10 Combining multiple technologies: Integrated soil fertility management

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Introduction

Smallholder farming systems in East and Southern Africa (ESA) are influenced by a wide range of ecological, social, economic, food security, and nutritional factors, as well as the prevailing political and institutional contexts. These farmers therefore produce an array of different crops and livestock. Local production challenges include unreliable rainfall, poor soil fertility, low feed and pasture quality, and a high incidence of pests and diseases. Informed largely by traditional knowledge and conventional practices, farmers are therefore interested in how integrating multiple technologies can help them increase their productivity in a sustainable manner.

Africa RISING focused on the sustainable intensification of smallholder farms through integrated multi-disciplinary research. This approach combines validated technologies with the aim of improving the productivity of the whole farm. By working in harmony with social, economic, and environmental considerations, this approach also enhances the resilience of farming households to such shocks as extreme weather events, which are occurring more often due to climate change.

This chapter builds on the previous ones, showing how the featured technologies can be combined and integrated further at farm and landscape levels to improve farming system performance. Integration begins when the practitioner implements a new technology and acknowledges the larger perspective of interdependencies at multiple scales and across multiple sustainability domains. Each technology therefore presents an opportunity around which integrated solutions can be created. The specific technologies selected are guided by the farmer’s knowledge and decisions based on available resources. Integrated Soil Fertility Management (ISFM) is an example of a system-wide technology. It has been promoted widely over the past 15 years, with Africa RISING research promoting its contribution to sustainable agricultural intensification on small-scale farms.

Description of the technology

ISFM is a set of soil fertility management practices, including use of industrial fertilizer, organic inputs, and improved crop varieties, combined with knowledge on how to adapt the practices to local conditions. The aim of adopting ISFM is to maximize agronomic efficiency of the applied nutrients and improve crop productivity (Vanlauwe *et al.*, 2010). All inputs need to be managed in accordance with sound agronomic principles (Figure 10.1).

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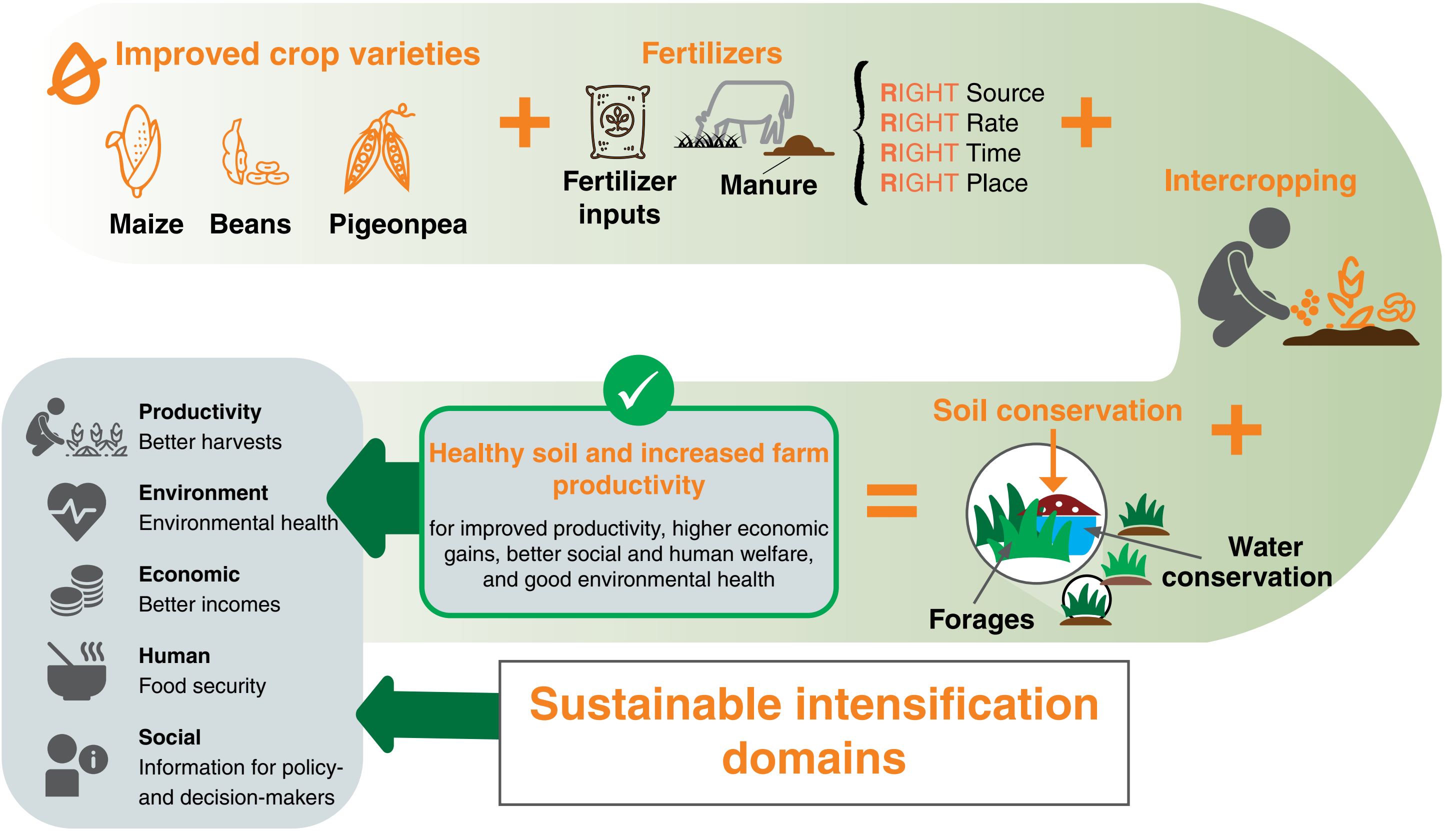

Figure 10.1. Integrated Soil Fertility Management: combining different soil fertility management practices for sustainable farming systems. Adapted from: Kizito *et al*. (2016a; CC BY 4.0).

Successful implementation of ISFM depends on starting with crop varieties of high productivity potential (genetic intensification). Any integrating technology contributes to attaining this potential by enhancing light, nutrient, and water use efficiency associated with the target crops. Resilience to biotic and abiotic stresses is an additional and desirable benefit of the improved crops. (Chapter 2 describes improved varieties with grain yields up to 123% higher than local commercial varieties, under drought and non-drought conditions.)

The second dimension of ISFM involves applying fertilizers (organic and industrial) according to the 4 'R's of nutrient stewardship (see Chapter 4). This has the potential to increase maize grain yields by up to 300% for industrial fertilizer, and 145% for farmyard manure. Intercropping and crop rotations (sometimes referred to as crop associations) promote useful legumes grown concurrently or in sequence with cereals (see Chapter 3). In intercrops, the legume component fixes atmospheric nitrogen to meet its own requirements, while sparing soil-derived nitrogen, or nitrogen supplied through fertilizers, for the cereal crop. When the legume crop is of short duration, such as some cowpea varieties, it is possible for the intercropped cereal to benefit directly through legume litter decomposition within the same cropping season. In the medium to long term, the high-quality legume residues and residues from cereal crops result in maintenance or gradual build-up of soil organic matter, thus leading to sustainable crop production. Soil and water conservation practices can be tailored to local conditions (see Chapters 5 and 6).

Based on sound agronomic practices provided by ISFM, there have been large initiatives to enhance the uptake of no-tillage agriculture systems that integrate minimum soil disturbance, crop residue retention, and crop diversification (see Chapter 6). These benefit ISFM through minimum soil disturbance and improved soil cover, which in turn result in reduced soil erosion, increased water infiltration, efficient water use, and increased nutrient uptake. Over the longer term, no-till systems also lead to a gradual increase in soil fertility (soil carbon sequestration) and increased productivity. Such improved ISFM systems are commonly grouped under the concept of conservation agriculture (Thierfelder *et al*., 2018).

Benefits of the technology

Agronomic efficiency

Agronomic efficiency is a short-term indicator of the impact of an applied technology on productivity, quantifying the difference in yield with or without the technology input. Figure 10.2 illustrates the conceptual relationship between the agronomic efficiency of industrial fertilizers and organic resources, and the implementation of various components of ISFM, culminating in 'complete ISFM'. Soils that are responsive to industrial fertilizer and those that are poor and less responsive are distinguished. Local adaptation includes all the other non- and indirect nutrient-contributing soil fertility management practices of soil and water conservation, no-till and intercropping. Agronomic efficiency increases as each additional step is taken. However, the steps do not necessarily have to be taken all at once; they can be added in whichever order is appropriate for local conditions.

Figure 10.2 essentially has the same components as Figure 10.1, in which local adaptation and increased knowledge are key to the integration of multiple technologies toward an improved, resilient, and sustainable farming system. Two clarifications are necessary. One is that the horizontal arrangement of the ISFM technology components is not fixed in the order given in Figure 10.2. They can be arranged according to their availability and affordability, and the ingenuity of the farmer. Vanlauwe *et al*. (2010) suggest the implementation of ISFM as a stepwise progression from local practices to improved crop varieties, crop associations, use of organic resources, application of industrial fertilizers, and local adaptations. This aligns with the second clarification: at any one implementation stage, ISFM can range from different partial combinations of *in-situ* component integration to full ISFM. It is evident that, while crops respond favorably to the application of nitrogen, phosphorus, and potassium-based fertilizers in some soils (so-called responsive soils), they do not respond to fertilizer application in any significant manner in other soils (the so-called non-responsive soils; Kihara *et al*., 2016). Application of organic resources thus becomes particularly important in the non-responsive soils.

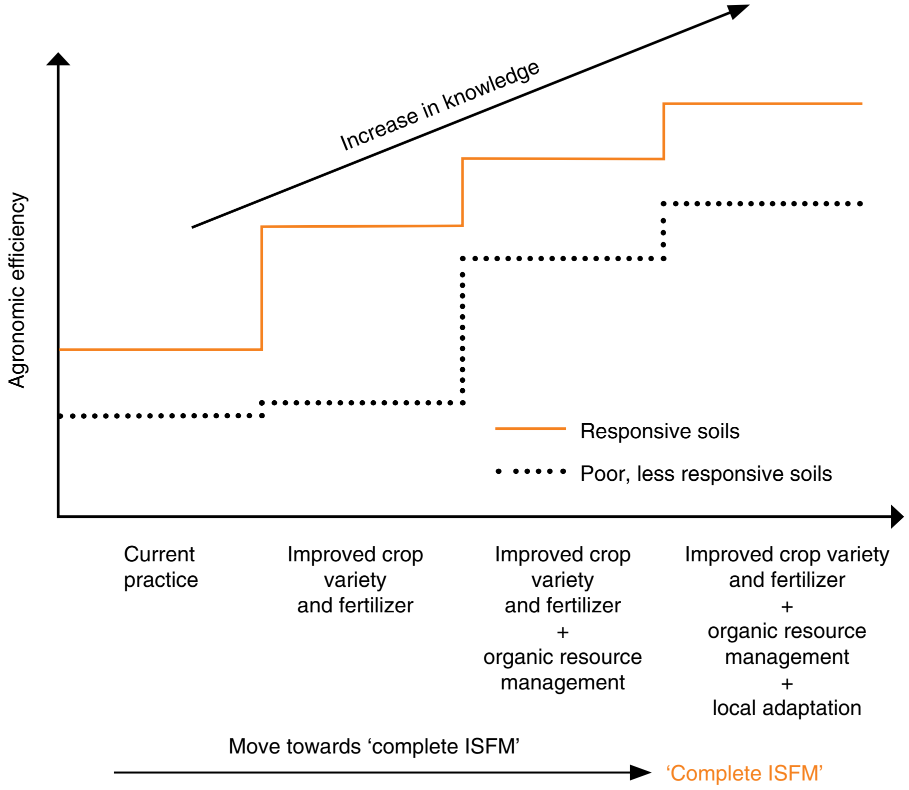

Figure 10.2. Conceptual relationship between the agronomic efficiency of fertilizers and organic resources, and the implementation of various components of ISFM. Adapted with permission from Vanlauwe *et al*. (2010). All rights reserved.

Enhanced productivity

Some integrated technologies have no clear indicators and metrics, making it difficult to calculate agronomic efficiency. Instead, it is possible to measure increases in productivity (see Table 10.1). Although the studies featured in the table did not aim to test ISFM principles directly, the results show the benefits of integration. In general, crop yields increase with added combinations of technologies; the results are most marked in trials on vegetable crops, and in high potential agroecosystems.

Reduced risk

ISFM is especially important in drier and low-potential agroecosystems where small-scale farmers face difficult conditions, such as droughts, which can significantly impact yields. In such areas, ISFM can improve productivity significantly in good years and help to mitigate risk of zero harvest in years of poor rainfall (Nkonya *et al.*, 2017).

Reduced need for industrial fertilizers

Reduced need for industrial fertilizers is most relevant to resource-poor farmers, who often face challenges in fertilizer access and affordability. Widespread adoption of nitrogen-fixing legumes can reduce the amount of industrial fertilizer needed by up to 50% without compromising the productivity of cereals grown in sequence (Chimonyo *et al.*, 2019), while also maintaining a healthy soil ecosystem. However,

Table 10.1. Productivity benefits of applied ISFM technologies.

	Productivity benefits of applied ISFM technologies (yield of grain, fresh fruits, fresh leaves, kg/ha)								
Agroecosystem, country	Farmer practice	Improved crop variety	Improved crop variety + crop association[1]	Improved crop variety + fertilizer[2]	Improved crop variety + crop association + fertilizer	Improved crop variety + local adaptation[3]	Improved crop variety + fertilizer + local adaptation	Improved crop variety + crop association + fertilizer + local adaptation	Data source
Low potential, southern Malawi	1,064[4]	n/a[5]	n/a	n/a	3,543	n/a	4,236	4,121	C. Thierfelder, CIMMYT
High potential, central Malawi	2,430[4]	n/a	n/a	n/a	3,976	n/a	4,967	5,409	C. Thierfelder, CIMMYT
Manual systems, eastern Zambia	2,221[4]	n/a	n/a	n/a	3,158	n/a	n/a	4,075	C. Thierfelder, CIMMYT
Animal traction, eastern Zambia	2,221[4]	n/a	n/a	n/a	3,194	n/a	n/a	4,272	C. Thierfelder, CIMMYT
Low potential, southern Malawi	500	800	900	2,800	2,900	900	3,200	3,500	R. Chikowo, MSU/IITA
Medium potential, central Malawi	600	900	1,000	3,000	3,300	1,200	3,500	3,800	R. Chikowo, MSU/IITA
High potential, central Malawi	700	1,200	1,300	3,500	3,900	1,500	4,200	4,400	R. Chikowo, MSU/IITA
Low potential, central Tanzania	1,574	2,481	2,536	n/a	n/a	2,566	n/a	n/a	P. Okori, ICRISAT
Medium potential, central Tanzania	1,472	2,421	2,230	n/a	n/a	2,056	n/a	n/a	P. Okori, ICRISAT
High potential, central Tanzania	1,307	2,005	n/a	n/a	n/a	2,741	n/a	n/a	P. Okori, ICRISAT
Medium potential, northern Tanzania	1,900	1,800	n/a	3,500	n/a	n/a	n/a	7,000	Kihara *et al.* (2020)
High potential, northern Tanzania	2,000	2,100	n/a	6,500	n/a	n/a	n/a	8,500	Kihara *et al.* (2020)

Central Tanzania[6]	13.3	28.3	n/a	n/a	n/a	36.1	64.4	n/a	Lukumay *et al.* (2018)
Central Tanzania[7]	3.4	23.0	n/a	n/a	n/a	32.4	53.5	n/a	P. Lukumay, WorldVeg
Central Tanzania[8]	4.5	8.5	n/a	n/a	n/a	10.0	14.9	n/a	P. Lukumay, WorldVeg

[1] Cereal/legume intercropping or rotations.

[2] Industrial or organic fertilizer.

[3] Physical soil and water conservation practices or conservation agriculture.

[4] The cropping systems done by Thierfelder, CIMMYT are all testing no-tillage agriculture systems. This means that improved practices will have different tillage systems than those from the other researchers.

[5] n/a = not applicable.

[6] Tomato yield (fresh fruit, t/ha).

[7] African eggplant yield (fresh fruit, t/ha).

[8] Amaranth yield (fresh leaves, t/ha).

CIMMYT = International Maize and Wheat Improvement Center; MSU/IITA = Michigan State University/International Institute of Tropical Agriculture; ICRISAT = International Crops Research Institute for the Semi-Arid Tropics; WorldVeg = World Vegetable Center.

legumes still require addition of other essential nutrients (e.g., phosphorus and potassium) for maximum yields.

Additional benefits

The range of benefits offered by ISFM also includes improved soil water retention and soil structure, and provision of animal fodder, nutritious food for humans, and fuelwood and timber. In addition to augmenting food security, these benefits create new income sources for small-scale farmers. ISFM can become a component of integrated pest management since desmodium will repel stem borer and Fall armyworm (insect larvae that bore into maize stems or feed on the leaves), while the Napier grass is a trap crop for both insects (Midega *et al*., 2018). Benefits to the environment include reduction in fertilizer runoff, improved water supplies, support for biodiversity, and enhanced carbon sequestration.

A study conducted in Babati, Tanzania, demonstrated the multiple benefits of ISFM, where the primary objective was to address nutrient mining and where there was a myth that industrial fertilizers spoil the soil. The trial introduced a systems approach for sustainable intensification. This included crop productivity, profitability, and the environment to help smallholder farmers produce more food and feed for nutritional security and livelihoods without damaging the natural resource base. First, the researchers demonstrated the principles of nutrient stewardship (the four 'R's) with intercropping to improve maize yields. Cover and fodder crops (Napier and brachiaria grass, lablab, desmodium, and pigeonpea) were introduced into specific niches, e.g., as strips on terraces in sloping fields, or planted between the lines of crops (Figure 10.3). Adding cover and fodder crops improved soil fertility, provided windbreaks to protect the main crop, increased soil moisture capture, and reduced surface water runoff by 60–120 mm per annum, thereby protecting the soil from erosion. This had a knock-on effect, increasing water infiltration, with 30% higher soil moisture storage over a depth of 50 cm in areas where forage-legume combinations were established compared to the control areas (Kizito *et al*., 2016b).

Reduction in post-harvest losses

Post-harvest losses in ESA can be very high, and will affect the potential gains accrued from introducing ISFM. Up to 47% of yields may be lost through poor harvesting, transportation, storage, processing, and packaging. Combining ISFM with improved post-harvest technologies ensures more efficient drying, processing, and storage and can reduce losses from 47% to just 7.5% (see Chapter 7 of this book). Therefore, combining ISFM and improved post-harvest technologies adds value to the whole system in terms of additional food available, economic savings, improved livelihoods, and better utilization of agricultural land.

Farmers' responses

During 2016, Africa RISING conducted a survey of 246 farmers in Babati district, Tanzania, which examined the practice and performance of ISFM (Figure 10.4). The number of ISFM technology components used ranged from one to a combination of all five (full ISFM), and the results show that increasing the number of ISFM components is associated with higher maize yields. The components used by farmers in the study were improved maize varieties, addition of manure, intercropping, crop residue retention, and industrial fertilizers. The majority of the farmers had adopted improved maize varieties, with industrial fertilizer being the second most common technology adopted. A similar survey conducted in 2013 showed that only 1.7% of 117 surveyed farmers had integrated all components, with few applying industrial fertilizer (Kihara *et al*., 2015). This shows that farmers are aware of the benefits of ISFM, but few have the capacity to implement full ISFM.

Another study in Babati with 240 households highlighted the benefits of integrating crop and livestock technologies on the ISFM process. These small-scale farmers adopted an integrated vegetable and poultry production

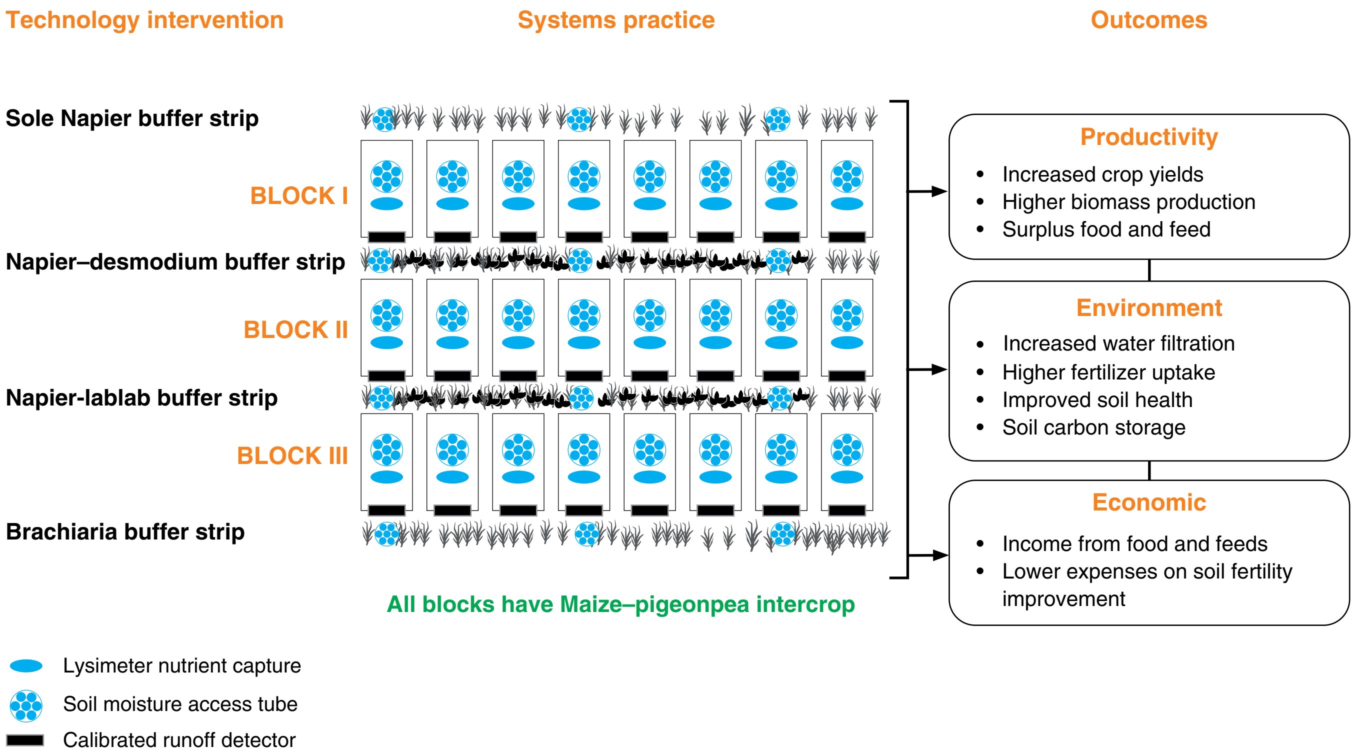

Figure 10.3. Experimental layout to test ISFM in Babati, Tanzania.

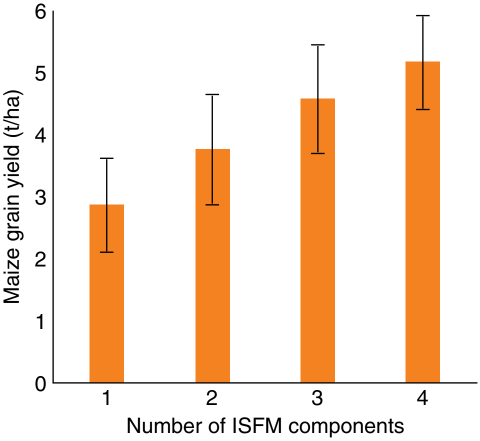

Figure 10.4. Mean increase in maize yields with additional components of ISFM, based on 246 farmers in Babati, Tanzania, in 2016 (showing standard deviations).

system, which was more profitable than vegetable farming alone, with profitability increasing as the poultry flock size grew. The farmers fed vegetable waste to the chickens (Figure 10.5) and returned the chicken manure to the vegetable gardens as organic fertilizer. Households keeping at least 18 birds obtained a significantly higher profit than non-adopters. The decision to adopt was governed by several factors, including gender and education level of the household head, awareness of integration benefits, land ownership, household size, off-farm income, and total household income (Habiyaremye *et al.*, 2021).

Opportunities for adoption

Figure 10.5. Chickens feeding on vegetable waste. (Photo courtesy of Wondmeneh Esatu, 2013.)

Farming systems are complex, and the introduction of a technology (and multiple, integrated technologies) is often associated with tradeoffs or synergies across productivity, economic, environmental, human, and social domains (Wortmann *et al.*, 2020). For example, adoption of an improved crop variety with soil and water management practices (e.g., construction of banks and ditches, see Chapter 5) will improve productivity and have additional potential environmental and economic benefits over adopting the improved variety alone. However, there may be conflicts with other social or human aspects, such as nutrition, gender equity, and labor (Figure 10.6). In this illustration, negative tradeoffs in the social and human condition domains associated with the integrated technology may make it unacceptable unless alternative plans to overcome the tradeoffs are made available. For example, adding the banks and ditches is labor intensive in terms of initial construction. Where family labor is not sufficient, the traditional community practice of pooling labor provides an alternative plan to overcome the labor limitation. Where there are tradeoffs, it is important that these are documented and the measures to overcome them discussed openly before ISFM can be adopted successfully.

Africa RISING research revealed that, while many of the technologies introduced led to clear benefits in productivity and profitability, tradeoffs in the social and human domains impeded their adoption on a large scale. Integration of socioeconomic analysis was required to improve understanding of farmers' decision-making, cultural behavior, and gender dynamics. When introducing integrated technologies, scientists and extension staff therefore need to collaborate between disciplines to ensure adequate expertise is provided to help farmers select the components, validate the outputs, and avoid giving conflicting messages during dissemination. It is important to invest time and effort in building partnerships among researchers, extension services, and public and private sectors, and to develop the capacity of all partners in the integrated technologies.

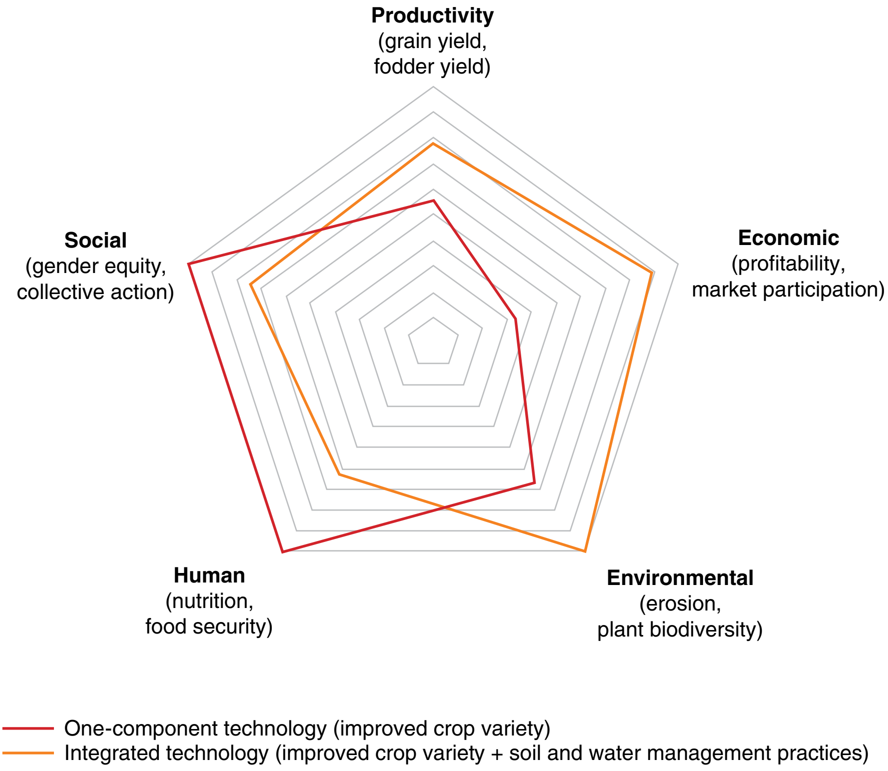

Figure 10.6. Hypothetical multi-disciplinary comparison of an integrated technology and one of its component technologies using the Sustainable Intensification ToolKit (Grabowski *et al*., 2018) across select indicators in the productivity, economic, environmental, human, and social domains. Adapted from Wortmann *et al*. (2020; CC BY 4.0).

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