Surveying the Evidence on Sustainable Intensification Strategies for Smallholder Agricultural Systems

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Abstract

Food demand is projected to increase significantly over the coming decades. Sustainable intensification (SI) is essential to meet this demand. SI is particularly important in smallholder systems, yet to date it remains unclear what the most promising SI strategies are to increase food production and farmer incomes at scale. We review the literature on SI to identify the most promising strategies, as manifest in replicated findings of favorable causal impacts. Adoption of improved cultivars generated the largest, most consistent, positive yield and economic outcomes. Two agro-ecological practices, push-pull systems and the System of Rice Intensification, also repeatedly led to large positive impacts. These strategies have considerable potential to scale to reach over 50% of smallholder farmers who plant staple crops. Significant barriers to adoption remain, however, and identifying ways to overcome barriers to scale these successful strategies will be critical to meeting SDGs 1 and 2 by 2030.

1. Introduction

Food demand is projected to increase sharply over the coming decades, with global calorie consumption estimated to increase by approximately 50% by 2050 (1). Meeting this demand sustainably requires increasing agricultural production, but in a way that minimizes adverse environmental impacts. This is because agricultural systems already contribute over one-fifth of global greenhouse gas emissions, use 70% of global freshwater withdrawals, are a major driver of deforestation and habitat loss, and are a leading cause of soil, air, and water pollution (2–4). Sustainable intensification (SI), which increases agricultural production while limiting environmental harm, has been touted as an essential way to increase agricultural production over the coming decades (5).

Increasing agricultural production through SI is particularly important in smallholder agricultural systems. Smallholder farms, defined as those that are less than two hectares (ha) in size, comprise 84% of all farms globally, produce 35% of the world's food, and employ two-thirds of the Global South's rural population (6, 7). While the Green Revolution led to large yield and production gains for staple crops in much of the world, yield growth has slowed, stagnated, or even reversed in much of the Global South, where most of the world's smallholder farms are located (8). Agricultural systems in these regions are also projected to be among those most negatively impacted by climate change (9, 10). Furthermore, agricultural systems across the Global South are also relatively low yielding and have large yield gaps, measured as the difference between actual and potential yield, suggesting that there is considerable room to increase production in these systems by promoting improved management strategies (11).

Finding ways to sustainably increase agricultural production in smallholder systems is also critical to meet several of the Sustainable Development Goals (SDGs), specifically SDG 2, Zero Hunger, and SDG 1, No Poverty. This is because in smallholder systems, agriculture is a primary source of livelihood for over two-thirds of the rural population, and staple grains provide over 40% of household calories (12). Increasing production of staple grains in these regions has led to dramatic decreases in poverty, hunger, and mortality, particularly for the poorest and most vulnerable (13, 14). Not only does increased smallholder productivity lead to improved outcomes for farmers and farmworkers, it also benefits food consumers due to reduced staple food prices from increased production (15). This is critically important given that most increases in food demand are projected to occur in the Global South, specifically Asia and Africa, and increased domestic production will be an important pathway to meeting this increased demand given the high rates of domestic food consumption in these regions (16, 17).

We reviewed the literature on SI in smallholder systems in the Global South to identify key technologies and practices that exhibit promise for increasing food supplies and farmer incomes without adverse environmental harm by 2030, the primary target year of the SDGs. We discuss a core set of promising strategies, describe the evidence on their potential impacts, assess the current state of adoption, characterize where the strategy might adapt or expand further, and identify what is needed to further promote successful adoption and adaptation at scale. We focus on smallholder agricultural systems in the Global South, as these are typically the systems with the largest productivity gaps and are critical for improving food security in the world's most malnourished regions (11, 18). Finally, we focus on practices and technologies that show particular promise for increasing productivity of the world's staple grain crops – rice, wheat, and maize – as these crops provide over 40% of the world's calories, exhibit some of the largest yield gaps across the Global South (11, 19), and occupy most of the cultivated lands in the world, thus having some of the greatest environmental impacts.

1.2. Defining sustainable intensification

The term sustainable intensification (SI) originated in the 1990s to promote the idea that regenerative and low-input agriculture could be highly productive (20). In its original form, the success of SI was seen as deeply intertwined with that of local farmers, predicated on the fact that farmers participate fully in all stages of technology development and extension (20, 21). Since then, the idea of SI has gained increasing prominence, particularly after 2010, in both the peer-reviewed literature (Figure 1) as well as through international development organizations, including the Food and Agricultural Organization and the Consultative Group on International Agricultural Research (22). SI is now seen as an essential way to meet growing food demand while limiting associated environmental impacts, though including farmers in all stages of development and deployment is no longer central (21). In its current definition, SI does not prescribe a specific set of technologies or practices, and instead encompasses any strategy that increases agricultural productivity without adverse environmental impacts or the conversion of additional non-agricultural land (23). In our review, we distinguish between 'technologies' that embody the adoption of an innovation – such as a new piece of machinery or improved seed – and 'practices' that require the user to change existing farm management behaviors – as with integrated soil fertility management or many agro-ecological innovations. In addition, the technology-vs.-practice distinction revolves around whether the end-user exercises discretion in combining elements or not; s/he determines the combination in a 'practice' but not with a pre-bundled 'technology'. We use the term 'strategy' to encompass all 'technologies' and 'practices'.

2. The most promising SI strategies across maize, rice, and wheat smallholder systems

We conducted a comprehensive literature review to identify key SI strategies in smallholder systems that have been studied over the last decade and are associated with positive outcomes for smallholder farmers. We specifically examined yield and economic impacts of SI strategies in the real world by only including studies where outcomes were measured on farmers' fields and when farmers were the ones deciding to use and how to implement a given strategy. Notably, we did not consider experimental station or on-farm field trials, which comprise the bulk of SI impact research, when someone other than the farmer (e.g., researchers, agricultural extension agents) oversaw implementation of a strategy. Furthermore, we restricted our review to those studies that used a credible causal inference design to ensure that reported impacts were likely due to the adoption of the SI strategy in question and not because of potential selection bias that could occur due to differences between adopters and non-adopters of a strategy.

All studies retrieved in the literature search were reviewed against predetermined criteria for inclusion (methods detailed in Supplementary Information). Most notably, we only included studies that (1) took place on smallholder farms in the Global South, (2) studied the impact of an SI strategy, (3) examined maize, rice, or wheat, (4) took place under real-world farmer management, (5) used credible causal inference methods to assess the impacts of SI, and (6) were published from 2010 onwards. In total, 46 studies met criteria for inclusion (Table S1). For each of these selected studies, we recorded data on the SI strategy, crop, and region studied as well as the magnitude of change in several outcome variables of interest, including yield and economic outcomes, and whether impacts were statistically significant (detailed in Supplementary Information). Of the 46 studies, most examined maize (48%), followed by rice (43%) and wheat (9%), and the majority of studies took place in Africa (59%) followed by Asia (41%; Figure 2). We provide a list of all studies reviewed as well as the location, crop type, SI strategy, and outcome variables considered in each study in the Supplementary Information (Table S2).

The SI strategies evaluated in the literature are strongly associated with region and crop. In the following section, we discuss the most promising SI strategies for the main cropping systems found across the studies in our review: maize systems in sub-Saharan Africa, rice systems in sub-Saharan Africa, rice systems in South and Southeast Asia, and wheat systems in South Asia. We identify the strategies that are most promising as the ones where yield and economic impacts were largely positive and statistically significant, and where percent changes in yield were particularly large, defined as > 40% yield increase (Figure 3). One finding that emerged nearly uniformly across systems was that the adoption of improved cultivars most consistently generated the largest, positive yield and economic outcomes, routinely of higher magnitude and more likely to be statistically significantly different from zero compared to other SI strategies.

2.1. Maize systems in sub-Saharan Africa

Maize is the most planted cereal in over half of the countries in sub-Saharan Africa, particularly in East, Central, and Southern Africa, providing over 30% of calories for households in these countries (24, 25). Maize yields are low across most of sub-Saharan Africa, and this region has some of the largest maize yield gaps globally (26). Increasing maize yields in this region is of critical importance, especially given that it is projected to experience the greatest increase in food demand over the coming decades (27).

We found several strategies that led to consistent positive yield and economic impacts and were associated with large maize yield gains (> 60% yield increase, Figure 3A). One of the most promising SI strategies for maize in sub-Saharan Africa was improved cultivars, specifically drought tolerant maize (DTM). The adoption of DTM was associated with yield gains ranging from 15% to 90% and an increase in per capita household expenditure of up to 50% compared to farmers who used traditional maize varieties (28–32). Not only did the adoption of DTM increase overall mean yields and incomes, it also reduced rates of crop failure and led to improved distributional impacts by increasing yields and incomes the most for the poorest households (31, 32). The yield and economic gains from DTM were not universal, however, and varied with local weather, soil and agroecological conditions, and farmers' ability to co-utilize costly inputs, such as inorganic fertilizers (33, 34).

Another strategy that led to consistent and large positive impacts was push-pull technology, an agro-ecological practice where plants that repel pests (push plants) and plants that attract pests (pull plants) are intercropped with the crop of interest, in this case maize. Such systems reduced pest damage and increased maize yields, farmer income, and per capita food consumption for farming households in multiple countries across sub-Saharan Africa (35, 36). Push-pull systems were particularly effective against stemborers, a parasitic insect, and striga, a parasitic weed, that affect cereal production in many parts of Africa.

A second tier of strategies were those that led to consistent positive impacts, but the magnitude of yield change was more modest (< 40% yield gain, Figure 3A). For example, intercropping staple grain crops with legumes or woody species that fix atmospheric nitrogen into the soil was associated with positive but modest yield and economic gains. Woody species were associated with consistent but small positive impacts on maize yields, especially on lower quality soils (37, 38). Legume intercropping resulted in higher maize yields and increased yield stability, particularly in years with poor weather conditions (39, 40), and higher farm incomes due in part to the additional income earned from legume crops. A second set of strategies that led to positive but modest yield gains were those that improved fertilizer use efficiency, including integrated soil fertility management (ISFM), which promotes locally appropriate technologies to increase soil fertility and nitrogen use efficiency. While ISFM increased yields, there was no systematic increase in household income (41).

The final tier of strategies was comprised of those that had mixed effects, often resulting in no increase in yield or income (Figure 3A). These strategies were reduced tillage, crop rotation, and residue retention, which are the main components of conservation agriculture (CA). CA aims to prevent losses of arable land and also regenerate degraded land (42) through a suite of practices that maintain permanent soil cover, promote minimum soil disturbance, and increase the diversification of plant species. The impacts of CA on maize systems in sub-Saharan Africa were mixed, with only some studies finding positive impacts on yield and economic outcomes (43–46). In general, the positive impacts of CA on yield were greater the more CA technologies and practices a farmer adopted and when rainfall conditions were low or variable (43, 47, 48).

2.2. Rice systems in sub-Saharan Africa

Rice is the main staple grain in West Africa and Madagascar, providing over 30% of household calories, and it is the fastest growing staple grain in the remainder of sub-Saharan Africa (49). Historically, rice yields have been low across sub-Saharan Africa and most increases in production have come from increases in area planted (50). However, rice area expansion is slowing, and increasing rice yields will be necessary to improve food security in this region; rice yields are approximately half of the worldwide average and closing yield gaps could significantly improve incomes and food security in the region (26, 49).

The most promising strategy we found for increasing rice yields in sub-Saharan Africa was the adoption of improved rice varieties, specifically hybrid rice developed through the New Rice for Africa (NERICA) program (Figure 3B). The associated yield gains from adopting NERICA rice varieties were modest, ranging from 10% to 40% (51, 52). The adoption of NERICA varieties was also associated with higher household per capita expenditures and income among adopters, and increased technical efficiency when using inputs, such as fertilizer and irrigation (53). Multiple studies also found that these benefits were larger for women farmers (51, 52), and that the benefit of NERICA varieties largely occurred in upland, rainfed ecologies, even though NERICA varieties have also been developed for lowland and irrigated systems (52).

2.3. Rice systems in South and Southeast Asia

Rice is perhaps even more critical for food security across Asia, where 90% of the world's rice is produced and consumed (54). In Southeast Asia, rice is the main staple grain and provides approximately 50% of household calories (55, 56), while in South Asia, rice along with wheat are the main staple grains, providing 50-70% of household calories (55, 57). Rice yields have increased substantially across Asia since the Green Revolution, but yield gaps remain large in some countries, such as Thailand and the Philippines, and rice yields are stagnating in some of the region's largest producers, including India and China (8, 58). Closing rice yield gaps is critical for the region and for the world, which depends heavily on rice exports from Asia (58).

We found two broad SI strategies were associated with consistently positive and modest to high yield gains (> 40% yield gain, Figure 3C). The first was the adoption of improved seeds that are more climate resilient, such as drought or flood tolerant rice varieties. These improved cultivars increased yields, ranging from 6-45%, particularly in years with sub-optimal growing conditions, such as years with heavy rainfall and flooding (59–61). These varieties also maintained yields when reducing inputs such as fertilizer and irrigation, which increased profitability (61). The adoption of flood-tolerant rice varieties also led to yield gains in non-flood years as farmers adopted additional agricultural investments, such as improved planting methods and fertilizer use (60). The adoption of improved rice cultivars also increased profits, ranging from 10-58%. These benefits were larger for farmers in flood-prone regions, who were often poorer and more marginalized (62).

The second most promising strategy was the System of Rice Intensification (SRI), which is a suite of agro-ecological practices that increase the productivity of irrigated rice by changing the way plants, soil, water, and nutrients are managed (63). Specifically, rice seedlings are transplanted at an earlier age and are widely spaced, organic matter is added to improve soil structure and nutrients, irrigation is applied intermittently and the field does not remain flooded (termed alternative wetting and drying), and weeds are managed using a rotary hoe (63). SRI was associated with large and consistent yield gains across multiple countries in Asia, ranging from 17-64%, and yield gains were typically larger for poorer farmers with smaller landholdings and in years with suboptimal weather (64–67). Economic gains were also consistently positive and significant, ranging from 22-107% when considering income generated from rice, however, were much smaller when considering overall household income gains (< 5%) (65–67).

The second set of strategies led to consistent and significant positive outcomes on yield, but with smaller magnitudes (largely < 20% yield gain, Figure 3C). Specifically, alternative wetting and drying, which is one component of SRI, was found to increase yields, increase farmer incomes, and reduce the cost of cultivation for rice (64). In addition, direct seeded rice, where rice seeds are directly planted into fields instead of being transplanted as seedlings from nurseries, was associated with increased yield and household income (64, 68). Direct seeding reduced the number of irrigations and the amount of labor needed to plant fields, and also allowed farmers to plant more profitable long duration rice varieties by facilitating earlier planting compared to transplanted rice (64, 68).

2.4. Wheat systems in South Asia

Wheat is a staple grain across parts of South Asia, particularly across the Indo-Gangetic Plains (IGP), providing 40-70% of household calories across this region (12, 57). Some regions within the IGP are low yielding and have large yield gaps, particularly in the eastern IGP (69). In addition, wheat yields have stagnated across much of the IGP, and climate change is projected to reduce wheat yields by up to 20% across South Asia (8, 70). Thus, identifying ways to increase wheat yields and make the crop more resilient to warming temperatures are critical for food security in the region.

There were two promising SI strategies for increasing wheat yields in South Asia (Figure 3D). The first was earlier sowing, which boosts wheat yields by allowing the crop to mature prior to heat stress that occurs at the end of the growing season, reducing the negative impacts of warming temperatures on wheat yields (71, 72). Earlier sowing was associated with yield gains in both India and Pakistan, particularly in the eastern IGP, where earlier sowing increased yields by up to 28% (73, 74). The second promising strategy was the use of zero tillage technologies, where farmers use special seed drills that can sow seeds into untilled soils and residue that remains from the previous crop harvest. The use of zero tillage raised wheat yields from 5-19%, likely due to improvements in soil fertility and irrigation efficiency (73–75). These yield gains were estimated independent of any additional yield gains that may occur from earlier sowing, as the use of zero tillage is associated with earlier planting since it reduces the amount of time needed to prepare fields (71).

3. Adoption rates and scalability of the most promising SI strategies

For each of the most promising strategies identified in Section 2, we discuss the current state of adoption and the ability to scale or expand the strategy further by 2030.

3.1. Maize systems in sub-Saharan Africa

Two SI strategies were found to be the most promising for maize systems in sub-Saharan Africa, drought tolerant maize (DTM) and push-pull systems. DTM was introduced to sub-Saharan Africa through the DTM for Africa project across 13 countries. This project was led by the International Maize and Wheat Improvement Center (CIMMYT) and the International Institute for Tropical Agriculture in collaboration with national agricultural research systems in participating countries. Since 2006, more than 100 new DTM varieties have been introduced across the region. DTM adoption is highly variable across sub-Saharan Africa, ranging from 9% to 26% of maize area in each country (29, 32, 76–78), though adoption levels are as high as 61% of maize area in Malawi due to that country's relatively large farm input subsidy program (FISP) (76, 77). It is estimated that more than 8 million farmers use DTM varieties, some in countries not directly involved in the DTM for Africa project (79). When considering the possible scalability of DTM adoption, studies suggest that DTM could result in yield gains for rain-fed maize grown in drought-prone regions. This amounts to approximately 40% of sub-Saharan Africa's maize area and up to 40 million smallholder farmers, suggesting the scalability of DTM is extremely large.

Push-pull technology was first developed at the International Centre of Insect Physiology and Ecology, based in Kenya, in 1997. Since then, the technology has been found to be effective against stemborer pests and striga weeds in maize systems across sub-Saharan Africa (35, 36, 80). Adoption rates remain relatively low, with over 150,000 farmers estimated to use push-pull technology, largely concentrated in East Africa (81, 82). The use of push-pull technology, however, is growing, with adoption numbers doubling since 2014 and expanding to countries outside of East Africa, including Malawi, Zambia, Zimbabwe, Rwanda, Burundi, and Burkina Faso (80, 81, 83). The potential scope to expand push-pull technology is large, given that stemborer pests are estimated to impact 30 million hectares of cropland (84) and striga is estimated to affect 15% of maize area in parts of sub-Saharan Africa (85).

3.2. Rice systems in sub-Saharan Africa

NERICA rice varieties were first developed in 1992 by breeders at the Africa Rice Center by crossing African rice species with high-yielding varieties from Asia. To date 82 varieties have been developed, tested, and distributed in 31 sub-Saharan African countries. NERICA rice has been widely adopted, reaching up to 59% of rice farmers in sub-Saharan Africa, covering over 1.4 million ha (86). Levels of adoption vary widely across countries, ranging from 10% (Ghana) to 95% (Sierra Leone) of all rice farmers (51, 52, 86–88). Although adoption levels are relatively high for NERICA rice, disadoption – where farmers discontinue use after initial experimentation with a new strategy – has also occurred at large scales in some regions. For example, studies have estimated that 20-50% of all farmers who planted NERICA rice in the early 2000s have since discontinued its use, either because the variety did not provide better profitability in years with poor rainfall or because farmers lacked information about the proper cultivation methods needed for high yields (89, 90). Considering the potential scalability of the technology, NERICA varieties have shown the most promise in upland ecologies, which comprise a large proportion (> 30%) of rice area in Central and West Africa (91), and could reach nearly 1.7 million farmers (92).

3.3. Rice systems in South and Southeast Asia

We found two SI strategies to be the most promising for increasing yields in rice systems in Asia: improved stress-tolerant rice varieties, particularly those tolerant to floods, and SRI. New stress-tolerant rice varieties that have been adopted in Asia have largely been developed by scientists and breeders working with the International Rice Research Institute (IRRI). Over the last two decades, IRRI has developed rice varieties more tolerant to climate variability, including drought, submergence, and floods. IRRI has developed three varieties of submergence-tolerant rice, the most examined improved cultivar type in our studies, that are widely planted in flooded regions of India, Bangladesh, and the Philippines (93). Adoption rates of these varieties range from 4-40% of farmers in the eastern, flood prone states of India and in Bangladesh (94) and estimated to be planted over 130,000 hectares in India (95). The potential scale for the adoption of stress-tolerant rice varieties is high, as it is estimated that approximately 30% of rice-growing areas in Asia are affected by environmental stressors that can be alleviated with improved cultivars (93).

SRI originated in Madagascar in the 1980s and was disseminated and further developed by the Association Tefy Saina and a range of farmer associations and non-profits (63). The strategy has been disseminated to over 60 countries, and more than 10 million farmers have adopted the strategy across the globe (63, 96). While adoption rates are relatively high compared to other SI strategies, disadoption rates are also high for SRI, estimated to be up to 30-40% of farmers who initially used the technology in some locations (67, 97). One apparent reason for high rates of disadoption is its high labor and water management demands. Considering the scalability of SRI, organizations have suggested that the method can be adopted across all rice growing systems across South and Southeast Asia. While SRI was originally developed for irrigated systems, SRI principles have been applied to rainfed rice as well (63).

3.4. Wheat systems in South Asia

The two strategies found to be the most promising for increasing yields in wheat systems in South Asia are earlier sowing of wheat and the adoption of zero tillage technologies. Currently, wheat is sown two to four weeks late, on average, in the eastern IGP, likely due to reduced access to irrigation, limited access to zero tillage machinery, and the high prevalence of soils that are easily flooded at the start of the wheat growing season (69, 71). Up to 40% of farmers delay wheat sowing in the western IGP but up to 90% of farmers sow wheat late in the eastern IGP (98). This suggests that there is substantial scope to promote earlier wheat sowing, particularly in the eastern IGP, reaching up to 2.25 million ha of wheat in this region (99).

The promotion of zero tillage in South Asia began in the 1990s when CIMMYT first introduced seed drilling machinery from Australia. Since then, there has been significant work to adapt the machinery to local conditions and provide government subsidies and access to the technology to increase adoption. Adoption of zero tillage varies widely across the IGP, with studies estimating that approximately one-sixth of wheat area is under zero tillage, but can reach up to 30% of area in regions where zero tillage extension agents are active (75, 100). Zero tillage is difficult to implement in fields that are very small in size (< 0.5 ha), and therefore this technology is likely scalable only to roughly half of wheat area across the IGP.

4. Potential leverage points to increase adoption at scale

The empirical literature on agricultural technology adoption consistently describes halting, and usually incomplete adoption of improved inputs or production processes (101, 102). Typically, the early adopters of new innovations are those for whom the technology is most agronomically and economically suitable, who have the social or institutional connections to become aware of both the innovation and how to employ it successfully, and who have the financial means to invest in experimenting with it, including potentially absorbing at least initial losses (101). Diffusion of a new technology typically begins slowly, then accelerates before tapering off again, following an S-shaped pattern in time. Incomplete adoption – and some disadoption – arises naturally from heterogeneity among farmers in agronomic and socioeconomic conditions that determine awareness of new methods and the net gains from changing strategies (103–105).

In this section we review the literature to identify the key leverage points that may increase the adoption and diffusion of each of the most promising strategies, pushing them further along the S-shaped diffusion pathway (Table 1). We focus on factors that can be promoted by external agents, such as agricultural extension agents, research institutions, non-governmental organizations, and policy-makers, and not individual-level characteristics of farmers that may influence adoption, such as education or risk preferences. Based on findings from our literature review, we offer some subjective, categorical – and admittedly speculative – estimates of the potential of each leverage point, ranking each as having low, moderate, or high prospective impact on increasing adoption at scale (Table 1). While we discuss broad categories of leverage points, such as increasing awareness about a given SI strategy, the evidence is too thin to enable us to prescribe the most effective way(s) to achieve this goal. We categorize our findings into three broad categories of leverage points: (1) awareness, or increasing farmers' knowledge about the specific strategy and its benefits; (2) access, or increasing the availability of the specific strategy to farmers; and (3) affordability, or increasing farmers' ability to afford the costs associated with the strategy. We describe each leverage point and which strategies would benefit the most from each in the sections below.

For some strategies, lack of awareness seems to be one of the biggest hurdles to increasing adoption. This is true for emerging strategies that are not yet widely adopted, such as push-pull technologies in maize systems in Africa and stress-tolerant rice varieties in Asia. Studies estimate that up to 90% of farmers would adopt push-pull technologies and up to 48% of farmers would adopt stress-tolerant rice varieties if they were aware of the strategy and its benefits (80, 106–109). Increased awareness was also posited to be one of the most important leverage points to increase the adoption of more-established crop varieties that have been available for a long time, such as DTM and NERICA rice varieties. Studies estimate that increasing awareness could increase adoption rates between 8-35%, with most studies estimating adoption rate increases of 20% or greater (90, 110–115). For other strategies, specifically zero tillage of wheat and SRI of rice in Asia, increasing awareness would likely lead to moderate increases in adoption. For these strategies, studies suggest that while increased training or interactions with agricultural extension agents does lead to increased adoption, the main constraints to adoption are related to price or technical challenges with implementing the strategy (67, 100, 116, 117). Finally, in the case of earlier sowing of wheat, increased awareness would likely have low impact because studies suggest that farmers are already aware of the benefits of earlier sowing, and are unable to plant early due to broader constraints in the annual cropping calendar (71, 98).

Access to technologies needed to implement a given strategy is one of the biggest constraints to increasing adoption for several strategies (Table 1). Considering earlier sowing of wheat, studies have suggested that increasing access to irrigation or direct seeding technologies is critical to help farmers plant their rice and subsequently wheat crops on time (71, 98, 99). In the case of push-pull technology, farmer adoption is limited by lack of access to *desmodium* seeds, which are often used as the push plant in these systems (81, 108, 118). For other strategies, increasing access to technologies would likely play a more moderate role. This is true in the case of zero tillage technologies, where high costs are the larger constraint to adoption (100, 119). For improved seed varieties, studies have suggested that increasing access to seeds in local markets or through farmer-to-farmer exchanges would increase adoption rates between 4-16%, which appears to be a smaller gain than could be obtained through increasing awareness (76, 110–115, 120). Finally, increasing access is not a viable way to significantly increase the adoption of SRI because farmers implement changes in management practices and do not require access to new seeds or machinery (63).

Reducing the costs associated with implementing a given strategy would greatly increase adoption rates for some strategies (Table 1). This is true for technologies that entail a large upfront cost, such as zero tillage and other direct seeding technologies where farmers require both access to a tractor as well as the direct seeding machinery. This constraint, however, has been alleviated in some regions through the creation of a service provider model, where richer farmers, who can afford the upfront machinery purchase costs, are trained as service providers then service or rent out their machinery to farmers who otherwise could not afford the technology (119, 121). For other strategies, reducing associated costs would play an important role. For example, several SI strategies require increased labor, which can serve as a major constraint to adoption, or may even induce disadoption. SRI requires considerable labor to frequently remove weeds that are more likely to occur compared to fields that remain perpetually flooded, and to monitor and manage water levels on a daily basis (97, 122, 123). Similarly, the adoption of zero tillage is constrained by the higher prevalence of weeds that grow in untilled fields compared to conventionally tilled fields, and can require added labor or herbicides to control weeds (100, 124). Finally, reduced costs would likely have a low impact in scaling some strategies. For the improved cultivars that we identified, studies have suggested that reducing the price of seeds would only have a marginal impact on adoption rates (typically less than 10%) compared to increasing awareness and access (77, 113, 114).

5. Emerging technologies and practices

Our literature review necessarily could not capture emerging strategies that are not yet widely adopted, nor evaluated, in smallholder systems. We therefore conducted a structured, online survey with researchers who previously published on SI in the peer-reviewed literature (methods detailed in the Supplementary Information). In this survey, we asked respondents about what they believed were the most effective SI strategies for increasing production in smallholder systems. We received 86 responses and used these to identify the most common emerging strategies not already identified through our literature review.

As with the established SI strategies, improved cultivars seem the dominant emerging technology. New seed varieties more tolerant of heat stress was a commonly identified emerging technology. Developing and promoting heat-tolerant varieties is critical given that climate change is already reducing staple crop yields, especially wheat and maize, with some studies estimating yield losses of up to 20% due to warming temperatures by mid-century (9). New wheat varieties that tolerate heat better, at either the grain filling or the juvenile stage, show promise (125). Developing increased heat tolerance during the stage of grain filling is especially important because this is the critical period when high temperatures most negatively impact wheat. New wheat varieties that have been developed to reduce the negative impacts of heat stress on grain filling have been shown to increase yields by up to 30% on average compared to currently planted varieties, with larger comparative yield gains in warmer years (126). Wheat varieties that better tolerate heat stress during the early juvenile stage would allow farmers to sow wheat earlier than is currently possible, better avoiding the co-occurrence of grain filling and high temperatures at the end of the growing season. Varieties that tolerate heat-stress during the juvenile period can be planted earlier than current varieties as they withstand warm temperatures better at the start of the growing season. It has been estimated that these varieties could increase yields by up to 33% on average (127). New maize varieties are likewise being developed to better tolerate heat stress, particularly during the critical grain filling stage (128). These varieties could reduce the negative yield impacts of heat stress by up to 93% by mid-century (129). New maize varieties that are both heat and drought tolerant have been shown to double yields in some regions, and increase yields relative to current varieties by up to 185% under an additional 2°C warming (130).

A second set of emerging strategies our survey identified revolves around precision agriculture, sensors, and digital technologies that allow farmers to use inputs more efficiently. To date such strategies have largely been adopted by large-scale, industrial farms in the developed world and mostly occur at the experimental level in smallholder systems (131). Among the most promising precision agriculture technologies is the use of on-the-ground soil and plant sensors, which can better manage nutrients and water and detect pests and disease (132). For example, wireless sensor technologies can detect crop water stress and help farmers apply irrigation only at critical times (133). Spectral sensors have also been used to identify nutrient deficiencies and help farmers target fertilizer application during periods and in locations where it is needed (131). Remote sensing using drone and/or satellite imagery also offers key advantages for precision agriculture, given that it is typically lower cost and can provide information at the full field and landscape scale (132, 134). Hyperspectral drone imagery has successfully mapped disease type and location, allowing farmers to apply pesticides at the optimal time and in specific affected parts of the field (135). Multi-spectral satellite imagery in combination with surface energy balance models have been used to map water stress, and help farmers identify the ideal time to use irrigation. Satellite data have also been used to identify which fields would benefit the most from improved fertilizer application, which can be used for precision targeting of agricultural interventions (134). Finally, in-field soil testing has been shown to increase yields and fertilizer use efficiency by identifying the specific macro- and micro-nutrient deficiencies that should be targeted with fertilizer application (131, 136). While these strategies have been shown to be effective in small-scale trials, large-scale adoption is currently hampered by the high costs of sensors and drones, data and infrastructure gaps that limit the ability to obtain, store, and share information, and the coarse resolution of readily-available satellite imagery that does not match field sizes in regions with very small fields (131, 134).

Finally, a third set of strategies our survey identified concerned interventions to improve risk management. For example, one strategy that has been adopted at relatively high rates is index insurance, where payouts are given to farmers based on a predetermined and easily measurable environmental index, such as rainfall, temperature, or average performance estimated using satellite data. While there has been extensive experimentation of index insurance in smallholder systems and widespread adoption in some countries, such as India, adoption has been low in regions that do not have large and sustained subsidies (137). One way to improve the cost effectiveness of index insurance is to bundle it with complementary strategies that reduce risks, such as stress-tolerant seed varieties (137). Improved quality control in index insurance product design is essential to scale uptake and impacts, however, and to safeguard smallholder farmers from financial product failures on top of crop failure or livestock loss (138).

6. Research gaps and future research needs

We identified several gaps within the current literature on the impacts and adoption of SI in smallholder systems, and these gaps represent high priority research needs. First, we found only 46 studies that used rigorous causal inference methods to assess the real-world impacts of SI strategies in farmers' fields. This is because the vast majority of research on SI strategies in smallholder systems comes from plot-level field trials, either performed on agricultural research fields or by researchers on farmers' fields. While these plot-level studies give an understanding of how effective an SI strategy may be under ideal management conditions, they do not indicate how effective the SI strategy may be under real-world farmer management, which may differ considerably from ideal conditions (139). For example, zero tillage technologies were developed with the goal of allowing farmers to sow seeds in remaining residue stubble, removing the need to till fields prior to planting (75). However, in the real world, many farmers till their fields prior to planting their crop using zero tillage machinery, and this real-world implementation of the SI strategy is typically overlooked in plot-level experiments (124). Farmers may also choose to bundle the adoption of multiple strategies, which may not be captured in field experiments (140). In addition, far too few studies use credible causal inference methods, but these are necessary to accurately estimate impacts by accounting for possible endogenous differences in adopters versus non-adopters of the strategy.

Second, there is bias in where studies are conducted and which crops are examined. The impact of SI strategies on sub-Saharan African maize systems seems overrepresented relative to the number of smallholder farmers affected or area cultivated, especially compared to wheat systems. Furthermore, our search included additional staple crops such as sorghum and barley, yet we only found three relevant studies for all other staple crops. We omit these from our review due to a sample size too small to identify generalizable findings. These alternative staple grains, however, are important for household dietary diversity and nutrition in smallholder systems, particularly in semi-arid regions in Africa and Asia, and could grow in importance due to climate change given that they are more drought-tolerant than other staple grains (141).

Considering geography, most studies were located in sub-Saharan Africa; none covered smallholder systems in Latin America and the Caribbean. This is likely because the proportion of food production that comes from smallholder farms is much smaller in this region (< 5%) compared to Africa and Asia. This is nonetheless an important gap given that smallholder farms comprise a sizeable proportion of farms in some countries in Latin America and the Caribbean, particularly Guatemala (90% of all farms), Panama (60% of all farms), and Ecuador (43% of all farms) (7). Finally, we were only able to access one relevant study that took place in China, yet China has the largest number and proportion of smallholder farms, which produce 80% of China's food (7).

A third gap we identified was related to outcomes measured. While our keywords identified a wide range of possible outcomes, most studies focused on the impact of SI strategies on crop yield. Yield, however, is only one component of total factor productivity (TFP), which quantifies the total amount of agricultural production produced from the combined set of land, labor, capital, and other material resources employed in farm production (142). TFP more realistically captures what farmers optimize, as farmers rarely prioritize yield maximization; rather they aim to maximize profits and/or household well-being (143). Several studies examined factors related to TFP, such as the technical efficiency of input use relative to the observed production frontier and how technical efficiencies changed when using SI strategies. But this was a small minority of studies. Moreover, we only found one study that examined environmental outcomes, and no studies coupled the measurement of environmental outcomes with yield or economic outcomes. Quantifying the joint impacts of SI strategies on both environmental and economic metrics in the real-world is critical, as purported environmental benefits may not actually occur under real-world farmer management. This would undermine the goal of SI interventions, which is to increase agricultural production without increasing environmental degradation.

Fourth, given that the central undernutrition challenges currently surround micronutrient deficiencies rather than undernourishment arising from insufficient calorie and protein intake, increased attention is needed on SI of mineral-and-vitamin-rich crops, especially vegetables, pulses, legumes and fruits (144). This could be through the uptake of new crops (e.g., through home gardens) or biofortified crops (e.g., iron or zinc biofortified cultivars) (145, 146). Rigorous research on the impacts and diffusion of SI strategies around these crops remain seriously understudied in smallholder farming systems.

Fifth, systems transformation is needed to ensure that all people have access to healthy diets based on agrifood systems that are resilient, sustainable, and provide equitable livelihoods (17, 147). Current agri-food systems are plagued with inefficiencies, resulting in almost one third of global food production being lost or wasted (148). In addition, while over 800 million people suffer undernourishment globally, over three billion people are unable to afford a healthy diet (18). SI is just one component of a broader agrifood systems transition. More research is needed that identifies complementary pathways to reaching the SDG of zero hunger by 2030, including SI as one, but not the sole, component.

Finally, considering environmental metrics that are typically measured in SI research, most are limited to those that can be measured on farm, such as soil quality, greenhouse gas emissions, or water conservation (139, 149). Few studies link the adoption of SI strategies with larger-scale, off-farm environmental outcomes, such as changes in tree cover and deforestation. This is of concern given that it is possible that the adoption of SI strategies could lead to increased area expansion of agriculture if it greatly increases the profitability of production, and this is an important avenue for future research.

7. Conclusions

Our review identified the most promising SI strategies in smallholder systems as revealed through a rapid review of evidence from studies using data from smallholder farmer-managed strategies and rigorous causal inference methods. We found that the most promising strategies varied considerably by cropping system. For maize in sub-Saharan Africa, improved cultivars, specifically DTM, and push-pull systems were associated with consistent positive impacts on yield and economic outcomes. For rice systems, improved NERICA rice cultivars appeared to be the most effective strategy in sub-Saharan Africa, while SRI and stress-tolerant rice varieties were the most promising strategies in Asia. Earlier planting and zero tillage were the most promising strategies to increase wheat yields and associated incomes in South Asia.

Overall, improved cultivars were associated with the largest, most consistent, and positive impacts on yield and economic outcomes compared to all other SI strategies examined. The potential to scale these strategies is large, with the possibility of reaching over 50% of smallholder farmers who plant rice, wheat, or maize in Africa and Asia. Yet, significant barriers to adoption exist, and current adoption rates remain relatively low. Increasing awareness appears to be the leverage point that could lead to the most consistent increases in adoption across the most promising strategies identified in this review. Finding ways to scale these successful strategies will be critical to meeting SDGs 1 and 2 by 2030.

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Table 1. Prospective impact from targeting key leverage points to scale the most promising strategies identified in our review.

		Prospective Impact of Increasing:		
System	**Strategy**	**Awareness**	**Access**	**Affordability**
Maize in sub-Saharan Africa	DTM varieties	High	Moderate	Low
	Push-pull technology	High	High	Low
Rice in sub-Saharan Africa	NERICA varieties	High	Moderate	Low
Rice in Asia	Stress-tolerant rice varieties	High	Moderate	Low
	SRI	Moderate	Low	Moderate
Wheat in Asia	Early sowing	Low	High	High
	Zero tillage	Moderate	Moderate	High

Figure 1. Number of papers on SI per year from 1990 to 2021 found in Web of Science. Search terms used were 'sustainabl* intensif*' AND 'agricultur*' in the field *topic*.

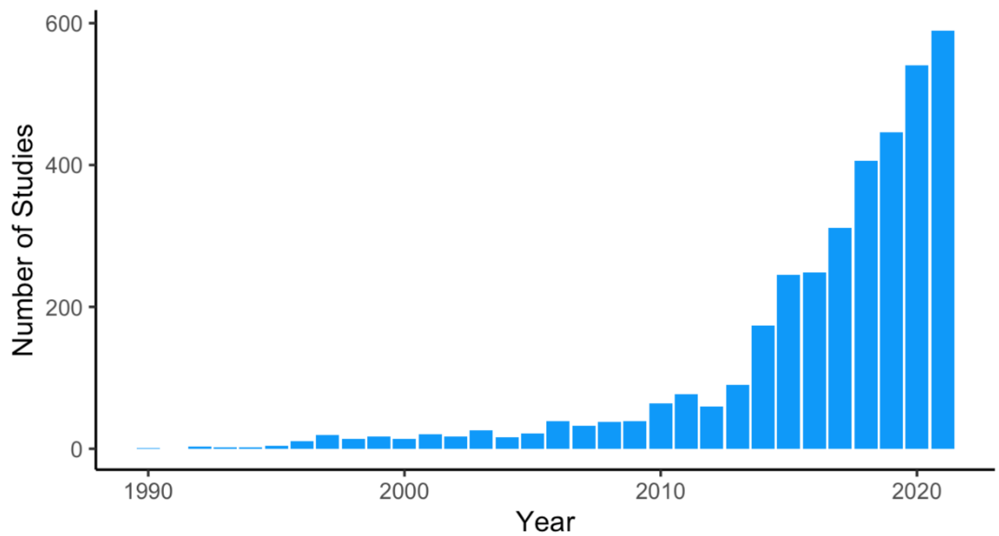


Figure 2. Location by crop type across the 46 studies found in our review.

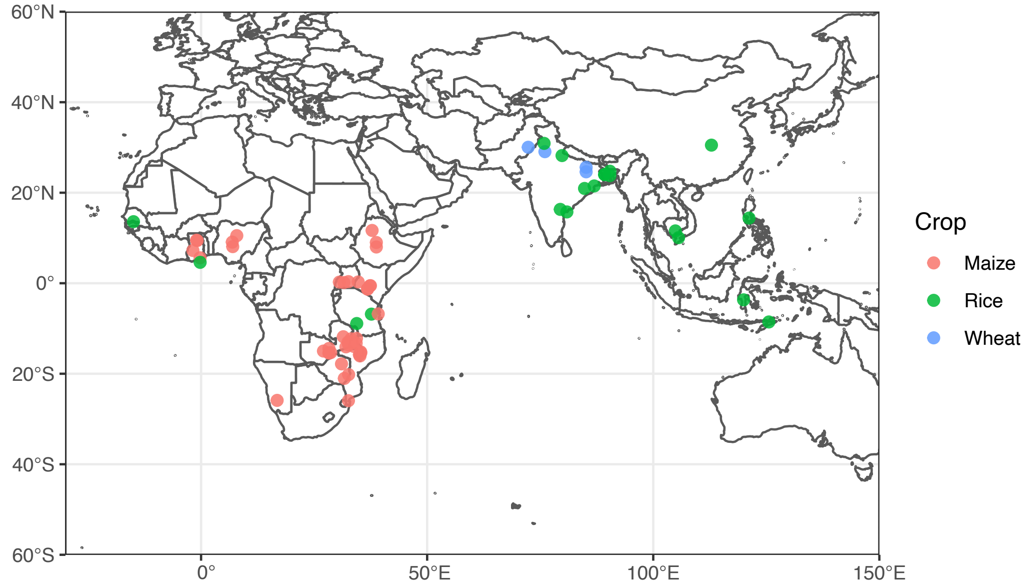
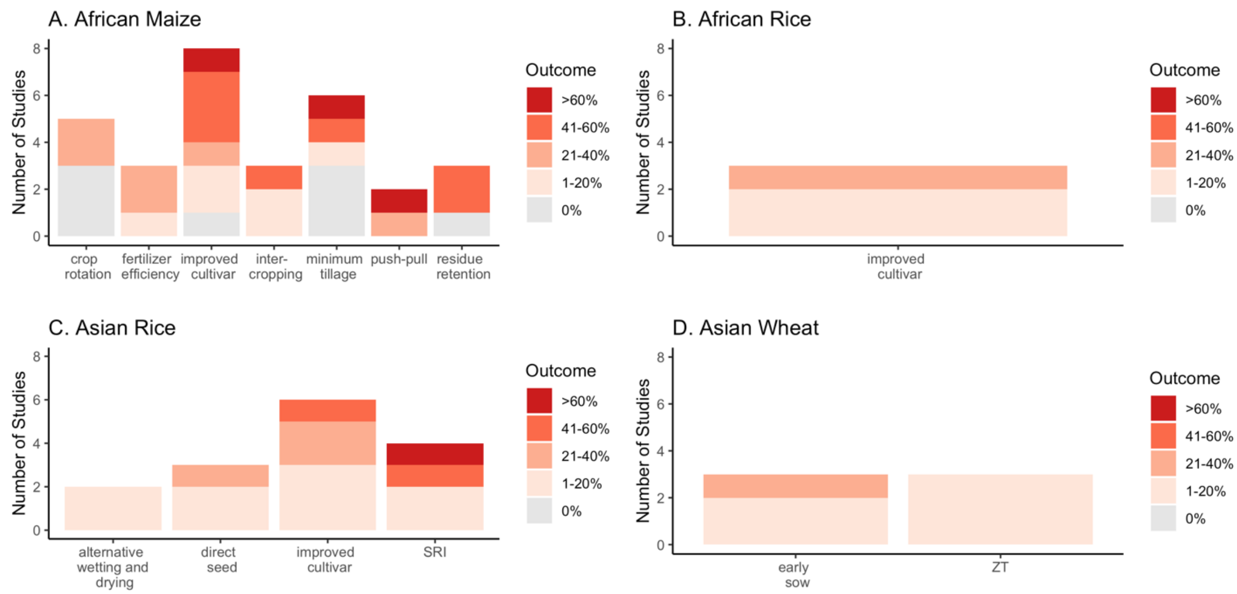


Figure 3. Number of studies that found a given magnitude of yield change for (A) maize in sub-Saharan Africa, (B) rice in sub-Saharan Africa, (C) rice in Asia, and (D) wheat in Asia grouped by SI strategy on the horizontal axis. Studies that found insignificant differences are listed as 0% change (gray bar). We only consider outcomes when a strategy was reviewed at least two times in the literature.



Surveying the Evidence on Sustainable Intensification Strategies for Smallholder Agricultural Systems

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Supplementary Information

1. Literature review methods

We conducted a rapid review, searching the CAB Abstracts and Scopus databases with a search strategy incorporating terms for smallholder farmers, low- and middle-income countries, and sustainable intensification. A full description of the literature search and retrieval methods is available in our protocol on Open Science Framework (https://osf.io/bcgqy). In a first stage of article selection, titles and abstracts of all search results were screened against the eligibility criteria by two independent reviewers (Table S1). Conflicts were resolved by a third, independent reviewer. Of 3,269 total papers retrieved in the initial search, 977 papers met criteria and were reviewed in full text. For this full text screening, PDFs of remaining papers were retrieved and reviewed in full by a single reviewer against eligibility criteria. Studies selected at this stage were then evaluated by an additional reviewer to confirm that all inclusion criteria were met. This resulted in a total of 35 papers found through our rapid review. Finally, we also included any known papers to the author team that met the eligibility criteria but were not found through our rapid review. This resulted in an additional 11 papers.

Information on the location of the study, type of SI strategy used, experimental design, crop studied, outcomes measured, and sample size were extracted from the final set of 46 included papers (Table S2).

2. Survey methods

To identify emerging SI strategies that are yet to be widely published on, and therefore would not have been identified through our literature review, we conducted a structured email survey with 86 researchers and practitioners who have studied SI in smallholder systems. We identified these authors as those who published papers in a previous review on SI in smallholder systems conducted by some of the authors (Jain et al., 2020). We also included researchers known to the authors who were not included in the previous review but have previously conducted work on SI in smallholder systems. The survey was administered using Qualtrics, and the full list of questions can be found at this link https://umich.qualtrics.com/jfe/form/SV_eQjd9tewQsuVBEG.

Table S1. A list of all inclusion and exclusion criteria for the articles considered in our review.

Inclusion	The study was published no earlier than 2010.
	The study took place in an LMIC in Africa, Asia, and/or Latin America/the Caribbean.
	Studies took place on-farm (not in a green house or as a pot experiment) and the intervention was managed by a smallholder (i.e., farm size ≤10 hectares) farmer on his/her farm
	The experiment was conducted for at least one of the following staple grain crops: maize, rice, wheat, barley, and sorghum.
	The study examines the effects of one or more sustainable intensification technologies and practices.
	The study examines quantitative outcomes on yields, total/multi-factor productivity, environmental outcomes or adoption/diffusion of the strategy(ies) studied
	The study must assess the effect of a practice using counterfactual comparison, such as a controlled field experiment, randomized controlled trial, among other design-based causal inference methods. For studies on adoption, diffusion, and disadoption we will also consider observational studies that do not use causal inference.
Exclusion	The study was published prior to 2010.
	The study did not take place in an LMIC in Africa, Asia, and/or Latin America/the Caribbean.
	Studies are not from smallholder farming systems or do not include smallholder farmers, strategies are not conducted on-farm, and/or farming decisions are not made by smallholder farmers.
	The study does not consider one of the five main staple grain crops: maize, rice, wheat, barley, and sorghum.
	The study does not examine the effects of one or more sustainable intensification technologies or practices.
	The study does not examine quantitative outcomes on yields, total/multi-factor productivity, environmental outcomes, or adoption/diffusion of the strategy(ies) studied
	The study does not assess the effect of a practices quantitatively and using counterfactual comparison, such as controlled field experiment, randomized controlled trial, among other design-based causal inference methods. For studies on adoption, diffusion, and disadoption, the study does not include quantitative estimates of adoption/diffusion such as the number of farmers or the land area using the strategy(ies) studied; these could be observational studies without a counterfactual.

Table S2. List of all papers that were included in our review, the country of study, the SI strategy examined, and the outcomes measured across each of the four cropping systems. This table is also hosted as a pivot table at https://deepblue.lib.umich.edu/data/concern/data_sets/qj72p761f.

Sub-Saharan Africa Maize (n = 22)			
Reference	**Country**	**SI Strategy**	**Outcome**
(Adego et al., 2019)	Ethiopia	Improved seed	Yield
(Adolwa et al., 2019)	Ghana, Kenya	Integrated soil fertility management	Yield, household income
(Amadu et al., 2020)	Malawi	Nitrogen-fixing woody species	Yield
(Arslan et al., 2015)	Zambia	Minimum soil disturbance, crop rotation, intercropping	Yield
(Boillat et al., 2019)	Kenya, Malawi	Reduced tillage, permanent ground cover, drop diversification	Yield
(Chepchirchir et al., 2017)	Uganda	Push-pull technology	Yield, income, per capita food consumption
(Holden and Fisher, 2015)	Malawi	Drought tolerant maize (DTM)	Yield
(Jena, 2019)	Kenya	Minimum tillage	Yield, labor use
(Katengeza and Holden, 2021)	Malawi	DTM	Yield
(Kuntashula et al., 2018)	Zambia	Nitrogen-fixing woody species	Yield
(Lunduka et al., 2019)	Zimbabwe	DTM	Yield, income
(Manda et al., 2016)	Zambia	Improved seed	Yield, income
(Martey et al., 2020)	Ghana	DTM	Yield, farm income
(Ngoma, 2018)	Zambia	Minimum tillage	Yield, crop income
(Obayelu et al., 2019)	Nigeria	DTM	Yield, poverty incidence
(Olagunju et al., 2020)	Nigeria	DTM	Yield, welfare
(Pedzisa et al., 2015)	Zimbabwe	Conservation agriculture	Yield

(Schader et al., 2021)	Ghana, Kenya	Organic farming	Yield, gross margins
(Schmidt and Tadesse, 2019)	Ethiopia	Sustainable land management project	Water storage
(Simtowe et al., 2019)	Uganda	DTM	Yield, crop failure
(Tambo and Kirui, 2021)	Zambia	Conservation farming	Yield
(Tambo and Mockshell, 2018)	Ghana, Nigeria, Ethiopia, Kenya, Tanzania, Uganda, Malawi, Mozambique, Zambia	Conservation agriculture	Household income
Sub-Saharan Africa Rice (n = 5)			
Reference	**Country**	**SI Strategy**	**Outcome**
(Alem et al., 2015)	Tanzania	SRI	Yield; profit
(Asante et al., 2014)	Ghana	NERICA	Technical efficiency of inputs
(Dibba et al., 2012)	Gambia	NERICA	Yield; profit
(Dontsop Nguezet et al., 2012)	Nigeria	NERICA	Yield
(Rashid, 2020)	Tanzania	NERICA	Yield
South and Southeast Asia Rice (n = 15)			
Reference	**Country**	**SI Strategy**	**Outcome**
(Alauddin et al., 2020)	Bangladesh	Alternative wetting and drying	Yield
(Ali et al., 2014)	Pakistan	Direct seeding	Yield; profit
(Bairagi et al., 2020)	Cambodia	Weather-resistant rice; integrated pest management; weather advisory	Yield; profit
(Bairagi et al., 2021)	Bangladesh	Flood-tolerant rice	Yield; profit; rice consumption
(Barrett et al., 2022)	Bangladesh	SRI	Yield; profit
(Dar et al., 2013)	India	Flood-tolerant rice	Yield

(Emerick et al., 2016)	India	Flood-tolerant rice	Yield; credit; rice savings
(Kakumanu et al., 2019)	India	Alternative wetting and drying; SRI; direct seeding	Yield; costs
(Kumara et al., 2020)	India	Tank rehabilitation	Yield
(Mishra et al., 2017)	India	Direct seeding	Yield; costs
(Noltze et al., 2013)	Timor Leste	SRI	Yield; household income
(Takahashi and Barrett, 2014)	Indonesia	SRI	Yield; rice income
(Tho et al., 2021)	Vietnam	Improved seeds; reduced inputs	Yield; profit
(Yorobe Jr. et al., 2016)	Philippines	Green super rice cultivar	Yield; farm income
(Zhou et al., 2018)	China	Stress-tolerant varieties	Yield
South Asia Wheat (n = 4)			
Reference	**Country**	**SI Strategy**	**Outcome**
(Abid et al., 2016)	Pakistan	Early sowing	Yield; profit
(Keil et al., 2015)	India	Zero tillage (ZT) and early sowing	Yield; total annual income
(Krishna and Veettil, 2014)	India	ZT and early sowing	Technical efficiency
(Keil et al., 2020)	India	ZT	Yield; household income

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