3-24-2022

Southeast Asia must narrow down the yield gap to continue to be a major rice bowl

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nature food

ARTICLES

https://doi.org/10.1038/s43016-022-00477-z

Southeast Asia must narrow down the yield gap to continue to be a major rice bowl

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Southeast Asia is a major rice-producing region with a high level of internal consumption and accounting for 40% of global rice exports. Limited land resources, climate change and yield stagnation during recent years have once again raised concerns about the capacity of the region to remain as a large net exporter. Here we use a modelling approach to map rice yield gaps and assess production potential and net exports by 2040. We find that the average yield gap represents 48% of the yield potential estimate for the region, but there are substantial differences among countries. Exploitable yield gaps are relatively large in Cambodia, Myanmar, Philippines and Thailand but comparably smaller in Indonesia and Vietnam. Continuation of current yield trends will not allow Indonesia and Philippines to meet their domestic rice demand. In contrast, closing the exploitable yield gap by half would drastically reduce the need for rice imports with an aggregated annual rice surplus of 54 million tons available for export. Our study provides insights for increasing regional production on existing cropland by narrowing existing yield gaps.

Southeast Asia has made remarkable progress in raising rice production over the past 50 years, mainly by increasing cropping intensity (that is, the number of crops grown on the same piece of land during a 12-month period) and average yield[1,2]. As a result, the rice systems located in the river basins and deltas of this region now produce a large and stable surplus of rice that not only meets the regional demand but also makes a substantial contribution to global food supply[1,3,4]. As a whole, the region accounts for 26% and 40% of global rice production and exports[3], respectively, being a major rice supplier for other regions of the world such as Africa and the Middle East[5]. Given the projected 30% increase in global rice demand by 2050, the continuing rise in rice trade and the limited scope available for other main rice-producing countries (for example, China and India) to generate a rice surplus[2,6,7], Southeast Asia will continue to play a critical role in ensuring global rice supply[8].

The new millennium has brought a number of challenges to rice systems in Southeast Asia. First, despite global equilibrium models on food supply and demand previously predicting an abrupt decline in rice demand per capita[9], we now know that this parameter will remain relatively stable for most countries[7,10]. Hence, by 2050, rice demand in Southeast Asia will increase by approximately 18% simply due to population growth[3,7,10]. Second, the two most populous countries in the region (Indonesia and Philippines), totalling nearly 380 million people, depend on rice imports to meet their domestic demand. Third, after a few decades of a steady increase in average rice yield, there is now evidence of yield stagnation in four of the six major rice-producing countries in Southeast Asia region (Indonesia, Myanmar, Thailand and Vietnam) (Fig. 1a and Supplementary Table 1). Finally, the rice harvested area has remained stable or even declined slightly in some countries recently (Fig. 1b) and is under growing threat of conversion for residential and industrial uses[11]. Meanwhile, irrigated rice-area expansion is unlikely to occur due to lack of investments in irrigation infrastructure, physical and economic water scarcity and environmental concerns[12]. Additionally, there is limited scope for further increasing cropping intensity, considering that two and up to three rice crops are now being grown in most of the rice systems in the region[13] (Supplementary Fig. 1). Although it has been demonstrated that rice yields can be maintained in such intensive monoculture systems, it has also proven to be very difficult to raise them further, even with the best available varieties and technologies[14].

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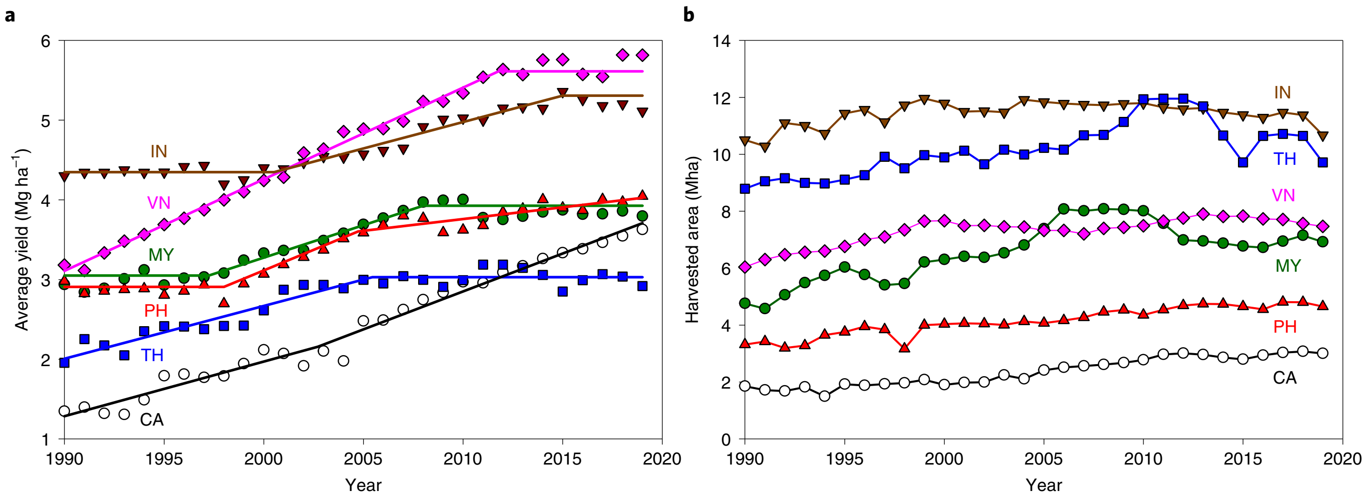

Fig. 1 | Trends in average yield and harvested area for rice. a,**b**, Panels show trends in average yield (**a**) and harvested area (**b**) for rice in six major rice-producing countries in Southeast Asia: Cambodia (CA), Indonesia (IN), Myanmar (MY), Philippines (PH), Thailand (TH) and Vietnam (VN) during the past 30 years (1990–2019). Fitted linear or linear-plateau models are shown in Supplementary Table 1. Data from FAOSTAT[3], provided in Source Data Fig. 1.

Over the past decades, through renewed efforts, countries in Southeast Asia were able to increase rice yields, and the region as a whole has continued to produce a large amount of rice that exceeded regional demand, allowing a rice surplus to be exported to other countries[4]. At issue is whether the region will be able to retain its title as a major global rice supplier in the context of increasing global and regional rice demand, yield stagnation and limited room for cropland expansion. Here we follow a data-intensive approach to estimate yield gaps (the difference between yield potential and average farmer yield, Methods) across the major rice-producing countries in the region to determine whether there is still sufficient potential for increasing production on existing land and provide insight on whether the region can remain a major global rice supplier.

Results

Current yield gaps vary substantially at the national and subnational level. We estimated yield gaps based on the simulated yield potential (irrigated crops) or water-limited yield potential (rainfed crops) across the six major rice-producing countries in Southeast Asia (Cambodia, Indonesia, Myanmar, Philippines, Thailand and Vietnam), which together account for 97% of total rice production in the region[3]. Our assessment included both irrigated and rainfed lowland rice systems, which roughly account for 98% of total rice production in these six countries[13,15], while deep-water and upland rice were not included. For irrigated rice, our definition of yield potential assumed no water and nutrient limitations and the absence of weeds, pests and diseases. The same definition applied to rainfed rice except for the inclusion of water limitation as a factor influencing the yield potential. At a regional level, yield potential averaged 8.9 Mg ha^{-1} per crop, ranging from 5.5 Mg ha^{-1} per crop to 10.2 Mg ha^{-1} per crop across the 11 country–water regime combinations included in our analysis (Fig. 2). Variation in yield potential portrayed differences in water regime and climate, with the highest values observed in irrigated systems or favourable environments for rainfed lowland rice production such as Indonesia and Philippines. In contrast, average water-limited yield potential was the lowest (5.3 Mg ha^{-1} per crop) for less productive but high-value aromatic (jasmine) rice varieties grown in water-limited environments in Thailand (Supplementary Fig. 2). The average annual yield potential in Southeast Asia was much higher in irrigated versus rainfed rice cropping systems because of higher seasonal yield potential in irrigated versus rainfed crops and because irrigation allowed production of two and up to three rice crop cycles within the same year, while most rainfed environments allowed cultivation of only a single rice crop (Fig. 2 and Supplementary Fig. 1). Yield potential was also influenced by the difference in weather between crop seasons, with yield potential being approximately 10% higher during the dry season compared with the wet season due to higher solar radiation[13] (Supplementary Fig. 3).

At the regional level, the average yield gap represented 48% of the potential (Fig. 2). This value represented the average across countries, water regimes, crop sequences and soil types after weighting by their relative share of total rice area. However, average values hid substantial differences in yield gaps among water regimes and countries. For example, average yield gaps were 42% and 55% for irrigated and rainfed rice, respectively. While the previous analysis focused on the average yield gap, the cropping intensity was also important to determine the available room for increasing annual rice production. For example, despite irrigated rice having a smaller yield gap than rainfed rice, its annual yield gap was larger due to higher cropping intensity (7.5 Mg ha^{-1} per year versus 5.2 Mg ha^{-1} per year) (Fig. 2). Regarding differences among countries, the yield gaps for irrigated rice were smaller in Indonesia and Vietnam (37–39%) than in Cambodia, Myanmar, Philippines and Thailand (51–60%). In the case of rainfed rice, Indonesia exhibited a relatively smaller yield gap (49%) compared with Cambodia, Myanmar, Philippines and Thailand (54–66%).

Our analysis also identified regions at the subnational level with the largest opportunities for increasing rice yield and production. For example, the yield gap was larger in the Red River delta compared with that of the Mekong delta in Vietnam (46% versus 39%). In some cases, the magnitude of the yield gap was related to the previous history of intensification of rice production in the country. For example, in the case of Indonesia and Philippines, yield gaps were smaller in typical Green Revolution areas such as Java and Central Luzon, respectively, compared with other comparably newer rice-producing regions within these countries (Fig. 3). Our analysis also identified differences in the magnitude of the yield gap between cropping seasons. For example, we found a 7–16% larger yield gap for irrigated rice grown during the dry versus wet season in Indonesia and Philippines, but this pattern was the opposite in the case of irrigated rice in Cambodia and Vietnam (Supplementary Fig. 3).

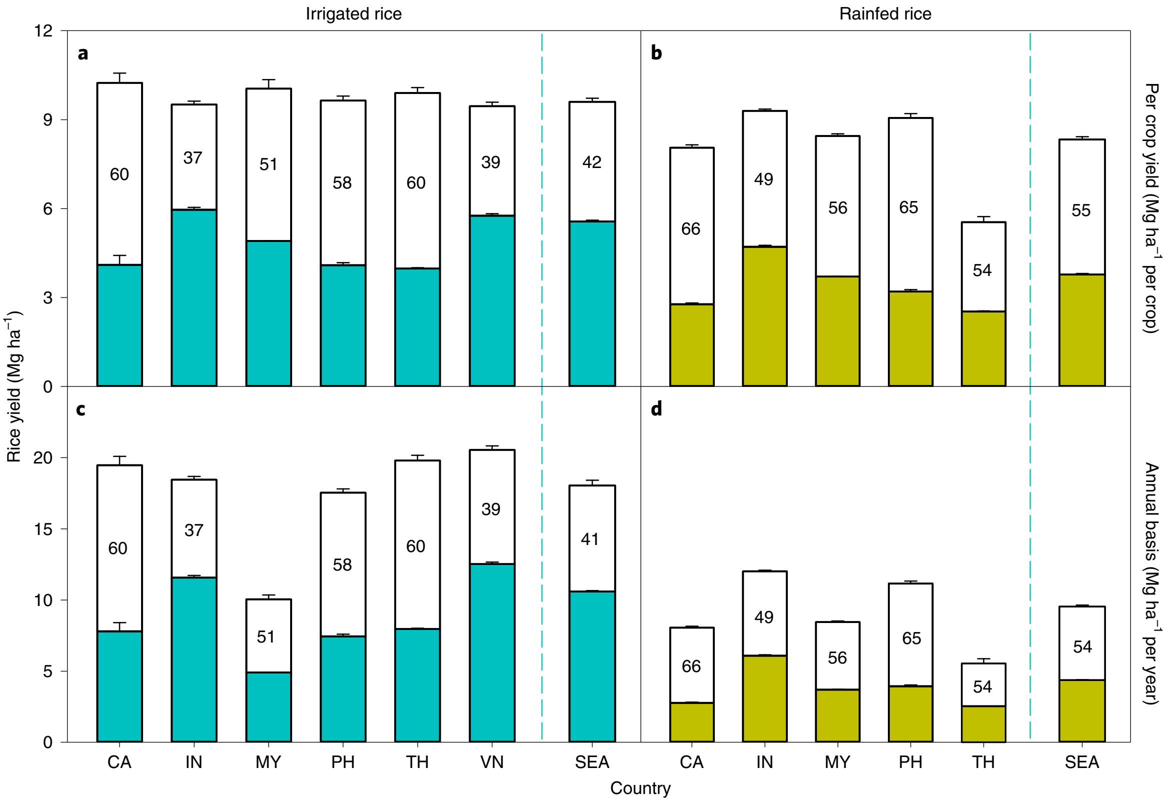

Fig. 2 | Average yield potential for irrigated rice and water-limited yield potential for rainfed rice. a–d, Panels show average yield potential and water-limited yield potential for irrigated (**a**,**c**) and rainfed (**b**,**d**) rice, respectively, for the six major rice-producing countries in Southeast Asia: Cambodia (CA), Indonesia (IN), Myanmar (MY), Philippines (PH), Thailand (TH) and Vietnam (VN) on a per crop (**a**,**b**) and annual basis (**c**,**d**). Solid and empty portions of bars indicate the average farmer yield and the yield gap, respectively. Vertical lines above solid and empty bars indicate standard errors of the mean (n = 5). Values inside the empty portion of the bars indicate the average yield gap as percentage of yield potential (irrigated) or water-limited yield potential (rainfed). Also shown are the regional area-weighted averages of Southeast Asia (SEA) for each water regime. Data provided in Source Data Fig. 2.

Prospects for rice self-sufficiency and rice surplus. The current average (2019–2020) rice self-sufficiency ratio (SSR) in the entire Southeast Asia region was 1.10, with an estimated surplus of 17 million tons (Mt) (Fig. 4). However, there were contrasting patterns among countries with rice production largely exceeding domestic consumption in Thailand and Vietnam, while Indonesia and Philippines relied on rice imports (Fig. 4, Supplementary Fig. 4 and Supplementary Table 1). The latter two countries have struggled consistently to meet their rice demand from their own production and considering strong population growth and agro-climatic constraints[8,16], this situation is not likely to change easily. The degree to which Southeast Asia can remain a net rice-exporting region in the future will ultimately depend upon changes in average yields and harvested area. Given the limited room for cropland expansion and cropping intensity, as one can infer from recent trajectories in harvested area (Fig. 1), we focused here on investigating rice SSR and surplus for different scenarios of yield increase during the next 20 years, assuming that net harvested area remained unchanged. We investigated three scenarios: continuation of current yield trends (S1), full closure of the exploitable yield gap (S2) and half closure of the current exploitable yield gap (S3) (Fig. 4). For the calculation of the exploitable yield gap, we assumed that achieving 80% of the yield potential for irrigated crops and 70% of the water-limited yield potential for rainfed crops was a reasonable goal for farmers with access to markets, inputs and extension services[17–19]. Such levels of productivity have also been consistently achieved in well-managed long-term experiments[14].

Assuming current trends in rice yield remains unchanged until 2040 (S1), the Southeast Asia regional SSR will drop from the current 1.10 to 1.03, almost eliminating the rice surplus at a regional level and with Indonesia and Philippines failing to achieve rice self-sufficiency (Fig. 4). In contrast, a scenario in which the exploitable yield gap is completely closed by 2040 (S2) would allow the six countries to be rice self sufficient, leading to a regional SSR of 1.55 and an aggregated rice surplus of 100 Mt, which is approximately six times larger than the current value. Closing the exploitable yield gap would require much faster rates of annual yield gain, ranging from 79 kg ha^{-1} per year to 135 kg ha^{-1} per year across countries, which may be difficult to achieve for the entire region and within the short time frame (20 years). Hence, we explored a more realistic third scenario in which the exploitable yield gap is closed by half (S3). In this scenario, the Southeast Asia regional SSR would increase to 1.29 and almost triple the rice surplus up to 54 Mt, allowing Indonesia to become self sufficient in rice and drastically reducing the need for rice imports in the Philippines. Achieving the level of yield-gap closure set as the target for S3 would require annual rates of yield gain ranging from 36 kg ha^{-1} to 67 kg ha^{-1} with the largest and smallest rates corresponding to Myanmar and Thailand, respectively.

Discussion

Concerns about rice shortages are not new in Southeast Asia. In the early 1960s, the threat of famine was a major driver for the Green Revolution that resulted in increased cropping intensity, higher yields, lower rice prices and greater food security throughout the

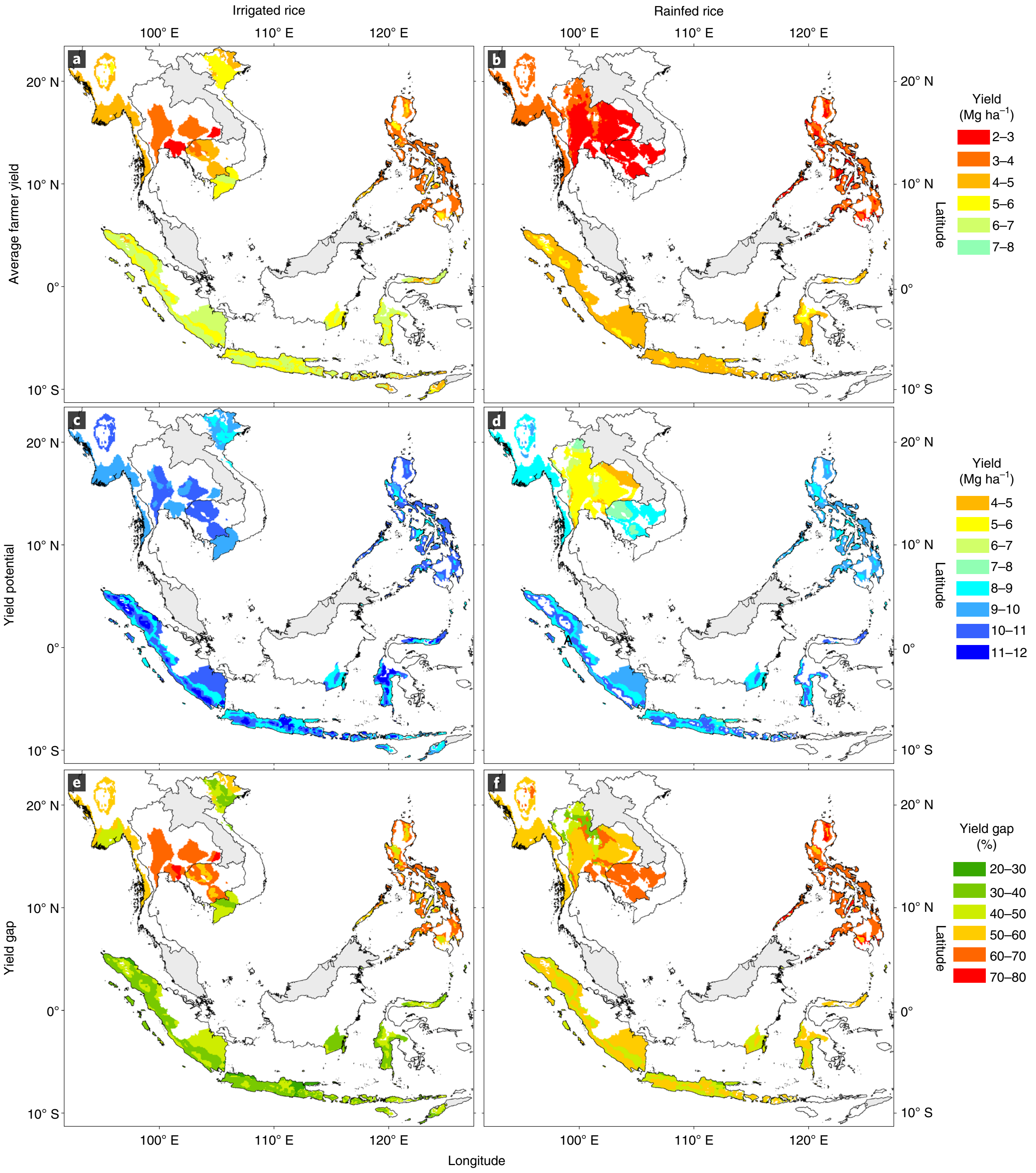

Fig. 3 | Average farmer yield, yield potential and yield gap (as a percentage of yield potential) for irrigated and rainfed rice. a–f, Panels show average farmer yield (**a**,**b**), yield potential (**c**,**d**), and yield gap (as a percentage of yield potential) (**e**,**f**) for irrigated (**a**,**c**,**e**) and rainfed (**b**,**d**,**f**) lowland rice for the six major rice-producing countries in Southeast Asia at the climate zone level. Other countries in Southeast Asia not included in our yield-gap analysis are shown in grey. Data provided in Source Data Fig. 3. The base map was applied without endorsement using data from the Database of Global Administrative Areas (https://gadm.org/).

region[4,8]. The initial step was a steep rise in the harvested rice area during the 1960s and 1970s. This was followed by a period of rapid yield increases in the decade from the mid-1970s to the mid-1980s due to nearly complete adoption of the first generations of the new rice varieties, associated increases in input use and other technology improvements[3,8,20]. Interestingly, while this initial Green Revolution

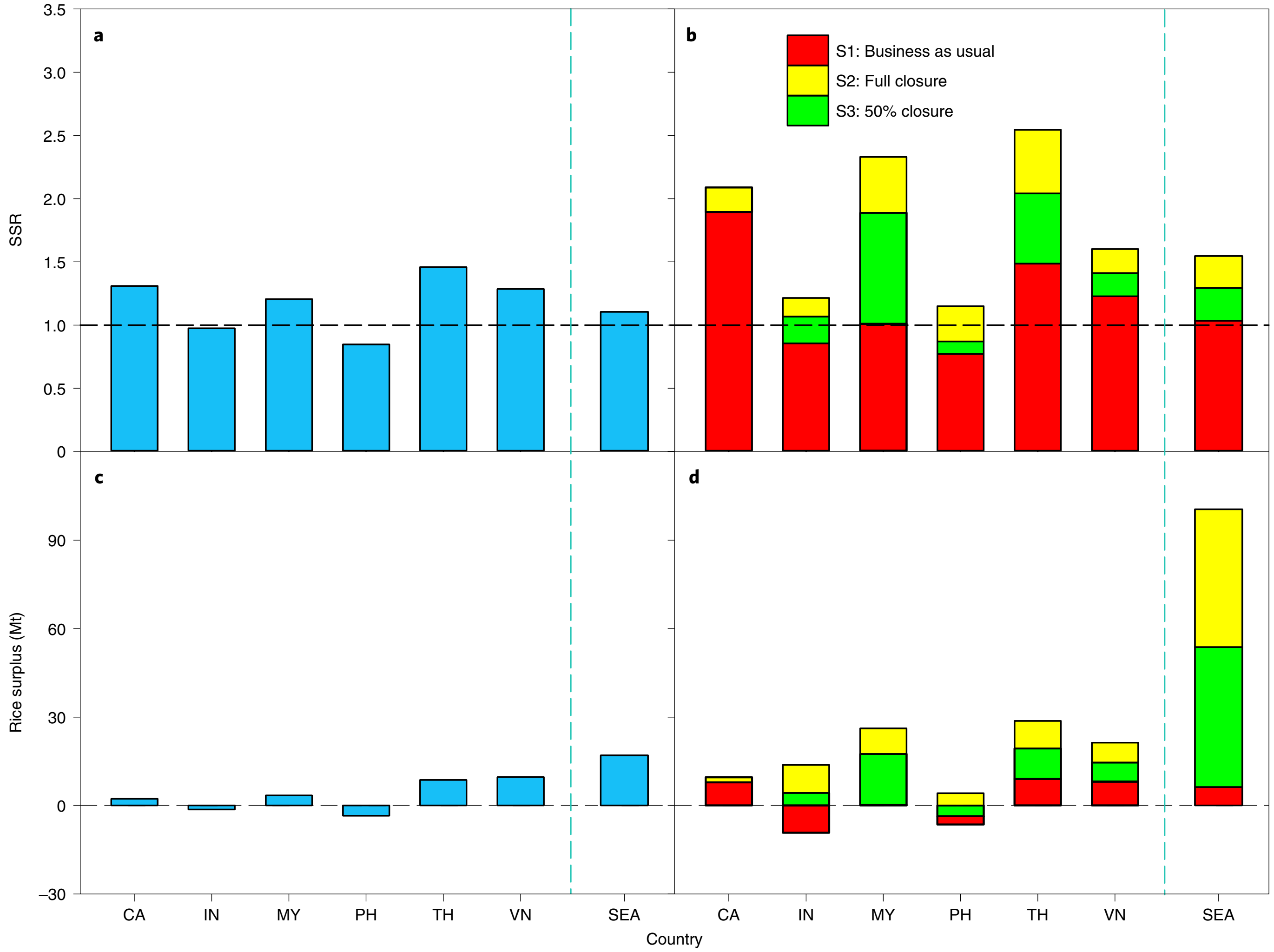

Fig. 4 | Projected trends in rice self-sufficiency ratio (SSR) and rice surplus. a–d, Panels show the rice SSR (**a**,**b**) and rice surplus (**c**,**d**) for the baseline (2019–2020) (**a**,**c**) and three scenarios of yield increase towards year 2040 (**b**,**d**): continuation of historical yield trends (S1, red), full closure of exploitable yield gap (S2, yellow) and half closure of exploitable yield gap (S3, green). Separate values are shown for each country: Cambodia (CA), Indonesia (IN), Myanmar (MY), Philippines (PH), Thailand (TH) and Vietnam (VN). Also shown are the aggregated values for the entire Southeast Asia (SEA) region (including six major rice-producing countries analysed in this study plus the other five countries located in this region as a whole, Methods). S3 is not shown for Cambodia as the current yield gain is adequate to achieve half closure of the exploitable yield gap by 2040. In (**a**,**b**), the horizontal dashed line shows SSR = 1 (that is, production equals demand) as a reference Data provided in Source Data Fig. 4.

period ended in the mid-1980s in Indonesia and Philippines, it steadily continued in Vietnam for several decades[21]. In the 1990s, concerns were raised about stagnating or even declining yields or total factor productivity in some of the most intensively cropped rice areas of Southeast Asia, reiterating the urgent need for closing existing yield gaps[22]. The concerns about rice shortages are back now. Our analysis shows that the Southeast Asia region will not be able to produce a large rice surplus in the future with the most recent rates of annual rice yield gains. Failure to increase yield on existing cropland area will drastically reduce the rice exports to other regions and the capacity of many countries in the region to achieve or sustain rice self-sufficiency. It also means that many countries in the region would need to rely on regional trade to meet their domestic rice demand, which in itself is not necessarily a disadvantage if rice market liberalization takes place[23]. Hence, although achieving rice self-sufficiency at the country level should not be taken as the ultimate goal, we note that reaching a reasonable level of SSR for key staple crops is desirable for countries with limited capacity to purchase and distribute large amounts of food imports[24]. Furthermore, for practically all Southeast Asian countries, rice is of strategic importance in terms of food security, political stability, economy and export potential.

Governments from many countries in Southeast Asia have made explicit their desire to secure stable food prices, completely avoid rice imports in the future and/or increase income from exports[25,26]. Our analysis shows that this is possible but only for a scenario where large and strategic investments in agricultural policies, innovation and research and development help accelerate rates of yield gains so that the exploitable yield gap is narrowed down substantially within the next 20 years. We believe that this is feasible considering that current yield gaps in Southeast Asia are comparably larger than those in other rice-producing countries such as China and the United States[27,28], especially in Cambodia, Myanmar, Philippines and Thailand where current yield gaps are 50–70% of yield potential. Also, we note that the required rates of annual yield gain to narrow down the exploitable yield gap by half are modest in relation to the historical yield gains observed over the past 30 years in these countries (Fig. 1 and Supplementary Table 1). The importance of maintaining the capacity of Southeast Asia to produce a large rice surplus goes beyond the region as it can help reduce global price volatility and provide a stable and affordable rice supply to many countries in Sub-Saharan Africa and the Middle East[8,20].

Our estimated yield gaps are of similar magnitude to those reported by previous studies for specific countries or rice seasons in Southeast Asia[29–31]. However, the regional extent of our study, together with the level of detail in relation to spatial and temporal variation in yield gaps and specificity in terms of cropping systems is unique, providing a basis for prioritizing agricultural research and development and investments at regional, national and subnational levels[32]. These regional and seasonal differences in yield gaps would not have been detected using top-down modelling approaches that ignore the complexity and diversity of rice systems in Southeast Asia[33]. For example, while rainfed rice exhibits a larger yield gap, our study shows that closure of yield gaps in irrigated rice can lead to a larger impact on annual rice production due to higher cropping intensity. We note that our study did not include the negative potential impact of climate change on yield, which may reduce our estimates of rice production and add further pressure on yield-gap closure[34]. Climate change impacts on rice yields will require adaptation strategies to sustain yield growth against a backdrop of rising temperatures and seawater levels, which particularly affect the mega deltas of Southeast Asia[35]. However, climate change operates over longer time scales and its impact on rice yield trends are typically overwritten by agro-ecological, seasonal and management effects[36]. A previous study suggested that a global increase in temperature of 1 °C is likely to reduce rice yield by an average of 3.3% globally[37]. However, there is also evidence that climate change would be comparably smaller during the first half of the century[38] with average global surface temperature increasing 0.3 °C during the 2021–2040 period[39]. Hence, the magnitude of the impact of climate change on yield potential by 2040 is relatively small compared with the size of the yield gap reported in our study. Likewise, we also note that the effect of climate change on crops will depend not only on temperature but also other variables including precipitation and atmospheric CO_2 concentration, together posing a large uncertainty of the ultimate impact on rice yield potential[40–42]. It is also reasonable to assume that numerous adaptation measures will allow farmers to adapt their cropping systems and practices to a changing climate. Therefore, we believe it is reasonable to ignore the effect of climate change on rice production for our assessment considering our relatively short time frame (20 years) and the challenges in modelling changes in yield and crop management as determined by climate change[17,43].

Our estimated yield potential was similar to that reported in previous studies. For example, the range of yield potential for irrigated rice reported here, from 9.5 Mg ha^{-1} per crop to 10.2 Mg ha^{-1} per crop, compared well with that of approximately 10 Mg ha^{-1} per crop reported for modern rice varieties in tropical environments[44–46] and with measured yields in well-managed field experiments in Philippines, Vietnam and Indonesia[47–49]. Likewise, our water-limited yield potential of 5.3 Mg ha^{-1} per crop for rainfed lowland aromatic rice was consistent with that reported for similar varieties in northeastern Thailand (5.3 Mg ha^{-1} per crop) and measured yields in field experiments, ranging from 5.1 Mg ha^{-1} per crop to 5.5 Mg ha^{-1} per crop[50–52]. Our study does not consider the improvement in genetic rice yield potential over time[48,53], including adaptation to rising temperatures or more frequent droughts or floods. However, we are cautious about the associated timeline and potential impact. For example, we note that the yield potential of inbred rice varieties has not changed substantially over the past 65 years[48,53]. Similarly, efforts to achieve a step change in rice yield potential by incorporating a C_4 photosynthetic pathway will not lead to any commercially available variety in the near future (if ever)[54]. In the case of hybrid rice, which can produce 15–20% higher yield than inbred rice[55], we note that its adoption has been limited in Southeast Asia (less than 5% of regional harvested area) due to high seed prices and trade-offs with grain quality[56,57]. Even when yield potential can be increased, increasing production would still require continuous agronomic improvements to exploit the resulting larger yield gap. Finally, we recognize that besides yield-gap closure, there may be other opportunities to increase the total milled rice output, for example, by reducing harvest and post-harvest losses and improving milling rates[58].

In terms of the required interventions that are needed to close the current yield gap, improving crop management practices, especially nutrient and water management, and control of biotic factors are likely to play a central role[22,25,59,60]. Production risk is also important for prioritizing agricultural research and development. This is particularly the case of rainfed lowland rice, which accounts for nearly one-third of harvested rice area in Southeast Asia[14], where uncertainty in rainfall (either too much or too little) makes farmers reluctant to adopt improved crop management technologies and use external inputs such as fertilizers and pesticides[13,59]. Use of pumps and crop insurance can help these farmers to deal with inherently higher risk of growing rice in rainfed lowland environments. Closing of these gaps requires not only fine tuning of crop management but also the concerted effort of policymakers, researchers and extension services to facilitate farmers' access to technologies, information and markets. It is also important to recognize a number of challenges in achieving this next and greener 'Green Revolution' for rice in Southeast Asia. The first challenge is how to foster yield increases without substantial trade-offs in grain quality, which might limit rice acceptance in local and global markets, which is of critical importance for export countries such as Thailand and Vietnam[8,20]. Another challenge is how to increase yield while minimizing the negative environmental impact associated with intensive rice production[35]. We believe a number of lessons can be learned from the past. For example, we know now that knowledge-based site-specific nutrient management can help tailor nutrient management to each environment, helping to increase yield and farmer profits while reducing nutrient losses[22,61]. Likewise, integrated pest management is a knowledge-intensive but valuable approach if applied correctly and holistically to reduce yield losses to weeds, pests and diseases while minimizing excessive use of pesticides and associated risks to the environment and people[62]. While fluctuation in input and grain prices may influence producers' access to yield-enhancing technologies and practices, we note that the projected increase in global demand together with the strong desire of governments in Southeast Asia to avoid rice imports and/or increase rice exports will help maintain a favourable grain-to-input-price ratio in the foreseen future[63–65]. It can be argued that rearrangement of crop sequence in terms of sowing and harvest windows can also be explored as a way to increase productivity. We note, however, that farmers are often restricted in how they can allocate labour, time and resources within their socio-economic context, which may limit reconfiguration of current crop sequences[66]. Regardless of the means to achieve this next and greener 'Green Revolution', we note that failure to do it will not only cause political instability but also put additional pressure on land and water resources, thus risking further encroachment into natural ecosystems such as forests and wetlands[20,26,35].

Methods

Site selection. The six major rice-producing countries in Southeast Asia were selected for our analysis: Cambodia, Indonesia, Myanmar, Philippines, Thailand and Vietnam (Supplementary Table 2). Altogether, these countries account for 97% of total harvested rice area and production in Southeast Asia[3]. Rice cropping systems were diverse across Southeast Asia, including different ecosystems (lowland and upland), water regimes (rainfed and irrigated) and cropping intensity (single, double and triple)[13]. Here we focused on irrigated rice and rainfed lowland rice production. Only irrigated rice was considered for Vietnam as rainfed rice production was small. Similarly, we excluded rainfed upland rice and deep-water rice from our analysis as they account for only 3% of national rice production across our six selected rice-producing countries, and their contribution to national rice production has declined steadily over time[14,19]. Hence, our analysis included a total of 11 country–water regime combinations.

We followed the protocols established by the Global Yield Gap Atlas (www.yieldgap.org) to estimate yield potential and yield gaps[67,68]. Following these protocols, a number of representative sites were selected and site-specific data on weather, soil and crop management and a well-validated crop simulation model (ORYZA version 3) were used to estimate yield potential (irrigated rice) and water-limited yield potential (rainfed lowland rice)[69]. In relation to site selection, we first used the Spatial Production Allocation Model map (SPAM 2010; www.mapspam.info) together with expert opinion from local researchers to identify the spatial distribution of the rice harvest area in each country separately for each of the 11 country–water regime combinations (Supplementary Information Text Section 2 and Supplementary Fig. 5). Second, based on the current distribution of meteorological stations, we selected reference weather stations (RWS) for each country–water regime combination. In each country, climate zones accounting for >5% of total harvested rice area for each water regime were identified. Each climate zone represented a specific combination of annual growing-degree days, water balance and temperature seasonality[68]. Circular buffer zones with a 100 km radius were created around each RWS and clipped by the climate zones where the RWS was located in each country. For each country–water regime combination, buffers were iteratively selected starting from the one with largest harvested rice area, avoiding the buffers that overlapped with the selected buffers by 20%. This process was repeated until the sum of rice coverage across selected buffers reached at least 50% of the national total harvested rice area for each water regime. In the case of Indonesia and rainfed rice in Thailand, we created eight and three additional buffers (also further referred to as RWS buffers), respectively, to cover the rice area in Indonesia and the important rainfed lowland rice-producing area in northeastern Thailand that were not included due to the lack of meteorological stations. As a result, a total of 69 and 61 RWS buffers were selected for irrigated and rainfed lowland rice in the six selected rice-producing countries, respectively (Supplementary Information Text Section 2 and Supplementary Table 3).

Weather and soil data source. Long-term measured daily weather data were required for robust estimation of yield potential and its variability. Simulation of yield potential for irrigated rice required solar radiation and maximum and minimum temperature, and in the case of rainfed rice, precipitation and relative humidity were also needed. Daily measured data from the most recent ten years were available for the selected RWS buffers in our study except for the additional 11 buffers created for Thailand and Indonesia (Supplementary Information Text Section 3 and Supplementary Table 4). For these 11 sites, we used gridded data from the NASA-POWER Agro-climatic database[70]. Following Van Wart et al.[71] and Grassini et al.[34], both measured and gridded weather data used in this study were subjected to quality control measures to fill in missing data and/or identify and correct erroneous values.

For irrigated rice, soil properties were not specified as yield potential is not influenced by soil properties, that is water and nutrient supply were not considered limiting for plant growth[69,72]. In the case of rainfed rice, simulation of water-limited yield potential required specification of soil properties related to the soil–water balance, including water holding capacity, soil depth and water table depth[69]. In our study, default soil parameters from PADDYIN (a soil template file included in ORYZA version 3) for a clay soil were applied to simulate water-limited yield potential for rainfed lowland rice in Indonesia, Myanmar, and Philippines. However, soil parameters were modified for our simulations of water-limited yield potential for rainfed lowland rice in northern and northeastern Thailand to portray the coarse-texture soils that prevail in these regions[73–75]. In the case of Cambodia, separate simulations of water-limited yield potential for rainfed lowland rice were performed for clay and coarse-texture soils as these two soil types were important in the rice-growing area in Cambodia[76].

Crop management and actual yield. The dominant rice cropping systems were identified in the major rice-producing regions in each country. A rice cropping system was defined as a unique combination of ecosystem (lowland, upland), water regime (irrigated, rainfed) and rice cropping intensity (single, double, triple) as defined by the number, type,and temporal cycle of crops planted on the same piece of land over a 12-month period. As such, a total of 182 RWS buffer–cropping system combinations were identified in our study. For simulating yield potential, information on crop management including water regime, crop establishment method, sowing or transplanting window, maturity window, probability of drought and rice variety name were collected for each rice cycle in each cropping system via structured questionnaires completed by local agronomists and extension personnel in each country (Supplementary Information Text Section 4). Selected crop calendars for typical rice cropping systems in each country were shown in Supplementary Fig. 1. Data on average farmer yields and rice harvested area were retrieved from official statistics at the regional/state level for the most recent four years for Myanmar, at the regency administration level for the most recent six years for Indonesia and at the provincial level for at least the most recent five years for the other four countries (Supplementary Information Text Section 4 and Supplementary Table 5). Data on farmer yield were adjusted to a standard moisture content of 140 g H_2O kg^{-1} rice grain.

Yield potential simulation. Yield potential (irrigated rice) and water-limited yield potential (rainfed lowland rice) were simulated using the crop growth and development model ORYZA version 3 and data on actual crop management, measured daily weather, soil characteristics and characteristics of representative rice varieties[69]. This model has been well validated in field experiments established in a wide range of environments and extensively used to simulate yield potential in various rice cropping systems worldwide[77–80]. To the extent that it was possible, we attempted to simulate modern rice varieties with broad adaptability that represented varieties widely grown in each of the six countries as determined based on expert opinion and national reports[77,81–83]. These varieties included Inpari 32 (Indonesia), OM1490 (Vietnam and Cambodia), PSBRc80 (Philippines) and PSBRc10 (Myanmar). An exception was the aromatic (jasmine) rice variety KDML105, which was used for simulation of water-limited yield potential in the rainfed lowland rice environment in northeastern Thailand as these types of variety prevailed in this region. Genetic coefficients of Inpari 32 were obtained from Agustiani et al.[77], and crop parameters of OM1490, PSBRc80 and PSBRc10 were retrieved from Li et al.[84]. Briefly, the calibration and validation of the crop model in these previous studies were conducted with two independent datasets using measured data collected from well-managed field experiments. Genetic parameters were derived through iterating calibration and validation processes with initial values of crop parameters obtained from a well-characterized variety, IR72. Unfortunately, experimental data from well-managed crops were not available to calibrate model parameters for aromatic rice varieties. Hence, parameters of KDML105 were derived by using the crop parameters from OM1490 as initial values and subsequent addition of photoperiod sensitivity and lower partitioning to grain so that the simulated harvest index was around 0.40. These adjustments in model parameters for aromatic rice were based on previously published studies for aromatic rice in northeastern Thailand and elsewhere[31,74,85,86].

We simulated the yield potential (or water-limited yield potential in the case of rainfed lowland rice) for each rice cycle within each dominant cropping system for each of the RWS buffers selected for the 11 country–water regime combinations. For irrigated rice, we assumed no water limitation, while simulation of rainfed lowland rice considered precipitation, vapour pressure and soil properties influencing the soil–water balance, including soil texture and groundwater depth. For rainfed lowland rice, there was high uncertainty in relation to groundwater depth across sites, seasons and landscapes and its influence on rice yields[87]. Given the range of possible scenarios and associated uncertainties, we simulated water-limited yield potential for rainfed lowland rice for different scenarios of groundwater depth during the entire crop cycle (shallow, medium and deep). These three scenarios basically portrayed no water limitation (shallow), moderate-drought (medium) and drought-prone (deep) environments (Supplementary Information Text Section 5). A sensitivity analysis was performed for two selected locations with different degrees of water limitation to understand the impact of soil texture and groundwater depth on water-limited yield potential (Supplementary Fig. 6).

Yield gap estimation. For each rice cycle, the yield gap was calculated as the difference between yield potential (irrigated rice) or water-limited yield potential (rainfed lowland rice) and average farmer yield[18]. Average yield gap for each RWS was estimated by weighting yield potential and average yield based on the fraction of rice harvested area within each buffer accounted for by each cropping sequence–crop cycle combination. The annual yield gap was calculated based on the average rice cropping intensity in each RWS. In all cases, the yield gap was estimated separately for each country–water regime combination.

Current and future rice demand. Current (2019–2020) annual domestic rice demand was set as a baseline in our study. Current national rice demand in each of the six selected major rice-producing countries was estimated as the average annual national rice production, imports, exports and stock change during 2019–2020[88] (Supplementary Table 6). Future (2040) rice demand for each country was estimated by multiplying the projected population derived from the medium fertility variant (https://population.un.org/wpp/) by the per capita rice demand by year 2040. The latter was estimated based on the relative change in average per capita rice demand between the baseline (2019–2020) and year 2040 derived for each country from the outputs of three econometric food supply–demand models: the International Rice Research Institute Global Rice Model[89], the International Model for Policy Analysis of Agricultural Commodities and Trade model[10] and the Rice Economy Climate Change model[90] (Supplementary Table 6). Projected total rice demand by year 2040 is expected to be higher than the current (2019–2020) demand for all countries except for Thailand and Vietnam where it will remain relatively similar. In this study, we also analysed total rice demand and production at the regional level by considering all 11 countries in Southeast Asia, that is, the six selected major rice-producing countries included in this study plus other five countries: Brunei, Laos, Malaysia, Singapore and Timor-Leste[91]. To do this, current rice demand in all of Southeast Asia was estimated as the average of annual regional total rice production, import, export and stock variation (average of 2019–2020)[88]. We noted that the five countries not included in our analysis (Brunei, Laos, Malaysia, Singapore and Timor-Leste) are net rice importers and their aggregated annual rice demand represents 5% of that calculated for the six countries selected for our study[88]. Hence, future (2040) total rice demand in Southeast Asia was estimated by multiplying the projected rice demand from the six countries by 1.05. In our study, all rice yield, production, per capita rice demand and total rice demand were reported as paddy rice at a standard moisture content of $140\,\mathrm{g\,H_2O\,kg^{-1}}$ rice grain. We noted that per capita rice demand was converted to paddy rice by dividing originally reported milled rice from the US Department of Agriculture databases and the three models by rice milling rate of each major rice-producing country[10,88–90] (Supplementary Table 6).

Scenario assessment. We assessed rice production potential and its impact on rice surplus by comparing the projected rice production against rice demand by 2040[17–19]. We performed scenario analyses individually at the national level for the six selected major rice-producing countries and separately for the entire Southeast Asia. Similar to other studies assessing food supply–demand scenarios[92,93], we used 2040 as the target year for our scenario assessment. A 20-year time span would be long enough to facilitate long-term policies, investments and technologies devoted to closing exploitable yield gap and it is short enough to minimize long-term effects from climate change on crop yields and cropping systems. Similarly, we noted that population growth rates will start to decline for the majority of the countries in Southeast Asia around or after 2040 (https://population.un.org/wpp/).

Reaching 80% of the yield potential (irrigated crops) or 70% of the water-limited yield potential (rainfed crops) is a reasonable yield goal for farmers with good access to markets, inputs and extension services as evidenced by rainfed wheat in Germany and France, rainfed maize in the United States and irrigated rice in Egypt and China[18,94] (www.yieldgap.org). Hence, the exploitable yield gap was defined here as the difference between 80% of yield potential (irrigated) or 70% of water-limited yield potential (rainfed) and current average farmer yield. For our scenario assessment, we considered three scenarios of yield-gap closure. The first scenario was business as usual (S1), that is, continuation of current yield trends based on most recent rates of yield gains as derived from our analysis (Fig. 1 and Supplementary Table 1). To quantify the available scope for increasing rice production on existing harvested rice area, the second scenario (S2) assumed full closure of the exploitable yield gap between now and 2040 so that average yield reached the attainable yield for white rice, ranging from $7.6\,\mathrm{Mg\,ha^{-1}}$ per crop to $8.2\,\mathrm{Mg\,ha^{-1}}$ per crop (irrigated) and $5.5\,\mathrm{Mg\,ha^{-1}}$ per crop to $6.5\,\mathrm{Mg\,ha^{-1}}$ per crop (rainfed lowland) across countries and $3.7\,\mathrm{Mg\,ha^{-1}}$ per crop in the case of rainfed lowland aromatic rice in Thailand (Fig. 2 and Supplementary Fig. 2). Because it is difficult to achieve full closure of the exploitable yield gap for the entire population of rice farmers in Southeast Asia in only 20 years, we explored a more realistic third scenario (S3) that assumed 50% closure of the existing exploitable yield gap by 2040.

We assumed that the current harvested rice area remained unchanged for all three scenarios, which was reasonable considering the flat trajectories in harvested area over past decades. Indeed, our assumption can be considered optimistic considering current pressure on converting lowland rice fields for urban and industrial uses or diversifying into other crops[95]. We also assumed no change in upland rice production, which currently accounted for less than 3% of national production across the six countries, although its area may decline further over time. We also assumed no change in the fraction of irrigated rice area, given lack of investments for irrigation schemes, physical and economic water scarcity and environmental concerns[12]. At a regional level of Southeast Asia, total rice production was estimated as the sum of projected rice production from the six selected rice-producing countries and that from the other five countries in each of the three scenarios. We assumed that rice production in the other five countries remained unchanged (in relative terms), which totalled an annual average of 5.6 Mt from 2019 to 2020, representing 3% of rice production in the six selected countries[88]. We noted that for the current baseline and for each of the three scenarios by 2040, we calculated the aggregated rice production, rice surplus and the SSR. Rice surplus and SSR were estimated as the difference and ratio between annual rice production and annual rice demand, respectively[17] (Fig. 4).

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Data on yield potential from the Global Yield Gap Atlas are available at www.yieldgap.org. Data on national average rice yield, harvested area, production, exports and imports from FAOSTAT are available at www.fao.org/faostat. Data on rice distribution from SPAM map are available at www.mapspam.info. Data on population size from the United Nations are available at https://population.un.org/wpp/. Data on the current per capita rice demand from USDA are available at https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery. Source data are provided with this paper.

Received: 23 October 2021; Accepted: 15 February 2022;

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Acknowledgements

We would like to thank local agronomists and extension agents in each country for their help in data collection. We acknowledge the Swiss Agency for Development and Cooperation for financial support to conduct the CORIGAP survey (Grant 681 number 7F-08412.02 to A.M.S.) and also the Bill and Melinda Gates Foundation for their support through the CGIAR Excellence in Agronomy 2030 Incubation Phase (Grant number INV-005431 to P.G.). We also thank the China Postdoctoral Science Foundation (2020M682439 to S.Y.), the China Scholarship Council (201706760015 to S.Y.), the Belt and Road Center for Sustainable Rice Production, the Indonesian Agency for Agricultural Research and Development (IAARD), the Office of Global Engagement at the Institute of Agriculture and Natural Resources (IANR) at the University of Nebraska-Lincoln (UNL) and the UNL Daugherty Water for Food Global Institute.

Author contributions

S.Y., A.M.S. and P.G. conceived and designed the study. A.M.S., A.G.L., J.I.R.E., A.D., L.V.N.K., L.T.T., K.P., P.T., K.M.T., S.S.S., S.Y., M.Q.V., E.D.Q., R.T., R.J.F., N.T., A.R.P.P., N.D., N.A., F.A. and T.L. provided and compiled the data analysed in this study. S.Y., J.I.R.E., N.D. and P.G. performed the spatial analysis, simulation and data analysis. S.Y. and P.G. wrote the paper with contribution from other authors.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-022-00477-z.

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Peer review information *Nature Food* thanks Stephan Haefele, Zvi Hochman and Guy Kirk their contribution to the peer review of this work.

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Last updated by author(s): Feb 10, 2022

Reporting Summary

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☐	☒	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Data on national rice yield, area, production, export, and import were download from FAOSTAT, data on rice distribution were downloaded from SPAM map, data on population size were downloaded from UN, data on the current per-capita rice demand were downloaded from USDA, data on relative change in per-capita rice demand were retrieved from publishes studies, data on genetic coefficient and dominate crop management practices used for yield potential simulation were provided by agricultural specialists, data on average farmer yields were retrieved from official statistics in each country, and data on daily weather were collected from the local weather stations and NASA-POWER.
Data analysis	Statistix 8, SigmaPlot 14.0, and ArcGIS 10.8 were used for statistical analysis.

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- A list of figures that have associated raw data
- A description of any restrictions on data availability

Data on national rice yield, area, production, export, and import from FAOSTAT are available at www.fao.org/faostat. Data on rice distribution from SPAM map are available at www.mapspam.info. Data on population size from UN are available at https://population.un.org/wpp/. Data on the current per-capita rice demand from USDA are available at https://apps.fas.usda.gov/psdonline/app/index.html#/app/advQuery. Data on daily weather from NASA-POWER are available at https://power.larc.nasa.gov/.

Field-specific reporting

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We assess yield potential and yield gap of irrigated and rainfed lowland rice across the six major rice-producing countries (together accounting for 97% of total regional rice production) in Southeast Asia and determine rice self-sufficiency ratio and rice surplus for each of the six countries and the Southeast Asia as a whole by 2040 under different exploitable yield gap closure scenarios.
Research sample	Our study includes a total of 11 country-water regime combinations.
Sampling strategy	We include a total of 182 reference weather station buffer-cropping system combinations by following Global Yield Gap Atlas protocol within six major rice-producing countries, which together account for 97% of the regional total rice production and harvested area in Southeast Asia. The 182 reference weather station buffer-cropping system combinations encompassed a wide range of biophysical and socio-economic context in Southeast Asia.
Data collection	Data on rice yield, area, production, export, and import were from FAOSTAT, data on rice distribution were from SPAM map, data on population size were from UN, data on the current per-capita rice demand were from USDA, data on relative change in per-capita rice demand were from publishes studies, data on genetic coefficient and dominate crop management practices used for yield potential simulation were from agricultural specialists, and data on daily weather were from the local weather stations and NASA-POWER.
Timing and spatial scale	Yield potential of each of the 182 reference weather station buffer-cropping systems were simulated using the most recent weather data, and then were upscaled to larger spatial scales by following Global Yield Gap Atlas protocol. Yield potential and yield gap in 11 country-water regime combinations were estimated at both per rice cycle and per year basis. The current annual domestic rice demand during the period from 2019-2020 was set as a baseline for self-sufficiency ratio and rice surplus estimation. The current and future rice self-sufficiency ratio and surplus were estimated for each of the six countries and the Southeast Asia region as a whole.
Data exclusions	No data were excluded from the analysis.
Reproducibility	Data used in this study are available within the paper [and its supplementary information files].
Randomization	Not applicable as we did not conduct field experiments.
Blinding	Not applicable.

Did the study involve field work? ☐ Yes ☒ No

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☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
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