How much can sustainable intensification increase yields across South Asia? a systematic review of the evidence

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Abstract

Food security will become increasingly challenged over the coming decades, and sustainable intensification is often touted as an ideal way to increase yields while limiting negative environmental impacts. Yet, the extent to which sustainable intensification can increase yields remains unclear. We systematically reviewed the literature to assess the extent to which sustainable intensification can increase yields across South Asia, a region that is expected to face some of the greatest food security challenges over the coming decades. We found that yield gains from sustainable intensification interventions were heterogeneous, and that the average yield gain across all studies was 21%. Residue retention and the use of organic fertilizers were, in particular, associated with significant and positive yield gains, though the use of organic fertilizers was not always profitable, likely due to large subsidies provided for mineral fertilizers across South Asia. Our work also revealed biases in the current sustainable intensification literature, with research clustered in highly productive, irrigated, and commodity cropping systems, which do not represent large portions of agricultural systems across South Asia. Our results highlight that sustainable intensification interventions should play an important role in increasing food production across South Asia, but yield gains from these interventions are modest compared to estimated yield gaps across the region.

1. Introduction

Global food demand will increase over the coming decades due to a growing population with changing diets (Godfray et al 2010, Tilman et al 2011). Simultaneously, the yields of some staple crops are expected to decrease as climate change and natural resource degradation challenge production (Lobell et al 2008, Challinor et al 2014). One way to meet growing food demand is to increase yields by closing existing yield gaps, defined as the difference between current average yields and the potential yields that could be achieved under ideal management practices (Lobell et al 2009). For example, previous studies have suggested that intensifying agricultural production through increased nitrogen and irrigation application, improved soil quality, and reduced pest burdens could double yields in some regions, closing existing yield gaps (Mueller et al 2012, Pradhan et al 2015). Yet, in many agricultural systems across the globe, such intensification has been associated with large environmental costs, including nitrogen runoff and eutrophication and the depletion of fresh water (Beman et al 2005, Konikow and Kendy 2005, Dalin et al 2017). In response, many scholars and policy makers have called for growing food demand to be met by sustainable intensification, where yields are increased without adverse environmental impacts and without the conversion of additional agricultural land (Tilman et al 2011, Garnett et al 2013, Pretty and Bharucha 2014).

Sustainable intensification is a broad concept that does not prescribe or prioritize a specific set of interventions (Mbow et al 2019). Instead it considers
any intervention that has been shown to increase yields while reducing environmental harm (Garnett et al. 2013, Pretty and Bharucha 2014) or improving input use efficiency (Struik and Kuyper 2017). By valuing additional impacts of agricultural intensification other than yield, sustainable intensification may lead to lower yield growth rates than typical intensification strategies that only prioritize yield gains (Mbow et al. 2019). While sustainable intensification has gained much traction over the last decade as a way to help ensure global food security, limitations of sustainable intensification have also been acknowledged. For example, sustainable intensification is only one supply-side tool to enhance food security, and additional supply-side strategies such as reducing food waste and demand-side strategies such as reducing over-consumption and changing diets will likely be needed to ensure global food security (Bajzelj et al. 2014, Keating et al. 2014, Hic et al. 2016, Mbow et al. 2019). Furthermore, current definitions of sustainable intensification do not engage with all aspects of sustainability, including social outcomes such as food access and justice (Loos et al. 2014).

While sustainable intensification is often touted as an ideal way to help meet growing food demand, it remains unclear the extent to which sustainable intensification can increase yields (Godfray and Garnett 2014). Several previous reviews have attempted to estimate the potential yield gains that can be achieved by sustainable intensification. For example, Pretty and colleagues found that, on average, sustainable intensification interventions led to yield gains of 79% across developing countries (Pretty et al. 2006) and by 213% in sub-Saharan Africa (Pretty et al. 2011). These yield gains were estimated by considering a wide range of interventions, including integrated pest management, conservation agriculture, and water conservation techniques. While these reviews offer estimates of potential yield gains across a wide range of studies and interventions, the studies considered in these reviews were solicited from experts in the field of sustainable intensification and were not drawn systematically from the literature. Yet systematic reviews offer the benefit of providing an overview of all of the available evidence surrounding a given research topic, reducing potential bias in which studies are considered and evaluated within a given review (Mallett et al. 2012). Several existing reviews on the impacts of sustainable intensification have been systematic, selecting studies from literature search engines based on a set of keywords and criteria. These reviews, however, were limited in scope, focusing on a narrow set of practices and interventions, such as sustainable rice intensification or conservation agriculture (e.g. Gathorne-Hardy et al. 2016, Milder et al. 2019). Reviews that consider a wide range of practices and interventions may better capture the potential effects of sustainable intensification on yields since sustainable intensification is technology or intervention agnostic.

Our work builds on these existing studies by conducting an unbiased, systematic review of the peer-reviewed literature that considers a broad range of sustainable intensification strategies, technologies, and interventions. Specifically, we conducted a systematic review of all sustainable intensification literature across South Asia and quantified the overall yield gains achieved across this region. We focus on South Asia because it is one of the regions with the largest yield gaps and that will be most impacted by climate change (Lobell et al. 2008, Mueller et al. 2012). Currently, South Asia has reached approximately 40% of its maximum yield potential considering total calories produced and yield gaps range from 40%–80% for the main staple grains in the region (Pradhan et al. 2015, Mueller et al. 2012, Global Yield Gap Atlas 2020). At the same time, the region is expected to face rapid population gains over the coming decades, and food production will likely have to increase to meet growing demand and for South Asia to become food self-sufficient (Rosegrant et al. 2001, Bongaarts 2009, Pradhan et al. 2014). Finally, increasing agricultural production is not only a matter of food security in this region, but also welfare given that millions of people in this region depend on agriculture as a primary livelihood (Aryal et al. 2019). Through this systematic literature review, we aim to understand how much sustainable intensification may be able to increase grain yields across South Asia, and which specific intervention types are associated with positive yield, environmental, and profit outcomes. We also assess whether there are any biases in study location (e.g. country, cropping system) and study design to identify potential research gaps in the existing literature. Specifically we ask:

(a) To what extent can sustainable intensification strategies increase grain yields across South Asia?
(b) Which sustainable intensification interventions are associated with positive yield, environmental, and profit outcomes?
(c) Are there any biases in existing studies, and potential gaps in the literature?

This work will help elucidate the extent to which sustainable intensification can increase yields and close yield gaps in this globally-important agricultural region, and fill a key gap in the literature on sustainable intensification.

2. Data and methods

2.1. Literature review

We conducted three stages in our systematic literature review (table S1 (available online at stacks.iop.org/ERL/15/083004/mmedia)).
Table 1. Percent of studies that found positive, neutral, or negative impacts of the specified intervention on yield, environmental and profit outcomes. We considered the subset of studies that found a significant difference in yield between treatment and control plots. We also include the number of studies that were available for each intervention and outcome combination.

| Interventions          | Organic fertilizer | Tillage | Residue | Irrigation | Fungi | Rotations |
|------------------------|--------------------|---------|---------|------------|-------|-----------|
| **Yield outcomes**     |                    |         |         |            |       |           |
| % Positive             | 92%                | 75%     | 90%     | 80%        | 100%  | 100%      |
| % Neutral              | —                  | —       | —       | —          | —     | —         |
| % Negative             | 8%                 | 25%     | 10%     | 20%        | 0%    | 0%        |
| **Environmental outcomes** |                |         |         |            |       |           |
| % Positive             | 95%                | 40%     | 87.5%   | 100%       | 67%   | 100%      |
| % Neutral              | 0%                 | 40%     | 12.5%   | 0%         | 33%   | 0%        |
| % Negative             | 5%                 | 20%     | 0%      | 0%         | 0%    | 0%        |
| **Profit outcomes**    |                    |         |         |            |       |           |
| % Positive             | 50%                | 100%    | 100%    | 50%        | —     | 100%      |
| % Neutral              | 0%                 | 0%      | 0%      | 0%         | —     | 0%        |
| % Negative             | 50%                | 0%      | 0%      | 50%        | —     | 0%        |

| Outcomes | Number of studies |
|----------|-------------------|
| Yield    | 25                |
| Environment | 21               |
| Profit   | 4                 |

In the first stage of the literature review, we searched for all papers in the Web of Science database (https://apps.webofknowledge.com/) that focused on sustainable intensification in agriculture (specific search terms can be found in table S1) and were published over the last 10 years (from 2008 to 2018). It is important to note that we focused only on peer-reviewed literature and did not consider any gray literature on this topic, which may have downward biased the number of studies considered in our review and led to potential biases in the types of studies returned. This is because we were interested in only including manuscripts with robust study designs that had been validated by the peer-review process. We considered literature only from the last 10 years as the main research questions in our paper focus on how much sustainable intensification can increase current levels of production; it is likely that studies published over 10 years ago may not give accurate estimates of current potential yield gains due to yield improvements that occur through time due to advances in agriculture (Ray et al 2012). This search returned 1579 papers in total, and we read through all abstracts and selected papers that (1) were about terrestrial agriculture, and (2) included data on yields of the sustainable intensification strategy. We focused on terrestrial agriculture since this is the primary mode of food production across South Asia (FAO 2018) and we only considered studies that included estimates of yield since we were interested in quantifying the yield gains that may be associated with sustainable intensification interventions. This reduced the number of papers found in the first stage of the literature review to 290. We then read the abstracts and skimmed each paper to identify which sustainable intensification strategies were examined in each study. We made note of all sustainable intensification strategies that were mentioned at least three times across all studies (table S2).

We then used these sustainable intensification strategies as additional search terms in a second stage literature review (specific search terms can be found in table S1), as we wanted to avoid any potential bias that may have occurred if we only selected studies that included the terms ‘sustainable intensification.’ This is because there are many published studies that examine the yield impacts of the intensification strategies listed in table 1 that do not use the terms ‘sustainable intensification.’ We searched for studies that examined the main grain crops grown across South Asia: wheat, rice, maize, millet, and sorghum (FAO 2018). We focused our study on grain crops because this is the main food group contributing to overall calorie consumption across South Asia (FAO 2018). We then read through the abstracts and skimmed through papers as needed to select only those studies that (1) were conducted in South Asian countries (Pakistan, India, Nepal, Bhutan, Bangladesh, Sri Lanka) and (2) had estimates of yield from the intervention. This resulted in a total of 195 papers, which also included papers found
during the first stage of the literature review that met these criteria.

In the third and final stage of the literature review, we read through all studies selected at the end of the second stage of the literature review and identified those that (1) had yield estimates for both the sustainable intensification strategy of interest and (2) for fields that represented realistic farmer management in the region. This is because we were interested in quantifying the yield gains that occurred relative to current yields found on farmers’ fields, and not compared to unrealistic hypothetical controls. For example, there were many studies that compared the yields achieved when organic fertilizers were used with the yields of fields that used no fertilizer, but we believed such comparisons to be unrealistic since fertilizers are commonly used for grain crops across South Asia (Hossain and Singh 2000); thus, a no fertilizer control would likely upward bias yield gain estimates if we considered these studies in our review. We defined a realistic control as one where the study measured the yield on a farmer’s field or in an experiment that used typical or recommended farmer management practices for the region. This realistic control filter was the strictest filter used in all three stages of the literature review. We also did not include any studies on intercropping because in the studies that were returned in our review it was challenging to compare yields between treatment (fields with intercropping) and control plots (fields without intercropping) in similar yield units. Overall, the third stage of the literature review resulted in a total of 100 studies reviewed in this paper.

2.2. Data collection
We collected a range of variables for each study, which are detailed in Table S3. These variables included descriptive variables about where the study was conducted, what was measured, and the study design used. The variables also included information about which crops and specific sustainable intensification interventions were considered. Finally, we also quantified the outcomes measured in each study. Specifically, we recorded the yield that was reported for the sustainable intensification intervention, as well as the yield that was reported for the control plot. Since many studies included multiple treatment levels for a given sustainable intensification strategy, we selected the treatment level that was associated with the greatest yield gain. For example, in many tillage studies, treatments would include different levels of reduced tillage, and in many organic fertilizer studies, treatments would include different levels of organic fertilizer addition. We acknowledge that this approach may identify the maximum amount that a sustainable intensification intervention may increase yields since we selected for the treatment level that led to the largest yield gains. We also acknowledge that these treatments were not always the ones that were associated with the lowest environmental impact. However, this approach is in line with our review objectives since we are interested in understanding the potential extent to which sustainable intensification may increase yields across South Asia. When multiple sustainable intensification interventions or multiple crops were considered within the same study, we recorded data for all interventions and all crops separately. We were unable to examine the impact of specific intervention combinations (e.g. zero tillage and residue retention) because the sample size of any given combination was small (N < 5). This resulted in 118 experiments that were evaluated from the 100 studies that we surveyed.

2.3. Analyses
We produced descriptive statistics for all of our variables of interest (Table S3). We also quantified yield gains by comparing the yield from the sustainable intensification treatment with the yield from its associated control. If yield information was collected for both farmers’ typical practice and the recommended practice for the region, we selected the plot with farmers’ typical practice as our control since this inherently better represents real-world farmer management. We produced summary statistics of these yield gain estimates, and examined how much these yield gain estimates varied based on the types of studies considered. Specifically, we assessed yield gains across all experiments (n = 118) and those experiments that found a significant difference between treatment and control plots (n = 78). We also quantified the average yield gain for the interventions that were most examined across significant studies (n ≥ 10). We measured yield gains in several ways. First, we did a simple vote count where we counted the number of studies that showed positive, neutral, or negative yield impacts from the intervention. Second, we quantified the range of yield gains estimated across all studies. Finally, we calculated mean overall yield gain across all studies and also the mean yield gain per intervention type. To test whether average yield gains were statistically different from zero, we used one-sample t tests with µ equal to 0. We also produced descriptive results showing average yield gains when disaggregated by country, crop type, and irrigation status for those studies with a significant difference.

For all subsequent analyses, we focused on the subset of studies that found a significant difference between treatment versus control plots (n = 78). This is because we were unable to identify whether non-significant studies did not find a significant result because there really was no difference between treatment and control plots, or because of small sample size. For each broad intervention category (Table S4), we quantified the number of studies that found positive, neutral, or negative impacts on yield, environment, and profit outcomes. For this analysis, we did not include papers that considered...
multiple interventions in the same experiment since it is challenging to identify the impact of individual interventions in these studies. In addition, for those studies that considered multiple outcomes (e.g. environmental or profit outcome in addition to yield), we also summarized the number of studies that led to positive-positive, mixed, or negative-negative impacts across multiple outcomes. For environmental outcomes, we considered impacts measured on any aspect of the environment, and then categorized these into broad environmental outcome categories (table S5).

3. Results and discussion

3.1. Yield gain estimates

We assessed yield gain estimates for (1) all studies and (2) studies that found a significant difference between treatment and control plots (figure 1). The range of yield gains varied drastically across studies, from a 30% yield loss to a 125% yield gain. Most studies (70%–80%) found that the sustainable intensification intervention under consideration resulted in yield gains, though a large proportion of studies (20%–30%) found that the intervention resulted in yield losses (figure 1(A)). These results highlight the large amount of heterogeneity in yield outcomes, and that common sustainable intensification interventions may not lead to yield gains in all contexts. Overall, we found that the interventions considered in our systematic review led to a significant positive gain in yield on average, with either a 14% or 21% yield increase depending on the subset of studies considered (figure 1(B)). Grain yield gaps range between 40%–80% across this region (Mueller et al 2012, Global Yield Gap Atlas 2020), and finding sustainable ways to increase grain yields is of critical importance. Considering mean yield gain by intervention type (figure 1(C)), we found that residue retention and the use of organic fertilizers were associated with significant and positive increases in yield (25% and 15.6%, respectively), and the use of zero/reduced tillage was associated with a marginally significant and positive increase in yield (7.6%). The reasons for why these interventions may be associated with different yield outcomes are discussed in the next section. When disaggregating yield gain estimates across different cropping systems, we find that average yield gains are fairly similar across country, crop type, and irrigation status (figure S2), ranging from 18% to 39%. This suggests that even though South Asia is a diverse region in terms of climate, soil, policies, and cropping patterns, sustainable intensification may lead to modest yield gains across these diverse systems. Interestingly, our yield gain estimates differ from previous studies in that we find higher values than previous systematic reviews or meta-analyses that have focused on one set of interventions (e.g. conservation agriculture; Pittelkow et al 2015) and smaller values than studies that have estimated yield gains from sustainable intensification without using a systematic review approach (e.g. Pretty et al 2006).

Interpreting average yield gain estimates (figures 1(B), (C) and S2) as the amount that sustainable intensification can lead to yield gains across South Asia should be done with caution for several reasons. First, the yield gains included in our analysis may provide upper bound estimates of the impact of a given intervention because most studies were conducted in experimental settings under researcher direction and did not measure yield gains based on real-world farmer management (figure S1(D)). Yet, studies have shown that the yield gains that have been achieved in experimental settings are often higher than what is typically achieved in farmers’ fields (Barrett et al 2004). This is because farmer management strategies may be different than the optimal management strategies that were practiced in experimental field trials, potentially resulting in smaller yield gains on farm than expected. Second, we do not consider sample size or study quality explicitly in our analysis, which is often done in meta-analyses (Haidich 2010), and instead we weighted each study equally. To better control for study quality, we provided average yield gain estimates for those studies that found a significant difference between treatment versus control plots, as doing so inherently includes studies that had a large enough sample size and high enough study quality to detect a statistical difference. Third, our overall estimates of yield gain are likely influenced by the number of studies found for a given intervention type. For example, approximately 30% of studies assessed in our review were of reduced or zero tillage (figure S1(A)), yet our results suggest that this intervention is particularly associated with small yield gains (figure 1(C)) and negative yield outcomes (table 1); thus, the large amount of tillage studies found in our review likely reduced our estimated average yield gain calculated across all studies. Finally, though we provide average yield gain estimates disaggregated by cropping system (figure S2), it is important to note that we are unable to say whether yield gains are higher or lower in a given system. This is because we were unable to conduct a robust statistical analysis given the high variability in study type and design across the studies considered in our review.

While our results give an estimate of how much sustainable intensification may be able to increase yields on average across South Asia, we are unable to quantify what percent of yield gaps could be closed with the given interventions considered in this review. This is because our estimates of 40%–80% yield gaps are from large-scale, regional studies and it is challenging to directly match the yield gains achieved in the localized studies considered in our review with these broader scale yield gap estimates. That being said, the 20% yield gains estimated by our review are modest relative to average yield gaps across South Asia,
suggesting that the sustainable intensification interventions considered in our study will likely not be able to close all existing yield gaps across South Asia.

3.2. Yield, environment, and profit outcomes

We found that different intervention types were associated with different rates of positive, neutral, or negative impacts on yield, environmental, and profit outcomes (table 1). Given that some of the interventions we considered were only examined in a few studies ($\leq 5$ studies), we discuss results for the most common intensification interventions found in our review: zero/reduced tillage (16 studies), organic fertilizer use (25 studies), and residue retention (10 studies).

We found that zero/reduced tillage is the intervention with the largest proportion of studies finding negative yield impacts (25% of studies; table 1), which may partially explain why average yield gains for this intervention were smaller than those of other interventions and only marginally significant (figure 1(C)). Interestingly, this intervention type was
Figure 2. Map of South Asia that includes study locations highlighted in black dots and the percent of studies that took place in each country.

also associated with the greatest proportion of studies finding a negative environmental outcome (20% of studies; table 1), though all three studies that analyzed profit found that zero/reduced tillage was associated with positive profit outcomes (table 1). These results suggest that the yield, environmental, and profit outcomes of zero/reduced tillage may be mixed and context dependent, which has been echoed by previous studies. Zero/reduced tillage has been found to have positive yield impacts in dry, water-limited systems, after multiple years, and in systems like the Indo-Gangetic Plains (IGP) where it allows for more timely sowing of wheat (Erenstein and Laxmi 2008, Stevenson et al 2014, Pittelkow et al 2015). Environmental outcomes have been found to be mixed depending on what outcome is being measured; zero/reduced tillage has been found to be associated with improvements in soil parameters, such as soil organic carbon and available nitrogen, and water use efficiency, but with no improvements in soil carbon sequestration (Mina et al 2008, Bhattacharyya et al 2009, Stevenson et al 2014). Finally, previous literature highlights that the profit impacts of zero/reduced tillage in South Asia are also mixed (Erenstein and Laxmi 2008, Stevenson et al 2014), despite all studies in our review finding a positive impact. This may be because zero/reduced tillage has been found to be associated with increased profits across the IGP (Erenstein and Laxmi 2008), which is where most of the studies in our systematic review were conducted (figure 2).

The use of organic fertilizers was largely associated with positive yield and environmental outcomes. The specific interventions that were classified under organic fertilizer interventions were diverse (table S4), and included a variety of compost (e.g. farm yard waste, vermicompost) and manure (e.g. cow dung, poultry manure) additions. Across the studies considered in our review, the use of organic fertilizers was associated with improvements in soil parameters, including soil organic carbon, soil nitrogen availability, soil micronutrient availability, and improved nitrogen use efficiency. However, we found that the use of organic fertilizers had mixed impacts on profits, with 50% of studies finding positive and 50% of studies finding negative outcomes. This is likely because across the countries considered in our
Figure 3. Percent of studies that showed win-win and win-lose outcomes for yield and environmental outcomes (A) and yield and profit outcomes (B). The size of each dot is scaled by the number of studies that falls into each category, and the percent of all studies available that falls into each category are also presented.

study, the use of mineral fertilizers is heavily subsid-ized by governments (except for Bhutan; Fan et al 2008, Nasrin et al 2018, Ali et al 2019), organic fertilizer markets are weak resulting in high costs for organic fertilizers (Ghosh 2004), and the use of organic fertilizers has been found to be profitable largely when farmers can sell crops at a premium price (Ramesh et al 2010).

Finally, residue retention was associated with mostly positive yield outcomes (90% of studies), neutral or positive environmental outcomes, and positive profit outcomes. We defined the category of residue retention broadly, by including mulching, crop residue retention, and the use of cover crops since all of these interventions maintain soil cover. Previous studies have shown that crop residue retention and mulching are associated with improved yield outcomes by increasing water use efficiency, improving soil infiltration rates, cooling surface soil temperatures, and suppressing weed growth (Sharma et al 2011, Ram et al 2013, Singh and Sidhu 2014). Yet, whether the retention of crop residues is profitable appears to be more complex and context dependent, given that crop residues are often used for other livelihoods in South Asia, such as feed for livestock. Studies that have examined the profitability of maintaining crop residues on farm find that it depends on the demand for livestock feed for a given household and the availability of cheap alternative feed sources in local markets (Valbuena et al 2015). This context dependency, however, was not captured in the studies examined in our review, likely because only two studies in our review examined profit outcomes.

For those studies that considered multiple outcomes within the same study, we found that approximately 70% of studies led to win-win outcomes regarding either yield and environmental outcomes, or yield and profit outcomes (figure 3). Considering win-lose or lose-lose outcomes, we found that only 5% of studies found negative environmental impacts (figure 3(A)) but 23% of studies found negative impacts on profit (figure 3(B)). These results highlight that even though we did not search for papers that used the terms ‘sustainable intensification’ explicitly, the interventions considered in our review largely led to yield gains without negatively impacting the environmental outcomes measured. In addition, these findings suggest that even though interventions may lead to yield gains in field, they may do so by increasing costs to farmers and reducing profits. While understanding the ultimate adoption patterns of interventions was out of the scope of the studies considered in our review, these results suggest that even though some intensification strategies may lead to yield gains on farm, they may not be widely adopted if they result in reduced profits compared to current management practices (Feder et al 1985, Stevenson et al 2014). Despite the importance of this point for understanding whether farmers may actually adopt a given intervention, only 27% of the studies considered in our review measured profit outcomes (figure S3(A)).

3.3. Biases and potential research gaps
Our systematic literature review provides information about potential gaps in the existing literature on sustainable intensification interventions across South Asia. Specifically, we find that studies were clustered in highly productive and irrigated cropping systems, with few studies taking place in lower productivity and rainfed cropping systems (figure S1(C)). In
particular, most studies were conducted in the Indo-Gangetic Plains (IGP; figure 2), which has rich, fertile soils and is known as the ‘bread basket’ of South Asia (Aggarwal et al 2004); this area is highly productive and contributes to over 60% of the region’s rice and wheat production (Jain et al 2017). Yet, a significant portion of land is devoted to grain crops outside of the IGP (Gumma 2011, Mueller et al 2012, Zhang et al 2017), and it is possible that the impacts of sustainable intensification that are measured in the IGP are not applicable to South Asia as a whole. For example, while much of rice and maize is irrigated across the IGP, a large proportion of rice and maize area outside of this region is primarily rainfed (Portmann et al 2010, Gumma 2011), and it is unclear how applicable findings about sustainable intensification interventions in irrigated systems would be to these rainfed regions. In fact, previous studies have shown that the same intensification intervention can have significantly different effects on crop yield depending on whether the intervention was implemented in dry, rainfed or humid, irrigated systems (Pittelkow et al 2015). These differences are substantiated by our disaggregated yield gain analysis that compares irrigated versus rainfed systems (figure S2). These results suggest that yield gains in rainfed systems may be slightly larger than those from irrigated systems, though we are unable to definitively say this given that we did not conduct a statistical analysis to test whether this difference is significant. Furthermore, few to no studies were conducted in the smaller nations of Nepal, Bhutan, Bangladesh, and Sri Lanka, even though rice, wheat, and/or maize are the main staple grain crops grown in these countries (FAO 2018). These findings suggest that there is a need for future research on sustainable intensification to take place outside of the IGP, particularly in the smaller nations of South Asia that are still heavily reliant on grain crops for food security.

In conclusion, we find that yield gains from sustainable intensification interventions across South Asia are heterogeneous, and that the average yield gain across all studies is 21%. In particular, residue retention and the use of organic fertilizers were associated with significant yield gains across all studies. These results suggest that sustainable intensification interventions should play an important role in closing yield gaps across South Asia, which likely range between 40%–80% for maize, rice, and wheat in this region (Mueller et al 2012, Crop Yield Gap Atlas 2020). When considering outcomes other than yield, the interventions considered in our study led to largely positive or neutral environmental outcomes, but approximately 20% of studies found a negative impact on profit. Understanding the profitability of sustainable intensification interventions is critical, as unprofitable interventions are unlikely to be adopted by farmers at scale even if they lead to positive yield outcomes (Feder et al 1985). In this regard, future work should benefit from examining primarily subsistence grain crops such as sorghum and millet.

Considering study design of the interventions that we reviewed, we found that 73% of studies measured an environmental outcome and only 27% of studies examined a profit outcome in addition to yield. Yet, we argue that it is critical for studies to measure the impact of interventions across all three indicators as our work has shown that interventions that lead to yield gains do not always result in positive environmental and profit outcomes (figure 3). In particular, a large proportion of studies (23%) found negative profit outcomes, which is concerning given that previous work has shown that farmers are much less likely to adopt interventions that result in reduced profits compared to current management strategies (Feder et al 1985). Similarly, a previous systematic review found that the impacts of agricultural intensification interventions are mixed, and do not always have positive outcomes considering ecosystem services and human well-being (Rasmussen et al 2018). In addition, we found that a majority of studies (88%) were conducted in agricultural experimental field stations under researcher direction (figure S1(D)). Yet, as discussed above, previous work has shown that the yield gains achieved on farm can often be less than what is achieved in experimental field trials given that real-world farmer management may not match optimal management under experimental conditions (Barrett et al 2004). Thus, to understand the potential for sustainable intensification interventions to close existing yield gaps, it is critical that future studies estimate yield gains on real farmer fields under real-world farmer management of a given technology.

4. Conclusion

In conclusion, we find that yield gains from sustainable intensification interventions across South Asia are heterogeneous, and that the average yield gain across all studies is 21%. In particular, residue retention and the use of organic fertilizers were associated with significant yield gains across all studies. These results suggest that sustainable intensification interventions should play an important role in closing yield gaps across South Asia, which likely range between 40%–80% for maize, rice, and wheat in this region (Mueller et al 2012, Crop Yield Gap Atlas 2020). When considering outcomes other than yield, the interventions considered in our study led to largely positive or neutral environmental outcomes, but approximately 20% of studies found a negative impact on profit. Understanding the profitability of sustainable intensification interventions is critical, as unprofitable interventions are unlikely to be adopted by farmers at scale even if they lead to positive yield outcomes (Feder et al 1985). We find that there are some key gaps in the sustainable intensification literature reviewed in our study. Current research is clustered...
in the IGP in Pakistan and India, in irrigated systems, and on the main grain commodity crops (rice, wheat, and maize). Future work should examine the impacts of sustainable intensification interventions in other countries (Nepal, Bangladesh, Sri Lanka, and Bhutan), rainfed systems, and on subsistence grain crops (sorghum, millet) that are important for food and nutritional security in the region. Finally, most analysis of intervention outcomes was done through experimental field trials led by researchers, and future work should quantify what the outcomes of interventions are under real-world farmer management as this may better represent the true ability of sustainable intensification interventions to increase yields across South Asia.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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