention or spread of disease and making use of environmental microvariability. Another factor contributing to the artificiality of polyculture experiments is that they usually involve only two crops while most farmers use mixtures of more than two crops.

The only experiments with regular planting patterns that actually reflected farmers' practices were conducted with soybean and maize mixtures in the eastern United States prior to 1940, when farmers regularly planted in hills or alternate or cross rows. Indeed, the relative benefits of this type of polyculture was the subject of a considerable amount of research in this period (Kinney and Roberts, 1921; Etheridge and Helm, 1924; Ayres, 1925; Hackleman et al., 1928; McClelland, 1928; Odland, 1930; Brown, 1935). Maize yields were often found to be least reduced by planting the soybeans in hills in the same row as maize (Kinney and Roberts, 1921; Ayres, 1925; Hackleman et al., 1928; Brown, 1935). Soybeans, on the other hand, appeared to do best when drilled between the rows of maize (Kinney and Roberts, 1921; Etheridge and Helm, 1924; Hackleman et al., 1928; Brown, 1935) although Ayres (1925) did not find this to be always

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[2] *The patterns may be less random than they appear; Schilling (1965) and Miracle (1967) have suggested that farmers match crops with the microvariability of the field.*

the case. Hence, the method of planting would to some degree determine the composition of the mixture. Most authors (Etheridge and Helm, 1924, McClelland, 1928; Odland, 1930; Brown, 1935) concluded by recommending planting maize and soybeans in alternate rows, because it would both increase protein production by fostering better soybean growth and make operations easier, but Ayres (1925) and Kinney and Roberts (1921) recommended alternate hills because they result in smaller reductions in maize yields.

Subsequent investigations have generally shown alternate rows of "intercropping," to be superior to mixed cropping with pigeon peas, which tends to shade the associated crops excessively (Gooding, 1963). Intercropping was also found to be preferable for pea-barley, pea-wheat, and pea-oat mixtures although the peas themselves do better with mixed cropping (Shannon and Lawson, 1975), for cropping systems involving maize, rice, sorghum, groundnuts, rice bean, and manioc, where use of alternate rows reduced labor requirements and hence returns (Syarifuddin et al., 1975), and for maize when associated with various legumes (IITA, 1975). Minchandi and Misra (1957) found that either intercropping or cross seeding of wheat with lentils or peas was superior to planting the legumes within the wheat rows or to alternating double rows with wheat. The most extensive evidence of the superiority of intercropping over mixed cropping was presented by Dalal (1974), who found that the yield, total dry matter, K and N content of maize; and the dry matter production, Ca, Mg, and N content of pigeon peas were significantly higher when they were intercropped than when planted in the same row. He also found that soil nitrogen ($NH_4$ and $NO_3^-$) levels were higher with intercropping than mixed cropping. He attributed this to the possibility that maize roots, in closer contact with the pigeon pea roots in mixed cropping, inhibited nitrogen fixation, because when tested in this situation pigeon pea roots had more ineffective nodules (Dalal, 1974).

Harper (1961) and Donald (1963) presented evidence that planting patterns did not affect yields. Harper's experiments were done in pots with two bromegrass species, however, and the evidence cited by Donald was obtained with pure stands of maize and wheat. Nonetheless, Evans (1960) found no difference between maize or groundnut yields when grown in alternate rows or uniformly mixed. Agboola and Fayemi (1971) could find no significant differences in maize and legume yields with or without fertilizer in four different cropping seasons when maize was grown in the same or alternate rows with greengram, calopogon, or cowpeas. Francis et al. (1976) found significantly lower bean yields but no effect on maize yields when maize and beans were planted in alternate rows rather than in the same row at a bean population of 110,000 plants per hectare. However, none of these authors considered as many parameters as did Dalal (1974).

It must therefore be concluded that intercropping will produce higher yields than mixed cropping. Although intercropping experiments are easier to conduct and their results may be applicable to higher levels of management (Enyi, 1973; Willey and Osiru, 1972; Andrews, 1972), such experiments have little bearing on polyculture as it is actually practiced.

Intercropping by alternating single rows will produce maximum contact of the

two species, which seemed to be very beneficial for maize–rice mixtures, especially at low maize populations. However, with maize–groundnut mixtures, yields stayed the same at various row orientations, so long as the same populations were maintained (IRRI, 1975). HI A (1975) reported that maize yielded significantly more when planted in alternate rows with various legumes (pole or bush lima beans, yam beans, dwarf pigeon peas) than when planted in alternating four-row plots. Chao (1975) reported greater returns principally due to higher maize yields, when 1 row of maize was planted for every 5 rows of soybeans than when 2 rows of maize alternated with 10 rows of soybeans. Andrews (1972) also found intercropping effects to be reduced as the species became more and more separated. Intercropping millet and sorghum was less beneficial in alternating double rows than single ones. Planting one row of sorghum for two of millet increased millet yield but decreased sorghum yield. Patil and Koladdi (1960) found that cotton yields decreased and groundnut yields increased as the number of rows of groundnuts between cotton rows became greater, but overall returns were greatest when one row of cotton alternated with one row of groundnuts. In general, therefore, planting in alternating single rows has given greater returns than other intercropping patterns. The only exception appears to be in the research of Singh, Negi and Tripathi (1973), who found slightly higher yields of maize and soybeans and of sorghum and soybeans when planted in alternating double rather than single rows.

**Plant populations**

The plant population used in a study of polyculture affects both the results obtained and validity of comparing them to pure stands (Donald, 1963). If the populations used in pure stands are not optimal, polyculture might appear to be of greater benefit than it actually is. Even if the investigators knew the pure-stand populations that give maximum yields, they would have no way of knowing what populations to use in polyculture. Many investigators, aware of this difficulty, combine two species in different proportions or use a range of plant populations in polyculture experiments (Evans, 1960; Willey and Osiru, 1972; Reddy and Chatterjee, 1973; IRRI, 1974).

The extensive experiments carried out by the International Rice Research Institute have provided some insight into the effect of plant populations on polyculture (IRRI, 1973, 1974, 1975). With either maize and soybeans or sweet corn and mungbeans, maize yields grew larger and legume yields smaller as maize population was increased. However, curves relating density to yield had practically the same shape for maize in monoculture or in polyculture with legumes (IRRI, 1973). On the other hand, benefits of a sweet corn–mungbean association remained remarkably constant at a particular management level when sweet corn population varied and mung population remained constant. However, with a sweet corn–sweet potato mixture, maize population played a greater role in making poiyculture beneficial, probably because the growth cycles of the two species overlapped less than sweet corn and mungbeans (IRRI, 1974). At a constant population of maize and groundnuts, varying row arrangements had little effect on yields (IRRI, 1975). The rather obvious conclusion seems to be that

plant population becomes most critical when competition between two species is greatest and that high populations will intensify competition. Norman (1971) and Lepitz (1971) have generally found that increasing plant populations increases the benefits from polyculture, but both of these authors also used a higher level than most farmers practice, and such results would be expected under those conditions. Whether competition from a different species is more beneficial than competition from the same species will be discussed more fully later.

Haizel (1971) has described three methods of combining plant populations in polyculture: the additive method, where each species is planted at the same population as in pure stands, the substitutive method, where the total plant population in pure stands and mixtures is the same; and the replacement series, where a certain number of individuals of one species is regarded as being equivalent to a single individual of the other species and this relationship is used to determine the populations in polyculture. Serious objections can be raised to each of these methods, however. The additive method will probably result in too high a population in the crop mixture (Donald, 1963), it is unlikely that both species will be at optimal populations in pure stands as in the substitutive methods, and the decision of how many individuals of one species are equivalent to one individual of another is completely arbitrary without sufficient experimentation to calculate the competition index (Donald, 1963). Nonetheless, the additive method has been used by Agboola and Fayemi (1971) and by Evans and Sreedharan (1962); the substitutive method by Anthony and Willmott (1957), Grimes (1962), and Dalal (1974); while the replacement series was used by Willey and Osiru (1972) and Osiru and Willey (1972).

The methods enumerated by Haizel (1974) by no means included all those used by investigators of polyculture. Some appear to combine species in a completely arbitrary manner while others use what would appear to be a reasonable plant population for the mixture. When the effect of polyculture on only one of the species in the mixture is of concern, as was often the case with older studies of maize–soybean mixtures, the population of one species remains the same in both monoculture and polyculture while pure stands of the associated species are not grown. Andrews (1972) reduces the population of both species in the mixture but also includes as treatments pure stands grown at the reduced populations. Thus, he feels that the effects of competition and population can be distinguished.

The literature cannot be said to provide much guidance on selecting the correct plant populations beyond indicating that the choice can significantly affect the results. The appropriate crop densities to use probably depend upon the species and management levels involved in the experiments.

## Advantages and Disadvantages of Polyculture

Many claims have been made for polyculture (Aiyer, 1949, Andrews, 1972; Willey and Osiru, 1972) while others have regarded it as a traditional practice that has no place in modern agriculture (Grimes, 1962; Noll and Lewis, 1921;

Donald, 1963). In this section, an attempt will be made to review the experimental evidence objectively for such factors as crop yields, productivity of various plant constituents, economic return, yield stability, social benefits, pest control, and fertilizer efficiency.

### Crop yields

As has been pointed out, evaluation of the effect of polyculture on crop yields is complicated by the difficulty in comparing yields of two different crops. We will discuss each method of evaluating yields that was enumerated earlier.

***Direct comparison with pure-stand yields.*** In general, yields of each species in polyculture are reduced in comparison to pure stands (Donald, 1963; Trenbath, 1974). Sometimes, however, the yield of only one species was considered of primary importance and it was increased, or at least not significantly decreased, by being grown with another crop. Such a situation is most frequently observed when the intercrop is a legume and the soil is of low fertility or has been exhausted by several years of continuous cropping (Brown, 1935; Viegas, Freire, and Fraga, 1960; Agboola and Fayemi, 1972a).

Very few polyculture experiments have been repeated in the same area for several years. Brown (1935), however, conducted an experiment with maize in pure stand and interplanted soybeans on a Denham silt loam in Louisiana for five years (1925–1929). Fertilizer (7 lbs/acre of N as $NaNO_3$, 48 lbs/acre of $P_2O_5$ as superphosphate, 30 lbs/acre of $K_2O$ as KCl) was applied each year. In the first two years, maize yields were higher in the pure-stand plots, but in the third, fourth, and fifth years, maize yields were considerably higher in the plots in which it was intercropped with soybeans.

Agboola and Fayemi (1971, 1972 a & b) found yields of maize increased when it was intercropped with any of three different legumes (cowpeas, calapogon, and greengram) in the absence of fertilization. The soils, Iwo and Ibadan series, in the experiments belong to the broad group of Ferruginous Tropical Soils and are derived from granitic rocks and gneisses. They are well-drained, brown to greyish brown, fairly clayey, and contain considerable coarse-textured material. Predictably, pure-stand maize did as well as that intercropped with legumes when fertilized with 45, 90, or 135 lbs of N (Agboola and Fayemi, 1972 a), or with a complete fertilizer consisting of 50 lb/acre of N as ammonium sulfate, 9 lb/acre of P as simple superphosphate, and 50 lb/acre of K as KCl (Agboola and Fayemi, 1971). Maize yields were higher with greengram than with other legumes. In this study involving a total of four crops, the effect of interplanting legumes increased with succeeding crops, with maize yields averaging 500–1000 lbs/acre more with intercropping in the final crop.

A long-term experiment with maize grown in pure stands and intercropped with velvetbeans was carried out at five sites in São Paulo State, Brazil (Viegas et al., 1960). At three sites, where the experiment was run for ten years, legume interplanting significantly increased maize yields. At two others, where the experiment was carried on for only four years, no response to legume intercropping was registered; but the soil at these sites was of lower fertility, and low P might have restricted velvetbean development.

Even where continuous cropping experiments were not performed, maize yields have been increased by association with legumes. Summarizing several experiments in Arkansas, McClelland (1928) found that maize yields were increased by drilling cowpeas between the maize rows when the maize was 24″ high or drilling soybeans between them when the maize was 6–12″ high. Broadcasting legumes reduced maize yields by less than 3 percent from pure-stand yields; while wider rows (3240 maize plants per acre) reduced maize yields by 20 percent. On a Typic Dystandept, fine, isohyperthermic in Costa Rica (Pinchinat and Oelshigle, 1974), yields of a tall-statured maize (Eladio Hernandez) were always greater than for pure stands. With a shorter maize and a taller soybean, maize yields were significantly reduced by soybeans in a dry period but were not in a subsequent planting. Singh et al. (1973) consistently found that, when intercropped with soybeans, yields of maize (but not of sorghum) were higher than in pure stands. In a trial carried out for three years on a reddish upland soil (pH 5.6; N 0.0598%) in Kanke, India, maize yields did not differ when grown in pure stands or associated with various legumes. IITA (1975) also reported no significant differences or increase in maize yields, intercropped with various legumes (African vambeans, bush and pole limas, soybeans). In fact, only intercropping maize with climbing cowpeas significantly decreased its yields.

In conclusion, maize yields in several experiments have been increased or else significantly reduced by intercropping with a legume. An increase has been most commonly reported where a nitrogen deficiency probably was induced by several years of continuous cropping. However, there have been many reports of maize yields being decreased in simultaneous polyculture with a legume. Work at IRRI (1973) showed yield increases of polycultured maize over pure stands only when it was intercropped with mungbeans and not weeded. Soybeans had no effect on maize yields, but in other cases, yields decreased considerably when it was intercropped with various legumes (IRRI, 1973, 1974, 1975). Similarly, many researchers (Lipman, 1912; Noll and Lewis, 1921; Kinney and Roberts, 1921; Ftheridge and Helm, 1924; Ayres, 1925; Thatcher, 1925; Mooers 1927; Hackleman et al., 1928; Odland, 1930; and Wiggans, 1935) reported no increases in the yields of maize associated with soybeans. However, none of these were continuous cropping experiments, and it should be clear that experimental conditions have a considerable effect on results. Thus, Francis et al. (1976) found a significant decrease in maize yields when bush beans were planted at the same time or later than maize but not when intercropped beans were planted 5–15 days before maize. Maize yields were actually increased, but not significantly, by planting a dwarf maize with a different bean variety. Finally, in a third experiment, the yield of normal maize (ICA 207) was significantly increased by intercropping with bush or climbing beans, while the yield of brachytic maize was not significantly affected by either bean variety (Francis et al., 1976).

This author was able to find four cases in the literature on crops other than maize showing no significant difference in yield when grown in monoculture or in polyculture with a legume. Mirchandi and Misra (1957) found that wheat yields were almost always slightly increased by polyculture with peas and lentils at different populations and crop arrangements near New Delhi, India. On an

upland loam soil, poor in N and P, polyculture with groundnuts did not significantly affect cotton yields; although P. mungo, maize, rice, sweet potato, and *Eleusine coracana* all significantly reduced them (Varma and Subba Rao Kenke, 1969). *Crotolaria juncea* did not significantly lower the yield of elephant yam (*Amorphophallus campanulatus*, Blume) on two sites in Poona, India, while other crops, including some legumes, had a negative effect (Koregave, 1964). Finally, on a sandy loam soil, poor in N with pH 8.5, near New Delhi, India, pigeon pea yields were increased by intercropping with mungbeans or urdbeans, not significantly affected by cowpeas or soybeans, and significantly reduced by maize and sorghum (Sarat Singh, and Ahlawat, 1975).

Increases in yield of a crop because of association with nonlegumes have occasionally been reported. At Bologna, Italy, intercropping of potatoes and sunflowers had little effect on potato yield and actually increased sunflower yield, although potato and maize had a mutually detrimental effect (Crocioni, 1951). Crocioni surmised that the potato induced the sunflower to root more deeply and hence made it better able to sustain dry conditions than either sunflowers grown in pure stand or maize and potatoes, both of which have shallow root systems. Paner (1975) reported that ame and gabi yielded more when grown under coconut in the Laguna area of the Philippines. Coconut palms appeared more vigorous when interplanted with various annuals. Hatzel (1974) reported that cowpeas yielded more when intercropped with maize than when grown alone, apparently because the maize provided support for the climbing cowpeas.

The fact that almost all cases of increase or no significant decrease of the yield of one crop when intercropped with legumes would seem to imply that this practice has some effect on the nitrogen economy. This topic will be discussed more fully in subsequent sections.

***Comparison of yield in polyculture with the mean of pure-stand yields.*** The practice of comparing the yield of a crop mixture with the mean yields of the component species in pure stand is less objectionable when applied to mixtures of small grains that are generally used for feed purposes and not separated after harvest. Thus, oat-barley mixtures were found to outyield the means of pure-stand yield of oats and barley by up to 10 percent in New York State (Bussell, 1937; Jensen, 1952), by up to 15 percent in Michigan (Morrish, 1934), and by up to 20 percent in Ontario (Zavitz, 1927). Oat-barley mixtures generally appeared to do better than other mixtures of small grains (Zavitz, 1927; Morrish, 1934; Bussell, 1967).

***Comparisons of yields of a hectare of polyculture with yields of half hectares of pure stand.*** Until objections were raised by Willey and Osiru (1972) and use of the land equivalent ratio became widespread (IRRI, 1974; 1975; Pinchinat and Oelshlegle, 1974; Francis et al., 1976; Sorna et al., 1975), polyculture was most frequently evaluated by comparing yields of each crop in an area with yields that would have been obtained had the area been divided equally between pure stands of the crops involved. First suggested by Pilz (1911), the method was also recommended by Evans (1960) for all evaluations of polyculture. Use of this

method requires, of course, growing pure stands of both crops in the mixture, a practice not followed by investigators who were interested only in the effect on one crop (Noll and Lewis, 1921; Thatcher, 1925; Hackleman et al., 1928; McClelland, 1928; Odland, 1930, Brown, 1935, Kurtz, Melstead and Bray 1952, Lugo-Lopez, Capo, Arostegui, and Riollano, 1953; Iso, 1954; Anthony and Willmot, 1957, Divekar, 1960, Narang, Kaul, and Gill, 1969, Singh and Prem Chad, 1969; Enyi, 1973a; Hildebrand and French, 1974, Saraf et al., 1975)

None of the investigators of maize-soybean mixtures in the United States were able to present any evidence that polyculture was inferior to growing two half-hectare pure stands of maize and soybeans. Mooers (1927) summarized the results of six years of experiments with maize and Tokio soybeans at two different sites in Tennessee by showing that an acre of the mixture produced an average yield of 33.3 bu of maize and 17.1 bu of soybeans, while maize alone had averaged 50 bu/acre or 25 bu/half acre and soybeans averaged 26 bu/acre or 13 bu/half acre. He concluded that intercropping would lead to increased grain production of both crops. Although Kinney and Roberts (1921) did not recommend intercropping maize and soybeans, alternate rows of Iowa Silver Mine or Reids Yellow Dent maize and Haberlandt soybeans produced an average of 40.2 bu of maize and 11.7 bu of soybeans per acre in three years of experiments on a sandy "bluegrass" soil in Kentucky, while pure stands of maize and soybeans averaged 23.6 and 10.0 bushels per half acre.

Sufficient information to compare yields in polyculture with yields of half-hectare pure stands of the same crops was determined for millet and sorghum (Andrews, 1972; Kassam and Stockinger, 1973); groundnuts and sorghum (Bodade, 1964), soybeans relay-planted into oats (Brown and Graffis, 1976); sorghum, groundnuts, and cowpeas (Baker and Norman, 1975); maize and beans (CIAT/MYC, 1974; Lepiz, 1971; Francis et al., 1976); mungbeans and maize (Pookpakdi, 1975; Panet, 1975; IRRI, 1973, 1974, 1975); ragi, cotton, and groundnuts (Pillai, 1957); oats and peas (Shannon and Lawson, 1975; Gheme-roth, 1950; Lapman, 1912); potatoes with maize or sunflowers (Crocioni, 1951); maize and soybeans (Lapman, 1912), maize and pigeon peas (Dalal, 1974); soybeans relay-planted into wheat (Dillon and McKibben, 1972); maize or sorghum with groundnuts (Evans, 1960; IRRI, 1974); castorbeans and groundnuts (Evans and Sreedharan, 1962); maize and cotton (Grimes, 1962), wheat, gram, and linseed (Gupta and Mathur, 1964), maize and cowpeas (Hazel, 1974; Lapman, 1912); cotton and groundnuts (Joshi and Joshi, 1965), and wheat with peas or lentils (Murchandi and Mista, 1957). With the exception of Murchandi and Mista, all of these investigators were able to find at least one situation (a standard range of crop densities and spacings which they had tested) in which yields from polyculture were greater than those of half-hectare pure stands of the same crops, while Andrews (1972), Dillon and McKibben (1972), Kassam and Stockinger (1973), Dalal (1974), Brown and Graffis (1976), Pillai et al. (1957), and Bodade (1964) found polyculture to be superior by this criterion in all situations tested.

It must be concluded that polyculture has shown itself superior to monoculture with a wide range of crops and experimental conditions when the yields obtained were compared with the potential of equally dividing the experimental area between pure stands of the crops involved.

***Comparison of yield in polyculture with that obtained if the area had been divided between pure stands in the same proportion as the species yielded in the mixture.*** Using an unusual approach, Willey and Osiru (1972) found that the yield of a polyculture of maize and beans was greater than the yield of the same area divided between pure stands of maize and beans in the same proportion as in the harvested mixture. This result was found with maize and beans seeded in the mixture at 2:1 and 1:2 ratios at four different populations. The same result was obtained by Osiru and Willey (1972) for maize and sorghum combined in 2:1 and 1:2 ratios at four populations. In all situations reported on by these researchers in 1972, the margin of superiority of polyculture over monoculture by their method was less than if the comparison were made on the basis of the area being divided equally between pure stands of the two species. Cases might exist where polyculture was found superior by comparison with pure stands dividing the area equally but *not* by the method of Willey and Osiru. The experiments these researchers conducted in 1972 were carried out on soils described as deep ferralitic — high in potash and low in nitrogen and phosphorus. Crops were planted in a well-fertilized pasture and received 70 kg/ha of $P_2O_5$ as single superphosphate prior to planting. In the previous chapter, we discussed the calculations used to compare the performance of polyculture to pure stands.

Using a slightly different method, Morrish (1934) found that barley, oats and peas; barley, oats, and wheat; and barley and peas; and twice differential varietal mixtures of barley and oats were superior to pure stands of these crops. Two varietal mixtures of oats and peas were, however, inferior. No description of the soils or fertilization used in these experiments was given, although they were apparently carried out at East Lansing, Michigan.

***Land Equivalent Ratio.*** We pointed out earlier that the Land Equivalent Ratio (LER) will show polyculture beneficial in certain cases where comparison with yields of half hectare pure stands of the crops involved will not. This can be demonstrated for the above case in which polyculture was not found to be beneficial in comparison with the yields of half-hectare pure stands. Mirchandi and Mista (1957) report that, when peas and wheat were combined in a 1:2 mixture, wheat yielded 279.4 kg/ha while peas yielded 74.7 kg/ha. In pure stands, the wheat yielded 291 kg/ha and the peas 464.5 kg/ha, or 145.5 and 232.3 kg per half hectare for wheat and peas, respectively. Hence, polyculture here is beneficial for wheat but clearly detrimental for peas. If we calculate the LER for this experiment, we find that to be $\frac{74.7}{464.5} + \frac{279.4}{291}$ or 1.12, indicating that it would take 1.12 hectares of pure stands of wheat and peas to produce what was produced on one hectare with polyculture. The very low yields indicate a serious limiting factor that could affect the interpretation of the data.

The LER has been used extensively by IRRI (1974, 1975) to evaluate experiments with polyculture. In many cases, their annual reports have listed only the LER and not crop yields. Furthermore, IRRI often plotted relative yields of each crop in polyculture under different management practices against each other to show how management practices affect polyculture. With maize and mungbeans, the LER was always greater than unity, being as high as 1.6 with

high nitrogen levels (180–270 kg/ha) with and without weed control. As noted earlier, although the relative yields did not, the LER remained remarkably constant at a given management level as maize population was varied. When maize was intercropped with soybeans (harvested both green and dry), mungbeans, sweet potatoes, or groundnuts, the LER was always greater than 1.3, even when the maize planting was delayed by various intervals in the soybean–maize combination. With maize and sweet potatoes, the LER decreased at certain populations and management levels but was greater than 1.2 at all but two spacings and management levels. With maize and rice, a very high LER occurred when contact between the two crops was greatest, but it was unity or less when separation was greater (15, 9, or 5 rice rows to 3, 2, or 1 maize rows, respectively), especially at lower populations (IRRI, 1973).

In subsequent experiments, the LER of a maize–peanut polyculture increased from 1.2 to 1.7 when maize or peanut populations were increased but planting patterns were not changed. In a similar experiment, an LER greater than unity (1.4–1.5) was achieved for a rice–maize mixture only at high populations. It must be concluded that populations in the majority of the treatments were too low for the varieties used. With a maize–soybean combination, the LER decreased from 1.47 to 1.12 as N levels were increased from 0 to 240 kg/ha. Maize and rice, however, showed relatively stable LER's (1.33–1.46) as N levels were increased from 0 to 270 kg/ha. When one crop was heavily attacked by disease, the LER was reduced but never fell below unity with mungbean–maize and maize–rice combinations on farms in the Philippines (IRRI, 1975).

Sastrawinata (1976) reported an LER of greater than unity for both maize–soybean and maize–rice combinations at four different levels of N fertilization on a Mahaas clay (pH 6.6, O.M. 2.1%; CEC 40.2 meq/100 g) which was probably similar to the soils used in the IRRI experiments. Similarly, Pinchinat and Oelshlgle (1974) found LER's greater than unity for all experimental situations when maize and beans were intercropped on a Typic Dystrandept at four different N levels and three different maize and bean populations. Surprisingly, LER values were greatest at the highest N levels (300 kg/ha), especially at high maize populations. Except where the crop was heavily damaged by drought, the LER was greater than unity for a maize–soybean combination at a similar site, being highest when maize and soybeans were planted in alternating 30 cm rows.

Schilling (1965) found an LER of 1.3 for groundnut–millet mixtures, only slightly greater than one for groundnut–sorghum mixtures at a site in Senegal for which no soils information was given. Evans (1960) calculated the land area which would be required in pure stands to produce the yields he observed with mixtures of maize and groundnuts and of sorghum and groundnuts at two sites in Tanzania. Values were always greater than unity for both combinations at the more fertile site but were less than unity for maize–groundnut combinations with high maize populations at the less fertile site. Niqueux (1959) always found LER values greater than unity at six sites in Chad when sorghum rows were 2.1 m apart with three groundnut rows planted between them; but values were less than unity at three of the six sites when sorghum rows were 1.9 m apart with two rows of groundnuts planted between them.

Crookston (1976) reported on a variety of experiments resulting in an LER of from 1.3–1.6 for the following crop combinations: maize–rice (Philippines), maize–groundnuts (Taiwan), sorghum–cotton (USA), maize–dry beans (Colombia), maize–soybeans (India), maize–sugarbeet (Canada), and cowpeas–sorghum (Nigeria). Although he did not state his sources, some of them were presumably identical with those reported here. Francis et al. (1976) reported an LER of greater than unity and as high as 1.88 for combinations of dwarf and normal maize and bush and climbing bean types. The LER was lowest when maize was planted before the beans and when climbing bean types were used. Sorta et al. (1975) reported that all of the cropping systems they used on a Typic Dystropept in Costa Rica produced an LER greater than unity when compared to corresponding monocultures at the same management levels. In this case, monocultures of short-cycle crops were grown consecutively so that the time periods for all cropping systems would be approximately the same.

It can be seen that, except under good management and climatic conditions, polyculture has produced LER values of greater than unity with a variety of crops in various parts of the world. What is most interesting and surprising is that LER values tend to be closer to unity under poor climatic and management conditions even though polyculture is supposed to be a way of adapting to adverse conditions (IRRI, 1974).

## Comparison of common parameters

Comparing polyculture and monoculture by means of a parameter common to both crops avoids the problem of comparing different substances. On the other hand, if the comparison is made only with regard to a particular component, a major effect of polyculture may be overlooked; for instance, if polyculture maximizes the production of two components such as protein and calories, the crops in the mixture may be complementary.

This argument was made most cogently by Thatcher (1925) for crude protein and total digestible nutrient (TDN) production by maize–soybean mixtures. Based on 23 separate tests in corn belt states, he found that a mixture of maize and soybeans would be expected to yield 41.4 bu of maize and 5.79 bu of soybeans per acre, while maize alone would produce 48.47 bu/acre. Since, as previously noted, pure stands of soybeans were generally not included in such trials, Thatcher estimated a pure-stand soybean yield of 17 bu/acre. Based on this estimate, he calculated that maize alone would produce 262.03 lbs of crude protein and 2230 lbs of TDN per acre, soybeans alone, 372.30 lbs of protein and 959.8 lbs of TDN, and the mixture 346.35 lbs of protein and 2221.7 lbs of TDN. He then calculated how an acre would have to be divided between pure stands of soybeans and maize to yield 346.35 lbs of protein, the amount produced by the maize–soybean mixture. This would require planting 76.4 percent of the acre with soybeans and 23.6 percent with maize. However, such a combination would only produce 1259.5 lbs/acre of TDN, much less than the mixture. Thus, the maize–soybean mixture was the best way to maximize the production of TDN and protein.

***Dry matter production.*** Comparison of dry matter (DM) production may be criticized on the grounds that it is only a measure of biological productivity, not of usable plant products. On the other hand, it is a parameter common to all crops. Although not immediately relevant to food production, studies in which dry matter production was determined may illuminate some of the interactions that occur in crop mixtures.

Nobbe and Richter (1902) grew oats and soybeans alone and in mixtures in pots at three nitrogen levels with and without inoculation. At all N levels without inoculation, the mixtures produced more DM than either pure stand.

Pilz (1911) performed extensive field experiments in Austria, using different legume and cereal combinations. Soils at the two sites were both clay loams, but one had a slightly higher clay content. On the soil with less clay, mixtures of barley and peas produced slightly less DM than the barley alone and slightly more than the peas alone. On the same site, however, oat and vetch mixtures produced more DM than pure stands of either crop. On the heavier soil, mixtures of oats-barley, or maize with peas, vetch, or horsebeans (all possible legume-cereal combinations were tested) produced more DM than pure stands in all combinations, with low and high legume populations being combined with low and high cereal populations.

As evidenced by their results, the field experiments of Lapman (1912) suffered from inadequate replication and generally poorer technique than those of Pilz. Pure stands and mixtures of maize and cowpeas, maize and soybeans, and oats and peas were grown for one or more years with varying degrees of replication. In general, mixtures produced less DM than the pure stands of maize or oats but more than the pure stand of legumes. However, these results were by no means obtained consistently. Lapman gave no description of the soils used for most of these studies. With pea and oat mixtures, the soils formed from red shale were fairly deep. In all cases, plots received 300 lbs/acre acid phosphate and 200 lbs/acre muriate of potash.

Ellett, Hill, and Harris (1915) reported that DM production of maize was increased when grown with beans on a Hagerstown loam in a greenhouse. Odland (1930) showed that by planting maize and soybeans in alternate 7″ drills near Morgantown, W. Virginia, the mixture would produce more DM than either pure-stand maize or soybeans at various plant populations. Planting the mixture in hills led to DM production inferior to that of some pure-stand maize plantings but still superior to that of pure-stand soybeans. Wartiovaara (1933) found that an oat-pea mixture that was 50 or 75 percent peas by weight produced more DM than either oats or peas in pure stand on a well-drained loam (pH 5.7) near Malmi, Finland, to which 1500 kg/ha of slaked lime, 800 kg/ha Thomas slag, and 400 kg/ha of 40 percent K salt had been applied. Similarly, Nicol (1934) found that DM production of a mixture of oats and vetch combined in a 3:1 or 2:2 ratio was greater than for vetch alone with or without nitrogen fertilization.

Henderson and Davies (1955) in West Wales found that a mixture of oats, beans and peas produced more DM per unit area at seven different stages of growth of the Penrhyn and Givern series of medium fertility. They repeated the experiment for three years and 200 lbs/acre of 12-12-15 was applied each year.

Robinson (1960) found that oat-pea and oat-vetch mixtures produced more DM than oats alone on lighter-textured soils (sands and sandy loams) in Minnesota, but on heavier soils (silt loams and clay loams), mixtures produced about the same DM as oats alone. No fertilization was used.

Kassam and Stockinger (1973) found that in northern Nigeria total DM production of a millet-sorghum mixture was greater than the DM production of either millet or sorghum grown alone. No soil description was given. Fertilization was with 627 kg/ha of 21-14-14 fertilizer, one-third at sowing, two-thirds four weeks after emergence. Hazel (1974) carried out polyculture experiments on a light silty loam near Accra, Ghana, previously in grass fallow, to which no fertilizer was applied. He found that in one experiment, maize in pure stands at a 90 × 30 cm spacing produced more DM than a maize-cowpea mixture, but in another experiment, a maize-cowpea mixture at 90 × 90 cm spacing in alternate rows produced more DM than maize alone. Dalal (1974) conducted mixed cropping trials on loam soils (clay 12%, pH 5.2, C.E.C. 12 meq/100g) near St. Augustine, Trinidad. He reported that at the time of its harvest, a pure stand of maize had accumulated more DM than a maize-pigeon pea mixture. Total DM accumulation up to the time of pigeon pea harvest was greater for a maize-pigeon pea mixture than for pure stands of either maize or pigeon peas if the mixture was planted in alternate rows. If the maize and pigeon peas were planted in the same row, DM accumulation was greater in pure stands.

On an undescribed soil at CIAT in Colombia, Francis et al. (1976) found that DM production by two maize types — normal (CIAT-207) and brachytic (CIAT-210) — in monoculture was not significantly different from the DM produced by maize when associated with a climbing or bush bean type. Sastrawinata (1976) studied DM accumulation in the Philippines on Tolhaas clay (2.4% O.M., C.E.C. 40.2 meq/100g; pH 6.6, montmorillonitic mineralogy) fertilized with 60 kg/ha of $P_2O_5$ and $K_2O$. He found that total dry matter accumulation by maize-soybeans and maize-rice mixtures was greater than by pure stands of the component crops when measured 34, 59, and 89 days after seeding with N applied at 45 or 90 kg/ha. When 180 kg/ha of N were applied, maize alone produced more DM than the mixture when sampled 34 or 85 but not 59 days after seeding.

With the exception of Sastrawinata et al. (1976) and Kassam and Stockinger (1973) who worked with maize-rice and millet-sorghum mixtures, respectively, all of the mixtures for which DM production was determined involved a cereal and a legume. The most frequently observed and expected phenomenon would be that the mixture would produce more DM than the leguminous component and less than the graminaceous one when grown in pure stands. Most of the experimental work showed however, that with proper management, the mixture's DM production could exceed that of either component in pure stand (Nobbe and Richter, 1902, Pilz, 1911, Lipman, 1912, Ellett, Hills, and Harris, 1915, Knapp and Roberts, 1921, Wattovaara, 1933, Nicol, 1934, Henderson and Davies, 1955; Robinson, 1960, Dalal, 1974, Francis et al., 1976; Sastrawinata, 1976). Only two investigators determined dry matter production by pure stands and mixtures over a range of soil types. Pilz (1911) found somewhat greater production of DM by the mixtures on the heavier soil. Robinson (1960) found the

reverse to be the case; but he was working with soils of considerably higher texture than Pilz.

***Nitrogen production.*** In the view of most workers prior to 1940 the main justification for using polyculture with a legume and nonlegume was to supply nitrogen to the latter (Lapman, 1912, Fred et al., 1932, Nicol 1934, 1936, Wilson, 1940). As a result, N production was measured more frequently by crop mixtures in earlier work than recently. As reviewers (Fred et al., 1932, Nicol, 1934, 1936) of the earlier studies pointed out, an association of legumes and nonlegumes can contain more N than either crop in pure stand even though crop yields need not be higher. Several investigators determined only how the percentage of N of cereals or legumes was affected by polyculture (Lyon and Bizzell 1911, Stallings, 1926). This procedure provides little measurement of total N production since increases in N content often occur when yields and dry matter production are reduced (Lapman, 1912).

Although they only performed pot studies, Nobbe and Richter (1902) did attempt to clarify the effects of inoculation and applied N on N fixation by legumes and legume-cereal mixtures. Without applied N oat-soybean mixtures contained more N than oats grown alone and less N than soybeans alone with or without inoculation. When 500 mg of N was added per pot the mixture contained more N than either species in pure stand without inoculation. With inoculation, the soybeans alone contained more N than the mixture. When 1000 mg N was added per pot, the mixture contained more N than either species in pure stand with or without inoculation. A defect of this research was the relatively high N content of both the inoculum and the soil. Soybeans were used as a legume since rhizobia specific for soybeans were not expected to be present in the soils used for the studies.

Pilz (1911) determined N content of barley and peas in pure stands and grown together, seven and eleven weeks after seeding, on a clay loam soil in Austria. At seven weeks, a mixture of barley at a low seeding rate (132 kg/ha) and peas at a high seeding rate (204 kg/ha) produced more N per hectare than did pure stands of either crop, except for peas at the high seeding rate. Barley at a high seeding rate (270 kg/ha) and peas at a low seeding rate (101 kg/ha) produced more N than did pure stands of either crop at the lower seeding rate but the reverse was true with pure stands at the higher seeding rate. At the second cutting, when both barley and peas were mature, the mixture yielded more N than either pure stand, although results were not broken down according to the different seeding rates. At the first cutting of vetch and oats, the mixtures produced more N than oats alone at both seeding rates and than vetch alone at the lower seeding rate (124 kg/ha) but not at the higher rate (200 kg/ha). At the second cutting, the mixture produced more N than oats alone but not more than vetch alone. At another site, which had a clay loam with a somewhat higher clay content but was otherwise similar, oats, barley, and maize were combined with peas, vetch and horsebeans at different seeding rates in all possible combinations. The mixtures of a high legume and a low cereal seeding rate produced as much or more N than did pure stands of all crops at high or low seeding rates. At a high seeding rate of both legumes and cereals, N production by the mixture was greater than

for all pure stands, except for vetch at a high seeding rate. At a low legume and a high cereal rate, N production by the mixture was higher than for all pure stands, except for vetch at both seeding rates and for maize at the lower rate; with a low cereal and a high legume seeding rate, the mixture's N production was less than pure-stand vetch at both rates, than maize at the lower rate, and than peas at the higher rate, but was still higher than for all other pure stands.

In two of three determinations made in 1908 and 1909, Lipman (1912) found N production by a maize-cowpea mixture to be greater than by maize or cowpeas alone on a "poor" limed soil to which 300 lbs/acre of acid phosphate and 200 lbs/acre of muriate of potash were applied. In the third trial, there was little difference between the mixture and cowpeas alone. However, in a maize-soybean mixture, the mixture produced less N than did soybeans grown alone, although it resulted in more N than pure-stand maize. In four trials with oats and peas carried out under similar conditions, Lipman found the mixtures to be higher in N than both pure stands in one trial, and lower in N than the peas alone but higher than the oats alone in the other trials. In general, Lipman's findings did not make a very good case for increased N production by legume-cereal mixtures. In summarizing the results of these and other pot and greenhouse studies, Lipman concluded that "the presence of the nonlegume in the mixed growth need not decrease the yields of dry matter and nitrogen in the legume," and, "in the associated growth of legumes and nonlegumes, the development of the latter may be depressed rather than enhanced when factors other than the supply of combined nitrogen limit production."

Kellerman and Wright (1914) found that barley grown in pots with peas or beans yielded more N than when grown alone. The mixture contained more N than either crop grown in pure stand or than the sum of the nitrogen yield of the two crops in pure stand. On a well-drained loam near Malmi, Finland, to which 1500 kg/ha of slaked lime, 800 kg/ha of Thomas slag, and 400 kg/ha of 40 percent K salt had been applied, an oat-pea mixture that was 75 or 85 percent peas produced more N than either crop in pure stand (Wartiovaara, 1933). Nicol (1934) found that the total N production of oat-vetch mixtures combined in a 1:3 proportion was greater than that of either oats or vetch grown alone without the application of N. When it was applied, the N production by the mixture was the same as for vetch alone but greater than that for oats alone. Nowotnowna (1937) found that barley grown in pots with peas, but not with lucerne or serdella, contained more N than barley grown alone. However, Madhok (1940) reported that a wheat-chickpea mixture grown in pots always produced less N than chickpeas grown alone but more N than wheat grown alone.

In more recent work, Schilling (1965) found that both N and P content of leaves of millet and sorghum was increased by intercropping with groundnuts at two sites in Senegal. The effect of legumes on P content is somewhat difficult to explain.

Kassam and Stockinger (1973) found that in northern Nigeria total N uptake of a millet-sorghum mixture was 180 kg/ha, while for millet and sorghum in pure stands it was 140 kg/ha. This indicates that the mixture had obtained more soil N since only 137 kg/ha of N had been applied. No soil descriptions were given for the site.

Working at a site in Byelorussia, USSR, about which no information was given, Kanov and Bodkevitch (1973) reported that, when they were grown together, the N content of oats increased and that of peas decreased in comparison with pure stands.

On a loam soil near St. Augustine, Trinidad, Dalal (1974) found that pigeon peas and maize planted in alternate rows produced more N than pure stands of maize or pigeon peas, although the difference for pigeon peas was not significant. At the time of the maize harvest (8 weeks prior to the pigeon pea harvest), maize in pure stand contained more N than did any of the mixtures.

IRRI (1975) reported that when grown at four different N levels (60, 120, 180, or 240 kg/ha), maize and rice mixtures always contained more N than either crop in pure stand. Similarly, Sastrawinata (1976) found that maize–soybean and maize–rice mixtures always contained more N than did pure stands of the component crops at any of four N levels (0, 45, 90, and 180 kg/ha), the difference becoming especially marked 50 and 85 days after seeding.

Although the evidence might not be completely consistent, more recent studies (Dalal, 1974, Sastrawinata, 1976) found that mixtures of legumes and cereals produced more N than did pure stands of either crop. Less surprising was the finding that mixtures of nonlegumes appear to make use of soil and applied N more completely than do monocultures (Kassam and Stockinger, 1973, IRRI, 1974, Sastrawinata, 1976). Although most of the earlier researchers found instances where pure stands of legumes produced more nitrogen per hectare than did legume–cereal mixtures, the nitrogen yield of mixtures was nonetheless greater than that of pure-stand legumes in a significant number of cases. This indicates that under proper management, mixtures might produce more nitrogen than pure stands of either legumes or grasses.

***Production of total digestible nutrients (TDN).*** Earlier researchers, who were primarily interested in using mixtures for feed purposes, determined total digestible nutrient production by mixtures as compared to pure stands. The fact that maize–soybean mixtures produced less TDN than pure stands of maize was frequently used by earlier investigators as an argument against their use (Noll and Lewis, 1921; Kinney and Roberts, 1921; Thatcher, 1925; Odland, 1930). Those presenting data for comparison generally found small differences in TDN production between maize grown alone and mixtures of maize and soybeans. Thus Odland (1930) determined TDN production by maize and soybeans in alternate 7″ drills to be 5142 lbs/acre, while the best results with pure-stand maize (7″ drills) were 4881 lbs/acre. Hackleman et al. (1928) found that pure-stand maize produced 2685 lbs/acre of TDN, while maize associated with Ebony, Hong Kong, or Ito San soybeans produced 2706, 2727, or 2631 lbs/acre of TDN respectively. Hence, even without the compensating effect of legume protein which will be discussed in the following section, maize–soybean mixtures offered no disadvantages as compared to pure-stand maize insofar as TDN production was concerned.

Using his proportionate method of comparison of mixtures with pure stands (see preceding section), Morrish (1934) found that mixtures of barley and oats, barley, oats, and peas; and barley, oats, and wheat produced more TDN than pure

stands of these crops. However, mixtures of peas and oats were inferior to pure stands in terms of TDN production.

***Protein production.*** Most calculations of protein production are based on multiplication of nitrogen content by a constant; and therefore, comparisons of protein production should not differ from comparisons of nitrogen production. However, in some cases protein-production calculations were based only upon edible portions of the crops (Mirchandi and Mista, 1957, Kassam and Stockinger, 1973, Dalal, 1974, CIMMYT, 1974, IRRI, 1974), and thus they would substantially differ from calculations of N production determined for the whole plant or its above-ground parts. In the case of earlier authors, who were primarily concerned with feed production, calculations of N production by the above-ground plant parts and crude protein production would not be expected to differ substantially. However, usually only data for crude protein production were given (Noll and Lewis, 1921, Odland, 1930, Hackleman et al., 1928, Thatcher, 1925).

In a five-year trial in Pennsylvania, Noll and Lewis (1921) found no difference in protein content of maize grain nor of silage when the maize was grown either in pure stands or with soybeans. Odland (1930) found that protein production by maize–soybean mixtures was always lower than that of pure-stand soybeans. Protein production by the mixture was higher than for maize alone only if soybeans and maize were planted in alternate 7″ drills. Similarly, Thatcher (1925) found that soybean–maize mixtures produce less crude protein than pure-stand soybeans but more than pure-stand maize. Hackleman et al. (1928) found that crude protein and net protein (determined by multiplying the crude protein by the biological value of the protein) of maize–soybean mixtures were greater than for maize grown alone in experiments run for six years near Urbana, Illinois. In five years of experiments at the Agronomy Farm near Morgantown, West Virginia, about which no soils information was given, Odland (1930) found no change in protein content of maize resulting from association with soybeans. It appears that the benefits in terms of protein production with polyculture depend on the basis of comparison. When compared to pure-stand soybeans, crude protein production by the maize–soybean mixture was invariably inferior, but when compared to pure-stand maize, protein production by the mixture was greater, except in the experiments of Noll and Lewis (1921) and some of the planting patterns used by Odland (1930).

More recent work has focused on the protein contained in edible plant parts. Mirchandi and Mista (1957) reported that the percentage of protein in wheat was considerably increased by polyculture with peas and slightly increased with lentils. Since wheat yields were also greater with polyculture, total protein production per hectare would have been considerably increased. The protein content of the legume was not even considered. However, wheat yields were generally low in the experiment run for a single year on an unspecified soil near Delhi, India. In research in northern Nigeria, Kassam and Stockinger (1973) found that total protein production in the harvested grain of a millet–sorghum mixture was greater than pure stands of either millet or sorghum. On a loam soil near St. Augustine, Trinidad, protein production per hectare was found to

be significantly higher with a maize-pigeon pea mixture than with either crop in monoculture (Dalal, 1974).

Crude protein production by total above-ground plant parts has been measured in more recent experiments in the United Kingdom, the United States, and Canada. On soils of the Perthyn and Gwern series in West Wales, Henderson and Davies (1955) found that an oat-pea mixture produced less protein per unit area than does either crop alone, especially at later stages of development. However, the mixture always produced considerably more crude protein than did oats alone. Robinson (1966) determined that oat-pea and oat-vetch mixtures produced more protein than did oats alone on sands, sandy loams, silt loams, and clay loams in Minnesota. Shannon and Lawson (1975), in experiments near Montreal, Canada, also found crude protein yields of oat-peas mixtures to be slightly lower than those of pure-stand peas, but considerably higher than those of pure-stand oats.

In connection with the Puebla project in Mexico, trials were run with pure stands and mixtures of maize and beans at different spacings and levels of N and P fertilization. These took place on volcanic soils with a loam or clay loam texture overlain by light brown volcanic ash and on soils with a compacted layer at a depth of 20-60 cm (CIMMYT, 1974). Both soils were near neutral (pH 6.5-7.0, with about 0.5-1.0% O.M.), well supplied with K, and fairly high in available P. Protein production of common maize, opaque maize, and beans in pure stands was compared with that of polyculture of beans and common maize at different managerial levels. Common maize at 40,000 plants per hectare in pure stand, with 120 kg/ha of N and 40 kg/ha of $P_2O_5$, produced an average of 391 kg/ha of protein and 9.9 kg/ha of lysine. In an experiment at CIMMYT in Mexico, opaque maize in pure stand at 50,000 plants per hectare with 130 kg/ha of N and 50 kg/ha of $P_2O_5$ yielded 4700 kg/ha of grain containing 423 kg/ha proetin and 19.9 kg/ha lysine. In another experiment, 40,000 common maize plants associated with 60,000 bean plants per hectare, and fertilized with 150 kg/ha N and 40 kg/ha $P_2O_5$, produced 3258 kg/ha of maize and 1361 kg/ha of beans. The latter contained 623 kg/ha of protein and 30.3 kg/ha of lysine. When, in addition to the mineral fertilization, 10 tons/ha of manure was applied to the maize-bean combination, 4056 kg/ha of maize and 2446 kg/ha of beans containing 45.5 kg/ha of lysine was produced. To supply this quantity of lysine, opaque maize would have to yield 11.3 T/ha; this has not yet been achieved with present technology. The researchers concluded that mixtures of maize and beans offered nutritional benefits not attainable by monoculture, even at high fertility levels (CIMMYT, 1974).

Pinchinat and Oelsligle (1974) compared protein production of four different polyculture treatments with that of some of the component crops in pure stands at two fertility levels on a Typic Dystrandept, fine, isohyperthermic, in Costa Rica. A polyculture system of maize, cassava, and beans followed by soybeans produced more protein than did all monocultural sequences, including beans followed by soybeans at a lower fertility level. However, at a high fertility level, the soybean-bean monoculture sequence produced more protein than did the polyculture; but the polyculture, as we shall see, maximized energy and protein pro-

duction. On a similar soil, the greatest protein production by maize and beans was obtained when 300 kg/ha of N was applied. Without N fertilization, maximum protein production was achieved with a maize–bean mixture when each crop was planted at the population used in pure stands, thus obtaining greatest population pressure.

IRRI (1974) compared production of protein with five different cropping systems, three of which included polyculture. However, crops differed in the systems so that reliable comparisons could not be made. Protein production seemed to depend to some degree on the crops included and only one system involved soybeans. In irrigated rotations, a tomato and bush sitao mixture produced more total protein and protein per man-day of labor than tomato alone; an okra–mung mixture produced more protein and protein per man-day than mung alone; but a maize–cowpea mixture produced less total protein and protein per man-day than either maize or cowpeas in pure stand.

Soria et al. (1975) found that the crops and management level involved determined whether polyculture or monoculture systems produced more protein. At a high level of fertility on a Typic Dystropept in Costa Rica, maize–bean polyculture followed by pure-stand maize produced more protein per hectare than did a bean–maize–maize monoculture sequence. Without fertilizer, a single hectare of a manioc–bean mixture produced more protein than the total produced by one hectare of beans and one hectare of manioc in pure stands.

In summary, polyculture of a legume and nonlegume generally produced less total protein than did a legume grown alone. However, polyculture of legumes and nonlegumes always produced more total protein than pure stands of nonlegumes. As pointed out by Thatcher (1925) and Pinchinat and Oelshigle (1974), it would also require more than a hectare of pure stands of legumes and nonlegumes to produce the same amount of energy and protein that a hectare of polyculture of those crops could produce.

***Energy production.*** Caloric equivalents of crop production in polyculture and in monoculture have been given by relatively few investigators (Pinchinat and Oelshigle, 1974, Soria et al., 1974; Kass, 1976). Production of kilocalories per hectare by a polyculture system involving sweet potatoes was greater than that of two consecutive crops of sweet potatoes — the crop which was the most efficient producer of energy of those tested, both with and without fertilization, on a Typic Dystrandept in Costa Rica. In a maize–bean system, maximum energy production was obtained when the maize yields were greatest, either with a monoculture of maize or maize mixed with a low population of beans at all N levels (0, 100, 200, or 400 kg/ha of N) (Pinchinat and Oelshigle, 1974). On a Typic Dystropept in Costa Rica without fertilization, two sequential crops of sweet potatoes produced more kilocalories per hectare than a sweet potato–manioc association, the mixture did produce more energy than pure-stand manioc, however. With fertilization, the mixture produced more energy than the sweet potato sequence or than pure-stand manioc. Fertilization seems to have reduced sweet potato yields considerably in both pure stands and in polyculture. With or without fertilizer, polyculture of beans and sweet potatoes produced more kilo-

calories in one hectare than one hectare of beans and one hectare of sweet potatoes combined. Polyculture of maize, beans, and manioc produced more kilocalories per hectare than pure stands of manioc or beans or than three consecutive crops of maize with or without fertilizer (Soria et al., 1975). In the Amazon region of Brazil, Kass (1976) found energy production with polyculture of rice and manioc to be significantly greater than with pure stands of manioc or with pure stands of rice followed by pure stands of cowpeas; with and without weeding or potassium fertilization, the results were constant on a Quartzipsamment Haplorthox, sandy, oxidic, isohyperthermic.

Except for the situation of the sweet potato and manioc mixture in which one would expect competition between the crops to be great, polyculture appears to be a far more efficient producer of calories than sequential monocultures of the same crops. However, further determinations under a wider range of conditions probably are necessary before reaching more general conclusions.

***Mineral components.*** A small number of investigators have compared the yields of nutrients other than N of polyculture with those of monoculture of the same crops. If the experiments were properly carried out, so that the same amounts of these nutrients were available to each cropping system, the cropping system obtaining a greater yield of a particular nutrient would either be using that nutrient more efficiently or exploiting a greater volume of soil. On a well-drained, fairly clayey, coarse-textured soil of the two series derived from granitic and gneissic rock in western Nigeria high in available P (100kg/ha) and exchangeable K (600 kg/ha), Agboola and Fayemi (1972b) found that available P was reduced more under four crops of continuous maize than when a legume (cowpea, calopogon, or greengram) was intercropped with the maize.

On an unfertilized loam soil (pH 5.2; CEC 12 meq/100g; clay 12%) near St. Augustine, Trinidad, Dalal (1974) found that a maize-pigeon pea mixture contained more total P at the time of pigeon pea harvest than did monocultures of either crop. At the time of maize harvest, however, maize in pure stand contained more P than did the mixture. P accumulation (kg/ha/week) was not significantly greater than with pigeon peas alone. At two sites in Senegal, for which no soils information was given, Schilling (1965) reported higher levels of P in leaves of millet and sorghum grown with cowpeas than in leaves of those grown in monoculture. On an undescribed soil in the Byelorussia, USSR, Kamov and Bodkevitch (1973) reported that the $P_2O_5$ content of oats at the tillering or milk stage was higher when the oats were grown in a mixture with peas than when they were grown in pure stands.

In the Philippines, Sastrawinata (1976) determined, at 34, 50, and 85 days after seeding, the P content of maize, soybeans, and rice in pure stands and of maize-soybean and maize-rice mixtures grown at four levels of N (0, 45, 90, and 180 kg/ha). These crops were grown on a Mahaas clay of montmorillonite mineralogy (pH 6.6; available P 32 ppm) to which 60 kg/ha each of $P_2O_5$ and $K_2O$ had been applied. At 50 and 85 days after seeding, the mixture contained more P than did any of the component crops in pure stands at all N levels; but 34 days after seeding, at the highest N level, soybeans alone contained more P than was in the soybean-maize mixture. The available evidence indicates that crop

mixtures take up more applied and soil P than do monocultures of the same crops.

On the same soil described for P changes, Agboola and Fayemi (1972b) found that in general, exchangeable K was reduced more by maize intercropped with legumes than it was by continuous maize, but reduction of exchangeable K was least when maize was rotated rather than intercropped with legumes. Dalal (1974) found that total K accumulation was greater for pigeon pea–maize mixtures than for pure stands of either crop. At the time of its harvest, however, maize had accumulated more K than the pigeon pea–maize mixture had. K accumulation per hectare per week was significantly higher for mixtures than for pure stands of maize and pigeon peas. Kanov and Bodkevich (1973), on the other hand, found that the $K_2O$ content of both oats and peas was lower in a mixture than in pure stands, although no data about total dry matter production were given.

On a Mahaas clay in the Philippines (CEC 40.2 meq/100g, exchangeable K 1.19 meq/100g) fertilized with 60 kg/ha of both $K_2O$ and $P_2O_5$, Sastrawinata (1976) determined the K yield of maize, rice, and soybeans in pure stands and of maize–soybean mixtures at four different N levels, 34, 59, and 85 days after seeding. Unlike the situation with P, the level of N application appeared to affect K accumulation. Without N, the maize–soybean mixture always contained more K than did either crop in pure stand. The rice–maize mixture, however, did not contain more K than did maize alone at the first sampling date. When 45 kg/ha N was applied, the maize–soybean mixture still contained more K than was in either crop in pure stand at all sampling dates; the maize–rice mixture contained more K than was in the pure stands of the component crops only at the last sampling date. At 34 days, pure-stand maize, and at 59 days, pure-stand rice contained more K than did the mixture. At 90 kg/ha N, the maize–soybean mixture contained more K than was in maize alone at the last two sampling dates, at 34 days, maize alone contained more K. At this level of N, the maize–rice mixture was highest in K only at the last sampling date; at 34 days, maize alone was highest, while at 59 days, both pure stands contained more K than did the maize–rice mixture. Finally, when 180 kg/ha of N was applied, the maize–soybean mixture contained less K than did maize alone, but more than that of soybeans alone at all sampling dates. At this N level the rice and maize mixture contained more K than that of either pure stand at 59 and 85 days after seeding, but the maize alone contained the most K at the first sampling date. It must be concluded that the higher N levels permitted the pure-stand maize to grow more rapidly and make use of the applied K more quickly and efficiently than the maize–soybean mixture could.

On a Quartzipsamment/Haplorthox, sandy, oxidic, isohyperthermic in the Brazilian Amazon that was very low in exchangeable K, there was no difference in K content of manioc roots grown in pure stands or in polyculture with rice and (or) maize. However, when 300 kg/ha of $K_2O$ was applied to all cropping systems, the roots of manioc associated with maize had a significantly higher K content than did manioc grown alone or manioc associated with rice. A similar effect was noted with manioc stems but the differences were too small to be significant (Kass, 1976).

Although the evidence is fragmentary, it seems that a more rapidly growing plant will take up more K than a slower growing one does. If rapid growth of a monoculture can be brought about by high N fertilization, it will probably accumulate more K than will a crop mixture. This is especially true at early stages of development. However, if the mixture eventually produces more dry matter than the monoculture, it will probably also contain more K.

Calcium production by pure stands and mixtures has received very little attention. Dalal (1974) determined that the maize–pigeon pea mixture contained more Ca than either crop in pure stand at the time of pigeon pea harvest, but at the time of maize harvest, pure-stand maize contained more Ca than did the mixture. The rate of accumulation of Ca by the mixture was not significantly different from pure-stand pigeon peas, but was higher than with pure stand maize. It should be pointed out that this pattern was the opposite of that of P; in other words, pigeon peas take up more Ca than does maize while maize takes up more P than do pigeon peas. A mixture will take up as much Ca as pigeon peas and as much P as maize.

Kaurov and Bodkertich (1973) determined that the Ca content of both oats and peas was higher when they were grown together than when they were grown in monoculture. Kass (1976) found the Ca content of manioc roots to be significantly higher when intercropped with maize than when grown in pure stand. The admittedly meager evidence appears to indicate that crop mixtures take up more Ca than do pure stands of the component crops.

Dalal (1974) found that maize–pigeon pea mixtures contained more Mg than did maize or pigeon peas in pure stands at the time of pigeon pea harvest; but at the time of maize harvest, maize alone had accumulated more Mg than the mixture had. The mixture accumulated more Mg per hectare per week than either maize or pigeon peas grown alone. Kass (1976) found no difference in Mg accumulation by five cropping systems (manioc in pure stand, rice and cowpeas in sequential monoculture, maize–manioc mixture, rice–manioc mixture, rice–maize–manioc mixture) on a Quartzipsammentic Haplorthox in the Brazilian Amazon.

It must be concluded from the small number of experiments in which measurements were taken that crop mixtures will contain greater amounts of P, K, Ca, and Mg than will pure stands of the component crops grown under the same conditions. Only at very high N rates did pure stands of maize contain more K than was in maize–soybean mixtures 85 days after seeding. In all other cases, the initially greater accumulation of P and K by pure stands was surpassed by mixtures at later stages of development (Dalal, 1974; Sastrawinata, 1976).

### Economic return

Economic evaluation of polyculture in comparison to monoculture is a relatively recent development and was not determined by any of the earlier investigators (Pilz, 1911; Lapman, 1912; Noll and Lewis, 1921; Kinney and Roberts, 1921; Etheridge and Helm, 1924; Thatcher, 1925; Ayres, 1925; Mooers, 1927; McClelland, 1928; Hackleman et al., 1928; Odland, 1930; Wattiovaara, 1933; Morrish, 1934; Brown, 1935; Wiggans, 1935). Converting production to economic

values is complicated by the fact that prices and price relationships of the crops vary; some authors have therefore made their evaluations at more than one set of prices (Gliemeroth, 1950; Willey and Osiru, 1972; CIMMYT, 1971). Although Ayer (1949) suggested that polyculture offered economic benefits, Gliemeroth (1950) appears to be the first to determine the economic return from yields obtained in experimental plantings. More recently, several investigators have been making evaluations of polyculture and monoculture of the component crops with regard to labor utilization, considering labor requirements, provision of employment throughout the year, and return per unit of labor (Norman, Buntye, and Goddard, 1970; IRRI, 1973, 1974; Baker and Norman, 1975; Soria et al., 1975; Sastrawinata, 1976).

In a considerable number of studies in the past twenty-five years, economic analyses of polyculture compared to monoculture of one or all of component crops have been made, most frequently by calculating the net returns of different cropping systems. Some authors have merely used the cash value of the production, without taking costs into consideration. Such research has limited value. Because there are so many studies, they have been broken down according to the crops involved. Although some experiments may fit into more than one grouping, this procedure shows which combinations might be most beneficial.

***Association with cotton.*** As cotton is almost exclusively a cash crop, economic return would be a primary consideration in determining whether to associate it with other crops. Working on an unspecified soil in Madras, India, Pillai et al. (1957) found that the value of a crop of cotton grown with either groundnuts, ragi, or ragi and groundnuts, to be greater than that of cotton grown alone; they averaged their results over a four-year period in which relative prices varied. The mixtures also produced more value per day in the field than did cotton grown alone. In the transition tract of northern Karnatak, India, Patil and Koraddi (1960) found that intercropping cotton with groundnuts had considerable benefits, especially if the groundnut price was higher than Rs 13 per Bengali maund. In a year in which the cotton crop was damaged by heavy rains, groundnuts yielded more and gave a higher net income than in other years. Another advantage was that groundnuts were harvested first, giving the farmer cash earlier than if cotton had been planted alone.

At two sites in Kenya, Grimes (1962) found that cash return from planting one acre of alternate rows of cotton and maize would be greater than from two 1/2 acre pure stands of cotton and maize. On a light-textured soil of medium fertility, near Junagdh, Saurashtra, India, Joshi and Joshi (1965) determined that over three years the return would be much greater for cotton planted in 6′ rows with two or three rows of groundnuts between them than for pure stands of either crop. Near Ranchi, Bihar, India, Varma and Subba Rao (1969) found a greater return over two years from growing cotton intercropped with groundnuts than from growing cotton alone. Other crops (maize, rice, sweet potato, *P. mungo*, and *Eleusine coracana*) reduced profits as compared to cotton alone. In northern Nigeria, Baker and Norman (1975) found that the average values of the yield/ha were 62 percent higher for sorghum, groundnuts, and cotton when grown in mixtures than when grown in pure stands. However, the average value of produc-

tion per man-hour was 15 percent lower for the mixture than for the monoculture. All of these experiments led to the same conclusion: intercropping cotton with groundnuts or maize was more profitable than growing cotton alone, although in the one case where it was measured, the labor invested was greater with polyculture.

***Associations with sugarcane.*** Lugo Lopez et al. (1953) computed net returns for some situations tested in experiments with vegetables interplanted in sugarcane. At the Rio Piedras site, in Puerto Rico, on a poorly drained alluvial soil, Vega Baja silty clay, interplanting sugarcane with all vegetables (soybeans, cucumber, beans, tomatoes, and melons) except maize was more profitable than growing sugarcane alone. The profit from interplanting red beans with sugarcane at a 4′ *vs.* 8′ row spacing was significantly greater than for monoculture cane. In another experiment at the same site, all plantings led to losses but the losses were not significantly greater for cane interplanted with soybeans or maize than for sugarcane alone. With rattoon cane, it was more profitable not to interplant vegetables (Lugo Lopez et al., 1953). However, in two years of experiments at an unspecified site in India, Bhoj and Kapoor (1970) found that interplanting sugarcane with maize was more profitable than growing pure-stand cane, especially if 56 or 112 kg/ha of N were applied to the maize. Paner (1975) reported returns of 1.34, 2.84, and 2.48 pesos per peso invested for soybeans, mung, and groundnuts, respectively, interplanted with sugarcane at the Victorias Milling Co., Negros Occidental, Philippines. Although the experiments of Lugo Lopez et al. (1953) were heavily fertilized, the availability of sufficient nutrients, especially N, would seem to be critical for success with crops interplanted with sugarcane.

***Maize–legume systems.*** Associations of maize and legumes have been studied probably more than any other polyculture system. Although both crops can be used for on-farm consumption, farmers often sell some or all of their production.

On an irrigated sandy loam at Ludhiana, India, Narang, Kaul, and Gill (1969) found that it was more profitable to plant maize at a 60 × 30 cm spacing, with a single row of soybeans between maize rows, than to plant maize at 90 × 30 cm spacing with one or two rows of soybeans between maize rows or in pure stands at 60 × 30 cm spacing. Experimenting with various populations, Lepiz (1971) always obtained greater returns from maize–bean combinations than from pure-stand maize or beans on soils of low fertility near Mexico City, Mexico. Associations with pole beans were generally more profitable than with bush beans; but this effect probably resulted from the greater productivity of the pole bean variety used than from interaction with a maize.

Willey and Osiru (1972) calculated the return from maize–bean mixtures and from pure stands of the crops when the maize–bean price ratios were 1:1, 1:2, 1:3, or 1:4. When maize–bean price ratios were 1:1 or 1:2, mixing maize and beans in a 2:1 ratio was more profitable at all plant populations. When the price ratios were 1:3 or 1:4, seeding maize and beans in a 1:2 ratio was the most profitable treatment at high plant populations; but pure-stand beans were most profitable

at lower plant populations. This analysis was conducted on crops grown in a well-fertilized deep feralitic soil near Kabanyolo, Uganda.

On an unspecified soil in Pantnagir, India, Singh et al. (1973) found greater returns from maize intercropped with soybeans in double or single alternate rows than from maize alone. Intercropping sorghum with soybeans was not consistently more profitable than growing pure-stand sorghum.

Averaging the results from volcanic soils and nonvolcanic soils in Mexico, CIMMYT (1974) found a higher net return from all maize–bean combinations than from pure stands of maize or beans, but several of the polyculture treatments had been more heavily fertilized than the corresponding monocultures. However, when 60,000 bean plants per hectare were added to maize planted at 40,000 plants per hectare and fertilized with 120 kg/ha N and 40 kg/ha $P_2O_5$, net income increased by $66.96 or $166.64, depending on the price of beans.

At IRRI (1974), associations of maize with mungbeans, groundnuts, and sweet potatoes were compared with pure stands of these crops at high and low pest and water management levels during the 1973 dry season. The relative profitability of monoculture and polyculture appeared to depend upon the management level. At a high level of management and good growing conditions, monoculture appeared to give greater return over variable costs. Return per hectare was about the same for both systems but return per unit of labor was greater with monoculture. At a lower management level or where heavy rains or wet soil conditions restricted crop growth, polyculture appeared to be superior with regard to total return above variable costs, return above variable costs per hectare per day, and also per unit of cash expense. At the lower management level, the return per unit of labor of the two systems was about the same although more total labor was used with polyculture. From these data it was concluded that "it seems likely, based on very limited data, that intercropping may best fit land-limiting, labor surplus situations where management is less than optimal for monoculture" (IRRI, 1974).

On a Typic Dystrandept in Costa Rica, beans and maize were grown in pure stands and in mixtures at three different populations at four levels of N fertilization. The highest return was obtained with the application of 300 kg/ha N to bean monoculture, a result related to the high price of beans in Costa Rica. In the absence of N fertilization, maximum return was obtained with a bean–maize association with each crop at the population used in pure stands, 50,000 maize plants and 50,000 bean plants per hectare (Pinchinat and Oelshigle, 1974).

Chao (1975) found that associating maize with soybeans with 15 or 10 rows of soybeans to 2 rows of maize, or 4 or 5 rows of soybeans to 1 row of maize, gave a greater return than pure-stand soybeans in Taiwan (1975).

Associations of maize with legumes appear to be very profitable except when high levels of nitrogen fertilizer are applied, which is done by very few farmers.

***Groundnuts in mixtures with crops other than cotton and maize.*** Groundnuts are commonly grown as a cash crop by small farmers but are also used as a food crop. They appear to figure frequently in commonly grown crop mixtures (Seshadri et al., 1956; Evans, 1960). These mixtures have been evaluated economically by several authors.

On an unspecified site in Madras, India, Pillai et al. (1957) found that the total value of produce over four years was greater for ragi-groundnut and ragi-cotton-groundnut mixtures than for pure stands of these crops. However, groundnuts in pure stand had a greater cash value than a cotton-groundnut mixture. Per day in the field, the ragi-groundnut mixture produced the greatest value, followed by pure-stand groundnuts. Seshadri et al. (1956) conducted experiments at Tindivanam, India, on a unspecified site to which 10,000 lbs/acre of town rubbish had been added and incorporated. They found that groundnuts associated with cotton, redgram, or castorbeans produced a greater average net return over three years than did pure stands of bunch-type groundnuts. Mixtures of groundnuts with sorghum, pearl millet, or setaria millet were less profitable than pure stands of groundnuts.

Although they did not carry out a full economic analysis, Evans and Sreedharan (1962) concluded at Mwanhala, Tanzania, that castorbean prices would have to be three times those of groundnuts to make intercropping castorbeans with a low groundnut population unprofitable. On an unspecified soil at Amravati, India, Bodade (1964) found that mixtures of groundnuts with sorghum planted in alternate rows with 2 rows of sorghum to 4 or 8 rows of groundnuts, or planted in the same row with 1/3 sorghum, 2/3 groundnuts, produced more net profit averaged over three years than pure stands of either crop. He noted that the cost of production of planting sorghum and groundnuts in the same row was much higher than planting in alternate rows; as a result, 1/5 sorghum, 4/5 groundnut mixture planted in the same rows was relatively unprofitable even though this arrangement produced almost as much total value as groundnuts grown alone. When they averaged the results from four years of experiments on an unspecified soil at Kadiri, India, Reddy, Roa, and Reddy (1965) found the net profit from castorbeans intercropped with groundnuts to be twice that from castorbeans grown in pure stands. Other intercrops (greengram, cowpeas, *Setaria italica*, sorghum, and *Pennisetum typhoides*) were much less profitable than groundnuts and, with the exception of greengram, produced less net return than a castorbean monoculture. Although grain production was greater than with pure-stand sorghum, Langegouda (1972) found on a medium black soil at Dhawar, India, that net return over two years was greatest for groundnuts and sorghum planted in alternating 2:1 or 4:1 row patterns. Fertilization was with 67.2 kg/ha of $P_2O_5$ and 22.4 kg/ha of $K_2O$. N was applied at 112 kg/ha to pure-stand sorghum and was reduced according to the proportion of sorghum in the polyculture stands.

IRRI (1973) determined that, although groundnut yields were reduced by polyculture with both sweet corn and tomatoes, the value of produce was greater with polyculture and was highest when groundnuts, tomato, and sweet corn were all planted together.

These results indicate that widespread use of groundnuts in polyculture appears economically justified. Where comparisons have been made between groundnuts and other species in association with the same crops (Seshadri et al., 1956; Reddy et al., 1965; Varma and Subba Rao, 1969), groundnuts have always given the greatest economic return. Part of this success is doubtless due to their

relatively high cash value as well as their adaptability to association with other crops.

***Polyculture with small grains.*** In what was apparently the first economic analysis of polyculture, Gliemeroth (1950) showed that the difference in the relative prices of peas and oats had a considerable effect on the value of the mixtures. Profits with pea-oat mixtures were always 25–35 percent greater than with the pure-stand oats. As the proportion of peas in the mixture increased, profits increased because the peas brought a much higher price than the oats, this was still true even if the total crop yield decreased. The economic analyses were based on both pre-war and post-war prices. The experiments were carried out over three years at Weende and Holtensen, Germany, on a light soil and heavy loam soil, using three oat and three pea varieties of different plant type with the peas sown at three densities.

Another example of the difficulty that arises because of different prices and demand for products was provided by Gupta and Mathur (1964) who were trying to devise the most profitable way to produce linseed on a light loam soil of average fertility in India. Linseed, wheat, and gram (*Cicer arietinum*) were grown in pure stands and linseed was grown with wheat, gram, or wheat and gram at two populations of the intercrops. Averaging the results of five years of experiments, the most profitable planting was wheat grown in pure stand, a solution which does not satisfy the intention of producing linseed. The greatest linseed production was from pure stands, but this was one of the least profitable growing methods. The three-crop mixture at the higher population of intercrops was almost as profitable as growing wheat alone. This is another situation in which polyculture provided a means of maximizing the production of two parameters, in this case linseed and cash profit, which would not be possible through the use of monoculture.

On seven farms in the Zaria region of northern Nigeria, Norman, Bumpers, and Goddard (1970) attempted to evaluate the economics of incorporating a package of improved practices (N and P fertilization, closer spacing, and improved varieties) in two crop combinations: groundnuts-sorghum-millet and sorghum-millet. In the case of the three-crop mixture, increases in economic return resulting from improved practices were cancelled out by the 22 percent more labor they required. In the case of the soybean-millet system, improved practices increased yields of both crops, net economic return by 22 percent, and return per man-hour of labor by 10 percent with only a 3 percent increase in the total labor requirement. Farmers seemed to be more receptive to improving practices with the millet-sorghum association than with the millet-sorghum-groundnut mixture. In the same region of Nigeria, Andrews (1972) found the value of production from one row of sorghum alternating with one row of pearl millet followed by cowpeas, or two rows of sorghum alternating with two rows of millet followed by cowpeas, to be greater than from sorghum in pure stand or from a sequential monoculture of millet and cowpeas.

At a completely different environment and level of technology at Urbana, Illinois, Dillon and McKibben (1972) attempted to evaluate relay planting of

soybeans into winter wheat as compared to pure stands or consecutive monoculture, a practice not always feasible as a result of early frosts. It was found economically more advantageous to relay soybeans into wheat than to grow just a monoculture of wheat. However, because of the higher labor expenses involved, relay cropping was less advantageous than growing a monoculture of soybeans. Two consecutive soybean crops were no more successful than a single wheat monoculture because the soybeans were frost-killed. Thus, relay cropping was recommended to winter wheat farmers, but not to soybean farmers.

In an experiment with polyculture of maize and rice, IRRI (1975) showed that, because of variation in the relative prices of the different crops, an LER of greater than unity did not necessarily indicate greater profitability for polyculture. In an experiment with a mixture of IR-8 rice and Early Thai Composite maize, the LER ranged from 1.3–1.5 but the total value of the produce was greater with pure-stand maize at N levels above 50 kg/ha. However, the cost of the fertilizer was not included in the calculation and price relationships could change. In the eastern Amazon region of Brazil, Kass (1976) found that the net return of manioc–rice polyculture was greater than that of manioc alone with or without weeding. When no weeding was done, a monoculture sequence of rice and cowpeas produced a greater net return than a rice–manioc mixture. The situations were not strictly comparable, however, and cowpea prices were quite high at the time. The mixture had a slightly higher labor requirement than did either of the monocultures.

Economic analyses of experiments with polyculture of small grains and other crops have emphasized the importance of relative prices of the crops in determining the profitability of various cropping systems. In all the cases cited here, changes in prices would have considerably altered the results of the economic analyses since profits often had little relationship to other measures of productivity.

***Polyculture with pigeon peas.*** In experiments carried out for two years in a well drained sandy loam, poor in N, medium in P and K, with a pH of 8.0 near New Delhi, India, Sarat, Singh, and Ahlawat (1975) found that intercropping mungbeans, urdbeans, cowpeas, or soybeans (but not maize or sorghum) with T-21 pigeon peas produced a significantly greater net return than pigeon peas in pure stand. All plots received 25 kg/ha N and 75 kg/ha of $P_2O_5$, while sorghum and maize received an additional 75 kg/ha of N in two applications. On the other hand, Gooding (1963) reported that a five-year experiment at Kanpur, India, showed that pigeon peas in pure stands yielded more and gave a greater income than seven commonly grown mixtures.

***Complex mixtures.*** A number of experiments in recent years have measured the comparative profitability of rather complex cropping systems involving a considerable number of crops. While such experiments may approximate actual cropping systems, it is difficult to draw any general conclusions from them since the individual treatments usually differ from each other with respect to several factors.

In an experiment designed to find ways of recuperating losses when drought

destroyed a rice crop in the Philippines, seven cropping systems were tested. These included pure stands of sorghum, sweet corn, and sweet potatoes; and soybean-sweet corn-sweet potatoes, mungbean-sweet corn, sweet corn-sweet potatoes, and sweet potato-sorghum mixtures. The greatest net return was obtained with the soybean-sweet corn-sweet potato combination. Labor utilization was highest with combinations containing sweet potatoes and lowest with those containing sorghum (IRRI, 1973). In the same year, the researchers studied six different cropping systems containing sweet corn, cowpeas, mungbeans, soybeans, sweet potatoes, and sorghum in various monoculture and polyculture combinations. Although the systems involved anywhere from two to six crops, no relationship between cropping intensity and net return was observed. Labor requirement was also unrelated to net return. In terms of net income and net income per day of labor, sweet corn followed by a sweet corn-sweet potato mixture was the best system. Several of the more profitable systems had a high credit requirement, however. Net income of the systems was related to marketable carbohydrate products but not to digestible protein products (IRRI, 1973). These results appeared to be affected by the fact that sweet corn sold at a much higher price than any of the other crops so that any system containing it was extremely profitable. In the following year, cropping systems involving rice, cowpeas, sweet potatoes, soybeans, mungbeans, and various vegetables grown with and without weeding were investigated. The profitability of the different systems again appeared to be more related to the crops involved than to the degree to which polyculture was practiced. Systems involving sweet potatoes and vegetables were most profitable with respect to both cash and labor investment. Although systems including several legumes produced more digestible protein, they were generally not very profitable (IRRI, 1974).

Similarly, on a Typic Dystrandept, fine isohyperthermic, in Costa Rica (Pinchinat and Oelshlegel, 1975), the crops involved affected the profitability of the cropping systems. Systems involving beans and not rice were the most profitable. At three levels of fertilization, polyculture of maize, manioc, and beans followed by pure stands of soybeans or sweet potatoes produced greater gross returns (minus fertilizer costs), than did monoculture sequences of either soybeans and rice, bush beans and soybeans, or climbing beans and sweet potatoes. However, few farmers in the area used monoculture sequences.

Working with an eroded, poor, red-yellow podzolic soil in Lampung, South Sumatra, Indonesia, Syarifudin et al. (1975) compared mixed cropping and intercropping systems of maize, rice, sorghum, groundnuts, rice beans, and manioc with sequence monocultures of maize, rice, and rice beans with and without fertilizer, mulch, liming, and insecticide treatment. Without any inputs, costs of the three systems (mixed cropping, intercropping, and sequential monoculture) were about the same but the crop value from mixed cropping and intercropping was about twice the costs while there was no net return from sequential monoculture. For intercropping, costs of fertilizer, lime, mulch, and insecticide, increased by U.S. $250 per year and production by $663 per year; costs by $265 per year and production by $439 per year for mixed cropping; and costs by $306 per year and production by $506 per year for sequential monoculture. Time for

operations for fertilized plantings was 1722 man-hours/ha for mixed cropping, 1553 man-hours for sequential planting, and 1131 man-hours/ha for intercropping. Strip cultivation was practiced with intercropping which reduced the labor required considerably.

Paner (1975) reported a much greater return in the Philippines when ginger was intercropped with mungbeans, soybeans, bush sitao, or cowpeas than when it was grown alone. Greatest return was with bush sitao. Vegetables gave similar results with various intercrop sequences; the exception was a sweet corn-sweet potato-mungbean sequence that gave less profit than pure-stand ginger.

Soria et al. (1975) found that polyculture could equalize labor use during the year, especially for crops such as manioc, whose labor requirements are very poorly distributed. At the prices prevailing in Costa Rica when the analyses were made, monoculture systems involving manioc and sweet potatoes were profitable while those involving maize and beans were not. Combining the crops in polyculture systems reduced losses from the less profitable crops on the Typic Dystropept. Without fertilization, a system consisting of beans associated with manioc and followed by pure-stand maize was more profitable than pure stands of manioc and beans or than a three-crop monoculture of maize, but less so than two sequential monocultures of sweet potatoes. With fertilization, manioc in pure stands was also more profitable.

On a Mahaas clay of montmorillonitic mineralogy, pH 6.6, to which apparently no fertilizer was applied, Sastrawinata (1976) in the Philippines found higher gross and net returns above variable costs and higher returns on labor with polyculture of maize and manioc than a maize sequential monoculture or manioc in pure stands. Maize was planted at 50,000 plants/ha and manioc at 20,000/ha in all systems.

Although the work of IRRI (1973, 1974) showed that profitability of cropping systems was dependent chiefly on the crops involved and their relative prices, other researchers (Pinchinat and Oelshigle, 1974; Soria et al., 1975, Sastrawinata, 1976) showed polyculture to be more profitable than sequential monoculture of the same crops. Most investigators found the labor requirements for polyculture higher than for monoculture (Norman et al., 1970; IRRI, 1974; Baker and Norman, 1975, Sastrawinata, 1976), although Syarifuddin (1975) did not. The return per unit labor was not necessarily higher for polyculture (IRRI, 1974, Sastrawinata, 1976). However, Baker and Norman (1975) found it less than in monoculture for sorghum, groundnuts, and cotton; but in an earlier publication (Norman, 1974), the greater return-per-unit-labor was cited as a benefit of polyculture. Probably, the crops involved have a greater effect on the labor requirements and returns per unit labor of the cropping system rather than do any specific characteristics of the system itself (IRRI, 1973; Norman et al., 1970).

***Conclusions.*** Experimental findings have emphasized the importance of the choice of crops and their relative prices in determining the profitability of polyculture. While the advantages of cotton–groundnut and maize–bean mixtures seem relatively independent of price relationships (Pillai et al., 1957; Lepiz, 1971; CIMMYT, 1974), it was shown that extremes of prices may affect the profitability of these mixtures as well (Patil and Koraddi, 1960, Willey and Osiru, 1972; Pin-

chinat and Oelshigle 1971). With other combinations, price differentials had a considerable effect, making polyculture extremely profitable when a high value crop was introduced into a monoculture of a low value one (Ghemeroth, 1950; Bodade, 1964; Gupta and Mathur, 1964). It would be wrong to assert, however, that this would be a good criterion for determining which crops to combine in polyculture. The growth habit of groundnuts, as well as its relatively higher price, was responsible for its success in association with cotton or castorbeans, both of which bring a higher price than groundnuts. On the other hand, crops such as sorghum, millet, maize, or cowpeas reduced returns (Reddy et al., 1965; Varma and Subba Rao, 1969).

With regard to labor requirements, choice of crops appeared to be significant in determining both a cropping system's total labor requirement and return per unit of labor, although such analyses have not been made for a great range of crops or cropping systems (IRRI, 1973, 1974; Syarifuddin, 1975; Sastrawinata, 1976).

There was considerable evidence, however, that polyculture was distinctly less profitable at higher management levels, especially at high fertility levels (Norman et al., 1970; IRRI, 1974, 1975; Pinchinat and Oelshigle, 1971; Sorta et al., 1975), which indicates that its widespread use at low management levels is justified.

Probably considerably more information could be derived from economic analyses of production of the same crops in monoculture and polyculture systems if experiments were designed to keep the effect of differences in price and labor requirements from becoming overly significant. In the more complex experiments, the choice of crops generally had a greater effect on economic returns than did the choice of cropping systems.

### Effect of polyculture on incidence of pests and diseases

It has been suggested that species grown in polyculture would be less subject to attack by plant diseases and pests (Evans, 1960; Ruthenberg, 1971; Apple, 1972; Norman, 1974). Aiyer (1949) suggested that polyculture would reduce the incidence of diseases and pests by (1) preventing spread because of greater separation between susceptible plants, (2) one species serving as a trap crop for a disease or pest to which another is susceptible, and by (3) the associated species serving as a repellant for a disease or pest of another species. However, Aiyer also cited three ways by which polyculture may increase the incidence of pests or diseases: (1) reduced cultivation and greater shading due to the presence of associated species, (2) associated species serving as alternate hosts, and (3) crop residues of the species first harvested remaining in the field and serving as a source of inoculum. One or more of these mechanisms have been invoked by investigators of polyculture to explain increased incidence of certain pests or diseases in cropping systems under study. However, most have not offered any suggestions on the mechanisms involved when noting that reduced or increased pest or disease incidence occurred. The cases of both increased or decreased pest incidence are enumerated below.

***Increased incidence of pests.*** Because of inability to cultivate a maize-soybean mixture, Brown (1935) stated that greater weed growth occurred with a

maize-soybean mixture than with pure-stand maize and that the weeds served as a breeding ground for Diabrotica beetles, whose larvae are a pest of maize. Robinson (1960) noted a greater incidence of pea aphids on peas grown with oats than on peas grown alone. Willey and Osiru (1972) noted that an attack of gall midges on the bean pods seemed to be worse in polyculture plots because the mixtures provided a more humid and shady environment. Soria et al. (1975) observed that Chrysomelidae preferred sweet potatoes during the establishment stage when grown with beans. These were the only instances of increased pest occurrence that the author reported, and in none of the cases did he state that the pests contributed to reduced yields.

***Decreased incidence of pests.*** Brown (1935) noted that in Louisiana budworm infestation in pure-stand maize was greater than in maize associated with soybeans, even though there appears to have been more moculum present in polyculture plots. Aiyer (1949) mentioned that polyculture with safflower, a spiny plant, would keep cattle out of fields. IRRI (1973) found that interplanting tomatoes with cabbage reduced the number of adults and eggs of the diamondback moth (*Plutella xylostella* L.) on cabbage plants. It was felt that the odor of the tomato plants repelled or disturbed the *Plutella* adults.

The most extensive study of the effect of polyculture on pests was carried out at IRRI (1973, 1974) to see how groundnuts intercropped with maize would reduce incidence of the corn borer (*Ostrinia furnacalis* Guenee) on the maize. It was found that interplanting groundnuts in the maize at either 20,000 or 40,000 maize plants/ha reduced infestation by the corn borer as measured by the number of borer-infested plants, borer number per plant, and the number of feeding or exit holes and tunnels. These parameters were also reduced by a lower maize population, but were even further lowered by intercropping with groundnuts at the lower population. The researchers felt that groundnuts provided a better habitat for borer predators. The results of further studies at IRRI (1974) are listed below.

1) Green interrow cover (green burlap) reduced oviposition on maize plants but not as much as groundnut intercrop. A combination of groundnuts and green burlap reduced oviposition still further, indicating that the borer adults responded to both olfactory and visual cues.

2) The groundnuts intercrop did not influence the survival or establishment of first instar larvae that were artificially introduced on the maize plants.

3) There was some evidence that groundnuts provided a more favorable habitat for spiders, especially *Lycosa* spp., which were significant predators on borer larvae. The effect of the groundnut intercrop on borer population and damage could be diminished considerably by use of a broad-spectrum insecticide that killed spiders.

Sastrawinata (1976), also working at IRRI, found that maize-groundnut and maize-soybean polycultures reduced the number of corn borer egg masses, tunnels, larvae, pupae, and pupa cases on maize plants at both 40,000 and 20,000 maize plants per hectare. Reducing the maize population lowered the borer population but not as much as did intercropping. At 40,000 maize plants/ha but not at 20,000 plants/ha, maize-groundnut intercropping resulted in significantly

fewer pupae, pupal cases, and larva + pupa + pupal cases than did maize–soybean intercropping. Sastrawinata felt that maize monoculture in Indonesia would probably result in the corn borer becoming a significant pest.

In northern Nigeria, Baker and Norman (1975) reported that cowpeas were less attacked by insects when grown in mixtures. Crookston (1976) reported on work in Oklahoma in which untreated cotton yielded 24 percent higher in association with sorghum than did pure-stand cotton treated with insecticides. The reason for this was that the sorghum served as a habitat for cotton bollworm predators. Francis, Flor, and Prages (1977) reported a lower incidence of fall army worms (*Spodophera*, spp.) on maize associated with bush beans planted six days before the maize than on pure-stand maize or on maize associated with climbing beans planted seven days after the maize.

The work of IRRI and Crookston present the best documented cases of reduction of insect pests due to polyculture. All other reports amount to little more than casual observations.

***Increased incidence of diseases.*** IRRI (1973) reported increased incidence of soybean rust in a susceptible variety (Shih-Shih) when it was interplanted with maize and when the maize population increased. IRRI (1974) also noted greater incidence of leaf diseases (Cercospora and rust) in mungbeans intercropped with maize than when planted in monoculture. This was especially true when maize population and fertilization were high. In the eastern Amazon region of Brazil, a humid region where the disease is prevalent, Kass (1976) noted greater incidence of brown spot (*Cochliobolus miyabeanus*, Ito et Kuribayashi, Dreschsler ex Dastur) on rice grown in polyculture with maize and manioc than on rice grown in pure stands; this was evidenced by a greater percentage of rice leaves showing symptoms of the disease. Polyculture of rice with manioc had no effect on the number of leaves affected 70 days after rice emergence. This difference was attributed to the increased shade offered by the maize plants which were taller than the rice, while the manioc was shorter. IITA reported more severe Cercospora leaf spot in groundnuts grown with maize than in those grown in pure stand. Van den Bergh (1968) noted that a species may carry a virus not harmful to itself but destructive to an associated species.

***Decreased disease incidence.*** Paner (1975) reported no difference in the intensity of Cercospora leaf mold, bacterial wilt (*Pseudomonas solanacearum*), and Sclerotium stem rot on okra, tomato, bush sitao, and mungbeans, respectively, planted in the open or under coconut trees in the Philippines. Ubi showed more leaf spot (Gleosporium) when planted in the open than under coconut. Similarly, there was no difference in intensity of mosaic on squash, cowpeas, batao, pole beans, and pepper planted in the open and under coconut. On ginger, leaf spot was more severe in the open than when shaded, although leaf blight and red spot were not.

Sotta et al. (1975) reported that the incidences of *Oidium manihotis* and of rust were higher on beans grown in pure stand, especially during and after flowering, than in polyculture with manioc and maize, respectively. They felt that maize acted as a natural barrier impeding free dissemination of fungal spores.

IITA (1975) reported differential attack of rosette and leaf spot on groundnuts grown alone and intercropped with maize. Rosette attacked 64.9 percent of the groundnut plants in pure stand but only 36.5 percent of those intercropped with maize. Rust was more serious on maize, and virus on sweet potatoes, when they were grown alone than when grown together.

Sastrawinata (1976) reported no effect of intercropping on the incidence of downy mildew in maize, but lowering the maize population did reduce incidence of the disease. To make such a low maize population economic, it would be necessary to intercrop the maize with another crop.

***Conclusions.*** In general, there would seem to be no clearcut benefit or detriment from polyculture with regard to pest control. However, one exception was the clearly reduced incidence of the corn borer in polyculture with groundnuts and, to a lesser degree, with soybeans (IRRI, 1973, 1974; Sastrawinata, 1976). With diseases, it would be difficult to distinguish the effects of polyculture from those of reduced plant populations and increased shading (Paner, 1975; Kass, 1976; Sastrawinata, 1976), situations that are variously more favorable for some diseases and less favorable for others.

Another effect of polyculture on diseases and pests is that one species may show increased growth when the other is injured or destroyed by disease. De Wit (1960) suggested this possibility, citing as evidence the finding of Reestman (1946) that healthy potato plants surrounded by plants affected with leaf roll yielded more per plant than when surrounded by healthy plants. Etheridge and Helm (1924) suggested that soybeans would yield more in a maize–soybean mixture if the maize were attacked by chinch bugs, which generally do not infest soybeans. Klages (1936) showed that the percentage of durum wheat harvested from a mixture of hard red spring wheat and durum wheat was increased when the spring wheat was attacked by stem rust. However, an attack of rust on barley at a later stage of development had no effect on the proportion of barley harvested from an oat–barley mixture. Gliemeroth (1950) found that when oats were attacked by wireworms, leading to a reduced stand, the yield of peas sown with oats was much greater than the reduction in the oat yield — oat yield was reduced by one-half while pea yield was increased fourfold. Like Klages (1936), IRRI (1975) found that elimination of one species had to occur relatively early for the other to take advantage of the increased available space. However, as suggested by de Wit (1960), it would seem that the nature of the yield components of the particular crop, to a considerable degree, determine its ability to make use of increased environmental resources which become available at a later stage of development due to elimination of the associated specie by insects or disease.

### Long-term effects of polyculture

Most investigators have concentrated on the yields of crops in a particular mixture and not on the long-term effects of polyculture on soil condition and subsequent crops. Because, as was shown earlier, polyculture removes more N, P, K, Mg, and Ca from the soil than does monoculture, less of these elements are available for subsequent crops when this system is used. On the other hand, nu-

trients that remain in the soil are naturally subject to losses by leaching and erosion and perhaps are better removed in a crop. Furthermore, if polyculture exploits a larger volume of soil, residues from such a system might make nutrients available to subsequent crops with more restricted rooting systems.

When a legume was involved in a polyculture system, the possibility always existed that the N it fixed might be available to subsequent crops (Kinney and Roberts, 1921; Etheridge and Helm, 1924), perhaps even more than it is to crops grown concurrently (Agboola and Fayemi, 1972). Although they found them otherwise undesirable, Noll and Lewis (1921) recommended the use of maize-soybean mixtures for this purpose. Kellerman and Wright (1914) found that when grown in tarred, paraffined wire baskets filled with stiff, silty clay loam from the flats of the Potomac River, mixtures of peas or beans with barley depleted soil N less than pure stands of peas or barley but more than beans grown alone. However, the plant tissues of the mixtures contained more N than they did in all pure stands. On the basis of calculations using the N content of plants rather than of the soil, Etheridge and Helm (1924) concluded that less N would be removed from the soil by a soybean-maize mixture than by a pure-stand maize crop. They calculated that a maize-soybean mixture could only increase soil N if a low maize population were planted and the entire crop were pastured. On the other hand, Ayres (1925) reported that cotton yielded 2400 lbs/acre after a single year of soybean-maize mixture as compared to 1800 lbs/acre following pure-stand maize in the Mississippi delta.

Lyon (1925) carried out a five-year rotation, on a clay loam moderately responsive to N, apparently without added fertilizer. In the first year (1919), the whole area was planted with wheat. In the second year, it was divided into three parts, one planted with wheat undersown with red clover, one planted to timothy, and one planted with rye. In the following year (1921), each of the three areas with oats alone. In the fall, all six areas were planted with winter wheat. In the next year (1923), after the wheat was harvested, the whole area was planted next year (1923), after the wheat was harvested, the whole area was planted with fodder corn and in the following year with wheat (1924). In the area planted with red clover in the second year, there was little difference in wheat yields following oats or oats with peas, wheat yields following pure-stand oats were slightly greater. In areas planted with timothy or rye in the second year, the grain yields and, to a lesser extent, total dry matter yields of subsequent crops were considerably greater following the oat-pea mixture than following pure-stand oats. Unfortunately, the experiment was not replicated, for it is somewhat surprising that a single year of red clover or a single season of peas associated with oats could have such a considerable long-term effect. However, pea development was quite good in the mixture, yielding more than 3000 lbs/acre of grain + straw following timothy, and about 2500 lbs/acre following rye, but less than 1300 lbs/acre following clover. Yield of wheat grain, but not straw, was lower following the oat-pea mixture than after pure-stand oats in the area where peas had yielded most, but in subsequent years, yields were greater following the oat-pea mixture.

The greater yield of maize associated with soybeans than of maize grown in pure stand in the third, fourth, and fifth years of the continuous cropping

experiment of Brown (1935) has already been noted (page 17). Soil samples taken at the end of the five-year experiment showed total organic matter, percentage of N, and acid soluble K greater in the plots cropped with the maize–soybean mixture than in those planted with maize alone. There was no difference in total $P_2O_5$ or pH. Cotton planted on the plots in the following year, although heavily attacked by boll weevils, was taller and yielded twice as much following the maize–soybean mixture as it did following pure-stand maize. In contrast to the experiment of Lyon, there were four replicates in this experiment, carried out on a Denham silt loam in Louisiana.

Following unsuccessful polyculture with maize and various legumes, for which yields were not given, on an unspecified soil on the southern coast of Guatemala, Fuentes (1954) replanted all plots with pure-stand maize. He found that yields following certain legumes were up to twice as high following certain maize-legume mixtures as those following pure-stand maize. The best results were obtained with Crotolaria species and pigeon peas. Fuentes said that such a response was expected since the soil's fertility had been depleted by previous crops of rice, bananas, and maize.

Gautam, Shah, and Nair (1964) ran an experiment for two years in a sandy loam, pH 8.2, medium in N and available P, at the Indian Agricultural Research Institute near New Delhi, in which maize was both grown in pure stands and associated with various legumes and then was followed by a crop of wheat. In the first year, maize yields were low (about 1200 kg/ha), although slightly but insignificantly increased by association with soybeans, mungbeans, and sannhemp; but wheat yields following maize–mungbeans and maize–sannhemp were significantly higher than following maize alone. In the second year, maize yields were higher (3200 kg/ha) but were not affected by association with legumes even when 90 kg/ha of $P_2O_5$ were applied by different methods (banding, broadcast, and banding combined with foliar application). Wheat yields following the maize–legume mixture were about the same following pure-stand maize. In the second year, 132 kg/ha N, 90 kg/ha $P_2O_5$, and 67 kg/ha $K_2O$ were applied to the plantings. Fertilization in the first year was with two levels of N, P, and K but the quantities were not stated. The authors felt that in the second year (in contrast to the first) the maize had taken up all of the applied N, leaving little for the subsequent wheat crop, which appeared N deficient. Yields of wheat were higher in the second year, however.

Koregave (1964) found that associating sannhemp with elephant yam increased the N content more than did growing pure-stand elephant yam. This experiment was carried out at the Yeravda Central Prison Farm at Poona, India, on a medium black, well-drained fertile soil, previously planted to banjal, that was fertilized with 9 metric tons/acre of farmyard manure. Because N fertilizer (groundnut cake and ammonium sulfate) was topdressed during the course of the experiment, it was not surprising that N content of the soil increased in all plantings. Because the yield of the intercrops was not reported, it is difficult to determine what significance should be given to the finding that the increase in soil N was about the same for elephant yam grown in pure stand or associated with cluster beans or lucerne.

As described earlier, working with ferruginous tropical soils of the Ibadan and

Iwo Series in Nigeria, Agboola and Fayemi (1971) showed that over successive cropping seasons, yields of maize grown in association with cowpeas, calopogon, or greengram, increased in comparison with those of pure-stand maize. In another experiment on soils of the Ibadan series, with three replicates, to which 15 kg K and 20 kg P per hectare were applied, maize yields were 1790 kg/ha for pure-stand maize, 1850 kg/ha for maize associated with cowpeas, 3080 kg/ha for maize associated with greengram, and 1850 kg/ha for maize associated with calopogon (Agboola and Fayemi, 1972a). When residues of these legumes and maize were ploughed under and maize alone replanted five months after the first planting, the plot which had pure-stand maize yielded 1210 kg/ha; that which had had maize and cowpeas, 1970 kg/ha; that with greengram, 1510 kg/ha; and that with calopogon 2120 kg/ha. This indicates that greengram had a greater benefit on associated maize while cowpeas and calopogon had a greater benefit to subsequent maize crops. Application of 45, 90, or 135 kg/ha of N to the plantings made the effect of the associated legumes completely insignificant. In an ancillary experiment, soils from 0–15 and 15–30 cm depth of the plots were taken at the time the first planting was harvested, placed in pots, and planted with maize. There were four replicates. After eight weeks, the tops were harvested and analyzed for N. It was found that maize grown in soil from pure-stand maize plots contained 21 mg N; from the maize-greengram plots, 51 mg N; from the maize-cowpea plots, 43 mg N; and from the maize-calopogon plots, 35 mg N. They calculated that the legumes had increased the N content of the top 30 cm of the soil by 23–30 kg/ha, the greatest increase being with greengram. Follow-up experiments attempted to show that greegram released more soluble N compounds into the soil solution than did cowpeas or calopogon. The researchers speculated that cowpeas and calopogon increased soil nitrogen levels chiefly through decomposition of crop residues. Total N fixation by cowpeas and calopogon was greater than it was by greengram, however.

Sixteen weeks after maize planting in a loam soil in Trinidad, Dalal (1974) could find no significant differences among pure-stand maize or pigeon peas, pigeon peas planted either in the same or alternate rows as maize, and plots left fallow, with respect to soil pH, exchangeable Mg and K, available P, and total N. Exchangeable Ca was lower in the plot with pure-stand maize than in those grown with pure-stand pigeon peas or left fallow, but was not significantly different from the polyculture plots. Organic C was highest after sixteen weeks of pure-stand pigeon peas, but did not differ between the fallow and polyculture plots; it was lowest by a significant degree with pure-stand maize. Alternate rows of maize and pigeon peas led to significantly more mineral N in the surface soil than did all other systems. It should be remembered, although the maize was mature at the time of sampling, the pigeon peas were not harvested until eight weeks later and produced most of their growth in the later stages of development. Thus, Ca content of the maize was higher than in all other cropping systems at 16 weeks; but by 24 weeks, all plantings containing pigeon peas had accumulated more Ca than did maize in pure stands.

On a Quartzipsammentic Haplorthox, sandy, oxidic, isohyperthermic, under a high rainfall regime in the eastern Brazilian Amazon, Kass (1976) measured changes in exchangeable soil Mg and K to a 40 cm depth over one year under dif-

ferent cropping systems. He found very small differences in changes in soil K; but loss of soil Mg was significantly less under polyculture of rice and manioc than under pure-stand manioc.

With the exception of Kass (1976), all polyculture systems whose effects on soils or subsequent crops were determined involved legumes; and with the above exception and that of Brown (1935), who reported higher soil K following maize-soybean mixtures than following pure-stand maize, all effects could be explained by increases in soil nitrogen. Of the experiments reviewed in this section, only two authors (Lyon, 1925; Gautam et al., 1964) reported instances where polyculture with a legume failed to benefit subsequent crops; but too few experiments have been run to be certain that this practice will always have a positive effect. As Lyon (1925) showed, the fertility of the soil as well as its preceding use will have a considerable influence on the long-term effects of polyculture.

**Stability of yields**

Morrish (1931) suggested that because conditions for growing either crop might vary considerably over the course of several years, an oat-barley mixture would produce a more stable yield than pure stands. Thus, in the three years in which he ran experiments in Michigan, yields of mixtures of Wisconsin 38 barley and Wolverine oats varied from 1724 to 2805 lbs/acre while pure-stand yields varied from 1377 to 2730 lbs/acre. Mixtures of Spartan barley and Markton oats varied from 1852 to 2428 lbs/acre as compared to a range of 1544 to 2292 lbs/acre for pure stands. Papadakis (1941) grew six different legume-cereal mixtures at six sites in Greece. The coefficient of variability for yields among different sites was 49 percent for pure-stand cereals, 65 percent for pure-stand legumes, but only 34 percent for mixtures of the two. He concluded that mixtures were less hazardous than single crops.

Similarly, Gliemeroth (1950), in a three-year experiment at two sites in Germany, showed that yields of mixed stands of oats and peas exhibited a smaller variance over different years and locations as well as within each site than did pure-stand oats and peas. His results also showed that the benefits of an oat-pea mixture would be greater where conditions for pure-stand oats were unfavorable.

Greater yield stability was suggested by Jensen (1952) as an advantage offered by multilines of cereal crops. Subsequent experiments with multilines of oats (Jensen, 1965) and soybeans (Lin and Torrie, 1971) showed that yields of multilines indeed varied less from year to year than did pure lines of these crops.

Prine (1960) stated that there would be less chance of total crop failure with polyculture since environmental conditions might be favorable for one, if not both, of the crops in a mixture. Thus, Patil and Koladdi (1960) found that polyculture of cotton and groundnuts was most profitable in a year in which excessive rainfall practically destroyed the cotton crop. Bodade (1964) also stated that polyculture would minimize the effect of crop failures. Singh et al. (1973) recommended that soybeans always be planted in polyculture rather than in pure stands because the chances of crop failure from virus and rust in India are so great that an associated crop could prevent a planting from being a total loss. As discussed earlier, they found that maize yielded more when associated with soybeans than when

grown alone and that adjacent pure stands of maize and soybeans would not be as beneficial as the mixture.

In the area of Mexico where the Puebla project was set up (CIMMYT, 1974), rainfall was not sufficient for production of a maize crop every year; some drought damage occurred in 60 percent of the years. The researchers felt that associating beans with maize would assure a successful crop every year.

The hypothesis of greater yield stability for polyculture was doubted by IRRI (1975), but their contention was based on the results of a single year's experiments. They pointed out that unless a crop were eliminated relatively early, the other crop would be unable to make use of the added space and the eliminated crop might still reduce yields of the surviving one considerably. They concluded that there was no real benefit to polyculture. They felt that damage to a crop at the early stage when the associated crop could compensate for the loss could just as readily be overcome by replanting. Their evidence was based on a limited number of crop combinations (maize-mungbeans, maize-rice, and maize-soybeans) in which both crops had generally similar growth cycles and climatic requirements. Cases of drought damage, not considered by IRRI, but frequently cited by other authors (Crocioni, 1951; Anthony and Willimott, 1957; Andrews, 1972; CIMMYT, 1974) have generally occurred too late in the season to be offset by replanting.

Relay cropping of winter wheat in Ohio (Triplett, Beuerlein, and Kroetz, 1976) or oats in Illinois (Brown and Graffis, 1976), respectively, with soybeans was considered unreliable although experiments found an LER of greater than one for the oat-soybean combination in Illinois. The researchers felt that farmers would have considerable difficulty in achieving the rapidity of operations necessary for successful relay planting. Also, adequate rainfall and weed control for the soybean crop were unreliable. It should be noted that these conditions would also make sequential cropping of the wheat or oats with soybeans impossible and the choice for the midwestern farmer is generally between a single crop of soybeans, oats, or winter wheat and relay cropping.

In conclusion, those authors who measured yields from polyculture over several years generally found them to be more stable than those obtained from monoculture. Researchers who doubted this hypothesis did not measure the variability of yields over several years.

### Effects of polyculture on cultural practices

Cultural practices developed for monoculture might not be practicable with polyculture (Aiyer, 1949; Prine, 1960; Andrews, 1972). Mechanization and development of specific practices for monoculture have been cited as principal causes for the decline of polyculture of legumes and maize in southeastern U. S. (Prine, 1960).

Although they recognized that growing mixtures of maize and soybeans would create some difficulties in management, several of the earlier researchers (Etheridge and Helm, 1924; Ayres, 1925; Thatcher, 1925; Mooers, 1927; Hackleman et al., 1928; Brown, 1935) felt that benefits from the practice offset the disadvantages. Yet, Noll and Lewis (1921), Kinney and Roberts (1921), and Odland (1930) did not feel that the benefits were sufficient to counteract the added

work of planting, cultivation, and harvest. The authors who recommended the use of maize-soybean mixtures often suggested means of reducing the labor involved. Etheridge and Helm (1921) suggested that maize stover and soybeans be pastured by sheep and cattle following harvest of maize for grain. Lake Weaver (1924), they also reported benefits of hogging off the maize-soybean mixture, which would reduce the labor required in harvesting. Difficulty in planting could be reduced, they suggested, by planting alternating double rows of maize and soybeans. However, yields from this system were somewhat lower than with alternating single rows. Ayres (1925) suggested mixing the maize and beans and planting them together with conventional grain drilling equipment, while Brown (1935) used a one-horse planter with a duplex hopper with six cups on each side for planting alternate hills of maize and soybeans. He also suggested that the labor required for harvesting could be reduced by harvesting maize grain first and then gathering maize stover and soybeans for hay.

Aiyer (1949) felt that the additional operations required for harvesting and the difficulty of mechanization were major disadvantages of polyculture. He also felt that the fact that one crop remained on the field after the harvest of the other would prevent turning under residues, leading to problems with disease and insects. Mirchandi and Misra (1957) compared seeding wheat with peas or lentils in the same row, seeding one or two rows of wheat alternating with a single row of legume, and cross-sowing the wheat and legume. This latter practice was the most amenable to mechanization. No significant differences in yield of wheat, peas, or lentils were found to result from the different seeding methods although the yields of peas and wheat were slightly higher with cross-seeding than with the other methods. Evans (1960) felt that mechanization would be the only justification for the abandonment of traditional polyculture. Prime (1960) attributed abandonment of the common and, in his opinion, beneficial practice of intercropping groundnuts and maize in the southeastern U. S. to the widespread use of the farm tractor and heavy fertilization. Schilling (1965) also saw mechanization as a serious drawback to polyculture.

Dillon and McKibben (1972) showed that relay cropping was the only feasible way of realizing a double crop of winter wheat and soybeans under the conditions found in Urbana, Illinois; but the practice would require good management to get adequate plant populations and good weed control with the soybean crop. As was pointed out earlier, relay planting was found to be more economical than a single wheat crop but not more than a single soybean crop.

Recent work in Africa has shown polyculture to be superior to pure stands when crops were grown in alternate rows and at high levels of fertilization (Andrews, 1972; Willey and Osiru, 1972; Osiru and Willey, 1972; Haizel, 1974). According to these authors, such a system would be amenable to mechanization although they did not actually attempt it in their experiments. Such work has been criticized by Norman (1974) as being completely irrelevant to the social and economic constraints under which most polyculture in Africa is practiced. This paper has already shown that an attempt to introduce improved cultural practices (spacing, fertilization, and improved varieties) into traditional systems in northern Nigeria was promising for sorghum and millet but not for sorghum-groundnut-millet mixtures (Norman et al., 1970).

Work at IRRI (1972) uncovered rather obvious disadvantages to polyculture in a ridge and furrow system. The crop in the furrow interfered with drainage, and cultivation in the furrow could not be practiced with a hand tractor. When planted on the flat, however, maize intercropped with mungbeans yielded more than pure-stand maize at lower levels of weed control (no weeding, one pass with a hand tractor with a rotary cultivator, or butachlor at 0.6 or 1.2 kg active ingredients per hectare). With more complete weed control (hand weeding or 2.4 kg a.i./ha of butachlor), pure-stand maize yielded more than maize intercropped with mungbeans. In the following year, weed control increased economic return much less with polyculture of maize and mungbeans than with pure stands of these crops. Experiments in which different power sources were compared for planting and cultivation offered little information about the effect of polyculture because the same crops were not involved in the monoculture and polyculture systems (IRRI, 1974).

Labor requirements for all operations in sequential planting, intercropping, and mixed cropping of rice, maize, and ricebeans were determined by Syarifuddin et al. (1975) in South Sumatra, Indonesia. The polyculture treatments also included groundnuts and manioc. As was pointed out earlier, labor requirements were highest for mixed cropping and lowest for intercropping. All operations (planting, weeding, fertilizing, and harvesting) with the exception of harvesting manioc required less labor with intercropping than with mixed cropping even though they were all performed by hand.

At Urbana, Illinois, in 1975, encouraging results were obtained from cross-seeding Williams soybeans in Otee oats six weeks after the oats were planted. When the oats were cut for silage, seven weeks after the soybeans were planted, the soybeans were 12 in. tall. Leaving a 6 in. stubble, the soybeans were cut off above the unifoliate leaves and below the first trifoliate leaves. The soybeans recovered, however, producing one branch from each unifoliate leaf axil, and yielded 40 bu./acre as compared with 53 bu./acre for pure stand soybeans. The oats produced slightly more dry matter than in pure stand and had a higher crude protein content as a result of the presence of soybean tops. If the oats were combined for grain, about three weeks after the time of cutting for silage when the soybeans were almost as tall as the oats and had already flowered, the soybeans made little further growth and remained as tall as the oat straw. Yields were 83 bu./acre of oat grain and 28 bu./acre of soybeans as compared to 95 and 55 bu./acre for pure stands, giving an LER of 1.37. No herbicides were applied, and the soybeans matured two weeks earlier when the oats were combined for grain. In a related experiment, grain sorghum and a sorghum-sudan grass hybrid were successfully established in oats by cross-drilling. There was no reduction in yield of oats harvested for silage or grain. Although the plantings were only made in a single year, the authors felt that further experimentation with planting rate and row width as well as with variety selection would improve chances of success (Brown and Griffis, 1976).

Triplett et al. (1976) surveyed farmers in Ohio who had attempted to relay soybeans into winter wheat by both airplane and conventional seeding methods. Although fewer farmers had seeded by conventional methods, soybean yields were no lower than with airplane seeding. Only 40 percent of the fields surveyed

produced enough soybeans to pay for the cost of seeding. Low stands, resulting from unevenness and weediness, insufficient rainfall, and late wheat harvest, were considered to be the major cause of poor soybean yields. They felt that reliable herbicides for the relay-cropped soybeans were not yet available. The researchers felt that under Ohio conditions, sequential planting would produce reliable results in 5 of 6 years and that attempts at relay cropping were not justified.

Crookston (1976) reported on a completely mechanized harvest of maize intercropped with sugarbeets in Canada. Maize and sugarbeet tops were harvested for silage, then the beets were dug. The results of these different experiments suggest that mechanization of polyculture is thoroughly practicable at least with certain crops. As more attention is turned to the practice, the technological difficulties will probably be solved. The problem of the small farmer who lacks the means to mechanize any of his operations and adapt practices which could benefit traditional systems remains.

### Other effects

Several results of crop mixtures, such as the provision of a continuous and varied supply of fresh food (Aiyer, 1949; Bodade, 1961, Miracle, 1967) could just as well as be provided by a diversity of pure stands (IRRI, 1975) as by polyculture. Most crop quality considerations have been previously discussed in the section on protein production. Bhoj and Kapoor (1970) reported that the percentage of sucrose in sugarcane juice did not change as a result of intercropping, although such an increase had been previously reported in India.

Reduced lodging is, however, frequently cited as a benefit of polyculture (de Witt, 1960; Robinson, 1960; Andrews, 1972, Brown and Graffis, 1976), but whether this results from one species supporting another or the decreased nitrogen status of the plants does not appear to have been examined.

### Conclusions

In all of the different aspects of polyculture considered — yield, plant constituents, economic return, pest and disease control, yield stability, long-term effects, and the effects of cultural practices — experimental evidence suggests that polyculture is more often beneficial than detrimental. The case for polyculture appears weakest with regard to the incidence of pests and diseases and the difficulty of the cultural practices it requires. The literature on polyculture includes as many cases of increased incidence of pests and diseases as it does decreases. With regard to cultural practices, polyculture certainly provides problems for a mechanized operation, but recent work (Brown and Graffis, 1976, Crookston, 1976) has shown that methods can be devised to make use of the system's possible advantages. As for the majority of the world's farmers, who do not possess the means to mechanize their operations, considerable evidence has been presented on the yields, economic returns, labor requirements, and long-term effects on soil fertility of polyculture to indicate that their situations could worsen if they adopted monoculture cropping systems. Because there appears to be little justification for them to abandon their present cropping systems, research should

be directed toward increasing the efficiency with which these farmers use the resources available to them.

## General Conclusions and Recommendations

### Advantages and disadvantages of polyculture

We have shown that the literature generally indicates that polyculture is beneficial. However, the choice of crops and other environmental variables will, to a considerable extent, determine whether the practice is advantageous in specific situations. Assuming that the experimental work carried out thus far represents an adequate sample of the situations in which polyculture is practiced, it can nonetheless be concluded that definite advantages over monoculture exist. In terms of withdrawal of nutrients from the soil, economic return, improvement of the nitrogen status of the soil-plant system when one of the crops is a legume, and greater stability of yields over time, the benefits of polyculture are clear. With regard to ease of harvest and other mechanized operations, polyculture offers some problems, but recent research, aimed at reducing these difficulties, has been surprisingly successful (Brown and Griffis, 1975; Triplett, 1976).

### Effect of cultural and environmental variables on success of polyculture

The question remains whether the experimental work carried out thus far permits the prediction of situations in which polyculture will be more beneficial than monoculture. In the following sections, the effects of species, soil type, climate, plant type, and social factors on the relative benefits of polyculture and monoculture will be considered.

***Species.*** It was pointed out in the section on economic analyses that certain species and combinations of species appear to perform more successfully in polyculture than do others. Associations involving cotton, groundnuts, and maize-legume combinations appear to be more successful than other mixtures. It is interesting to note that these systems are most frequently encountered in the literature, perhaps indicating that they are the most commonly used by farmers. More complex mixtures, often involving one or more vegetable crops, have often proven to be quite successful (IRRI, 1974). However, it was the price relationships of specific crops, rather than the cropping systems themselves, that appeared to be the critical factor in this case.

Although never subjected to economic analyses, mixtures of small grains appear to give a slight yield advantage over pure stands (Zavitz, 1927; Jensen, 1952), such mixtures are still grown in Europe, Turkey, and Canada. Mixtures of small grains with other crops would appear to be less consistently worthwhile (Dillon and McKibben, 1972; IRRI, 1975) and success would appear to depend on the price of the associated crop (Gliemeroth, 1950).

***Soils.*** An extremely small number of investigators have carried out experimental work with polyculture over a range of well-characterized soils. Gliemeroth (1950) suggested that pea-oat mixtures would do better in sandy soils than in

heavier soils because of the better adaptability of peas to the lighter-textured soils; this supposition was confirmed by Robinson (1960) in Minnesota. Pilz (1911) had somewhat more success with barley–pea mixtures in heavy clay loam than in a light clay loam, but the experimental designs differed with the two soils. Lyon (1924) stated the benefits to subsequent crops from an oat–pea mixture would probably be less on a light-textured soil, but he performed no experiments to confirm this. Brown (1935), however, found less benefit from a soybean–maize mixture in a heavier alluvial soil than he did in a Denham silt loam in Louisiana, although the experiments on the two soil types were not strictly comparable. As Lyon (1924) pointed out, fertility status, especially with regard to N and soil type, would have a great effect on the benefits resulting from polyculture, particularly when a legume was involved. Lugo Lopez et al. (1953) observed in Puerto Rico that soybeans reduced the yield of associated sugarcane in a Coto clay but not in a Vega Baja silty clay.

It would appear from these few experiments that polyculture is more advantageous in lighter-textured soils, possibly either because the lower fertility makes graminaceous crops more likely to benefit from an associated legume or because the legumes themselves do better in the lighter-textured soils. Speculation about other combinations is impossible because all experiments involving more than one soil type included leguminous crops.

***Climate.*** The effects of climatic changes on polyculture have been somewhat more documented than the consequences of variability in soil type. Most of these observations involve performance in a wet and dry season in the tropics, rather than year-to-year variability in the same cropping season.

IRRI (1974) found that maize–legume mixtures were most advantageous in the dry season, with the LER always greater than one. Maize–rice systems, on the other hand, were more advantageous in the wet season when they made better use of the farmer's resources and gave a greater cash return. Another series of experiments (IRRI, 1975) showed greater mutual interference of maize and mungbeans when grown in the wet season, because of its more cloudy weather and lower light intensities. Also, in the Philippines, Paner (1975) found that several legumes (mungbeans, bush sitao, peanuts, and soybeans) yielded more if planted one week prior to maize harvest during the dry season but did best when planted following the maize harvest in the wet season. Similarly, Reddy and Chatterjee (1973) in W. Bengal, India, found that soybean–rice intercropping was more successful in the dry season than in the rainy season when the soybeans produced luxuriant vegetative growth and competed with the rice.

An interesting example of how climatic relationships may affect the advantages of polyculture was provided by Patil and Koraddi (1960) working in North Karnotak, India. They found that, in rainy years when cotton yielded less, the associated groundnuts did so much better that the intercropped system was more profitable.

However, polyculture systems are more common in dry areas and generally perform better during dry seasons. Perhaps, as several authors observed (Gupta and Mathur, 1964; Bodade, 1964), polyculture makes more efficient use of water. Although this does not appear to be consistent with the greater exploitation of soil resources by crop mixtures, several authors have described mechanisms by

which associated crops may use water more efficiently than monoculture or obtain soil water not available to the monoculture crop.

Aiyer (1949) stated that polyculture would only be beneficial in this regard if the associated crops had different rooting depths; if the rooting zones overlapped, no benefit would result. In this connection, Crocioni (1951) reported that a maize-potato association was more successful than a sunflower-potato association because the root system of maize was more superficial than that of sunflower; in other words, the sunflower root system competed more with the potato. However, in a dry year, when maize yields were decreased by drought, the potato yields were greater since competition from the maize also declined. The potato-sunflower association, on the other hand, was not affected by variations in climate.

Baldy (1964) maintained that cover crops would induce deeper rooting of apples and grapes in orchards. A similar mechanism was proposed by Andrews (1972) for millet-sorghum polyculture in which plant densities of each species are lower. In this situation each plant would produce a larger root system, with that of sorghum going deeper than that of millet, and permitting it to sustain drought better in the dry season. The same argument was given by Kassam and Stockinger (1973) who also noted that the sorghum grown in association with millet would have a somewhat smaller above-ground mass at the time of millet harvest than sorghum grown in pure stand. The smaller plants would transpire less and hence have a smaller demand for water. Describing a cropping system involving maize, sorghum, and millet used in northern Nigeria, Baker and Norman (1975) stated that the demand for water was reduced since the millet was planted first at the beginning of the rainy season and sorghum alone remained at the end of the rainy season.

Paner (1975) measured water consumption by different crops grown in pure stands and in polyculture in the Philippines. Total consumptive use was greater for polyculture than for monoculture but total yield was also greater. Pure stands, however, produced more yield per inch of water consumed than either crop in polyculture. Despite this fact, Paner claimed that his data showed that polyculture made more efficient use of water than monoculture. At best, interpretation of his data is complicated by the very different water requirements of the crops (soybeans and sorghum) involved.

Some authors maintain that polyculture consumes more water than corresponding monocultures. Singh (1973) got better results from intercropping sorghum and soybeans in a wet year than in a dry year, and Prine (1960) observed that maize intercropped with groundnuts and soybeans appeared to suffer more from drought than a monoculture of maize grown at the same time.

In summary, despite the more obvious conclusion that polyculture, in producing more dry matter and consuming more nutrients than corresponding monocultures, will require more water, several authors maintain that polyculture is able to obtain water not available to the monocultures or to use the water obtained more efficiently. Unfortunately, experiments of the sophistication necessary to determine whether these mechanisms indeed operate are yet to be performed.

***Plant type.*** Because the nutritional requirements and physiology of varieties within a single species may vary more than those of different species, it is not surprising this phenomenon has also been described in the literature on polyculture.

Ghemeroth (1950) grew three different pea varieties in all possible combinations with three different oat varieties at three different seeding densities in Germany. He found that a short high-yielding pea (Zeiners *kurz-und-gut*) did best in pure stand. In polyculture, tall pea varieties did best and did not reduce oat yields significantly. Also, the yields of the oat variety (Flaming) which yielded highest in pure stand were reduced more sharply than the other oat varieties in polyculture. All three oat varieties yielded about the same in monoculture. Pea yields were highest with a short-statured oat (Silberhafer) with narrow, erect leaves and were lowest with a tall oat type (Baseler) with wide, droopy leaves. Total grain yield was highest with Flaming oats and the taller pea variety. However, monetary return was greatest with Silberhafer oats where yield of peas, whose price was much higher than that of oats, was highest.

In Mexico, Lepiz (1971) grew bush and pole beans in association with maize at different plant populations. He found that maize yields were more negatively affected by increased populations of pole beans than of bush beans. However, maize yield was not always higher with bush beans, and the pole bean variety used appeared to be more productive than the bush bean variety in all situations, perhaps because it matured later. Hence, combinations with pole beans were always more profitable. The work of Lepiz illustrates the complexity of interactions frequently encountered in experimentation with polyculture.

Further work with the interaction of different plant types of maize and beans has been carried out by Francis (1976) at CIAT in Colombia. Maize of two different plant types (Normal ICA H-2080; and Brachytic ICA H-210) were grown with bush (ICA Pijao) and climbing (PI 282-230) bean types. Higher populations were used for the tall maize and bean types. Total biological yield of the maize varieties did not differ but the harvest index (HI) for the tall maize was greater. Bush bean yields were reduced by 52 and 63 percent respectively when intercropped with normal and dwarf maize, while climbing bean yields were reduced 90 and 80 percent when cropped with normal and dwarf maize. Maize yields did not differ significantly in any planting so that the highest LER was obtained with normal maize and bush beans; however, total grain yield was highest with brachytic maize combined with bush beans. Francis (1976) listed the following varietal characteristics that should be desirable for species grown in polyculture:

1. *Photoperiod insensitivity* — allowing the planting of varieties at any time during the year and giving flexibility to new systems requiring planting outside the traditional dates;
2. *Early maturity* — permitting more intensive organization and greater flexibility for intercropping or relay-cropping systems;
3. *Short and nonlodging plant types* — reducing competition for foliage and light;
4. *Population responsiveness* — allowing greater flexibility for varying the population of crops in a mixture according to the current economic returns, and for obtaining the highest total field population of the intercropped system.

Working with different crops under high levels of management in the 1973 wet season in the Philippines, IRRI (1974) found that rice yields were reduced more by a tall maize (Thai Early composite) than by a short maize (Penjalinan) although maize yields were reduced only slightly over pure stand yields in both cases. Since it yielded more, return was greater with the taller maize despite its longer growing season. These results suggest that the plant characteristics listed above would not always ensure good performance in polyculture.

IRRI (1974) has also screened mungbean varieties for suitability for intercropping with maize, and of the 12 tested, reductions in yields were found to be less for two varieties in particular. In polyculture experiments in Taiwan, Chao (1975) found that Tainan-5 corn reduced soybean yields less than did Tainan-9 corn. Although it yielded less, total return with Tainan-5 corn was greater.

These findings should illustrate that it is necessary to consider the effects of both crops on each other in determining the most suitable plant type for use in polyculture. In most of the above cases, results contrary to those expected were obtained because plant characteristics of only one species were considered. Furthermore, the widely differing cash values of the crops involved may make an increase in the yield of one crop less profitable if the yield of the associated crop is reduced.

***Social factors.*** Several investigators (Igbozurike, 1971; Norman, 1974; Harwood, 1975) have emphasized the important role that polyculture plays in the human and physical environment of traditional agricultural communities in the tropics. The system is widely recognized as being as characteristic of such communities as is slash-and-burn agriculture (Nicol, 1935; Webster and Wilson, 1966). It should be clear from this paper that the present restriction of polyculture to such communities is a relatively recent phenomenon; and the practice was once much more widespread (Brown, 1935; Jensen, 1952; Prime, 1960).

We have pointed out that polyculture probably does not account for a large share of the world's total food production; but, in communities where it is practiced, it is common to find almost all of the food supply coming from polyculture systems (Baker and Norman, 1975; Francis et al., 1976). Because there is little prospect that the food supply systems of these communities will change in the near future, whatever schemes are proposed to improve their food supply must deal with the reality of polyculture.

It has been shown that while actual labor requirements of polyculture may be higher than of monocultures of the same crops, return per unit labor is often higher with polyculture. Under traditional agriculture, polyculture appears also to equalize labor requirements over the year and to make better use of other limited resources. The often inconsistent results obtained by IRRI (1973, 1974, 1975) from experiments in farmers' fields should emphasize the necessity of taking into consideration how profoundly polyculture appears to interact with human and social factors in traditional farming communities.

## Suggestions for further research

This paper probably does not cover all of the research that has been carried out in the world on the relative merits of polyculture and monoculture cropping

systems. What does emerge from a consideration of the literature, however, is the realization that most of the supposed advantages or disadvantages of polyculture are poorly documented. Experiments were generally run over a limited range of environmental and cultural variables and insufficient data were presented to conclude whether a specific mechanism was indeed operating. Adequate characterization of the soils in the experiments was also generally lacking. Specifically, the following areas appear to require further clarification:

— Recent studies (Pinchinat and Oelsligle, 1971, Kassam and Stockinger, 1973; Sastrawinata, 1976) indicate that polyculture delivers more nutrients into the biomass than do monoculture systems. Further studies are necessary to confirm these results and measure more accurately the comparative efficiencies of the systems;

— The possibility that water use by polyculture systems is more efficient or that more water is available to these systems should be investigated further, such a finding could have considerable implications for areas with limited rainfall;

— The relative efficiency of the use of energy and other resources by polyculture and monoculture systems should be measured more carefully and over a wider range of conditions than it has been up to the present;

— More research is necessary on long-term effects of the two kinds of systems on the fertility status and physical condition of soils;

— Ways should be found to lower the labor requirements of polyculture which some research has found to be higher than for monoculture;

— Communities where polyculture is important should be studied in order to understand better the role it plays in their economies and the consequence of changes in polyculture systems;

— A methodology should be developed for making adequate comparisons of polyculture and monoculture;

A better understanding of the interactions involved in polyculture systems is necessary so that research, especially in plant breeding, can improve their efficiency.

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