33 Long-Term Evaluation of Crop Production Systems Based on Locally Available Biological Inputs in India

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CONTENTS

Crop production systems that require chemical fertilizers, pesticides, machinery for tillage, and irrigation water, being input-intensive, present challenges for long-term sustainability, especially as climate change creates new constraints. Agricultural practices should be both regenerative to sustain their productivity and resilient so as not to succumb to stresses. In countries like India, current production systems have started to undermine the water security of the economy and population, and increasing soil and water pollution, particularly when synthetic pesticides are used injudiciously, presents hazards for both soil health and human health.

It is true that agriculture as practiced a century ago without modern inputs had lower productivity than most of the present systems of production now. However, many "premodern" agronomic practices, such as the use of organic manures to enhance soil fertility and herbal extracts to protect crops from pests and disease, can now be produced and used more effectively with the scientific knowledge that has been gained over the past century, making crop production more sustainable, even regenerative, while achieving higher productivity.

Higher crop productivity can be achieved by using environmentally friendly options such as microbial inoculants and plant products (including canopy extract, seed extract, herbal compost wash, *Gliricidia sepium* loppings, etc.) that can help convert animal and vegetable wastes, seaweed, leaf fall from trees, and crop residues into effective alternatives to synthetic fertilizers and pesticides. These options are becoming more popular as evident from the published literature such as on the use of organic manures (Jannoura et al., 2013) and biopesticides (El-Tarabily, 2008) and growing experience with conservation tillage (Chapter 23) and green manures (Chapter 25).

This chapter reports the results from a full decade of research conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) at Patancheru near Hyderabad in Telangana, India, between 1999 and 2009 on a rainfed vertisol. The first six years of these trials were reported in the first edition of this book. For this second edition, we have gone back and analyzed all ten years of data. The experiment would have been extended longer but for the untimely death of its principal investigator, Dr. O.M. Rupela.

The project examined the possibility of achieving high yields with low-cost inputs, plant biomass in particular, that are available in the vicinity of the farm or that could be produced *in situ*. The field trials utilized biological approaches that are reported in the published literature and/or from traditional farmer knowledge. While some of these methods require considerable labor – more than many farmers might be able or willing to invest at present – these approaches are relevant to a very large number of households in the semi-arid and humid tropics that have small landholdings and family labor available, but with very little cash on hand. As seen below, the methods reviewed here have proved themselves to be profitable in terms of their returns to labor as well as to land and the other factors of production. With further innovation and adaptation, they could be scaled up for use in larger farming operations, substituting capital for labor.

Production practices such as using crop residues or other biomass as surface mulch; applying green manures (Chapter 25), compost (Chapter 27), plant growth-promoting rhizobacteria (PGPR), and *Trichoderma* (Chapters 15 and 31); intercropping of legumes in cropping systems; and the biocontrol of insect pests and diseases (Chapter 32) can all help to enhance yields and sustain soil fertility and health (Fettell and Gill, 1995; Mäder et al., 2002; Delate and Cambardella, 2004; Gopalakrishnan et al., 2011a; 2014; 2015; 2016; 2018; Sathya et al., 2016; Vijayabharathi et al., 2018).

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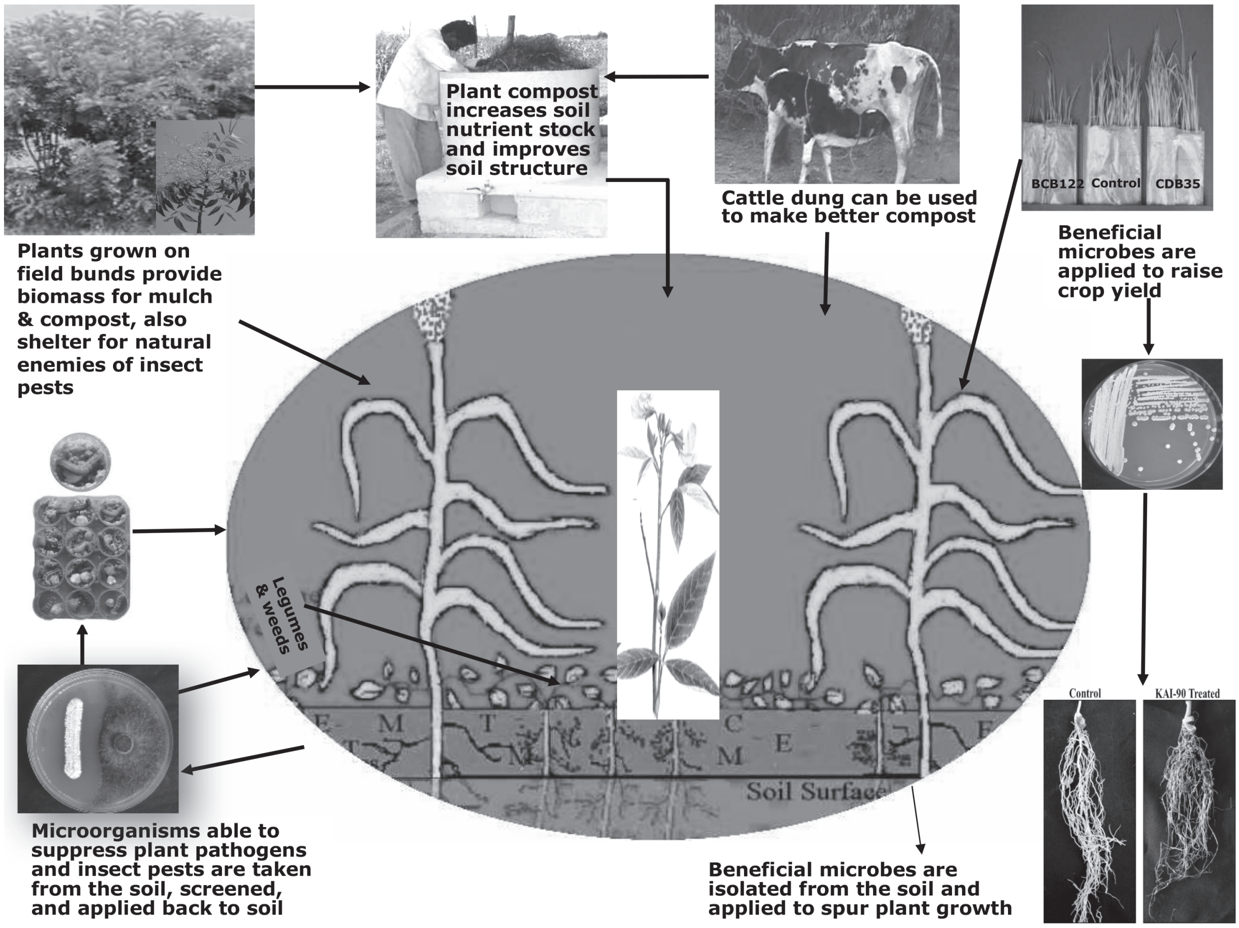

FIGURE 33.1 Elements of a biology-based integrated soil-plant-microbial and animal cropping system.

Appropriate use of such biological approaches had been previously reported to enhance the populations of soil microorganisms and macrofauna, thereby enhancing microbial transformations of different nutrients from their bound forms to available forms (Birkhofer et al., 2008; Rana et al., 2012; Sreevidya et al., 2016; Chander et al., 2018). These various approaches can be combined into an integrated soil-plant-microbial cropping system for attaining sustainable and high yields. Such a system, explained in the next section, is sketched in Figure 33.1.

33.1 DESIGNING CROP PRODUCTION SYSTEMS FOR SUSTAINABILITY

While a variety of crops and practices are known to contribute to the success of farming systems, it is not known to what extent they can be integrated in ways that are sufficiently productive and profitable, as well as sustainable, to improve crop and ecosystem productivity. It is not necessary that any particular system be advantageous for all farmers, since no single farming system can be expected to be optimal for everyone, particularly in rainfed cultivation.

Our effort was to develop a basket of options for crop production systems that could be beneficial particularly for small landholdings in semi-arid tropical regions, which is the mandate of ICRISAT as an international research center within the CGIAR system. The management options drew on existing knowledge that:

- Legume and nonlegume crops can improve soil fertility when grown as intercrops.
- Crop residues produced *in situ* when retained as surface mulch, without tillage, can improve the physical and biological properties of the soil.
- Some weed species can promote crop growth when grown under the main crop, i.e., not all weeds are competitive with crop production.
- Where relevant or required, some small amounts of external inputs, preferably low cost, can be applied to the soil or crop as per demand and as needed.
- Certain soil microorganisms, especially PGPR, have beneficial traits, e.g., biological nitrogen fixation, plant growth promotion, or antagonism to disease-causing soil organisms (fungi, nematodes) and to insect pests. These organisms can

be applied either as soil inoculants or sprayed on plants.

- Some plant extracts when sprayed on crops in a timely manner, 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, as it is also a soil-building substance and a food source for beneficial microorganisms and for soil fauna such as earthworms and mites.

It is well-known that these practices are quite compatible with one another and that cattle should be regarded as an important component in such a system, as discussed in Chapter 22. In the production system that we designed and tested, only the grain produced was taken out of the system. Crop stover and other crop residues were retained as surface mulch. Where the stover was needed for economic purposes, such as for cattle feed, an equivalent quantity of biomass that had no such economic value was returned to the field, i.e., foliage or loppings from shrubs, or trees growing on field bunds, or from outside the farm. The farming system was thus designed to function as an entity within which all of the functions in the soil system, the interactions among plants and at the soil-plant-microbial interface, are highly interactive and regenerative for enhancing crop yield.

Such a farming system is relevant to millions of smallholder and marginal farmers in developing countries of the humid, subhumid, and semi-arid tropics. About three-quarters of farmers in India have either small landholdings (<0.4 ha) or marginal landholdings (0.4–1.4 ha). They have limited scope for benefiting from newer technologies or farm implements that have been designed for larger farms. This does not mean that these small holdings are less productive, however. On the contrary, in per-hectare terms, they usually outproduce larger farms.

Larger farms, because of their size, use their resources more extensively than intensively, and their higher total returns from agriculture usually derive more from their size of operation than from greater factor productivity or efficiency. The model presented in Figure 33.1 assumes that small and marginal landholding farmers can and will be able to 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 that they invest in agricultural activity.

33.2 DESIGN FOR A LONG-TERM EXPERIMENT BASED ON LOCALLY AVAILABLE INPUTS

To examine whether yields comparable to those from conventional agriculture could be attained using the strategies and farm inputs reviewed in the preceding section, a multiyear experiment was designed to compare and evaluate four different systems of crop husbandry (Table 33.1). The four different systems were represented as four treatments:

T1: Low-cost, no-external-input system that used rice straw as mulch,
T2: Low-cost, no-external-input system that used farm waste as mulch,
T3: Conventional agricultural practices, and
T4: Conventional agricultural practices, using farm waste as mulch, as in T2.

Both T1 and T2 represent low-cost systems where the soil and crop nutrients were provided from inputs of biomass, in addition to what could be mobilized from the soil through biotic activity. T3 was the treatment most similar to conventional cropping systems in Andhra Pradesh, relying mostly on inorganic fertilizers for soil nutrient inputs. T4 was a combination of conventional and alternative systems receiving the same organic inputs provided for T2, plus the T3 chemical fertilizer applications.

It was assumed that actual smallholder farmers would own very few farm animals and therefore would not have enough manure to apply on their land, so the use of other organic material was planned for, just vegetative biomass. However, both low-cost systems being tested (T1 and T2) would benefit from animal production (poultry, dairy, goats, and piggery) being part of the farming system, having then also animal wastes to incorporate into the soil system. The results reported here could thus be improved upon to the extent that animals become part of these biologically based farming systems. But animal wastes were not built into the experimental design because we did not want our findings to be limited just to "better-case" scenarios.

The major objective of the experiment was to determine whether plant biomass, added to three of the four systems evaluated, could be sufficient and profitable if used as a surface mulch serving as the main source of crop nutrients instead of being burned. Crop residue burning is a common practice in South Asia that is being curtailed as much as possible because it is environmentally deleterious. Details of these four systems are given in Table 33.1.

The experiment was conducted on a vertisol with 1.5 m soil depth. pH in the top 15 cm ranged between 8.0 and 8.2, and electrical conductivity was 0.16–0.22 dS m^{-1}. This soil has a high clay content and is low in soil organic matter. The area was fully rainfed, with annual mean rainfall of 783 mm. This allows two crops to be grown in a year either as intercrops (in all years) or as sequential crops. In the region where the trials were conducted, it should be noted that the probability of a successful crop is just six out of ten years, given the significant possibility that the rains will fail toward the sowing time for a second crop. Given the variability in the timing of rainfall, to be certain of having some

TABLE 33.1
Treatments Used in a Long-Term Experiment at ICRISAT, Patancheru, India, June 1999 to December 2009[a]

Treatment	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 + biomass as in T2
Land preparation and intercultivation	None	None	Conventional (bullock-drawn plow)	Conventional (bullock-drawn 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} 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 years 2, 4, 6
N fertilizer	None	None	80 kg N ha^{-1} in split doses yr^{-1}	80 kg N ha^{-1} in split doses yr^{-1}
P fertilizer	20 kg ha^{-1} as rock phosphate	20 kg ha^{-1} as rock phosphate	20 kg ha^{-1} as single superphosphate (SSP)	20 kg ha^{-1} as single superphosphate (SSP)
Plant protection	Biopesticides	Biopesticides	Chemical pesticides	Chemical pesticides
Weeding	Manual, weeds retained in plot	Manual, weeds retained in plot	Manual, weeds discarded	Manual, weeds discarded

[a] Each year, the same crops were grown in all of the plots:
Year 1. Pigeon pea-chickpea 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. Cowpea/cotton intercrop (June 2003 to May 2004)
Year 6. Maize/pigeon pea intercrop (June 2004 to May 2005)
Year 7. Cowpea/cotton intercrop (June 2005 to May 2006)
Year 8. Sorghum/pigeon pea intercrop (June 2006 to May 2007)
Year 9. Cowpea/cotton intercrop (June 2007 to May 2008)
Year 10. Sorghum/pigeon pea intercrop (June 2008 to May 2009)

production, second crops are best grown as intercrops during the rainy season in June or July.

In each year of the experiment, different crops were grown, as shown in Table 33.1, but they were always the same each year across all four treatments. The experiment provided a straightforward test of the hypothesis that farming systems relying entirely or mostly on biomass inputs as a source of nutrients – and that consequently exhibit high soil biodiversity and support higher levels of biological activity in the soil – can produce good and profitable crop yields. Both of these intervening variables (soil biodiversity and biological activity) were tested in our experiment.

Rather than conduct the experiment on a large number of small replicated plots, the design used larger plots, 0.2 ha for each treatment, with a total area of l.02 ha including the noncropped area and field bunds. The treatment plots maintained their same location throughout the experiment rather than being randomly assigned each year as that would have eliminated any long-term effects of management practices on soil system fertility.

This design also permitted observation of the effects of using biopesticides for insect-pest management on fields of fairly "normal" size and under conditions that match those of farmers' fields. We monitored the major pests in the area, especially *Helicoverpa* pod borer and two of its natural enemies. This approach of evaluating field-scale treatments was not new (Guthery, 1987). It seemed acceptable and appropriate for our purposes of evaluation since small replicated plots could not assess the effects of above- and belowground biotic relationships reliably.

Each of the treatments, T1 to T4, was subdivided into 30 subplots, each 9 × 7.5 m, in six strips with five subplots in each strip. Observations for yield and other parameters were made for all 30 subplots. For observations that are more costly, such as soil properties, samples were drawn from all of the plots and were pooled strip-wise (and depth-wise where relevant) before analysis. Thus, there were 30 data points (internal replications) for parameters such as yield, with six data points (based on internal replications) for assessing the different soil properties.

The concepts of sustainable agriculture depicted in Figure 33.1 applied to the first two of the four treatments in this experiment, T1 and T2. These treatments received plant biomass as their major source of crop nutrients and depended on herbal extracts and agriculturally beneficial microorganisms (PGPRs) as soil inoculants and biopesticides. Both T1 and T2 were cultivated with minimum tillage as in conservation agriculture (Chapter 23), with the sowing being done with bullock-drawn implements. For the first three years, T1 received 10 t ha^{-1} of rice straw, while 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 implement); chemical pesticides for managing pests; manual weeding as needed; and 1.8 t ha^{-1} compost in alternate years. The T4 plots received the same inputs that were used for conventional agriculture (T3), but in addition, they received 10 t ha^{-1} yr^{-1} of biomass for the first three years, similar to the T2 plots. This biomass was incorporated into the T4 plots rather than being left as surface mulch. From year 4 on, no further biomass from external sources was added to any of the four treatments, except for compost applied at the rates given in Table 33.1. The leaves and stem stover from the crops were retained on the plots in treatments T1, T2, and T4. From year 5, loppings of *Gliricidia* grown on the field bunds were added two to three times a year during the crop growth period to all four treatment plots in equal quantities.

As depicted in Figure 33.1, the foliage of *Gliricidia* and neem (*Azadirachta indica*) was composted in separate container tanks, and the wash from this was sprayed on plants in T1 and T2 (50 L ha^{-1} at least 5 times $season^{-1}$) to protect the crops from insect pests. The wash from neem and *Gliricidia* composts has been found to contain PGPR and is reported to have plant growth-promoting traits (Kloepper et al., 1980). Further, certain preparations of bacteria, e.g., *Bacillus circulans* EB35 and *Pseudomonas* sp. CDB35, which have been identified as degrading cellulose, solubilizing P, promoting plant growth, and suppressing disease-causing fungi (Hameeda et al., 2006), were applied as sand-coat inoculants and sown along with seeds in T1 and T2 plots.

Also, the entomopathogenic bacterium *Bacillus subtilis* (strain BCB 19) and a fungus *Metarhizium anisopliae* were used as biopesticides in T1 and T2 treatments to kill the young larvae of the two major pests of cotton and legumes, *Helicoverpa armigera* and *Spodoptera litura* (Gopalakrishnan et al., 2011b). Earthworms plus cattle dung (applied as 1% dung slurry in water to soak into the biomass as a food for earthworms) were important ingredients for the composting in a tank as shown in Figure 33.1. The long-term experiment was concluded in May 2009, thus completing ten years, with data collection for nine years starting from year 2.

33.3 CROP GROWTH AND YIELD

The high variability in precipitation – more than a twofold range – can be seen from the differences among annual rainfall totals (in mm) for the years from 1999 to 2009: 580, 1,473, 688, 628, 926, 783, 1,194, 877, 707, and 1,105. The rainfed crops grown in these ten years were soybean, pigeon pea, maize, sorghum, cowpea, and cotton. Their germination and plant stand were good, including in the T1 and T2 plots where the seeds had to emerge through about 10 cm of biomass applied as surface mulch. The incidence of collar rot, caused by *Sclerotium rolfsii*, was expected to be high in the T1 and T2 plots in the presence of so much biomass, but this problem was virtually nonexistent (<5% mortality of seedlings), and it was on par with or even marginally less than in the T3 plots.

Over the ten years, the yields of the different crops in the T1 and T2 plots, all produced with lower cash cost of production, were on a par with those from T3 or as much as 14% less, except in year 1 when the T1 and T2 yields were 35–62% lower than from T3 as their soil systems were transitioning to biological production methods, discussed more below. The relatively high yield of pigeon pea in year 2 and of cotton in year 3 from both the T1 and T2 plots was associated with effective management of *Helicoverpa* through the use of biopesticides.

Conversely, the low T1 and T2 yields from pigeon pea in year 4 and from cotton in year 5 were associated with poor success in managing insect pests, mostly pests other than *Helicoverpa*. In years 6 and 8, the yields on T1 and T2 plots were relatively low compared to T3 mainly because the vigorous growth of their maize and sorghum crops appeared to stunt the growth of pigeon pea. Over the ten years of study, crop yields with low-cost, biologically based approaches (T1 and T2) were higher in eight of the years compared to the conventional agriculture treatment (T3) (see Table 33.2 and Figure 33.2).

The net income from crops in each year except the first (which was essentially a year of learning and transition) was higher in T1 and T2 compared to T3, except for years 7 and 8. The differences in yield ranged between 1.3 times and 4.6 times (Figure 33.3). This indicated that the low-input strategy was more profitable and economical for farmers. For calculating economic returns, the cost of each input was included (except for biomass and labor). Biomass was assumed to be available with little or no opportunity cost, having been either generated in the field or from activities managed by family labor rather than hired labor. Certainly labor is not a free resource, but it is a resource that is most available to poor households, these being primarily constrained in terms of their land area and their money resources. The low-input strategy of T1 and T2 in some years performed much better than the conventional cropping system, for instance, in years 2, 3, 4, 5, and 9, when yield was down, but expenditures were low. This makes the economic advantages, especially for poorer households, even greater.

TABLE 33.2
Yield (t ha⁻¹) of Crops in Different Years in the Field Experiment with Four Different Crop Husbandry Systems, ICRISAT, Patancheru

	Year 2		Year 3		Year 4		Year 5		Year 6		Year 7		Year 8		Year 9		Year 10	
Treatment	Rainy (S)	Post-rainy (P)	Rainy (C)	Post-rainy (Co)	Rainy (M)	Post-rainy (P)	Rainy (C)	Post-rainy (Co)	Rainy (M)	Post-rainy (P)	Rainy (C)[1]	Post-rainy (Co)	Rainy (S)[2]	Post-rainy (P)	Rainy (C)[3]	Post-rainy (Co)	Rainy (S)	Post-rainy (P)
T1	2.82	3.05	0.28	0.95 (0.02)	3.80	0.65	0.46	1.32	5.12	0.95	NC	1.40	NC	0.78	NC	0.95	1.60	0.95 (0.04)
	(0.14)	(0.12)	(0.02)		(0.05)	(0.02)	(0.02)	(0.04)	(0.16)	(0.02)		(0.03)		(0.03)		(0.05)	(0.07)	
T2	2.16	2.87	0.14	0.90 (0.03)	3.30	0.66	0.52	1.24	4.89	0.93	NC	1.00	NC	0.70	NC	0.90	1.53	0.64 (0.04)
	(0.11)	(0.11)	(0.02)*		(0.10)	(0.02)	(0.02)	(0.04)	(0.17)	(0.01)		(0.03)		(0.03)		(0.02)	(0.04)	
T3	3.29	1.45	0.29	0.44 (0.02)	3.04	0.72	0.34	1.42	5.27	0.89	NC	0.91	NC	1.03	NC	0.93	2.06	0.31 (0.04)
	(0.07)	(0.12)	(0.01)		(0.06)	(0.02)	(0.02)	(0.04)	(0.13)	(0.01)		(0.05)		(0.03)		(0.05)	(0.04)	
T4	3.19	1.94	0.39	0.68 (0.03)	3.68	0.57	0.38	1.63	6.06	0.85	NC	1.28	NC	1.11	NC	1.24	1.91	0.45 (0.04)
	(0.13)	(0.09)	(0.01)		(0.08)	(0.02)	(0.02)	(0.04)	(0.13)	(0.02)		(0.02)		(0.03)		(0.06)	(0.04)	
Mean	2.87	2.33	0.27	0.74	3.46	0.65	0.43	1.40	5.34	0.90		1.15		0.91		1.01	1.83	0.56

NC = Not collected, S = Sorghum, P = Pigeon pea, C = Cowpea, Co = Cotton, M = Maize. Data in parentheses are ± SEs.
* Extensive damage by aphids in this season.
[1] In the rainy season, cowpea grain was not collected; biomass was retained in the plots.
[2] In the rainy season, sweet sorghum was sown, but yield was not collected; biomass was retained in the plots.
[3] In the rainy season, cowpea was harvested at an early stage, and biomass was retained in the plots.

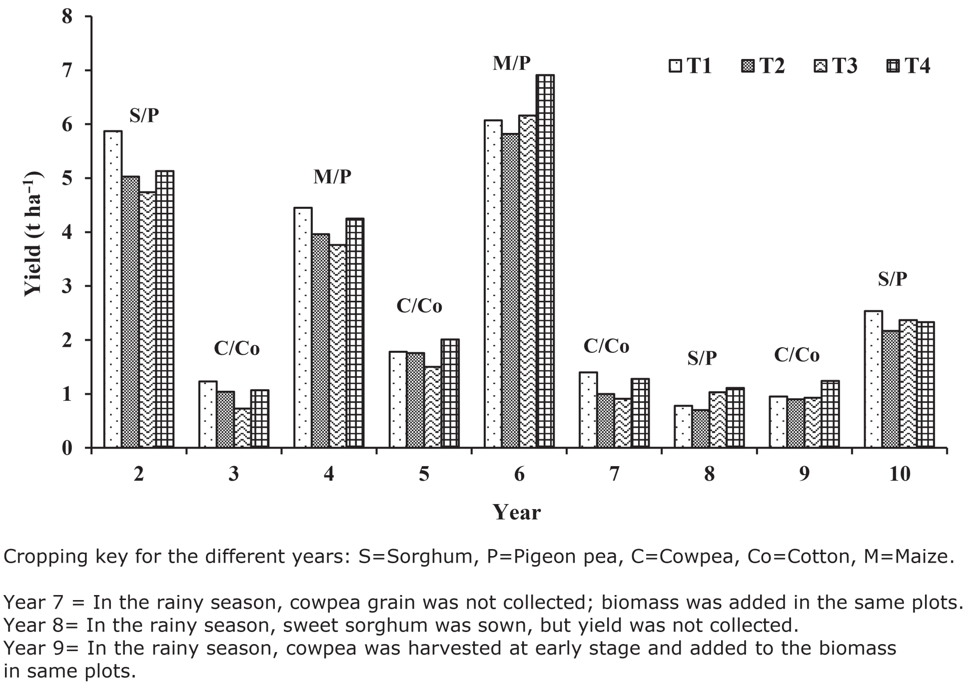

FIGURE 33.2 Total crop yields in the different years from the four crop husbandry systems; yields for both seasons were combined for all crops.

33.4 IMPACT ON SOIL PROPERTIES AND NUTRIENT BALANCES

Soil samples for all of the treatments were collected from each plot in April/May (the dry season when there were no crops in the field) from three depths (0–15, 15–30, and 30–60 cm) using a 40-mm-diameter soil corer. The samples from a set of five plots (one from each strip of each treatment) were pooled and analyzed for total N and available P. Methods of analysis for the different parameters were those described by Okalebo et al. (1993). Data for total N and available P for all years given in Table 33.3 are means from the three depths for which measurements were made.

The T1 and T2 cropping systems were able to produce yields comparable to T3 without receiving any chemical fertilizer amendments, and their plots actually showed some increases over time in the concentrations of soil nutrients compared with T3. In years 3, 4, 6, 7, and 9, there were increases of 11–54% in total N in the T1 and T2 soil systems, and 11–180% in total P, compared to those under T3

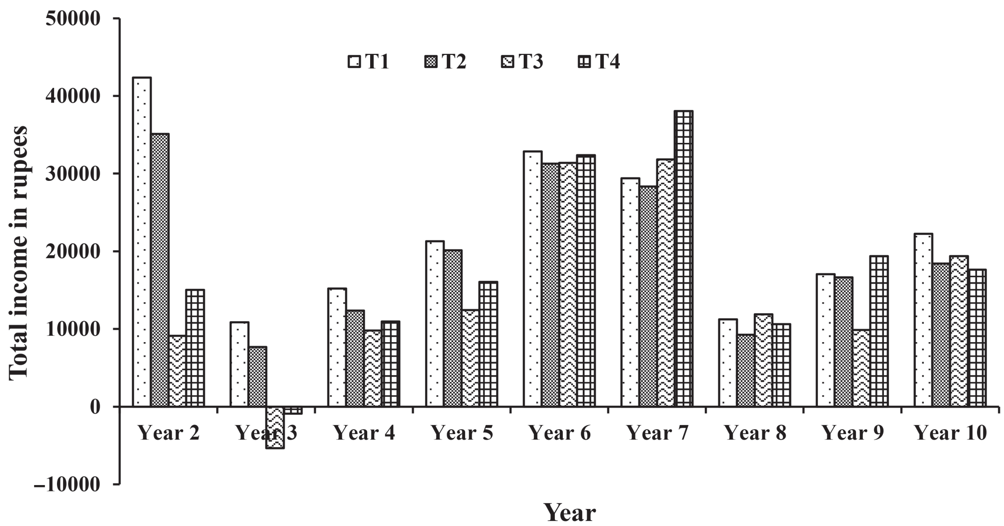

FIGURE 33.3 Yield and net income (in rupees) over years 2 through 9 from the four different systems of crop production (T1 to T4) in long-term experiment at ICRISAT, Patancheru, India. Income was calculated by putting a common price across all treatments for each item (both inputs and outputs). No data are shown for year 1 as yield data were not collected that year.

TABLE 33.3
Total Nitrogen (mg kg^{-1} Soil) and Available Phosphorus (mg kg^{-1} Soil) in Top 60 cm Profile

Treatment	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Mean
Total N										
T1	462 (18.0)	569 (21.1)	690 (30.1)	492 (17.5)	538 (44.7)	672 (54.6)	589 (51.5)	358 (33.5)	480 (52.8)	539
T2	488 (12.6)	643 (16.2)	681 (30.9)	489 (32.4)	510 (35.5)	614 (34.3)	548 (45.4)	353 (33.9)	408 (51.6)	526
T3	506 (22.1)	651 (73.4)	514 (12.3)	440 (17.9)	520 (36.3)	496 (22.1)	383 (34.1)	555 (31.2)	315 (58.2)	486
T4	500 (10.5)	588 (49.3)	586 (61.9)	429 (13.4)	494 (35.4)	535 (27.4)	388 (32.3)	640 (31.1)	402 (73.9)	507
Mean	489	613	618	462	515	579	477	477	401	
Available P										
T1	1.2 (0.08)	1.7 (0.34)	2.1 (0.31)	0.7 (0.24)	0.6 (0.13)	0.7 (0.19)	1.4 (0.56)	0.4 (0.09)	0.3 (0.00)	1.0
T2	0.7 (0.02)	1.3 (0.26)	1.7 (0.33)	0.6 (0.24)	0.3 (0.04)	0.4 (0.09)	0.4 (0.17)	0.3 (0.05)	0.3 (0.00)	0.7
T3	1.0 (0.13)	1.4 (0.34)	2.0 (0.29)	0.4 (0.11)	0.3 (0.04)	0.5 (0.07)	0.5 (0.13)	0.3 (0.07)	0.3 (0.00)	0.7
T4	0.5 (0.09)	1.6 (0.34)	2.4 (0.47)	0.3 (0.10)	0.4 (0.08)	0.5 (0.08)	0.5 (0.16)	0.2 (0.00)	0.3 (0.00)	0.7
Mean	0.8	1.5	2.0	0.5	0.4	0.5	0.7	0.3	0.3	

Numbers in parentheses are ± SE.

management. For nine of the ten years, the mean total N was higher in the T1 and T2 plots compared to T3 and T4, while the T1 plots contained higher values of available P than for the T2, T3, and T4 plots (Table 33.3).

Soil biological properties, presented in Table 33.4, were assessed only once, close to the time of crop harvest in year 5, using soil depths of 0–10 cm and 10–20 cm. The methods used for soil respiration were the same as those in Anderson (1982); for microbial biomass carbon and nitrogen, Anderson and Domsch (1978) and Jenkinson (1988); for organic carbon, Nelson and Sommers (1982); for acid and alkaline phosphatases, Eivazi and Tabatabai (1977); and for soil dehydrogenase activity, Casida et al. (1964).

Of the several parameters measured to assess biological activity in the soil samples from the four different systems of crop husbandry, more activity was noted in T1, T2, and T4 plots than in T3. Soil respiration was 17–27% higher than in T3; microbial biomass C was 28–29% higher; microbial biomass N was 23–28% more; and acid and alkaline phosphatases were 5–13% higher. While these parameters are reported as point-in-time measurements of microbial activity under laboratory conditions, they represent treatment differences (Table 33.4).

In this long-term experiment, 79–109 kg N ha^{-1} were found to be associated with microbial biomass in the top 20 cm profile, which is higher than usually reported for such soils, and this warrants further examination. Wani et al. (2003) reported 42 kg N ha^{-1} in the top 60 cm profile of the plots using traditional methods of cropping, compared with 86 kg N ha^{-1} in plots using an improved system of cropping. Microbial-bound N is likely to be mineralized for use by plants when microorganisms die naturally or due to unfavorable factors such as soil drying. The differences observed for the different soil biological parameters indicate that the soils from T1 and T2 plots were consistently more active microbiologically than those from T3 (Table 33.4).

TABLE 33.4
Biological Properties of Soils with Different Cropping System Treatments Assessed in the Top 20 cm of the Soil Profile, at 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})	1,550 (110.3)	1,535 (120.1)	1,202 (66.8)	1,510 (104.1)	1,449
Microbial biomass N (kg C 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)	1,008 (111.3)	890 (114.8)	1,011 (113.1)	962
Dehydrogenase (μg TPF g^{-1} 24 h^{-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 sp. ($\log_{10}$ g^{-1} soil)	4.1	4.6	3.3	3.2	3.8

Numbers in parentheses are ± SE.

[a] p-NP ¼ paranitrophenol,

[b] TPF ¼ triphenylformazan.

While the total bacterial populations, 5.3–5.7($\log_{10}$ g^{-1} soil, were not much different across the four treatments, the population of *Pseudomonas* spp. was about ten times more in T1 and T2 than in T3 and T4 (respectively, 4.1–4.6 $\log_{10}$ g^{-1} soil vs. 3.2–3.3 $\log_{10}$ g^{-1} soil). Several soil isolates of this species are known to be antagonistic to disease-causing fungi and to nematodes, so this trait can 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 <10% of the microorganisms that live in the soil can be cultured on laboratory media. Hence, some researchers consider that the number of culturable microorganisms is <5% or even <1% of the total; one cannot say the exact number since the denominator is unknown. This is indicative, however, of how little we know yet about the earth's microbiota. This fact suggests that soil respiration and microbial biomass C and N are going to be, for now, more reliable parameters of soil biological activity, reflecting the total microbial community, than are counts made of microbial populations using laboratory media.

For all four of the treatments, a balance sheet was prepared for N and P, the two macronutrients considered critical for crop production. For this purpose, all the materials added to plots of the different treatments (e.g., crop residues, compost) and all those removed (e.g., grain) were fully accounted for. The amounts of total N and P added and removed as well as the balance for the first five years across the four different crop husbandry systems are shown in Figure 33.4. T1 and T2, which received plant biomass, compost, and microorganisms as their major sources of crop nutrients, ended up receiving substantially more N (27–52%) and more P (50–58%) than was added to T3, largely as inorganic fertilizer (604 kg N ha^{-1} and 111 kg P ha^{-1}). T4 plots, according to the study design having both organic and inorganic nutrient sources, received the largest quantities of N (1,232 kg ha^{-1}) and P (193 kg ha^{-1}). It is therefore not surprising that T1, T2, and T4 plots ended up having a much larger balance of N (2.5–10 times) and P (12–13 times) in their soils than was available for the T3 cropping system (55 kg N ha^{-1} and 5 kg P ha^{-1}).

However, this does not mean that the crops in the low-cost systems, T1 and T2, had access to more N and P than those in T3, the conventional system. Nutrients, when added as biomass, are not readily available 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. Only a portion of the N applied to the soil as biomass would have been recovered by the crop (Thönnissen et al., 2000).

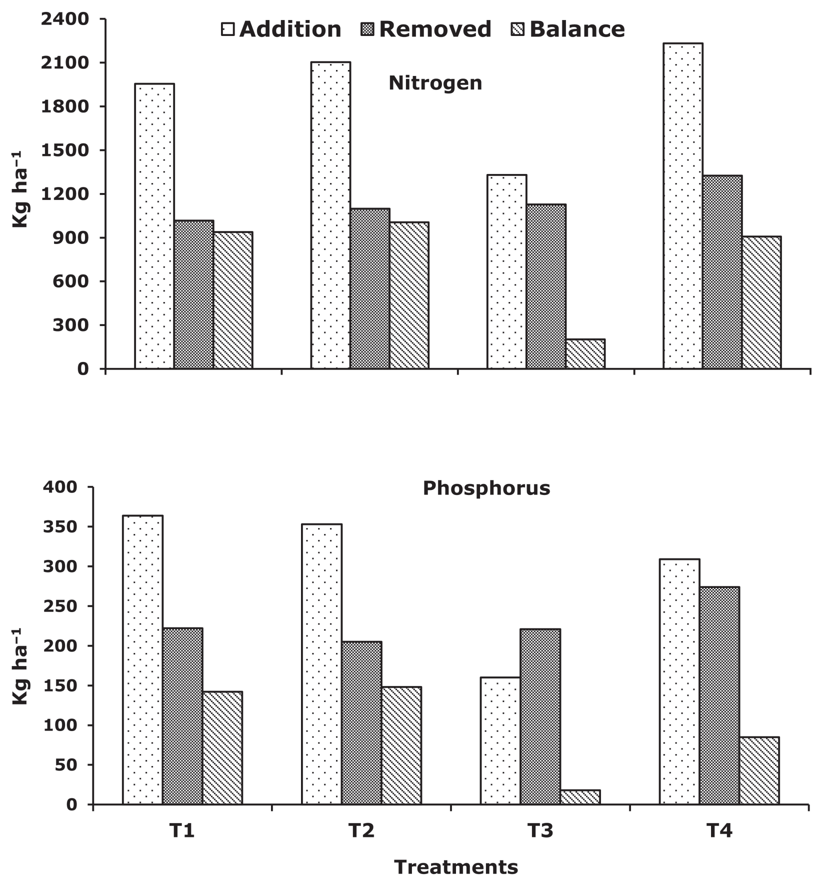

FIGURE 33.4 Nitrogen and phosphorus balances of the four different systems of crop production (T1 to T4) at the end of the fifth year.

This helps to explain the 35–62% lower yield obtained in year 1 in T1 and T2 compared with T3, which received chemical fertilizer. However, the long-term yield data indicated that in subsequent years, when T1 and T2 yields were on a par with or very close to those from T3, microorganisms, whether in the soil or applied externally, were able to decompose the biomass sufficiently so that released nutrients could meet the crop demand. Balance sheets for N and P were not calculated after year 5.

If T1 and T2 received substantially more N and P and their removal was similar to that in T3 (as indicated in Figure 33.4), then the soil systems of T1 and T2 should have substantially higher amounts of N and P. This was indeed observed in the top 15 cm of soil under T1 and T2, which had 30–41% more N (an additional 355–483 kg ha^{-1}) and 0.2–17% more P (an additional 2–129 kg ha^{-1}) compared with the levels of N and P under T3. Much of the biomass applied as mulch at sowing had largely disintegrated by the end of the rainy season each year, except for thick plant stems. This suggests that all of the leafy materials added at sowing time were decomposed during the growing season, particularly in a year with normal to good rainfall.

33.5 DISCUSSION

From the data collected from 1999 to 2009, it is apparent that T1 and T2, the two crop husbandry systems that 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 matched those from the T3 system that relied on purchased inputs (chemical fertilizers and pesticides) and conventional tillage practices. Labor was the major input in T1 and T2. While this has opportunity costs for smallholder and marginal landholder farmers, these producers have relatively more access to labor than to cash, so their binding constraints are land and capital more than labor. These are thus the resources whose productivity needs to be maximized.

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

Sowing crops when there is surface mulch is a potential hindrance to adopting the kind of sustainable agriculture represented in Figure 33.1. Sowing in the long-term experiment described here was done using a bullock-drawn implement for drilling the seed into the soil. 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 the sowing. New implements that are being promoted for no-till systems in the rice-wheat production systems of the Indo-Gangetic Plains (Western Uttar Pradesh, Haryana, and Punjab) that drill seeds into the soil through mulch will be useful in future versions of biologically driven systems, considerably reducing labor requirements.

Earthworms are widely accepted as having a beneficial influence on soil structure and chemistry that promotes plant, especially root, growth. It is likely that other agriculturally beneficial microorganisms, such as ones able to suppress disease-causing fungi, are present in compost made and used by organic farmers (Rupela et al., 2003; Gopalakrishnan et al., 2011a). If locally available earthworms that feed aggressively on biomass placed on the soil surface can be identified and introduced in large numbers, this will obviate the need to spray compost wash on the crop, further reducing the labor requirements for such biological management of the cropping systems.

In our study, PGPR including *B. subtilis* BCB 19, *M. anisopliae,* cellulose degraders EB35 and CDB35, and botanicals including neem and *Gliricidia* were successfully exploited for managing insect pests including pod borer. In addition, each insect pest has natural enemies that are referred to as beneficial insects, and these would have also played a major role in managing insect pests. For instance, the cotton bollworm (*H. armigera*) is reported to have about 300 natural enemies (Sharma, 2001). So, providing a more hospitable environment for these enemies can have large economic returns. Inputs of the agriculturally beneficial microorganisms that were used in this study are not yet widely available to farmers, although efforts are starting in India to produce them not just in large commercial operations but also at the village level by farmers, especially women (Chapter 34).

It was apparent that plant biomass was the "engine" for crop productivity in T1 and T2 plots mediated by multiple biological processes that enhance soil fertility. It is often argued in South Asia that plant biomass is required to feed cattle, and therefore, it cannot be made available for soil application to enhance crop production as was done in T1 and T2. It is true that being able to apply the levels of biomass used in T1 and T2 over time will require some special efforts from farmers who want to utilize this biologically based cropping system. However, there are several practical ways in which biomass supply can be augmented for implementing a low-cost cropping system.

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* plants that were grown on field bunds (190 m long × 1.5 m wide) that separated the four treatments, and on the boundary (218 m long) around the 1.02 ha field. Also, crops such as pigeon pea that drop their leaves contribute biomass and nutrients directly to the soil system. In this experiment, it was calculated that in year 2, 22 kg N and 2 kg P in year 2 were added from 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 available on-farm are another source of biomass for organic soil sustenance, and there are many nonarable areas within the farming community that could produce biomass cheaply from fast-growing shrubs and trees introduced on wasteland, not displacing any crops, provided that there is sufficient rainfall. It is important to note that deep-rooted shrubs and trees are themselves important biological tools that can acquire nutrients for crops, extracting them from lower layers of soil and providing them on the surface layer in the form of fallen leaves, thereby improving topsoil fertility. Alternatively, these materials 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. Farmers practicing alternative agriculture need to appreciate the value of biomass and to develop multiple practices, tools, and technologies that can harness this source of nutrients for sustaining crop production. Getting yields on a par with, or higher than, those of their neighbors who incur the cash costs of chemical fertilizers and pesticides offers farmers a significant incentive for change.

A study by Delate and Cambardella (2004) reported yields similar to those that we report here for the production of corn and soybeans in Iowa, United States, using organic (nonchemical) versus conventional farming practices over a three-year period when 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 that they have sufficient labor and its opportunity costs are not too high. In the future, there could be advances in simple mechanical technology for acquiring, processing, and applying off-field biomass to enhance organic matter in field soils. These would be labor-saving and should be quite cost-effective.

Making alternative agriculture systems more productive than conventional agriculture will be essential for their spread, although we must remember not to consider only crop yield. This physical measure of success ignores some important economic considerations. Costs of production per unit of output need to be assessed inclusively, including consideration of water-use efficiency. This was not considered in our trials because water provision was beyond our control in a purely rainfed system. However, rainwater utilization was better in the low-cost systems (T1 and T2) than from the conventional system (T3) because of reduced runoff (Rupela et al., 2005). More proactive methods for rainwater harvesting and storage, particularly if combined with intensification (horticulture and aquaculture), can have very high economic returns (Thakur et al., 2015).

The scientific underpinnings for more biologically based systems have been built up gradually 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 types of soil, and in different climatic regimes. Moreover, one cannot expect to evaluate the effects of biologically based systems in a single year or two. Long-term evaluations are necessary to track the dynamic changes, positive and/or negative, in the many factors that are operative in soil systems. That is why this particular long-term experiment was undertaken. But it is only a start.

Overall, the biological approaches reported here – use of plant biomass as a surface mulch, augmentation of agriculturally beneficial microorganisms, and other practices – have enhanced the soil biological and chemical properties of a rainfed vertisol in the semi-arid tropical environment in southern India. Yields were comparable to the conventional system of crop production that used standard, costly agrochemical inputs.

In the crop husbandry systems that received biological inputs only, depending on the crops grown that year, the annual stover yield ranged from 6.6 to 11.6 t ha^{-1}, and the grain yield ranged from 4.0 to 5.9 t ha^{-1}. This was with an average rainfall of only ≥628 mm. We expect that if livestock and other animals were integrated into such systems, there would be even higher production and profitability (Thakur et al., 2015). There is, however, a need to evaluate such systems in a variety of locations with soil and climate differences so that we can better understand the interfaces between biotic and abiotic subsystems, as they respond to anthropogenic interventions in pursuit of improved human livelihoods and sustenance.

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