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Evaluation of Crop Production Systems Based on Locally Available Biological Inputs

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Crop production systems that require chemical fertilizers, pesticides, machinery for tillage, and irrigation water are expensive. In countries such as India, they have started to undermine the water security of future generations, contributing to soil and water pollution particularly when synthetic pesticides are not used properly. It is true that agriculture as practiced 100 years ago without modern inputs had lower productivity than present systems of production. However, many premodern practices, such as the use of organic manures to enhance soil fertility and of herbal extracts to protect crops, can be made more efficient by the scientific knowledge that has been gained over the past century, making crop production more sustainable while still achieving high productivity.

This is becoming more evident from the published literature on practices such as the use of organic manures and biopesticides (e.g., Carpenter-Boggs et al., 2000; Stockdale et al., 2001; Kough, 2003) and experience with conservation tillage (discussed in Chapters 22 and 24). This chapter reports the results from an ongoing, long-term experiment started at ICRISAT in June 1999 on a rainfed Vertisol at Patancheru, Andhra Pradesh, India. It examines the possibility of achieving high yields using low-cost inputs, plant biomass in particular, that are available within the vicinity of the farm or that could be produced *in situ*. The field trials utilized biological approaches reported in the published literature and from traditional knowledge.

While some of these methods require considerable labor, more than many large farmers might be able or willing to invest, they could be relevant to a large number of small and marginal farm households in the semiarid tropics that have family labor available but very little cash. The methods reviewed here are proving to be profitable in terms of their returns to labor as well as to the other factors of production.

35.1 Designing Crop Production Systems for Sustainability

Production practices, such as putting on crop residues or other biomass as surface mulch, using compost and green manures, intercropping of legumes in cropping systems, and biocontrol of insect pests and diseases, all help to enhance yields and sustain soil fertility and health (e.g., Willey, 1990; Reganold et al., 1993; Fettell and Gill, 1995; van Keulen, 1995; Mäder et al., 2002; Delate and Cambardella, 2004;). Appropriate use of such biologically-based approaches has been reported to enhance soil microorganisms and macrofauna (e.g., Kukreja et al., 1991; Fatondji, 2002), thereby enhancing microbial transformations of different nutrients from bound to available form. These various approaches can be combined into an integrated soil–plant–animal cropping system for attaining sustainable high yields. Such a system, depicted in Figure 35.1 below, has been tested since 1999 and is explained below.

While a variety of crops and practices are known to be able to contribute to farming system success, it is not known to what extent they can be used jointly in ways that are sufficiently productive and profitable, as well as sustainable, to improve the lives of farmers. It is not necessary that any system be advantageous for all farmers, since no single

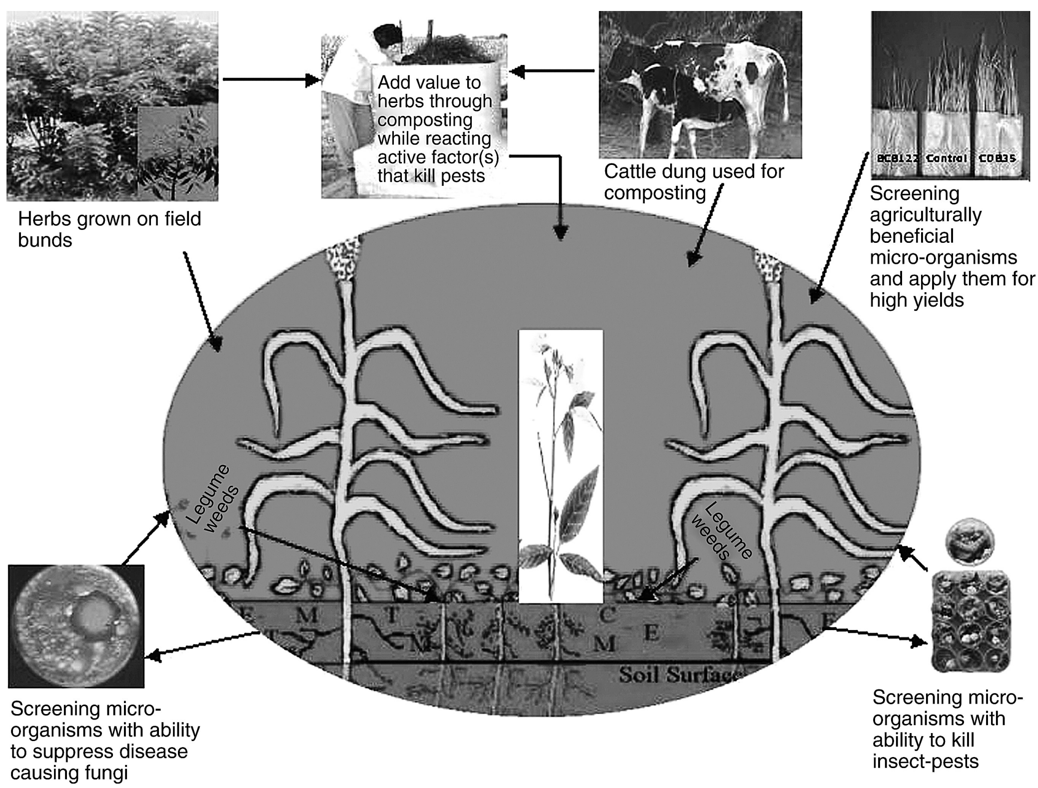

FIGURE 35.1
Elements of a biologically-based, integrated soil-plant-animal cropping system.

farming system should be expected to be optimal for everyone. Our effort was to design a crop production system that could be particularly beneficial for small landholdings. It drew on existing knowledge that:

- Legume and nonlegume crops can improve soil fertility when grown as intercrops (as examined further in Chapter 39).
- Crop residues produced *in situ* can improve the soil's physical and biological properties when retained as surface mulch, without tillage.
- Selected weeds can promote crop growth when grown under the main crop, i.e., not all weeds are deleterious.
- Where relevant or required, some amount of external inputs, preferably low cost, can be applied to the soil or crop on an as-needed basis to good effect.
- Certain soil microorganisms have beneficial traits, e.g., biological nitrogen fixation, plant growth promotion, or antagonism to disease-causing soil organisms (fungi, nematodes) or to insect pests. These can be effectively applied either as soil inoculants or sprayed on plants.
- Certain plant extracts sprayed on crops in a timely way, according to traditional knowledge, can protect crops from many if not all insect pests.
- Compost can be more than a source of nutrients for the soil, being also a soil-building substance and a source of beneficial microorganisms (Chapter 31).

As seen from our results, these practices are indeed quite compatible with one another, and as discussed in Chapter 17, cattle should be regarded as an important component of such systems. In the system that we designed and tested, only the grain produced is exported from the system. Crop stover is retained as surface mulch. Where stover is needed for economic purposes, e.g., as cattle feed, an equivalent quantity of biomass having no such economic value is returned to the field, i.e., foliage or loppings from shrubs or trees grown on field bunds or from outside the farm. The system is understood to function as a single entity, within which all of the functions in the soil, among plants, and at the soil−plant interface are highly interactive for producing yield.

Such a system is relevant to millions of small and marginal farmers in developing countries of the humid, subhumid, and semiarid tropics. About three-quarters of farmers in India have either small holdings (0.4 to 1.4 ha) or marginal holdings (<0.4 ha). They have little scope to benefit from technologies or implements designed for larger farms. This does not mean, however, that these small holdings are less productive. Actually, on a per-hectare basis they usually outperform larger farms, even by orders of magnitude (Feder, 1985; Rosset, 1999). Larger farms operate extensively rather than intensively and amass their higher total returns from their size of operation rather than from greater factor productivity or efficiency. The model presented in Figure 35.1 assumes that small and marginal farmers can and will mobilize family labor, their major asset, to undertake intensive crop and animal management if this is productive and profitable enough, i.e., if they can get higher returns per hour or per day of labor invested.

35.2 Design of the Long-Term Experiment

To examine whether yields comparable to conventional agriculture can be attained using the kinds of strategies and inputs reviewed in the preceding section, a multiyear experiment was designed to compare and evaluate four different systems of crop husbandry (T1 to T4). Since it was assumed that very small farmers would own few animals and therefore would not have enough manure, the use of other organic matter was planned for. However, the systems being tested would benefit from the addition and incorporation of animal production and the use of animal wastes, whatever the availability. The results reported can quite certainly be improved upon to the extent that animals are incorporated into the farming system. We did not want our findings to be limited to a better-case scenario.

The major objective of the experiment was to learn whether plant biomass, added to three of the four systems evaluated, could be used profitably as surface mulch (serving as a source of crop nutrients) instead of being burned, which is common practice in South Asia (Sidhu et al., 1988). Details of these four systems are given in Table 35.1. Note that T3 is the treatment most similar to conventional current cropping systems, i.e., relying for its nutrient inputs on inorganic fertilizers, while T1 and T2 represent low-cost systems where crop nutrients are provided from biomass inputs, in addition to what can be mobilized from the soil through biotic activity. T4 is a combination of conventional and alternative systems as it receives the same organic inputs that are provided for T2 plus the T3 chemical fertilizer applications.

The experiment is being conducted on a 1.5 m deep Vertisol, with pH in the top 15 cm ranging from 8 to 8.2 and with electrical conductivity 0.16 to 0.22 dSm^{-1}. The area is fully rainfed, with annual mean rainfall at Patancheru of 783 mm. This allows two crops to be grown in a year, either as intercrops (in all years) or as sequential crops, with a probability of success in 6 of 10 years, given the possibility that the rains can fail. To be certain of some production, given the variability in timing of rainfall, second crops have to be sown as intercrops during the rainy season, in June or July. In each year of the first 6 years of the experiment, different crops were grown, as seen in Footnote to Table 35.1, but they were always the same across all four treatments. The experiment is providing an excellent field site for testing the overall hypothesis that treatments receiving high biomass as a source of nutrients — and that consequently exhibit high soil biodiversity and support higher levels of biological activity (both intervening variables being tested in our experiment) — will produce good agronomic results.

Rather than conduct the experiment on a large number of small replicated plots, the design was to use larger plots, 0.2 ha for each treatment, with a total area of 1.02 ha including noncropped area. This design has permitted observation of the effects of using biopesticides (bacteria in particular) for insect–pest management on fields of normal size and under conditions matching those of farmers' fields. We have monitored *Helicoverpa* pod borer, the major pest in the area, and also two of its natural enemies as well. This approach to evaluation of field-scale treatments is not new (Guthery, 1987; Guldin and Heath, 2001). It seems acceptable and appropriate for our purposes of evaluation since small replicated plots could not control for and assess so well the effects of above- and belowground biotic relationships.

Each of the treatments, T1 to T4, has 30 plots, each 9 × 7.5 m, laid out in six strips with five plots. Observations for yield and some other parameters have been made and analyzed for all plots. For those observations that are more costly, such as soil properties, samples are drawn from all the plots and are pooled strip-wise (and depth-wise where relevant) before analysis. There are thus 30 data points (internal replications) for parameters such as yield in our evaluation, with six data points (based on internal replications) for the different soil properties.

The concepts of sustainable agriculture expressed in Figure 35.1 apply to the first two of the four treatments, T1 and T2, in this ongoing experiment. They receive plant biomass as their major source of crop nutrients and depend on herbal extracts and agriculturally

TABLE 35.1

Treatments Used in a Continuing Long-Term Experiment at ICRISAT, Patancheru, India, June 1999 to December 2004[a]

Treatments	T1	T2	T3	T4
Inputs	Low-cost system I, based on rice straw	Low-cost system II, based on farm waste	Conventional agriculture	Conventional agriculture + T2 biomass
Land preparation and intercultivation	None	None	Conventional (bullock plow)	Conventional (bullock plow)
Sowing	Bullock-drawn drill	Bullock-drawn drill	Bullock-drawn drill	Bullock-drawn drill
Microbial inoculants	Added	Added	None	None
Biomass (first 3 years only)	10 t ha^{-1} yr^{-1} with rice straw as surface mulch	10 t ha^{-1} yr^{-1} with farm waste, stubble and hedgerow foliage as surface mulch	None	10 t ha^{-1} yr^{-1} with farm waste, stubble and hedgerow foliage incorporated
Compost	1.5–1.7 t ha^{-1} yr^{-1}	1.5–1.7 t ha^{-1} yr^{-1}	1.8 t ha^{-1} in years 2, 4, 6	1.8 t ha^{-1} in year 2, 4, 6
Fertilizer (N)	None	None	80 kg N ha^{-1} in 2 split doses yr^{-1}	80 kg N ha^{-1} in 2 split doses yr^{-1}
Fertilizer (P)	20 kg ha^{-1} as rock phosphate	20 kg ha^{-1} as rock phosphate	20 kg ha^{-1} as single super phosphate (SSP)	20 kg ha^{-1} as single super phosphate (SSP)
Plant protection	Biopesticides	Biopesticides	Chemical pesticides	Chemical pesticides
Weeding	Manual, weeds retained	Manual, weeds retained	Manual, weeds discarded	Manual, weeds discarded

[a] Same crops were grown in all plots each year: Crop rotations for all four treatments were: *Year 1*. Pigeon pea-chick pea sequential (June 1999 to May 2000); *Year 2*. Sorghum/pigeon pea intercrop (June 2000 to May 2001); *Year 3*. Cowpea/cotton intercrop (June 2001 to May 2002); *Year 4*. Maize/pigeon pea intercrop (June 2002 to May 2003); *Year 5*. Cow pea/cotton intercrop (June 2003 to May 2004); *Year 6*. Maize/pigeon pea intercrop (June 2004 to May 2005), pigeon pea not yet harvested.

beneficial microorganisms as soil inoculants and biopesticides. Both are cultivated with minimum tillage, where only the sowing is done with bullock-drawn implements. For the first 3 years, T1 received 10 t ha^{-1} of rice straw and T2 was given the same quantity of farm waste (crop stubble, leftovers after cattle have eaten, and tree leaves). Both treatments received these applications as surface mulch soon after sowing.

The conventional agriculture treatment, T3, received: 80 kg N and 20 kg P ha^{-1} yr^{-1}; regular tillage (land preparation, sowing, and intercultivation to remove weeds with a bullock-drawn tropicultor); chemical pesticides for managing pests; manual weeding; and 1.8 t ha^{-1} compost in alternate years. The T4 plots had the same inputs used for conventional agriculture, but in addition, they received 10 t ha^{-1} yr^{-1} of biomass (for the first 3 years only) similar to the T2 plots. This biomass has been incorporated into the T4 plots rather than left as surface mulch. From year 4, no further biomass from external sources has been added to any of the four treatments, except compost at rates shown in Table 35.1. The uneconomic parts of plants, e.g., leaves and stem stover, have all been retained on plots in treatments T1, T2, and T4. From year 5, loppings of *Gliricidia* grown on the plot bunds have been added during the crop growth period in equal quantities two to three times a year to all four treatment plots.

As depicted in Figure 35.1, the foliage of *Gliricidia sepium* and neem (*Azidrachta indica*) has been composted in separate tanks, and the wash from this (50 l ha^{-1} at least five times per season) has been sprayed on plants in T1 and T2 to protect crops from insect pests. The wash from neem, a known biopesticide, and from *Gliricidia* has been found to contain siderophore-producing bacteria (O.P. Rupela, unpublished study). These microbes have also been reported as promoting plant growth (Kloepper et al., 1980).

Certain bacterial preparations, e.g., EB35 and CDB35, which degrade cellulose, solubilize phosphorus, promote plant growth, and suppress disease-causing fungi (H. Bee, unpublished studies), have been applied as sand-coat inoculants and sown along with seeds in T1 and T2. A certain bacterium (*Bacillus subtilis* strain BCB 19) and also a selected fungus (*Metarrhizium anisoplliae*), both ICRISAT research products, have shown the ability under laboratory conditions to kill young larvae of *Helicoverpa armigera*, a major pest of cotton and legumes in the region. These preparations have been used as biopesticides in T1 and T2 only, along with other low-cost materials of traditional knowledge. Earthworms plus cattle dung (applied as 1% dung slurry in water to soak into the biomass as a food for earthworms) are important ingredients for composting in the tank shown in Figure 35.1.

The experiment completed its first 5 years in May 2004, so we are able to report and discuss here all the variables, including yield, with particular attention to soil biological factors. The work is ongoing, so there are also some data from the sixth year. More details on the crop yields are published in Rupela et al. (2005).

35.3 Crop Growth and Yield

The high variability in precipitation that farmers in this region have to cope with can be seen from the annual rainfall totals (in mm) for the different years: 580 (year 1), 1473 (year 2), 688 (year 3), 628 (year 4), 926 (year 5), and 610 (year 6). The different crops grown in the last 6 years (soybean, pigeon pea, maize, sorghum, cow pea, and cotton) all emerged well, including those in T1 and T2, which had to emerge through about 10 cm of biomass applied as surface mulch. The incidence of collar rot, caused by Sclerotium, was expected to increase on T1 and T2 in the presence of biomass, but this problem has been virtually nonexistent ($<5\%$ mortality of seedlings), at par with or even marginally lower than in T3.

Except in year 1, when T1 and T2 yields were 35 to 62% lower as the transition was made to biological production methods, as discussed further below, the yields of the different crops in T1 and T2 over the first 5 years, produced with lower cash cost, have been on a par with T3 or at most 14% lower. The reasonably high yields of pigeon pea in year 2 and of cotton in year 3 for both T1 and T2 were associated with the effective management of *Helicoverpa* by using biopesticides. Conversely, the low yields in T1 and T2 from pigeon pea in 2002 (year 4) and cotton in 2003 (year 5) were associated with poor success in managing insect pests mostly other than *Helicoverpa*. Detailed information and data on crop yields in the different years are given in Rupela et al. (2005). Annual productivity of T1 and T2 — the combined yield of legumes + nonlegumes, e.g., the mass of cow pea grains and seed cotton (lint + seeds) in year 5 — was high in all 5 years except year 1 (Figure 35.2).

Most significant for farmers, the net income from crops in each year except year 1, which was essentially a year of learning, has been higher — even much higher — in T1 and T2 than T3. The differential has ranged between 1.3 and 4.6 times (Figure 35.2), showing that in economic terms, the low-input strategy is proving to be much more profitable. In this calculation, each input was costed (except the cost of biomass and labor). Biomass was assumed to be available with little or no opportunity cost, having been saved from burning and being handled by family labor. Labor is not a free resource, of course, but it is the one most available to poor households, who are primarily constrained in terms of their land area and cash. Thus, labor was not considered to be the resource from which economic returns had to be maximized.

It should be noted that in year 3, there was a substantial loss (US\$156 ha^{-1}) from growing cotton in T3 in contrast to a substantial net income gained from the cotton crop on the sustainable agriculture plots — US\$210 ha^{-1} from T1 and US\$140 ha^{-1} from T2

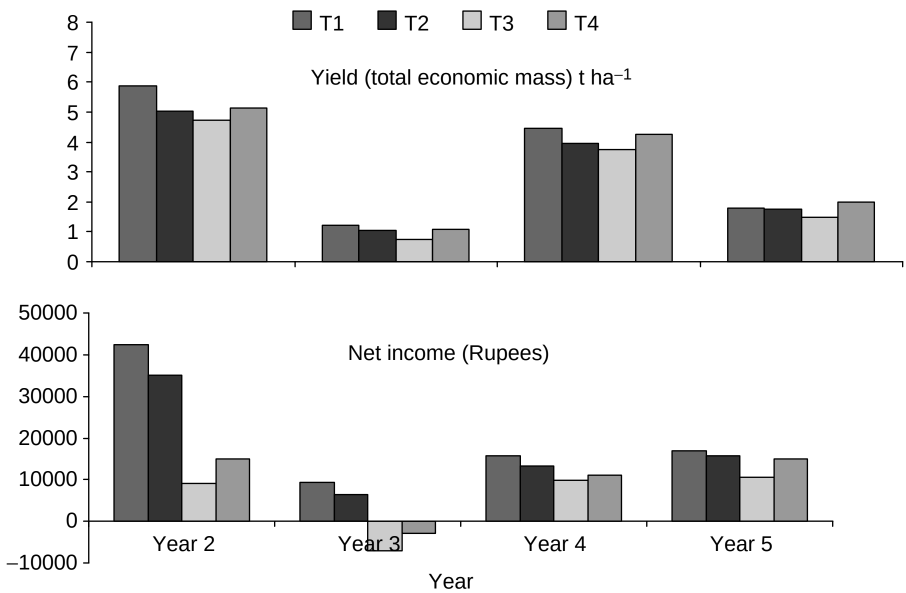

FIGURE 35.2
Yield and net income (in rupees) over years 2 through 5 from the four different systems of crop production (T1 to T4) in long-term experiment at ICRISAT, Patancheru, India. Income was calculated by putting a common price across all treatments for each item (both inputs and outputs). Per-day labor was priced @ Rs. 75 per day for both farmers and family members. (1 US\$ = ~Rs. 45)

(Figure 35.2). The low-input strategy of T1 and T2 has, therefore, in some years performed much better agronomically than the more costly conventional cropping system. This makes the economic advantages even greater.

35.4 Soil Properties and Nutrient Balances

Every year in April/May, for all treatments, soil samples from three depths (0 to 15, 15 to 30, and 30 to 60) were collected from each plot before sowing crops, using a 40 mm diameter soil core. The samples from a set of five plots were pooled as indicated previously and were analyzed for total and available nitrogen, total and available phosphorus, total potassium, and organic carbon. Methods of analysis for the different parameters were the same as described by Okalebo et al. (1993). Soil bulk density measured in April 2002 (at the end of year 3) was similar across the treatments and ranged from 1.19 to 1.36 at the different depths. Electrical conductivity and pH were measured. Data for total nitrogen, total and available phosphorus for the first 4 years are given in Table 35.2 as means from the three depths for which measurements were made.

It was important to note that at the same time that T1 and T2 produced yields comparable to T3 — without receiving any chemical fertilizer amendments — they actually showed increases (rather than decreases) in their concentrations of soil nutrients compared with T3. In years 3 and 4, there were increases of 11 to 34% in total nitrogen and 11 to 16% in total phosphorus in T1 and T2, relatively more than in T3. However, it was noted that the mean nitrogen and phosphorus in all four treatments, after improving up to year 3, was reduced in year 4 (Table 35.2). The reasons for this reduction are still being considered.

Soil biological properties, presented in Table 35.3, were assessed only once, close to the time of crop harvest in year 5, using soil depths of 0 to 10 and 10 to 20 cm. The methods used were the same as those in Jenkinson (1988) for microbial biomass and microbial biomass nitrogen; in Anderson and Domsch (1978) for microbial biomass carbon; in Casida et al. (1964) for soil dehydrogenase activity; and in Eivazi and Tabatabai (1977) for acid and alkaline phosphatases.

Of the different parameters measured to assess the biological activity in soil samples from the four different systems of crop husbandry, more activity was noted in T1, T2, and T4 compared with T3. Soil respiration was more by 17 to 27% than in T3; microbial biomass carbon was 28 to 29% higher; microbial biomass nitrogen was 23 to 28% more; and acid and alkaline phosphatases were 5 to 13% higher. While these different parameters are reported as point-in-time measurements of microbial activity under laboratory conditions, they depict treatment differences.

In this experiment, 79 to 109 kg N ha^{-1} were noted to be associated with microbial biomass in the top 20 cm profile, which is more than usually reported for such soils, and this needs further examination. Wani et al. (2003) reported 42 kg N ha^{-1} in the top 60 cm profile of plots using traditional methods of cropping, compared with 86 kg N ha^{-1} in plots using an improved system of cropping. The microbially bound nitrogen is likely to be mineralized for use by plants when microorganisms die naturally or due to unfavorable factors, such as soil drying or application of chemical pesticides to soils.

The overall results on the different soil biological parameters strongly suggest that the soils from plots T1 and T2 were consistently more active microbiologically than those of T3 (Table 35.3). While the total bacterial populations were not that different across all four treatments, 5.3 to 5.7 (log_{10} g^{-1} soil), the population of Pseudomonas spp. was about 10

TABLE 35.2

Total Nitrogen (mg kg^{-1} soil), Total and Available Phosphorus (mg kg^{-1} soil) in Top 60 cm profile (Mean of Three Depths: 0 to 15, 15 to 30 and 30 to 60 cm), Field BW3, ICRISAT, Patancheru, AP, India

	Total N					Total P					Available P				
Treatment	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Mean**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Mean**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Mean**
T1	462	569	690	492	553	175	231	253	194	213	1.2	1.7	2.1	0.7	1.4
	(18.0)	(21.1)	(30.1)	(17.5)		(6.3)	(7.0)	(15.7)	(9.0)		(0/08)	(0.34)	(0.31)	(0.24)	
T2	488	643	681	489	575	189	257	263	213	230	0.7	1.3	1.7	0.6	1.1
	(12.6)	(16.2)	(30.9)	(32.4)		(7.2)	(10.5)	(10.9)	(11.3)		(0.02)	(0.26)	(0.33)	(0.24)	
T3	506	651	514	440	528	204	263	227	175	222	1.00	1.4	2.0	0.4	1.2
	(22.1)	(73.4)	(12.3)	(17.9)		(3.9)	(49.2)	(3.3)	(8.1)		(0.13)	(0.34)	(0.29)	(0.11)	
T4	500	588	586	429	526	244	213	232	177	218	0.5	1.6	2.4	0.3	1.2
	(10.5)	(49.3)	(61.9)	(13.4)		(23.7)	(21.1)	(3.9)	(1.8)		(0.09)	(0.34)	(0.47)	(0.10)	
Mean	489	613	618	462		203	247	244	189		0.8	1.5	2.0	0.5	

Data in parentheses are ±SE.

TABLE 35.3

Biological Properties of Soils with Different Cropping System Treatments Assessed in top 20 cm Profile, Field BW3, ICRISAT, Patancheru, Close to Harvest in Year 5

Properties	T1	T2	T3	T4	Mean
Soil respiration (kg C ha^{-1}10 d^{-1})	330 (19.5)	360 (18.6)	283 (14.3)	436 (25.9)	352
Microbial biomass C (kg C ha^{-1})	1550 (110.3)	1535 (120.1)	1202 (66.8)	1510 (104.1)	1449
Microbial biomass N (kg N ha^{-1})	97 (6.7)	109 (8.9)	79 (4.0)	98 (7.5)	96
Organic carbon (t C ha^{-1})	23 (1.5)	20 (1.1)	17 (0.9)	22 (1.1)	20
Acid phosphatase (μg p-NP g^{-1} h^{-1})[a]	310 (38.8)	332 (32.5)	294 (36.0)	357 (39.8)	323
Alkaline phosphatase (μg p-NP g^{-1} h^{-1})[a]	937 (103.2)	1008 (111.3)	890 (114.8)	1011 (113.1)	962
Dehydrogenase (μg $TPFg^{-1}$ $24h^{-1}$)[b]	133 (28.0)	137 (29.2)	130 (23.8)	142 (27.7)	136
Bacterial population (log_{10} g^{-1} soil)	5.6	5.6	5.3	5.7	5.6
Pseudomonas spp populations (log_{10} g^{-1} soil)	4.1	4.6	3.3	3.2	3.8

Numbers in brackets are ±SE

[a] *p*-NP = para nitro phenol

[b] TPF = triphenylformazan

times more in T1 and T2 than in T3 and T4 (4.1 to 4.6 vs. 3.2 to 3.3 log_{10} g^{-1} soil). Several soil isolates of this species are suppressive to disease-causing fungi and nematodes, and this trait can therefore be regarded as an indicator of soil health. The measured differences are likely to be due to the inoculant bacteria that were added at sowing of the T1 and T2 crops each year.

It should be noted that less than 10% of microorganisms that live in the soil can be cultured in laboratory media (Ward et al., 1990). Some researchers think that this number is less than 5 or even 1%. One cannot say the exact number since the denominator is unknown, which is indicative of how little we know yet about the earth's microbiota. This fact suggests, in any case, that soil respiration and microbial biomass carbon and nitrogen are going to be more reliable parameters of soil biological activity, reflecting the total microbial community, than are counts of microbial population using laboratory media.

A balance sheet of nitrogen and phosphorus, the two macronutrients considered critical for crop production, was prepared for all four treatments. For this purpose, all the materials added to the different treatments plots, e.g., crop residues, compost, and those removed (e.g., grain), were fully accounted for. Figure 35.3 shows the amounts of total nitrogen and phosphorus added and removed, and the balance for the first 5 years across the four different crop husbandry systems. T1 and T2, which received plant biomass, compost, and microorganisms as their major sources of crop nutrients, ended up receiving substantially more nitrogen (27 to 52%) and phosphorus (50 to 58%) than was added to T3 (604 kg N ha^{-1} and 111 kg P ha^{-1}, largely as chemical fertilizers). Of course, T4, having both sources, received the largest quantities of nitrogen (1232 kg ha^{-1}) and phosphorus (193 kg ha^{-1}). It is therefore not surprising that T1, T2, and T4 resulted in having a much larger balance of nitrogen (2.5 to 10 times) and phosphorus (12 to 13 times) than was measured for T3 (55 kg N ha^{-1} and 5 kg P ha^{-1}).

This does not mean, however, that the crops in the low-cost systems, T1 and T2, had access to more nitrogen and phosphorus than those in T3, the conventional system. Nutrients when added as biomass are not in a readily available form for crops and need to be mineralized by microbial activity. Also, since the biomass was added as surface mulch, microbial activity at the soil surface might not be sufficient for its decomposition. It is

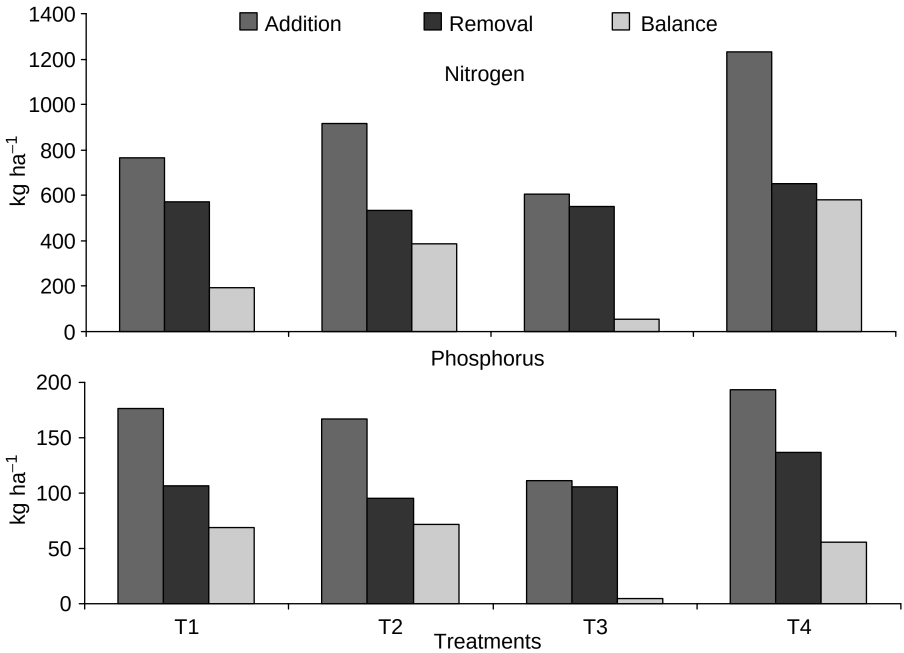

FIGURE 35.3
Nutrient (N and P) balance of the four different systems of crop production (T1 to T4) after five years, in long-term experiments, ICRISAT, Patancheru, India.

widely accepted that only a proportion of the nitrogen applied as biomass to the soil through soil incorporation is recovered by the crop (Schomberg et al., 1994; Thönnissen et al., 2000). According to T. J. Rego, ICRISAT (unpublished data), under Patancheru conditions this proportion would be less than 10% in year 1.

This helps to explain the lower yield obtained in year 1 in T1 and T2 (lower by 35 to 62%) than that produced by T3, which received chemical fertilizer. The longitudinal yield data suggest, however, that in subsequent years, microorganisms, whether in the soil or applied externally, were able to decompose the biomass sufficiently so that the released nutrients could readily meet crop demand, when T1 and T2 yields were on a par with or very close to those from T3.

If T1 and T2 received substantially more nitrogen and phosphorus and their removal was similar to that in T3 (Figure 35.3), then the soil systems of T1 and T2 should have substantially higher amounts of nitrogen and phosphorus. This was observed, at least in the measurements up to the end of year 4 (data for subsequent years are yet to be analyzed). The top 15 cm soil profile for T1 and T2 had 30 to 41% more nitrogen (an additional 355 to 483 kg ha^{-1}) and 0.2 to 17% more phosphorus (an additional 2 to 129 kg ha^{-1}) compared with the level of nitrogen and phosphorus for T3 (1192 kg N ha^{-1} and 746 kg P ha^{-1}). The amounts of nitrogen and phosphorus in the biomass still remaining as surface mulch on T1 and T2 from recent additions are not accounted for in this analysis. Much of the biomass applied at sowing had largely, except for thick plant stems, disintegrated by the end of the rainy season each year, suggesting that all the leafy materials added at sowing time were decomposed during the rains, particularly in a normal to good rainfall year.

35.5 Discussion

From the data collected during the first 5 years of the long-term experiment presented here, it is apparent that the two crop husbandry systems, T1 and T2, which received locally available, low-cost and eco-friendly materials such as biomass and compost, along with agriculturally-beneficial microorganisms, were able to produce yields that match those from the T3 system that relies on purchased inputs, e.g., chemical fertilizers and pesticides, and that also continued conventional tillage practices. Labor was the major input in T1 and T2. While this has opportunity costs for small and marginal farmers, these producers have relatively more access to labor than to cash, so their binding constraint is land and capital rather than labor.

Inputs of the agriculturally-beneficial microorganisms used in this study are not yet widely available, although efforts are beginning, in India, not just to produce them in large commercial operations but also at village level by villagers, as discussed in Chapter 45 (see also Bhattacharyya and Dwivedi, 2004).

In the second year, 20 mm of rain was received in the first week of January 2001, about 10 days before pigeon pea was to be harvested. For a conventional system (T3), this rain meant less strenuous tillage effort for the bullocks after harvest. For the no-till systems (T1 and T2), it was an opportunity to harvest more. Pigeon pea, particularly the non-determinate cultivars, has a tendency to regrow after harvest if soil moisture is conducive. Since such regrowth was noticed, it was decided to harvest by picking pods rather than by the normal method of cutting plants close to the ground. This resulted in 0.69 to 0.77 t ha^{-1} additional pigeon pea harvest, about 25% of total yield. The no-till system gives farmers more flexibility for using opportunities given by nature.

Sowing crops when there is surface mulch is a potential hindrance to adoption of the concept of sustainable agriculture represented in Figure 35.1. Sowing in the long-term experiment described here was done using a bullock-drawn implement. Manual sowing is an option, but both have high labor requirements. Before using the bullock-drawn implement for sowing, we had to rake off the biomass (largely crop stems) from the soil surface and spread it again soon after sowing. A machine punch-planter, which is able to sow crops through surface mulch, has recently become available in India and will be used and evaluated in the future. This machinery will reduce labor requirements substantially.

Earthworms are widely accepted as having a beneficial influence on soil structure and chemistry that promotes plant growth. We have recorded the presence of large numbers of siderophore-producing bacteria (1.2×10^4 to 4.5×10^6 ml^{-1}) in the wash of compost that was made from neem and *Gliricidia* foliage using earthworms (O.P. Rupela, unpublished study). It is likely that other agriculturally beneficial microorganisms, such as ones able to suppress disease-causing fungi, are present in certain compost used by organic farmers (Rupela et al., 2003). If locally available earthworms that feed aggressively on biomass placed on the soil surface can be identified and introduced in large numbers in the future, this will obviate the need to spray compost wash on the crop, reducing further the labor requirement for such biological management of the crop and soil systems.

It was apparent that plant biomass was the engine of crop productivity in T1 and T2, mediated by biological processes that enhance soil fertility. It is generally argued that biomass is required to feed cattle in South Asia, and therefore is not available for application to the soil to enhance crop production as has been done in T1 and T2. Being able to apply the levels of biomass used in T1 and T2 over time will require special efforts from any farmers who want to utilize this biologically-based cropping system. However, there are many ways in which biomass supply can be augmented for a system such as this.

In the long-term experiment, 4.5 t of biomass (containing 103 kg N and 6.7 kg P ha^{-1}) was available annually from year 5 on from the fast-growing Gliricidia grown on bunds (190 m long × 1.5 m wide, separating the four treatments) and on the boundary (218 m long) around the 1.02 ha field. Some crops, such as pigeon pea, which drop their leaves, can contribute biomass and nutrients directly to the soil system. In this experiment, 22 kg N and 2 kg P in year 2 were assessed to be added through the 3.1 t ha^{-1} of fallen leaves of pigeon pea when this was grown as the economic crop.

Fallen leaves and loppings of tree branches on-farm are another source of biomass, and many nonarable areas within the farming community could produce more biomass cheaply from fast-growing shrubs and trees introduced on wasteland, not displacing any agricultural production, provided that there is sufficient rainfall. It is important to note that deep-rooted shrubs and trees are an important biological tool that can acquire nutrients for crops, extracting them from lower layers of the soil and providing them on the surface layer in the form of fallen leaves, thus improving soil fertility; alternatively, these can be used as surface mulch or applied after composting.

A number of leguminous species offer opportunities to enhance biomass availability as cover crops or green manures, as discussed in Chapter 30. Farmers practicing alternative agriculture need to appreciate the value of biomass and to develop multiple practices and technologies that can harness this source of nutrients for crop production. Producing yields on a par with or higher than their neighbors without incurring the cash costs of chemical fertilizers and pesticides offers farmers a significant incentive for change.

A recent study by Delate and Cambardella (2004) has reported yields and differentials similar to those we report here, for the production of corn and soybeans in Iowa, U.S.A., using organic (nonchemical) vs. conventional farming practices over a 3-year period converting from conventional to organic production. The study reported here from India likewise suggests that biological approaches to crop production can sustain soil systems profitably for farmers, provided they have sufficient labor and its opportunity costs are not too high.

Making alternative agriculture systems more productive than conventional agriculture will be essential for their spread, although we must remember not to consider yield alone, a physical measure of success that ignores economic considerations. Costs of production per unit of output need to be assessed, including water-use efficiency. This was not considered in our trials because water provision was beyond our control in a purely rainfed system. However, rainwater harvesting was better in the low-cost systems (T1 and T2) than from the conventional system (T3), as seen from the reduced runoff (Rupela et al., 2005).

The scientific underpinnings for more biologically-based systems have been built up by researchers and practitioners over the past 50 years while Green Revolution technologies were receiving all the public attention and most of the public financial support. Many more studies are needed to be certain of the net value of alternative production systems, for different cropping patterns, on different soil types, and in different climatic regimes. Moreover, one cannot expect to evaluate the effects of biologically-based systems in a single year or two. Longitudinal evaluations are necessary to track the dynamic changes, positive and/or negative, in the many factors that operate in soil systems. This is why this particular long-term experiment was undertaken.

Overall, the biological approaches reported here — use of plant biomass as surface mulch, agriculturally beneficial microorganisms, and other practices — have enhanced soil biological and chemical properties of a rainfed Vertisol in the semiarid tropical environment in southern India. Yields were comparable to the conventional system of crop production that used standard agrochemical inputs. In the crop husbandry systems receiving biological inputs only, depending on the crops grown that year, stover yield ranging from 6.6 to 11.6 t ha^{-1} and grain yield ranging from 4 to 5.9 t ha^{-1} was harvested annually when there was ≥628 mm of rainfall. There is, however, the need to evaluate such systems in other locations for soil and climatic differences, so that we can better understand the many interfaces between biotic and abiotic subsystems as they respond to anthropogenic interventions in pursuit of human livelihoods and sustenance.

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