A roadmap towards sustainable intensification for a larger global rice bowl

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Abstract

Future rice systems will need to produce more grain while minimizing the environmental impact. A key question is how to orient agricultural research & development (R&D) programs at national to global scales to maximize the return on investment. Here we assess yield gap and resource-use efficiency (including water, pesticides, nitrogen, labor, and energy) across 32 rice cropping systems, together accounting for 88% of global rice production. We show that achieving high yields and high resource-use efficiencies are not conflicting goals. Most cropping systems have room for increasing yield, resource-use efficiency, or both. In aggregate, current total rice production of these systems can be increased by 36%, and excess nitrogen almost eliminated, by focusing on a relatively small number of cropping systems with large yield gaps and/or poor resource-use efficiencies. This study provides essential strategic insight for prioritizing national and global agricultural R&D investments to ensure adequate rice supply while minimizing negative environmental impact in coming decades.

Introduction

Rice (*Oryza sativa* L.) is the main staple food for nearly half the world's population, accounting for 21% of global calorie intake while using 11% of global cropland[1,2]. Rice yields have increased steadily since the onset of the Green Revolution in the late 1960s, driven by adoption of high-yielding rice cultivars, intensive use of agricultural inputs, and investments in irrigation infrastructure, extension education services, and subsidies[3,4]. Global rice consumption is projected to increase from 480 million tons (Mt) milled rice in 2014 to nearly 550 Mt by 2030, driven by both population increase and economic growth in developing countries[5]. However, there are a number of concerns about the future sustainability of rice cropping systems. First, yield growth rates have slowed down, and even reached a plateau, in some major rice-producing regions such as California (USA), China, Indonesia, and South Korea[6,7]. Second, negative environmental impact is a concern because rice production consumes 30%, 14%, and 10%, respectively, of global use of irrigation water, fertilizers, and pesticides[8–11], leading in some cases to negative environmental impacts. For example, rice cultivation is an important source of anthropogenic greenhouse gas (GHG) emissions, accounting for 30% and 11% of global agricultural methane (CH_4) and nitrous oxide (N_2O) emissions, respectively[12,13]. Third, high labor requirements and associated costs make rice production less attractive to farmers in some regions[9], especially where national governments are becoming reluctant to provide price support mechanisms and subsidies[14].

Increasing concerns about loss of natural habitats and conservation of biodiversity emphasize the importance to produce more rice on existing cropland and to do so while improving the efficiencies of energy, nutrient, water, and other inputs in a process called sustainable intensification[15–17]. Prioritizing investments on agricultural research and development (R&D) at national to global scales to increase rice production and minimize the environmental impact requires information on current yield gaps and resource-use efficiencies. The yield gap is defined as the difference between yield potential and average farmer yield. Yield potential is determined by solar radiation, temperature, water supply, cultivar traits and, in the case of water-limited crops, also by precipitation and soil properties and landscape characteristics influencing water balance[18,19]. Achieving *ca.* 70–80% of yield potential is a reasonable target for farmers who have good access to market, inputs, and extension services[3,20]. Further closure of the yield gap is difficult due to decreased return on additional inputs and labor, and the high degree of sophistication in crop management required to accommodate the spatial and temporal variation in weather, soil properties, pest pressure, etc[20]. In contrast, regions with large yield gaps have largest potential to increase current yield through use of existing cost-effective agronomic practices. In relation to the environmental impact, metrics on resource use (energy, water, nutrients, pesticides, etc.) on an area basis do not account for differences in yield level among cropping systems, which in turn affects land requirements to produce adequate national or global rice supply. Instead, metrics relating resource use with yield (*e.g.*, yield-scaled energy use, nutrient balances, etc.) are more appropriate for global assessments because they allow proper benchmarking of input use for a given yield level[21–23]. All else equal, the magnitude of the environmental impact is closely related to the efficiencies in use of energy, water, nutrients, and pesticides[23,24]. To summarize, information on yield gaps and resource-use efficiencies can help identify regions with greatest potential to increase production, reduce environmental impact, or both, and guide agricultural R&D prioritization.

There have been efforts to benchmark rice yield gaps and/or resource-use efficiencies for specific countries[24–27]. In contrast, we are not aware of yield gaps and resource-use efficiencies assessments for rice cropping systems that can serve to prioritize agricultural R&D investments at national to global scales to increase rice production while reducing associated environmental impact. Herein, we present the results from a global assessment of rice yield gaps and resource-use efficiencies based on yield potential reported in the Global Yield Gap Atlas (www.yieldgap.org) and actual yield and agricultural input data collected across 32 rice cropping systems in 18 rice-producing countries, accounting for 88% of global rice production[2] (**Supplementary Tables 1 and 2**). Pathways to narrow down existing yield gaps and reduce the negative environmental impact are discussed.

Results

Current yield gaps in rice cropping systems. Across cropping systems, the number of rice crops grown on the same piece of land during a 12-month period can range from one in non-tropical regions to three in tropical environments (**Supplementary Figs. 1 and 2**). Here we report metrics on a per-crop basis by averaging values across the rice crops within each cropping system where more than one rice crop is grown each year. Similarly, average values reported in this study are weighted according to the annual rice harvested area in each cropping system. At a global scale, yield potential averaged 9.4 Mg ha^{-1} $crop^{-1}$, ranging from 5.9 to 14.8 Mg ha^{-1} $crop^{-1}$ across the 32 rice cropping systems included in our analysis (**Supplementary Fig. 3A**). Average yield potential is higher in non-tropical regions than in tropical regions (9.8 *versus* 9.0 Mg ha^{-1} $crop^{-1}$). Lower productivity per crop of tropical rice is more than compensated by higher cropping intensity as tropical regions have longer growing seasons that allow up to three rice crops each year in the same field (**Supplementary Figs. 1 and 2**). As a result, rice systems in tropical areas have greater annual potential productivity than in non-tropical regions (18.3 *versus* 13.6 Mg ha^{-1} $year^{-1}$) (**Supplementary Fig. 3A**). In our study, all rainfed cropping systems are in lowland environments, except for upland rainfed rice in Brazil. Despite growing in flooded soil during much of the growing season, lowland rainfed rice is also exposed to water deficit and/or excess flooding during a significant portion of the cropping season[28], leading to lower and less stable yield potential compared with irrigated rice (**Supplementary Figs. 3A and 4**). Similar yield trends relative to water regime and rice cropping intensity are observed for comparisons based on average farmer yields (**Supplementary Fig. 3B**).

Expressing average actual farmer yields as a percentage of yield potential estimates the magnitude of yield gap closure, which in turn offers an objective measure of the degree to which rice growers efficiently utilize solar energy, water, and nutrient resources. At a global scale, average rice yield represents 54% of yield potential, with a wide range of yield gaps across rice systems (Fig. 1 **and Supplementary Fig. 5**). For example, irrigated rice systems in northern China, Australia, and California have reached *ca.* 75% of the yield potential. At the other end of the spectrum, average yields are low for lowland rainfed rice in Sub-Saharan Africa and upland rainfed rice in northern Brazil and represent 20–40% of the yield potential. About two thirds of global rice harvested area have yields lower than 75% of yield potential; the latter is considered a reasonable yield gap closure target for farmers[20]. Overall, our analysis indicates substantial room to increase global rice production on existing planted area *via* improved agronomic management.

Benchmarking resource-use efficiencies. We looked at key environmental and resource use metrics associated with rice cropping systems, including global warming potential (GWP), water supply (sum of irrigation plus in-season precipitation), pesticide use, nitrogen (N) balance, and labor inputs. Despite a strong positive correlation between the degree of yield gap closure and total input use per unit area expressed as GWP, high-yield systems have lower GWP on a yield-scaled basis due to higher resource-use efficiency (Fig. 2A, B). For example, high-yield systems in northern China, Australia, and California have larger GWP per hectare, but smaller yield-scaled GWP than low-yield, low-input systems in Sub-Saharan Africa. An implication from this finding is that, to reach a given grain production target, low-input systems would need larger crop production area, which, ultimately, would lead to a larger environmental impact compared to high-input, high-yield systems. These results are consistent regardless of whether GWP is considered on a per-crop or annual basis (**Supplementary Fig. 6**).

Across the 32 cropping systems, major contributors to GWP are CH_4 emissions from rice growing in lowland systems with soils kept purposely flooded (51%), emissions associated with manufacturing, packaging, and transportation of agricultural inputs (30%), and soil N_2O emissions derived from N application (19%) (**Supplementary Fig. 7**). Variation in CH_4 emissions across cropping systems are mostly associated with differences in water and straw management and length of the cropping season cycle, from field preparation to harvest. In the case of upland rice production in Brazil, rice is grown in aerobic (non-flooded) soil conditions, which reduces CH_4 emissions and GWP (Fig. 2A, B). In contrast, major drivers for differences in CH_4 emissions across flooded-rice systems are length of the rice crop growing cycle and straw management (**Supplementary Fig. 1 and Supplementary Table 3**). Cropping systems where straw is left in the field and/or with long crop cycle length (*e.g.*, Australia) have higher CH_4 emissions and GWP, on a per-crop basis, than systems where crop residues are removed from the field and/or with shorter duration of the rice crop growing cycle (*e.g.*, Indonesia). The positive effect of shorter crop cycle length at reducing CH_4 emissions is not apparent on an annual basis because short crop cycle length is associated with tropical rice systems, which, in turn, have a higher number of rice crops per year.

There is no relationship between the degree of yield gap closure and water supply ($p = 0.50$), probably because water supply is sufficient to meet crop water requirement in most cropping systems (Fig. 2C **and Supplementary Fig. 6; Supplementary Table 4**). For a similar degree of yield gap closure, there is a large range in water supply due to differences in climate among cropping systems[28]. For example, water supply is *ca*. 2x larger in the semiarid climate of California, USA compared with the humid southern USA. Similarly, there is large variation in yield gap at any water supply, with rainfed rice exhibiting a larger gap compared with irrigated rice. The yield-scaled water supply follows a relationship with the degree of yield gap closure similar to that for yield-scaled GWP (r=-0.75; $p < 0.01$), with smallest values corresponding to cropping systems with small yield gaps (Fig. 2D). Many of these systems are located in semiarid environments (*e.g.*, California, Egypt, and Australia) where crops are likely to be fully irrigated, with little precipitation to supplement crop water demand, and with high yield potential due to high solar radiation (Fig. 2D **and Supplementary Fig. 4**). Given the low production risk and favorable conditions, these systems are also likely to have a smaller yield gap. Assessing the long-term sustainability of irrigated rice systems in water-scarce environments would benefit from expanding the analysis to larger spatial scales (*e.g.*, watershed) and accounting for recharge rates and stream flows. While incomplete, our study makes a first step on this direction by benchmarking the efficiency in using water resources to produce rice at field scale.

In the case of pesticides, there was a positive relationship between the degree of yield gap closure and the number of applications ($r = 0.52$; $p < 0.01$) (Fig. 2E). It is difficult to interpret this relationship considering likely differences in edaphic and climatic environments and the severity of biotic stresses. Higher pesticide use in cropping systems with small yield gap was possibly related to greater pest and disease pressures as a result of large and denser leaf canopies that are achieved with improved plant nutrition[30]. Likewise, systems with high cropping intensity (*i.e.*, double and triple rice) in tropical areas receive a larger number of insecticide and fungicide applications per crop (up to nine) as in the case of Indonesia and Vietnam (Fig. 2E). There are also labor cost considerations. In contrast to tropical systems, where rural labor wage is low and weeds are mainly removed manually, chemical control prevails in non-tropical cropping systems (**Supplementary Table 3**). Due to these interrelationships, the relationship between yield-scaled pesticide applications and yield gap closure was not as clear as for GWP and water supply (Fig. 2F), although a similar trend was apparent when cropping systems from Sub-Sahara Africa were excluded from the analysis (r=-0.44; $p < 0.05$).

Relationships between yield, N input, and N balance (the latter calculated as N input from fertilizer, manure, and fixation *minus* N removal) are of interest because N is typically the most limiting factor in rice cropping systems and also an important source of environmental pollution[31,32]. In general, a large positive N balance is a strong indicator of inefficient fertilizer use and potential reactive N losses into the environment, while a negative N balance suggests high risk of soil N mining that degrades soil quality[33]. For example, data from cereal systems show that potential N losses increase substantially when N balance exceeds 75 kg N per ha[33–35]. Our analysis shows a positive linear relationship between the degree of yield gap closure and N input ($r = 0.73$; $p < 0.01$) and, to a lesser degree, with N balance ($r = 0.43$; $p < 0.05$) (Fig. 3A, B). Cropping systems with smallest yield gap tend to have N inputs and N balance greater than 150 and 50 kg N ha^{-1}, respectively, with a yield-scaled N balance ranging between zero and 20 kg N Mg^{-1} grain (Fig. 3). Within this group of cropping systems with small yield gaps, some have a relatively small N balance (50–75 kg N ha^{-1}) and yield-scaled N balance (< 10 kg N Mg^{-1} grain) as in California and Australia (Fig. 3B, C). In contrast, other cropping systems with small yield gaps, such as southern USA and southern and central China, exhibit a relatively large N balance (> 100 kg N ha^{-1}) and yield-scaled N balance (> 15 kg N Mg^{-1} grain), suggesting room for reducing N input and N balance without yield penalty.

The relationship between average yield and yield-scaled N balance follows a curvilinear pattern ($r = 0.64$; $p < 0.05$), with larger yield gaps at both ends of the range of yield-scaled N balance (Fig. 3C). On the one hand, there are a number of cropping systems in Sub-Saharan Africa and South-East Asia exhibiting negative N balance, suggesting soil N mining over time (Fig. 3 **and Supplementary Fig. 8**). These systems would clearly benefit from a larger N input or other methods to improve soil N supply. On the other hand, there is a group of systems with N input > 150 N ha^{-1} and large yield gaps, resulting in a large positive N balance on both area and yield-scaled basis, which is the case of several cropping systems in South and South-East Asia. In these systems, it seems feasible to reduce N inputs while maintaining yields or, perhaps more interestingly from a crop production perspective, to increase current yield with the same N input, in both cases leading to lower environmental impact and greater profit. This global analysis also shows that, while a small yield-scaled metric is desirable in the case of GWP, water, or pesticides, it is preferable that the (yield-scaled) N balance is maintained within an acceptable range (*i.e.*, not excessively high or excessively low) to avoid both soil N mining and reactive N losses. This range seems to correspond to a yield-scaled N balance between 5 and 10 kg N Mg^{-1} grain (Fig. 3C).

Labor in rice cropping systems. Labor use varied more than 100 times (ranging from 7 to 900 h ha^{-1} crop^{-1}) across rice cropping systems, with degree of mechanization explaining differences among countries (Fig. 4A **and Supplementary Table 3**). Although it is difficult to separate cause-effect, the analysis suggests that large field size, high mechanization level, and direct seeding are intrinsically linked. For example, labor input is less than 40 h ha^{-1} crop^{-1} in highly mechanized systems in the USA, Australia, and Uruguay, where field size is greater than 40 ha and most rice is direct seeded (Fig. 4A **and Supplementary Table 3**). In contrast, labor input is more than 400 h ha^{-1} crop^{-1} (and up to 900 h ha^{-1} crop^{-1}) in less mechanized systems such as those in Sub-Saharan Africa and Asia, where field size is smaller than 3 ha and most of the rice is transplanted.

One can still find large differences in yield-scaled labor (*i.e.*, number of hours per unit yield) for a given labor input and there is a negative association between degree of yield gap closure and yield-scaled labor (r=-0.71; p < 0.01), which is consistent for both less mechanized and highly mechanized systems (Fig. 4B). For example, in the case of less mechanized systems, yield-scaled labor is smaller in South-East Asia and China (average: 110 h Mg^{-1}) compared to Sub-Saharan Africa (> 200 h Mg^{-1}). Similar variation is observed across highly mechanized systems, with low yield-scaled labor in the USA and Australia compared to South America (1 *versus* 12 h Mg^{-1}). To summarize, our study shows no trade-offs between yield gap closure and labor requirements while yield-scaled labor decreased with smaller yield gaps in both labor intensive and highly mechanized cropping systems. This finding suggests that a simultaneous improvement in yield and labor productivity is possible, which is relevant in the context of increasing labor wages and shrinking rural population in developing countries[36,37].

Overall system performance. We computed an overall performance index for the 32 rice cropping systems in our study **(**Fig. 5**)**. Our analysis shows that the overall system performance is better in non-tropical *versus* tropical regions, probably due to inherent differences in soil and climate endowments leading to different resource-use efficiency and input requirements (*e.g.*, higher nutrient and pesticide requirement per unit of yield in tropical environments) [38]. Still, one can identify systems that outperform other systems within each environment, as it is the case of California, Australia, and northern China (non-tropical regions), and Vietnam and Thailand (tropical regions). The analysis shown in Fig. 5 is also useful to identify, for a given country, where largest opportunities exist (yield gap, resource-use efficiency, or labor) to improve the overall performance of the cropping system. For example, pesticide use and N balance per unit of production is disproportionally higher in a number of cropping systems in South-East Asia and South Asia.

Discussion

Our global assessment of rice production systems evaluates resource requirement for arable land, water, energy, nutrients, pest control, and labor across a wide range of climates, soils, and water supply. Knowing the comparative advantage that a country has in terms of producing high and stable yields with high efficiency in use of required resources provides essential strategic insight to government agencies, international organizations, and charitable foundations (*e.g.*, CGIAR, USAID, World Bank, UNEP, FAO, B&M Gates Foundation) for prioritizing investments on agricultural R&D at national to global scales. Our study also shows that an explicit focus on areas with large yield gap and/or large environmental impact could help increase the global return on investments in agricultural R&D programs. For example, increasing average yield to a level equivalent to 75% of the yield potential in 19 cropping systems where current yields are intermediate or low (< 60% of yield potential) would increase global annual rice production by 262 Mt (+ 36% of current level) (Table 1), which would be sufficient to meet projected global rice demand by 2030[5]. Similarly, reducing the current large N balance (> 100 kg N ha^{-1}) observed in eight cropping systems, so that N balance does not exceed 75 kg N ha^{-1}, could reduce the annual N excess by 3.1 Mt N, which is equivalent to a 97% reduction in the overall N excess across the 32 cropping systems.

Table 1
Potential production and environmental impact of (i) closing yield gap to 75% of yield potential in 19 cropping systems with relatively large yield gaps (i.e., average yield < 60% of yield potential) and (ii) reducing the nitrogen (N) balance to 75 kg N ha^{-1} in 8 cropping systems with large N balance (> 100 kg N ha^{-1}). Excess N was calculated as the amount of N balance exceeding 75 kg N ha^{-1}. See Methods section for a description of the scenario assessment.

Scenario	Rice production (Mt)*	Excess N (Mt)*
Baseline	726	3.2
Potential	988	0.1
Difference §	+ 262 (+ 36%)	-3.1 (-97%)
*Values are totals across the 32 rice cropping systems included in our analysis. For the potential scenario, we assumed no changes in current rice harvested area, cropping intensity, and proportion of irrigated area.		
§ Absolute and percentage difference between the potential scenario and current baseline.		

Current average yield has already reached 75% of the yield potential in a number of cropping systems, including California, Australia, and China (Fig. 1). The level of yield gap closure in these systems suggests limited room for substantial yield increases, which is consistent with evidence of yield plateaus[6,7,39]. Efforts to increase current yield potential *via* improved cultivars, in concert with fine tuning of current crop management, would likely provide small, but important, incremental improvements in the yield ceiling of those systems or, at least, to achieve modest yield gains by further closure of the existing yield gap[16,39,40]. Despite the positive relationship between yields and GWP, pesticides, N inputs, and labor, rice systems with small yield gaps tend to have lower yield-scaled resource use in comparison to other systems (Figs. 2–5). Hence, our study confirms that achieving high yields while minimizing negative environmental impact per unit of grain are not conflicting goals[23,41,42]. There are still cases of cropping systems with small yield gap but comparably poor resource-use efficiency, such as those in central China, where there is room to reduce the environmental impact while maintaining the same (high) yield level, which is consistent with empirical evidence from the literature[23,41,43,44].

At the other end of the spectrum, there are cropping systems where opportunities exist to narrow down the current (large) yield gap *via* larger application of fertilizers and/or pesticides[45,46], as it is the case of rice cropping systems in Sub-Saharan Africa and some countries in South-East Asia such as Philippines and Myanmar (Figs. 2 and 3). Measures to promote higher agricultural inputs application in these countries must be accompanied with robust extension services and proper crop and soil management to fully capture the positive effect of improved plant health and nutrition and to minimize negative environmental impact[43,47]. The yield gap is also large for upland rice in northern Brazil, which is a "transitional system" that starts as a low-input system after land conversion, shifting into a high-input soybean system a few years later[48]. We note that upland rice area has decreased sharply during past decades and its contribution to global rice production is small and less stable than in flooded lowland rice systems[9,49].

In between cropping systems with large and small yield gaps, there are a number of cropping systems that, for a given input level, exhibit consistently lower yield, suggesting room to produce more with current or less inputs. This is the case of many rice cropping systems in South and South-East Asia (*e.g.*, Bangladesh, India, and Indonesia), where it may be possible to increase yields further and do so while reducing environmental impact (Figs. 2, 3 and 5). These cases require fine tuning current crop, soil, and water management practices (and related policy) and a number of previous studies have shown how knowledge-intensive approaches can help increase yields and/or resource-use efficiencies, and, ultimately, improve farmers' profits[43,50,51]. Reducing production risks is also important to foster intensification[16]. This is the case for rainfed lowland rice systems, where farming is risk-prone because crops are more likely to be affected by drought, floods, pest diseases, and weed outbreaks, as well as soil constraints[52]. Because of higher risk, most farmers in rainfed lowlands are reluctant to apply inputs (*e.g.*, fertilizer) in similar amounts to irrigated lowland[9]. As a result, lowland rainfed rice consistently exhibit larger yield gaps compared with irrigated rice at any level of water supply, and larger water use per unit of production (Fig. 2). Overall, with implementation of improved measures to mitigate risk (*e.g.*, access to water pumps to apply partial irrigation during periods of water shortage, crop insurances), rainfed lowlands offer substantial room for increasing rice production because total rainfed lowland rice represents one third of global rice harvested area[9].

To be effective at increasing the global rice output while reducing associated negative environmental impact, it is also important to consider the socio-economic context. The strong association between the degree of yield gap closure and national gross domestic product (GDP) per capita ($r = 0.76$; $p < 0.01$) suggests that farmers in systems with largest opportunities to increase yield (from a biophysical perspective) are at a disadvantage in terms of access to inputs, markets, and extension education services as it is the case in Sub-Sahara Africa (**Supplementary Fig. 9**). Similarly, options to increase yield and/or reduce environmental impact should consider potential trade-offs[25,53]. For instance, water-saving techniques look promising but could increase production risk and may be difficult to implement considering the level of sophistication in water and crop management that is needed[54]. Hence, while our study shows that there are opportunities to improve yield and/or resource-use efficiency in most rice cropping systems around the world, the means to achieve the desired level of sustainable intensification have to be tailored for each environment based upon the biophysical and socio-economic background.

Methods

Data sources. Eighteen rice-producing countries were selected for our analysis (**Supplementary Table 1**). Those countries account for 88% and 86% of global rice production and harvested rice area[2], respectively (FAOSTAT, 2015–2017). Our study focuses on the most important rice cropping system(s) in each country, including a total of 32 rice cropping systems (**Supplementary Table 2**). We note that "cropping system” refers to a unique combination of number of rice crops planted on the same piece of land within a 12-month period (and their temporal arrangement), water regime (rainfed or irrigated), and ecosystem (upland or lowland) (**Supplementary Fig. 1 and Supplementary Table 2**). Agronomic information was collected *via* structure questionnaires completed by agricultural specialists in each country or region. The collected data included field size, tillage method, crop establishment method, degree of mechanization for each field operation, seeding rate, crop establishment and harvest dates, nutrient fertilizer rates, manure type and rate, pesticides (number of applications, products, and rates), irrigation amount (in irrigated systems), energy source for irrigation pumping, labor input, and straw management (see details for requested variables in **Supplementary Information Text Sect. 1**, **Supplementary Tables 3 and 4**). Average values for each cropping system reported by country experts were retrieved from survey data available from previous projects (**Supplementary Table 5**). Rice grain yield was reported at a standard moisture content of 140 g H_2O kg^{-1} grain, separately for each crop cycle, using data from, at least, three recent cropping seasons in each cropping system. In all cases, and wherever possible, data were cross-validated with other independent datasets (*e.g.*, FAOSTAT, World Bank, IFA). Measured daily weather data, including daily solar radiation, minimum and maximum temperatures, and precipitation, were derived from representative weather stations in each region (**Supplementary Fig. 2 and Supplementary Table 6**). Data on per-capita gross domestic product (GDP) during 2015–2017 were retrieved for each country[55] (**Supplementary Table 1**).

Estimation of yield gaps. The yield gap is defined as the difference between yield potential and average farmer yield. Estimates of yield potential for irrigated rice or water-limited yield potential for rainfed rice were derived from Global Yield Gap Atlas (GYGA)[56] (**Supplementary Table 5**). Yield potential simulation in GYGA was performed using crop growth and development model ORYZA2000 or ORYZA (v3) (except for APSIM in the case of India) and based on actual data on crop management, soil data, measured daily weather data, and representative rice varieties planted in each region (see details for yield potential simulation in **Supplementary Information Text Sect. 2**). Data on yield potential were not available for Australia (AUIS) in GYGA; hence, we used estimates of yield potential from Lacy et al[57]. Yield potential (or water-limited yield potential for rainfed rice) and average yields were computed separately for each rice crop in each rice cropping systems (**Supplementary Fig. 3**). The coefficient of variation (CV) of yield potential (or water-limited yield potential) was estimated for each cropping system (**Supplementary Fig. 4**). In this study, average rice yield was expressed as percentage of the yield potential (or water limited yield potential for rainfed rice) for each cropping system (Fig. 1 **and Supplementary Fig. 5**). In those cropping systems where more than one rice crop is grown within a 12-month period, we estimated yield potential and average yield on both per-crop and annual basis by averaging and summing up the estimates for each rice crop, respectively. However, for simplicity, the main text reports only the values on a per-crop basis; annual estimates are provided in the **Supplementary Information**.

Quantifying resource-use efficiency. We assessed the performance of rice production by calculating the following metrics: global warming potential (GWP), fossil-fuel energy inputs, water supply (irrigation plus in-season precipitation), number of pesticide applications, nitrogen (N) balance, and labor input, each expressed on an area and yield-scaled basis (Figs. 2, 3 and 4 **and Supplementary Figs. 6, 8 and 10**). In the case of GWP, it includes CO_2, CH_4, and N_2O emissions (expressed as CO_2-eq) from (i) production, packaging, and transportation of agricultural inputs (seed, fertilizer, pesticides, machinery, etc.), (ii) fossil-fuel energy directly used for farm operations (including irrigation pumping), and (iii) CH_4 and N_2O emission during rice cultivation[58]. Emissions from agricultural inputs were calculated on application rates and associated GHG emissions factors (see details in **Supplementary Information Text Sect. 3**, **Supplementary Table 7**). In the case of fossil fuel used for field operations, it was calculated based on the number and type of farm operations and associated fuel requirements (**Supplementary Table 8**). Total N_2O emissions were calculated as the sum of direct and indirect N_2O emissions. Direct soil N_2O emissions for a given rice crop cycle were estimated following van Groenigen et al. N-balance approach[21]. Indirect N_2O emissions were estimated based on the Intergovernmental Panel on Climate Change (IPCC) methodology[59], assuming indirect N_2O emissions represent 20% of direct N_2O emissions (see details for N_2O emissions estimates in **Supplementary Information Text Sect. 3**). The CH_4 emissions from rice paddy field were calculated following IPCC[60]. Following this approach, CH_4 emissions are estimated considering the duration of the rice cultivation period, water regime during the cultivation period and during the pre-season before the cultivation period, and type and amount of organic amendment applied (*e.g.*, straw, manure, compost) based on a baseline emission factor (see details for CH_4 emissions estimates in **Supplementary Information Text Sect. 3**). We assumed no net change in soil carbon stocks as soil organic matter is typically at steady state in lowland rice[61]. We did not attempt to estimate changes on soil C in the upland rice system in Brazil. All emissions were converted to CO_2-eq, with GWP for CH_4 set at 25 relatives to CO_2 and 298 for N_2O on a per mass basis over a 100-year time horizon[62]. For each rice crop cycle in each of the 32 rice systems, GWP was calculated as the sum of CO_2, CH_4, and N_2O emissions expressed as CO_2-eq (see details for GWP estimates in **Supplementary Information Text Sect. 3**).

Calculation of energy inputs was similar to that of GWP and was based on the reported rates of agricultural inputs and field operations and associated embodied energy (see details for energy input estimates in **Supplementary Information Text Sect. 3**, **Supplementary Table 9**). Human labor was also included in the calculation of energy inputs. There was a strong positive relationship between energy input and GWP on both per-crop ($r = 0.81$; $p < 0.01$) and annual basis ($r = 0.92$; $p < 0.01$), so we only showed results on GWP in the main text. Results on energy input and net energy yield (the difference between energy output and input) on a per-crop or annual basis can be found in **Supplementary Fig. 10**.

The N balance was calculated as the difference between N input from synthetic N fertilizer, manure, and biological N fixation *minus* N removal with the harvested grain (and straw if it was burned or removed from the field) following Dobermann and Witt[63] (see details for N balance estimates in **Supplementary Information Text Sect. 4**). The N input and N removal were estimated for each rice crop cycle. The N input *via* manure was calculated based on the amount and source of manure and N concentration. An average input of N from biological N fixation of 30 kg N ha^{-1} $crop^{-1}$ was assumed for lowland rice systems[64], while biological N fixation in upland rice was assumed to represent 10% of that in lowland rice[65]. Grain N removal was calculated based on average grain yield and rice grain N concentration. The N removal with straw was estimated assuming a typical percentage of straw remaining in the field and percentage of N lost from the crop residue in different straw managements (**Supplementary Table 10**). In our N balance calculation, we assumed N losses *via* lixiviation and denitrification to be similar to the amount of N inputs *via* irrigation water and atmospheric deposition[50]. We also assumed that N excess (and potentially large reactive N losses) occurs when the N balance > 75 kg N per ha[33–35].

We estimated the amount of active ingredient and environmental impact quotient (EIQ) of pesticides including insecticide, herbicide, and fungicide applied per hectare per crop following Kovach et al environmental risk assess methodology[66] **(**see details for toxicity estimation in **Supplementary Information Text Sect. 5)**. The two metrics showed a significant and positive relationship on a per-crop basis (**Supplementary Information Text Sect. 5**, $r = 0.96$; $p < 0.01$), and EIQ was also significantly and positively correlated with the number of pesticide applications ($r = 0.87$; $p < 0.01$). Given the uncertainty in EIQ estimates associated with sketchy reporting of products and application rate of pesticides, and considerable variation in the reliability of such data among countries or regions, the number of pesticide applications is used to evaluate environmental risk among cropping systems.

Labor requirement. Because labor requirement is a key driver explaining changes in rice area, systems, and profit[58,67], we calculated labor inputs associated with land preparation, seed preparation, crop establishment, water irrigation, fertilization, pesticide application, weeding, harvesting, threshing, and drying (**Supplementary Table 4**). Given the intrinsic relationships among labor input, mechanization level, establishment method (direct seeding *versus* transplanting) and field size[67], we characterized each rice cropping system in terms of these parameters and expressed labor input on both area and yield-scaled basis (see details for labor input and degree of mechanization in **Supplementary Information Text Sect. 6**, Fig. 4 **and Supplementary Fig. 6; Supplementary Table 3**).

Estimation of overall performance index. We computed a semi-quantitative index to quantify the performance of each cropping system in relation to six metrics, including the yield gap (as percentage of yield potential) and yield-scaled GWP, water supply, number of pesticide applications, N balance, and labor input. For each metric, the score was calculated by normalizing the data relative to the maximum value among all 32 cropping systems. An exception was the yield-scaled N balance, which was expressed as an absolute deviation from 8 kg N Mg^{-1} grain. This value corresponds to the average yield-scaled N balance estimated for Australia and California, which we assumed here to be a reasonable target to achieve the dual goal of minimizing the N balance and closing the yield gap, while avoid soil N mining (Fig. 3). Finally, we estimated an overall performance index for each rice cropping system by averaging the individual scores associated with the six metrics. Four out of the six metrics are related with resource-use efficiency (yield-scaled GWP, water supply, number of pesticide applications, and N balance), one with yield gaps, and another one with labor. To avoid biases, we weighted each individual score so that yield gap, resource-use efficiency, and labor will have a similar impact on the computation of the overall performance index. Lower (higher) overall index indicate better (worse) overall performance (Fig. 5). Finally, Pearson's correlation coefficients were calculated to investigate associations between resource-use efficiency and yield gaps **(Supplementary Table 11)**.

Scenario analysis. To illustrate the potential of our assessment to serve as basis to prioritize agricultural R&D, we explored an scenario in which there is an explicit effort to (i) increase average yield from current level to 75% of yield potential in cropping systems with relatively large yield gaps (defined here as average yield < 60% of yield potential), and (ii) reduce current N balance to 75 kg N ha^{-1} $crop^{-1}$ in cropping systems that currently exhibit a large N balance (defined here as N balance > 100 kg N ha^{-1} $crop^{-1}$). Selection of this N balance target (*i.e.*, 75 kg N ha^{-1} $crop^{-1}$) was based on data from the literature showing that large N losses occur when N balance exceeds that value[33–35]. Following these criteria, we selected a total of 19 cropping systems with large gaps (mostly in Sub-Saharan Africa and Asia) and 8 cropping systems with large N balance (mostly in China and South Asia). Following previous studies, the excess N was calculated as the amount of N balance exceeding 75 kg N per ha[68]. Because the goal was to understand how to produce more while reducing the environmental impact on existing global rice area, we calculated the potential extra rice production and reduction in excess N across the 32 cropping systems considering current rice harvested area, cropping intensity, and proportion of irrigated area (Table 1).

Uncertainty. We acknowledge the uncertainty related with estimation of yield potential and collection of actual yield and management data. In all cases, we used estimates of yield potential derived using well-calibrated models and best available sources of weather, soil, and management data. To the extent that it was possible, we cross-validated estimates of yield potential with measured yield data collected from well-managed crops that grew without nutrient limitation and without yield reductions due to biotic stresses. In the case of survey data, there is always uncertainty in relation to the representativeness of the regions and years included for the analysis. The analyses presented herein focused on the most intensively cropped area of each cropping system using data from at least three cropping seasons for each area. Likewise, estimation of GWP required a number of assumptions in relation to GHG emissions; in those cases, we relied on the most recent literature to derive appropriate emission factors. We do not expect these sources of uncertainty to affect the conclusions from this study. Detailed description of data sources and estimations of yield gaps, resource-use efficiency, and labor inputs can be found in **Supplementary Information**.

Declarations

Data availability

Data on yield potential are available *via* the Global Yield Gap Atlas website (www.yieldgap.org). All other data are available from the corresponding author upon reasonable request.

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Author contributions

S.Y., K.G.C., S.P., and P.G. conceived and designed the study. B.A.L., L.T.W., A.M.S., V.P., B.M., K.S., N.A., V.E.A., L.Y.K., A.J.Z., A.B.H., G.C., N.S., P.S.B., T.L., and S.P. provided the data analyzed in this study. S.Y. and P.G. compiled the data, performed the data analysis and wrote the paper. All authors contributed to editing the paper.

Ethics declarations

The authors declare no competing interests.

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Figures

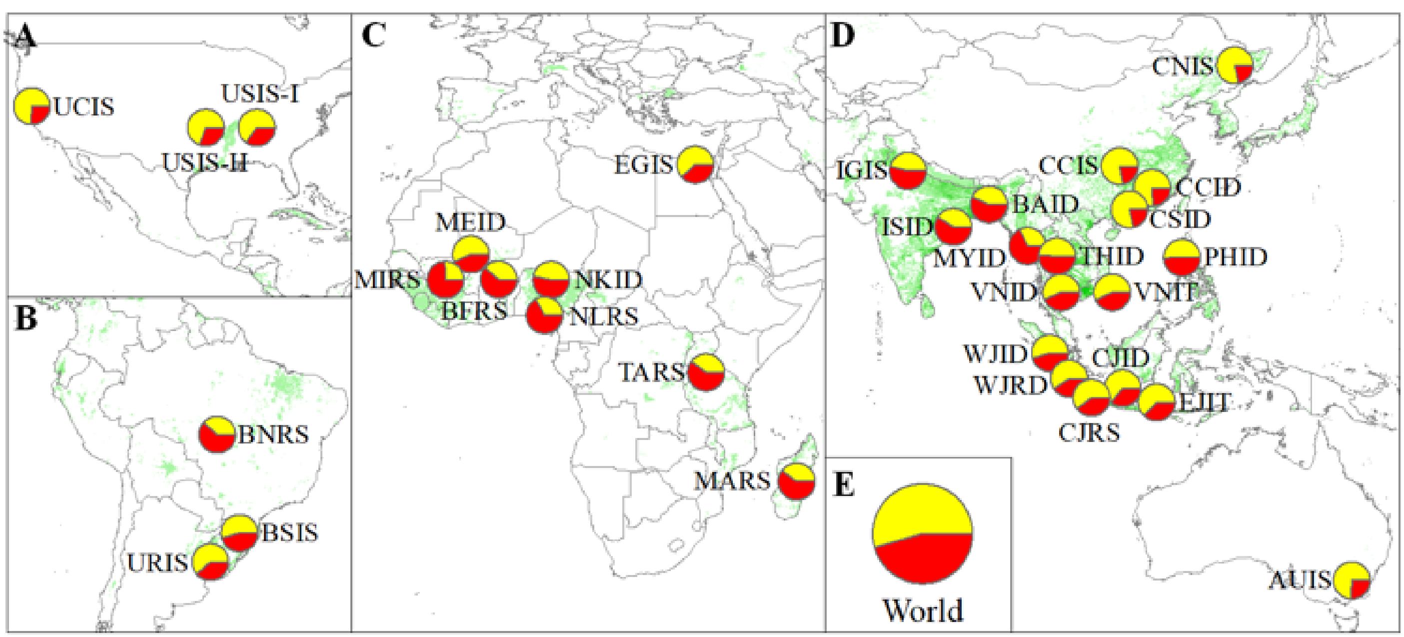

Figure 1

Map showing the rice systems assessed in this study and their associated yield gap and actual yield expressed as percentage of the yield potential (red and yellow portions of pie charts, respectively). Panels correspond to (A) North America, (B) South America, (C) Africa, (D) Asia and Australia, and (E) world. Rice area distribution is shown in green (SPAM maps29). Cropping system code consists of region (first two letters), water regime (third letter), and rice cropping intensity (fourth letter). Regions: Australia (AU); Bangladesh (BA); Burkina Faso (BF); northern and southern Brazil (BN and BS, respectively); central, northern, and southern China (CC, CN, and CS, respectively); Egypt (EG); central, east, and west Java, Indonesia (CJ, EJ, and WJ, respectively); Indo-Gangetic Plains and southern India (IG and IS, respectively); Madagascar (MA); Segou and Sikasso, Mali (ME and MI); Myanmar (MY); Kano and Lafia, Nigeria (NK and NL); Philippines (PH); central Thailand (TH); Tanzania (TA); southern USA and California (US and UC); Uruguay (UR); Vietnam (VN). In the case of the southern USA, hybrid (H) and inbred rice (I) are also distinguished. Water regime: irrigated (I) and rainfed (R). Cropping intensity: single (S), double (D), and triple rice (T). Description of each rice cropping system and associated yield potential and yield gap are provided in Supplementary Figs. 1-5 and Supplementary Tables 1-5. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

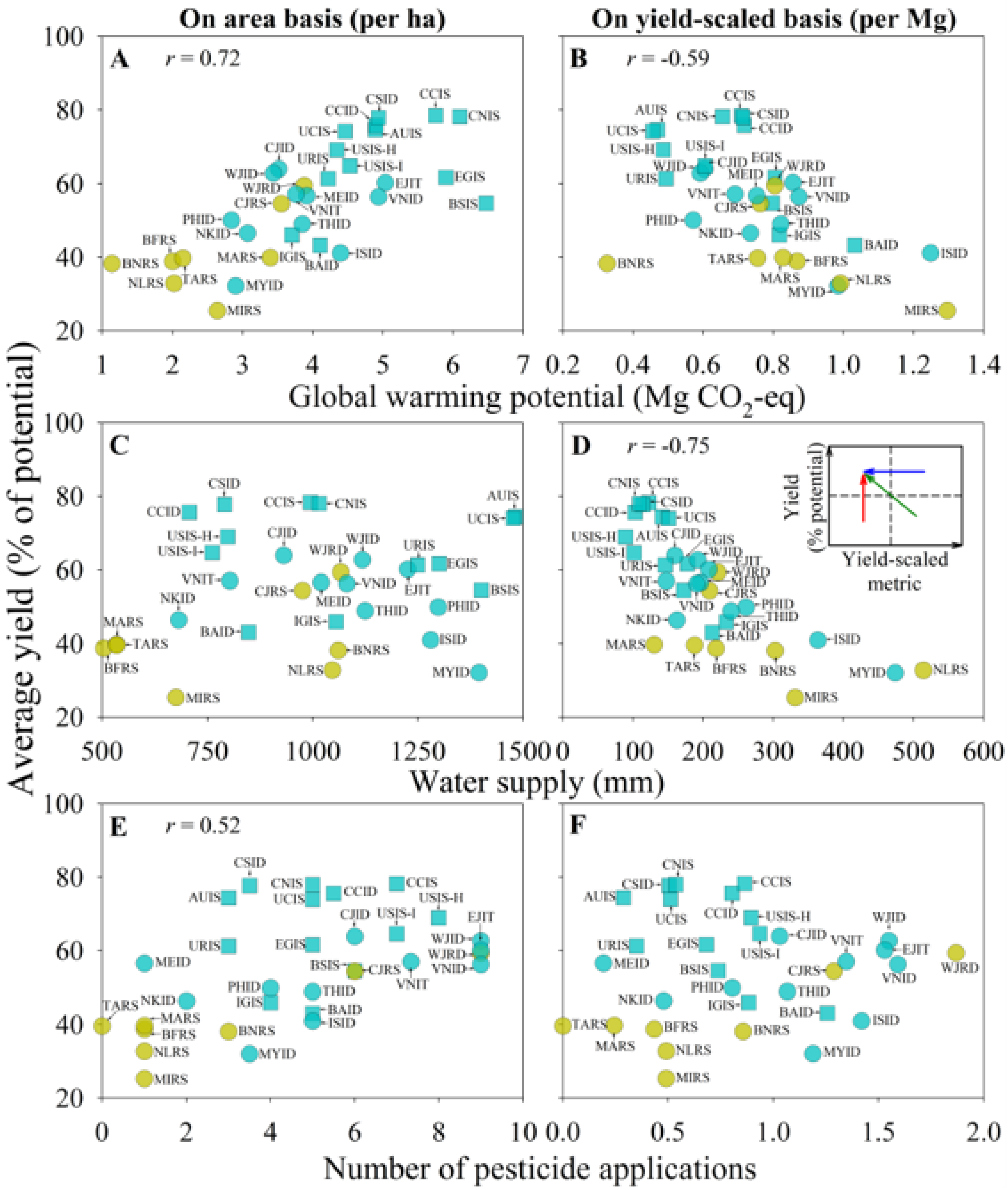

Figure 2

Average rice yield (expressed as percentage of yield potential) versus (A, B) global warming potential, (C, D) water supply (irrigation plus in-season precipitation), and (E, F) number of pesticide applications. Global warming potential, water supply, and number of pesticide applications are shown on an area (A, C, E) or yield-scaled basis (B, D, F). Each point represents the average for the rice crops in each cropping system (typically two or three for irrigated rice in tropical regions and one or two for rainfed rice in tropical regions and for irrigated rice in non-tropical regions). Symbol type and color are used to distinguish tropical versus non-tropical regions (circles and squares, respectively) and irrigated versus rainfed systems (blue and yellow, respectively). Inset in (D) shows hypothetical pathways to improve yield and/or reduce environmental impact. Pearson’s correlation coefficient (r) is shown only when the association between variables is significant (p<0.01). Cropping system codes are shown in the caption to Fig. 1.

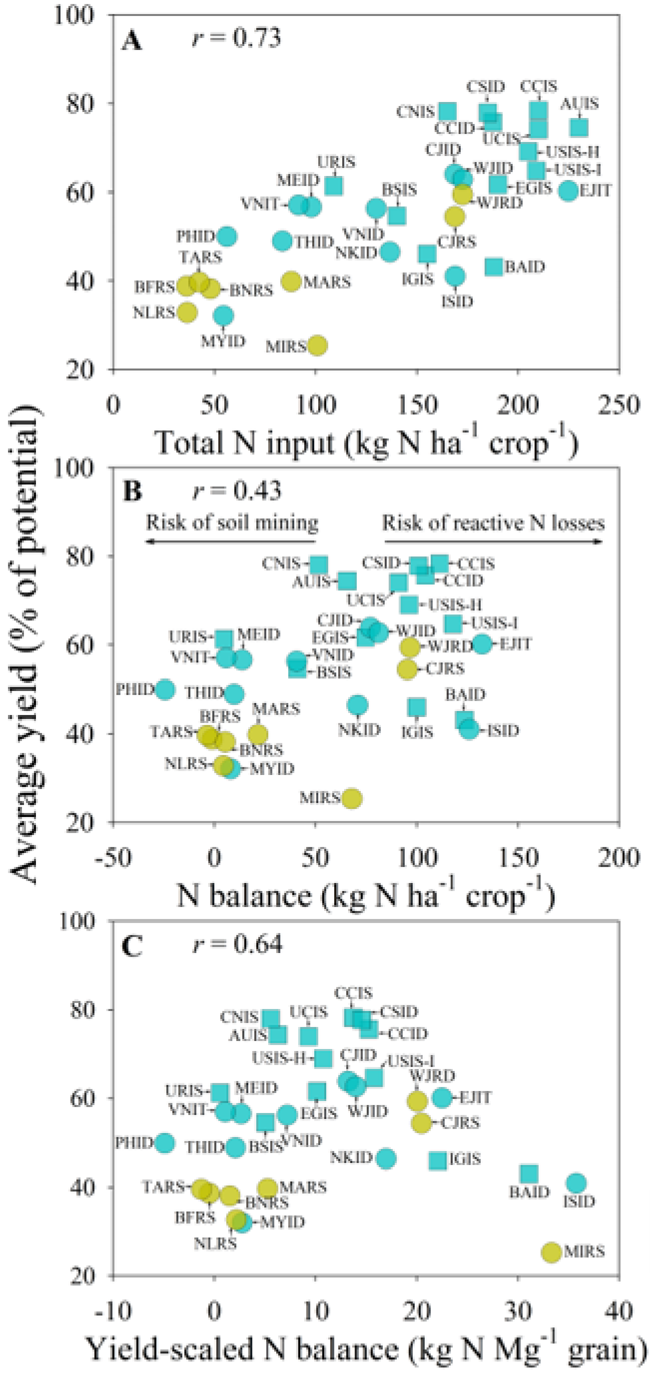

Figure 3

Average rice yield (expressed as percentage of yield potential) versus (A) total nitrogen (N) input (from fertilizer, manure, and fixation), (B) N balance calculated as N input minus N removal, and (C) yield-scaled N balance. Symbol type and color are used to distinguish tropical versus non-tropical regions (circles and squares, respectively) and irrigated versus rainfed systems (blue and yellow, respectively). Pearson’s correlation coefficient (r) is shown only when the association between variables is significant (p<0.05). Cropping system codes are shown in the caption to Fig. 1.

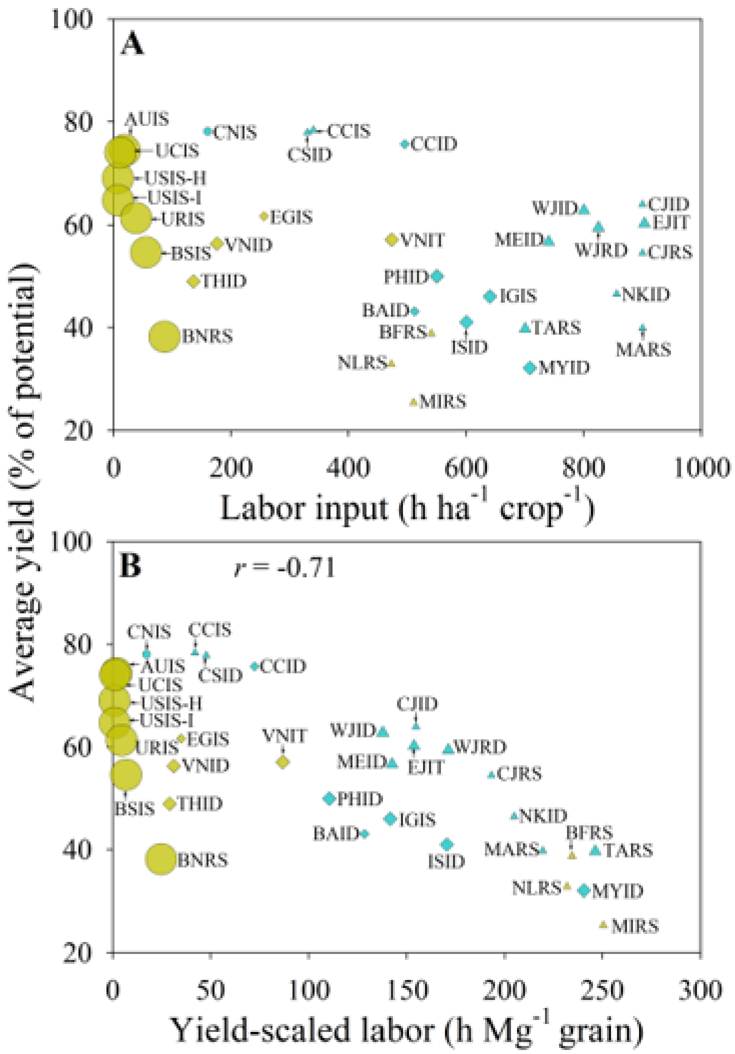

Figure 4

Average rice yield (expressed as percentage of yield potential) versus (A) labor input per hectare and (B) yield-scaled labor. Symbols are used to distinguish systems with high (circle), intermediate (diamond), and low (triangle) level of mechanization. Symbol color indicates the predominant establishment method in each system: transplanting (blue) or direct seeding (yellow). Symbol size is proportional to the average field size in each system. Pearson’s correlation coefficient (r) is shown only when the association between variables is significant (p<0.01). Cropping system codes are shown in Fig. 1.

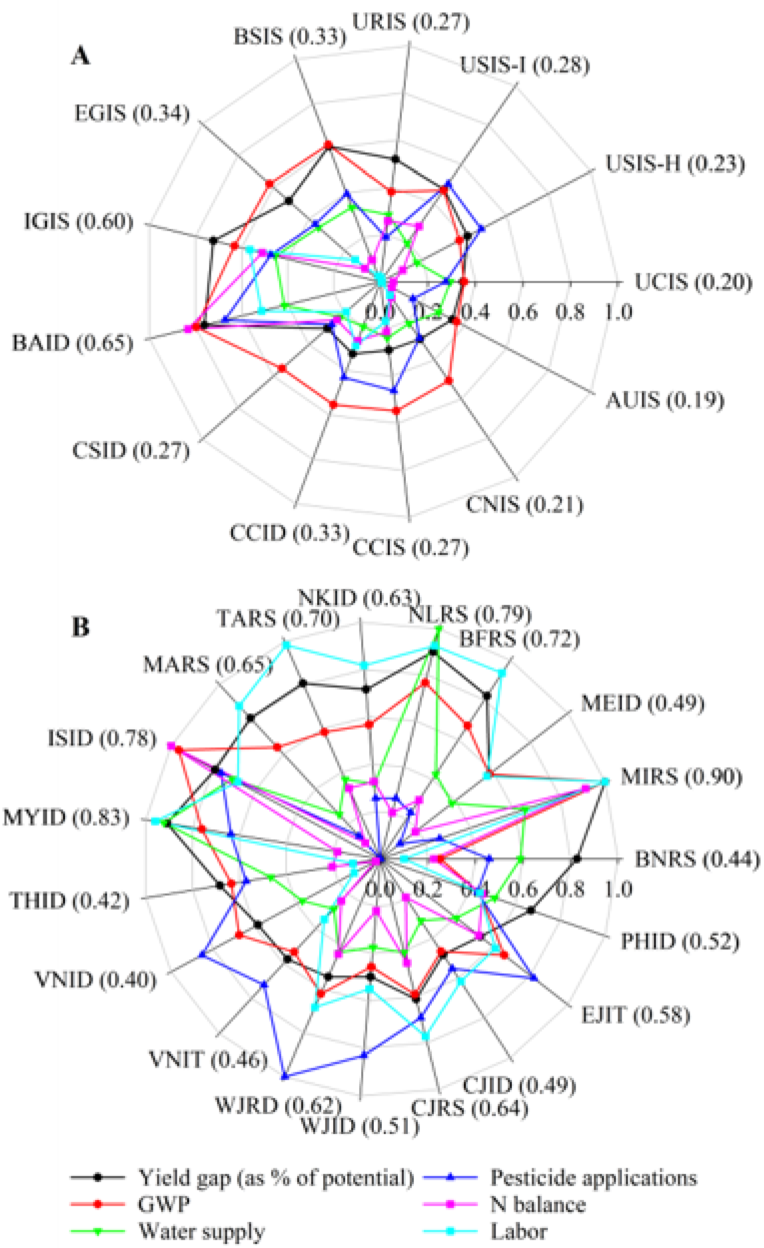

Figure 5

Radar chart comparing yield gap (as percentage of yield potential) and yield-scaled global warming potential (GWP), water supply, number of pesticide applications, nitrogen (N) balance, and labor across 32 rice cropping systems in (A) non-tropical and (B) tropical regions. For each metric, data were normalized relative to the maximum value across all cropping systems, except for the yield-scaled N balance, which was expressed as an absolute deviation from 8 kg N Mg-1 grain. Parenthetic values are the performance index of each system, with lower (higher) values indicating better (worse) overall performance. Cropping system codes are shown in caption to Fig. 1. See Methods section for explanation about the calculation of the overall performance index.

Supplementary Files

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