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Supplementary information

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

In the format provided by the authors and unedited

Supporting Information for "Southeast Asia must narrow down the yield gap to continue to be a major rice bowl" by Yuan et al.

CONTENTS

1. Historical yield trends

During the 2017-2019 period, global annual rice production and harvested rice area averaged 757 million tons (Mt paddy rice) and 164 million hectares (M ha), respectively[1]. The six selected major rice-producing countries in Southeast Asia, including Cambodia, Indonesia, Myanmar, Philippines, Thailand, and Vietnam, together accounted for 27% and 25% of the global total rice harvested area and rice production, respectively[1] (**Supplementary Table 2**). To assess historical rates of yield gain during the past 30 years (1990-2019) in each of the six countries, average rice yields at national level were regressed against years using five parsimonious regression models: linear model, piecewise model (with up to three phases), linear-plateau, quadratic model, and exponential model[2,3]. The 'best model' was chosen depending on the best fit for each country, as determined based on Akaike's Information Criterion (AIC), coefficient of determination (R^2), and statistical significance and confidence intervals of model coefficients (**Fig. 1 and Supplementary Table 1**).

2. Site selection

Following protocols established by the Global Yield Gap Atlas (www.yieldgap.org), a geospatial Spatial Production Allocation Model map (SPAM 2010; www.mapspam.info) was used to identify the major rice-producing regions in each of the six selected countries (**Supplementary Fig. 5**). In the case of Thailand, while the reported total rice area by SPAM map was fairly accurate, it exhibited important discrepancies in relation to the fraction of rice area that is irrigated based on expert opinion from local researchers. Hence, we modified the SPAM map using data on fraction of irrigated rice land reported in previous studies to better portray the spatial distribution of irrigated and rainfed lowland rice[4]. Southern Thailand was not included in our analysis as this region accounts for less than 2% of total rice production in the country, including areas of deep-water rice (MOAC; www.moac.go.th). Similarly, rainfed lowland rice in Vietnam was not included in the analysis as it accounts for less than 10% of the national rice harvested rice area[5].

Reference weather station (RWS) buffers and climate zones (CZ) were selected by following previous studies[6,7]. In total, 69 RWS buffers were identified for irrigated rice, with five buffers located in Cambodia, 31 in Indonesia, eight in Myanmar, 12 in Philippines, six in Thailand, and seven in Vietnam (**Supplementary Fig. 5 and Supplementary Table 3**). For rainfed lowland rice, a total of 61 RWS buffers were selected, including six in Cambodia, 24 in Indonesia, 10 in Philippines, 12 in Thailand, and nine in Myanmar. The proportion of national irrigated rice harvested area located within selected RWS buffers and CZs was 77% and 95% in Cambodia, 50% and 99% in Indonesia, 64% and 67% in Myanmar, 59% and 87% in Philippines, 40% and 65% in Thailand, and 69% and 81% in Vietnam, respectively (**Supplementary Table 3**). The proportion of national rainfed lowland rice harvested area located within selected RWS buffers and CZs was 56% and 73% in Cambodia, 24% and 92% in Indonesia, 51% and 62% in Myanmar, 32% and 74% in Philippines, and 32% and 75% in Thailand, respectively. We noted that area coverage was lower for rainfed lowland than irrigated rice at both RWS buffer and CZ levels because areas planted with rainfed lowland rice tend to be more spread out within countries in comparison with irrigated rice.

3. Weather and soil data source

Meteorological variables required for simulation of yield potential (Yp) included solar radiation and maximum and minimum temperatures (Tmax and Tmin, respectively). In the case of water-limited yield potential, simulations also required precipitation, wind speed and vapor pressure deficit[8]. Long-term (most recent 10 years) measured daily weather data required by yield potential simulation were available for all buffers in Cambodia, Myanmar, Philippines, and Vietnam, 28 out of the 36 selected buffers in Indonesia, and 15 of 18 buffers in Thailand (**Supplementary Table 4**). Following Allen et al.[9], vapor pressure deficit for RWS in Cambodia, Myanmar, and Thailand were computed from Tmax, Tmin, and relative humidity. In the case of Indonesia, reported sunshine hours were converted to incident solar radiation using the Angstrom equation. Because daily solar radiation, wind speed, and relative humidity were not available for RWS in Cambodia, Myanmar, and Thailand, we retrieved these variables from the NASA-POWER Agro-climatic database[10]. Similarly, daily weather data records were not available for the remaining 11 buffers, including eight in Indonesia and three in Thailand. For these 11 buffers, we also used gridded weather data from the NASA-POWER Agro-climatic database as a suitable substitute for Yp simulations[10,11].

4. Crop management and actual yield

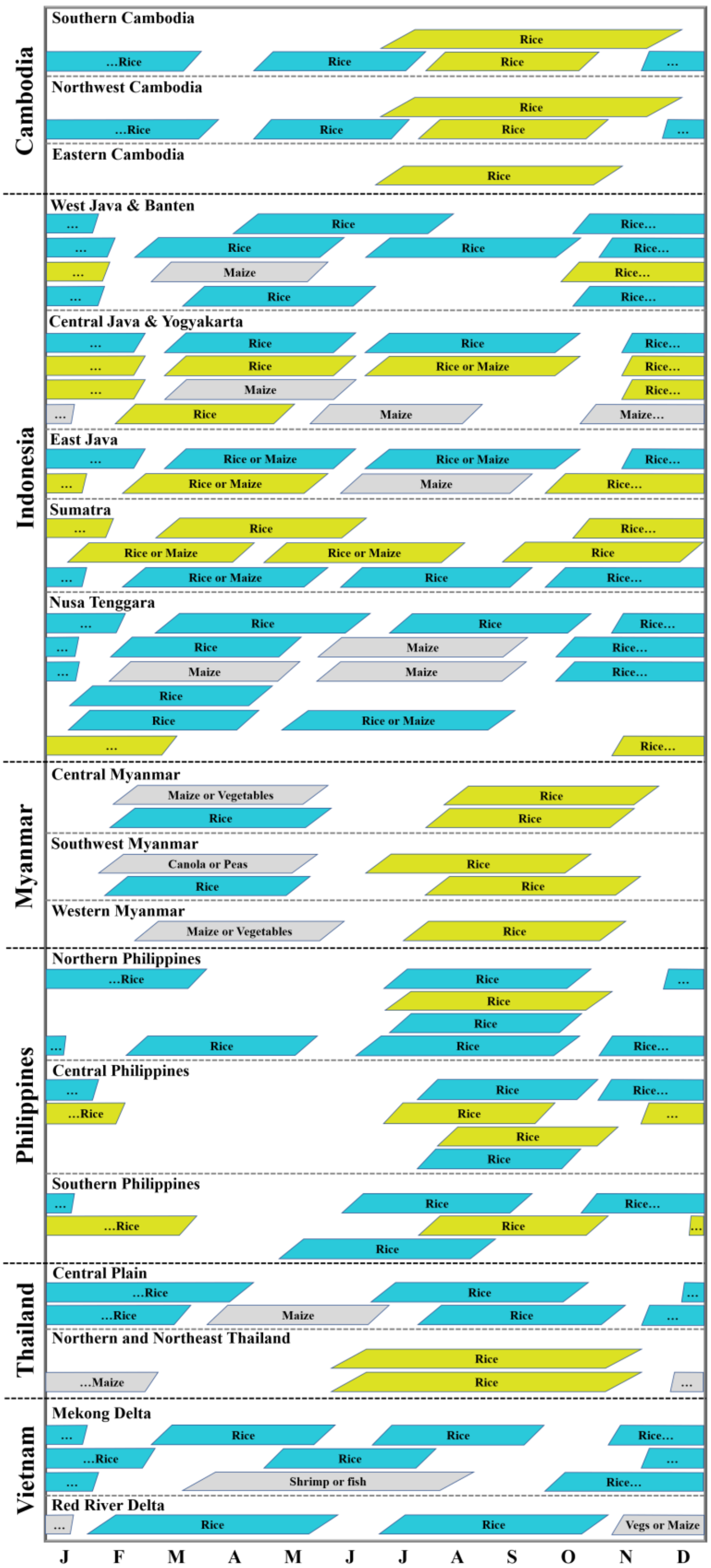
For each RWS buffer, the dominant rice cropping system(s) was (were) identified. A rice cropping system is defined as a unique combination of ecosystem (lowland, upland), water regime (irrigated, rainfed), and rice cropping intensity (single, double, triple) as defined by the number, type, and temporal cycle of crops planted on the same piece of land over a 12-month period (**Supplementary Fig. 1**). Structured questionnaires completed by local agronomists and extension personnel in each country were used to collect data on water regime (irrigated, rainfed), crop establishment method (direct-seeded, transplanted), sowing or transplanting (for transplanted rice only) window, maturity window, probability of drought, and rice variety name of each rice crop cycle in each cropping system, as well as the percentage of rice area under this cropping system to total rice area.. For direct-seeded rice, crop emergence was assumed to occur seven days after direct seeding. The date of crop establishment (either direct-seeded or transplanted rice) used in yield potential simulation corresponds to the mid-point of the reported establishment window (10-day) reported by local agronomists and extension personnel. Data on average farmer rice yields and rice harvested area were retrieved from national statistics reported at the finest level of spatial resolution available (**Supplementary Table 5**). Data on farmer yields were adjusted to a standard moisture content of 140 g H_2O kg^{-1} rice grain.

5. Yield potential simulation

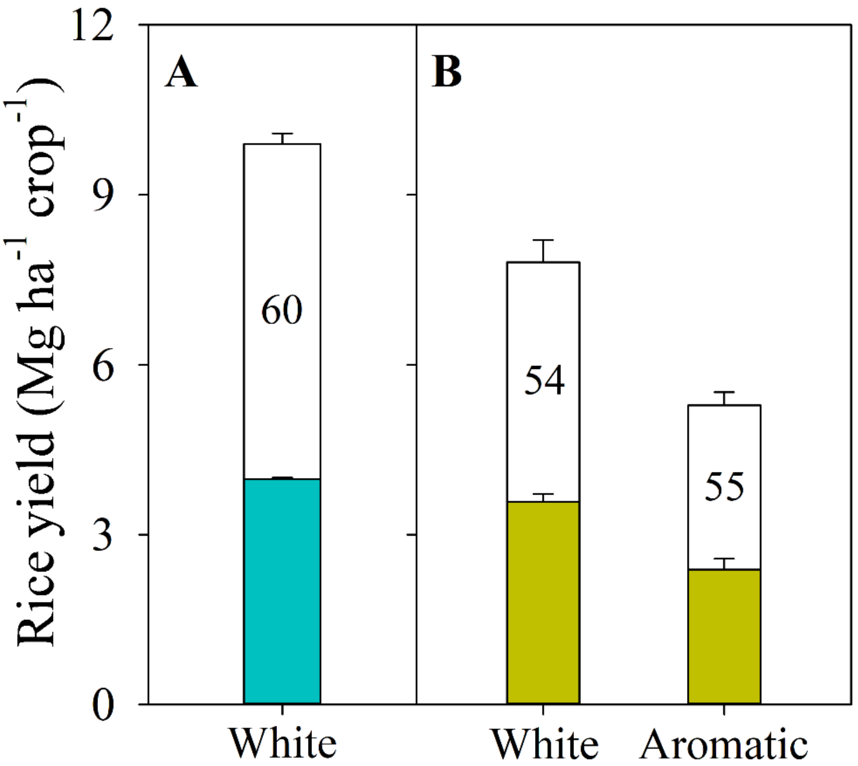
We attempted to simulate varieties with broad adaptability that are (or were) widely grown in each of the six selected countries as determined based on previous reports[12-15]. For example, Inpari 32 is a high-yielding inbred rice variety, which becomes one of the predominant varieties across major rice-producing areas in Indonesia[12]. OM1490 is a high-yielding rice variety widely cultivated by farmers in Cambodia and Vietnam[16]. Similarly, although PSBRc80 is a fairly old, short duration high-yielding rice variety released in 1999, it is still grown in the Philippines and similar to other modern varieties[17,18]. KDML105 is a widely grown aromatic rice variety in rainfed lowland environments in northern and northeastern Thailand, also known as Jasmine rice, or Thai Hom Mali Rice[19,20]. Genetic coefficients derived from well-managed experiments were not available for rice varieties in Myanmar. In this case, we simulated the variety that more closely represents the current varieties grown in this country as determined *via* expert opinion, which was PSBRc10.

Given the range of possible scenarios and associated uncertainties, we simulated water-limited yield potential for rainfed lowland rice for three different scenarios of groundwater depth during the entire rice season: shallow (10 cm), medium (75 cm), and deep (150 cm). These three scenarios represent non-water limitation (shallow), moderate-drought (medium) and drought-prone (deep) environments. For these simulations, we assumed a puddled clay loam soil and bund height of 25 cm. We also assumed that each groundwater scenario accounts for an equal share of the rainfed lowland rice area in each buffer. Given the sandy soils and high probability of water deficit of rainfed lowland rice in northern and northeastern Thailand, two different scenarios of groundwater depth during the entire crop cycle (favorable [75 cm] and no groundwater) were simulated, using a puddled sandy loam in both cases[21-23]. Each groundwater scenario was assumed to account for an equal (50:50) share of the rainfed lowland rice area in each buffer in northeastern Thailand. In the case of rainfed lowland rice in northern Thailand, separate simulations were performed for white rice and aromatic rice (because both rice types are grown widely in this area) and the overall water-limited yield potential was computed by averaging the water-limited yield potential for each rice type, after weighting by harvested area. In the case of Cambodia, considering the predominance of both clay loam and sandy loam soil types in rice growing area[24], we simulated water-limited yield potential for rainfed lowland rice separately for both soil types. In the case of clay loam soils, we simulated three scenarios of groundwater depth (shallow [10 cm], medium [75 cm], and deep [150 cm]), while two scenarios of groundwater depth (favorable [75 cm] and no groundwater) were simulated for the sandy loam soil. We assumed that each groundwater scenario accounts for an equal share (33:33:33 for clay loam soil and 50:50 for sandy loam soil) within each soil type, and each soil type accounts for an equal share (50:50) of rice harvested area in each buffer.

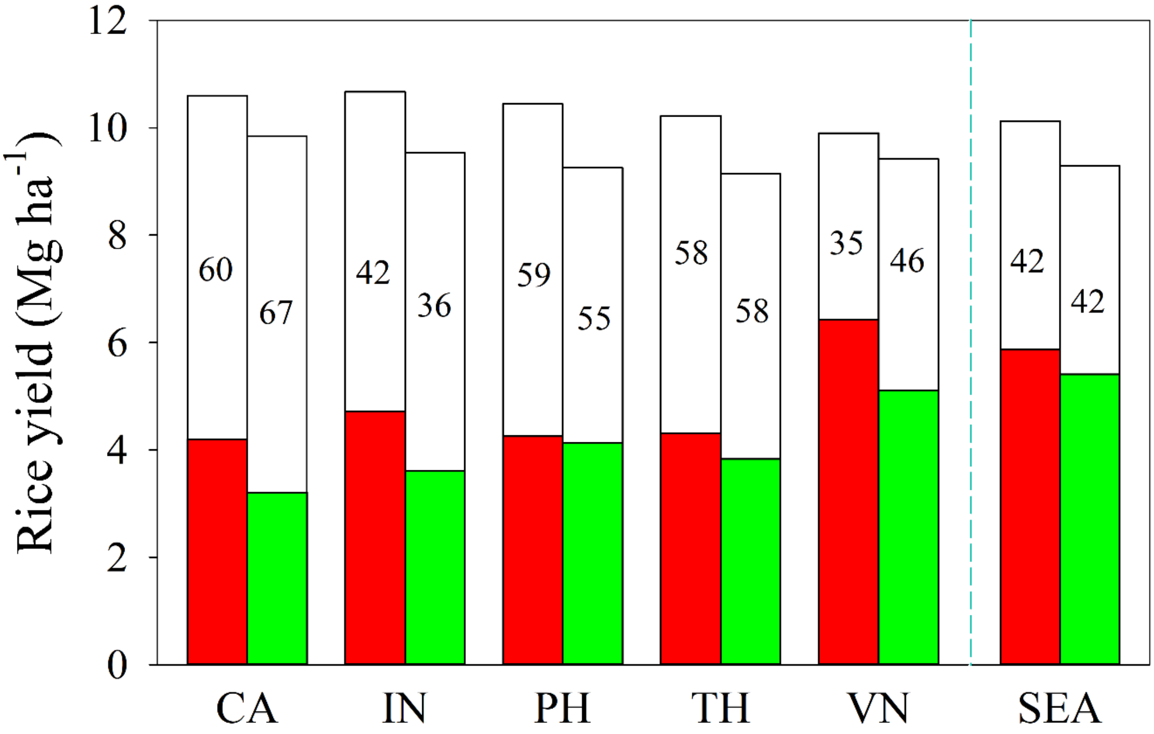
A sensitivity analysis was conducted to understand the impact of soil parameters on the simulation of water-limited yield potential for rainfed lowland rice. According to previous studies, soil texture and groundwater depth are key parameters affecting rainfed lowland rice yield[25,26,27]. Therefore, we explored how different combinations of soil texture (sandy loam and clay loam soil) and groundwater depth (shallow and deep) would influence water-limited yield potential in environments with contrasting seasonal water supply: Sri Saket, Thailand and Sittwe, Myanmar (**Supplementary Fig. 6**). Average (10-y) seasonal precipitation was 1085 mm (Sri Saket) and 3812 mm (Sittwe). For this analysis, we considered a clay loam soil with shallow water table as baseline. Our analysis showed that deep water table or sandy texture alone would reduce water-limited yield potential by less than 5%, but the combination of both can reduce yield potential up to 18% in water-limited environments. Except for northeastern Thailand, rainfed lowland rice is grown in environments in Southeast Asia with clay soils and abundant seasonal precipitation. Hence, the uncertainty in simulated water-limited yield potential due to specification of soil parameters is expected to be relatively small, especially when one considers the magnitude of the yield gaps (**Fig. 2**), suggesting that our findings are robust.



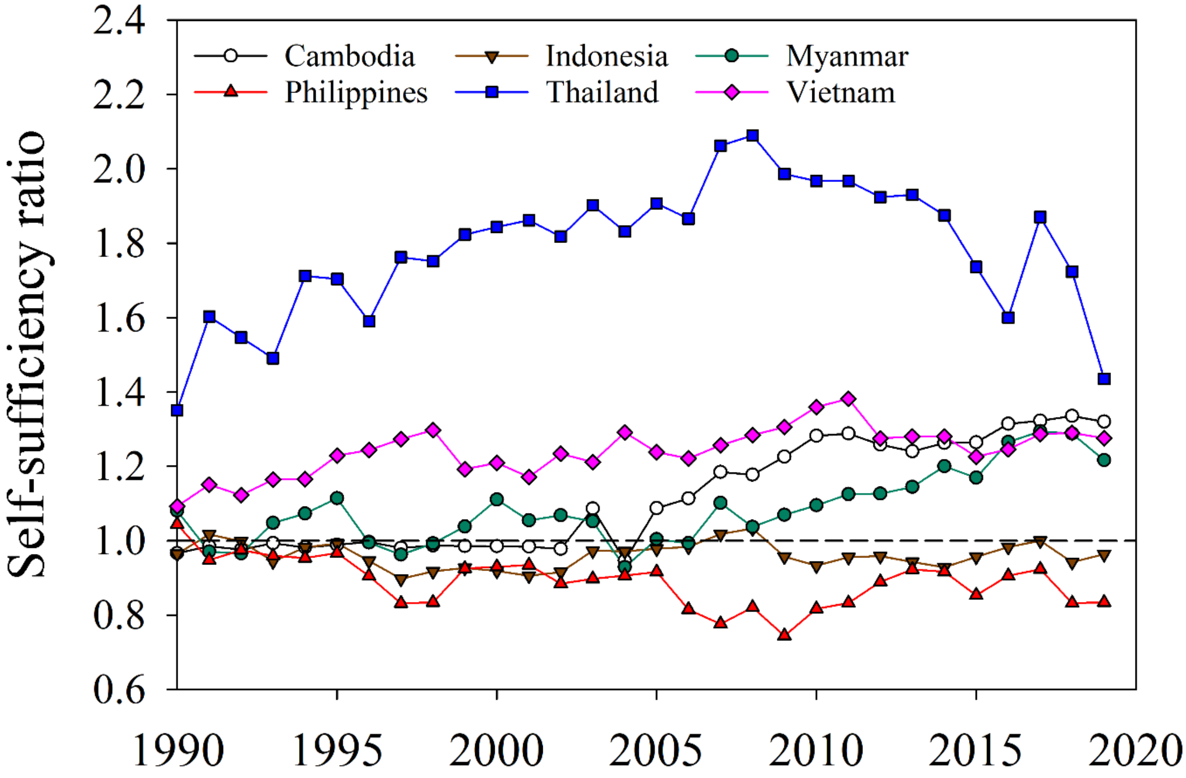
Supplementary Figure 1 *Dominant rice cropping systems in each country. Boxes show approximate crop cycle length (from establishment to harvest maturity). Blue and yellow colors indicate irrigated and rainfed lowland rice, respectively. Gray color represents other crops grown within each sequence.*



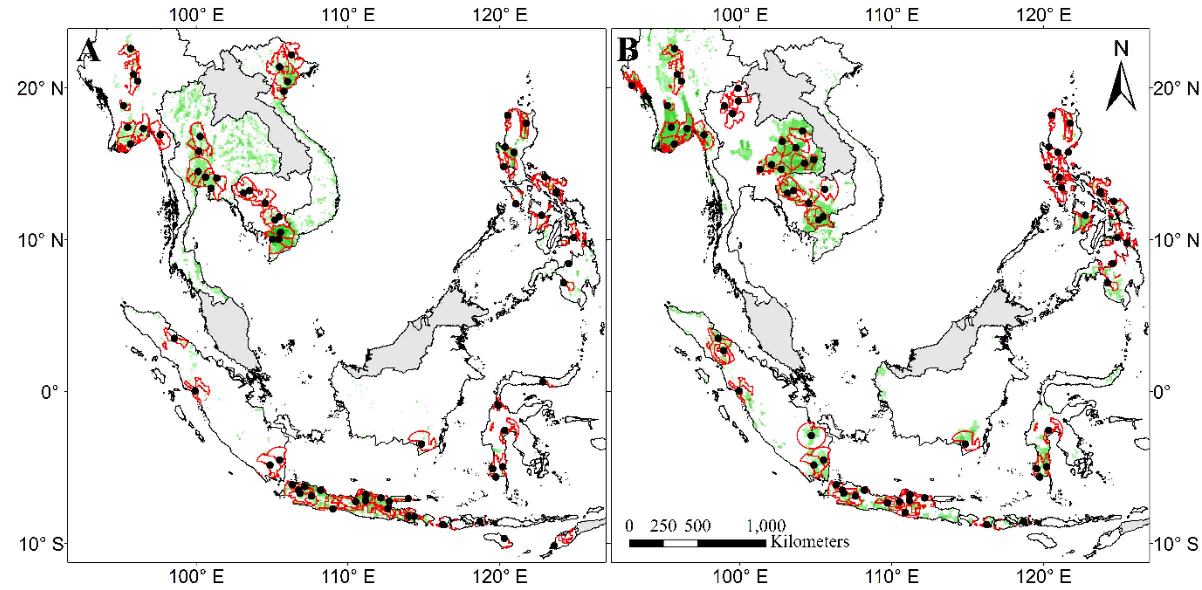
Supplementary Figure 2 *Yield potential and yield gap in Thailand disaggregated by (A) irrigated white rice and (B) rainfed lowland white rice and rainfed lowland aromatic rice. Solid and empty portions of bars indicate the average farmer yield and the yield gap, respectively. Vertical lines above solid and empty bars indicate standard errors. 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).*



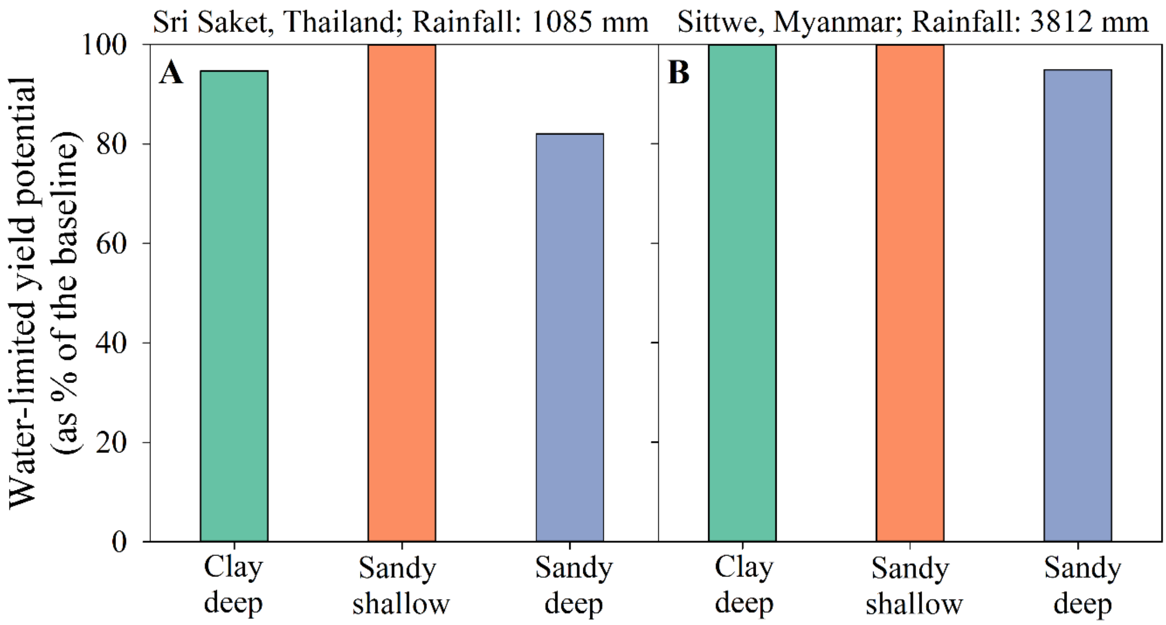
Supplementary Figure 3 *Average yield potential for irrigated rice in dry (red) and wet season (green), respectively, for five countries in Southeast Asia (CA: Cambodia, IN: Indonesia, PH: Philippines, TH: Thailand, and VN: Vietnam). Solid and empty portions of bars indicate the average farmer yield and the yield gap, respectively. Values inside the empty portion of the bars indicate the average yield gap as a percentage of yield potential. Also shown are the regional averages of Southeast Asia (SEA) for each season. Yield potential for irrigated rice during the dry and wet seasons is not shown for Myanmar as all irrigated and rainfed rice is grown in the dry and wet season, respectively.*



Supplementary Figure 4 *Trends in rice self-sufficiency ratio, which was estimated as the ratio of rice production to domestic rice consumption (calculated as rice production plus import amount minus export amount) in six selected major rice-producing countries in Southeast Asia: Cambodia, Indonesia, Myanmar, Philippines, Thailand, and Vietnam during the past 30 years (1990-2019). Source: USDA*[28].



Supplementary Figure 5 *Selected buffers (red polygons) for (A) irrigated and (B) rainfed lowland rice. Reference weather stations (black circles) and SPAM crop harvested area distribution (green) are shown (SPAM 2010; www.mapspam.info) in six major rice-producing countries in Southeast Asia: Cambodia, Indonesia, Myanmar, Philippines, Thailand, and Vietnam. Other countries in Southeast Asia not included in our yield-gap analysis (but included for our rice self-sufficiency assessment) are shown in gray (Brunei, Laos, Malaysia, Singapore, and Timor-Leste). The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).*



Supplementary Figure 6 *Relative change (%) in water-limited yield potential for different soil textures (sandy loam and clay loam) and groundwater depth (shallow and deep) at two locations with contrasting seasonal precipitation: (A) Sri Saket, Thailand and (B) Sittwe, Myanmar. For comparison purposes, the baseline corresponds to a clay loam soil with shallow water table.*

Supplementary Table 1. *Coefficient of determination (R^2), breakpoint indicating the year when a change in the slope occurred and 95% confidence interval (CI), slopes, 95% CI, and 95% CI of each segment of regression models fitted to the relationship between rice yield and years for six 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).*

Country	R^2	Year and 95% CI of breakpoint		Slope, 95% CI, and stand error of each segment		
		1st breakpoint	2nd breakpoint	1st segment	2nd segment	3rd segment
CA	0.98	2003 [1996, 2009]		68 [52, 85] (8)*	95 [84, 106] (6)*	
IN	0.97	2000 [1999, 2002]	2015 [2013, 2016]	0 (7)	67 [58, 77] (5)*	0 (22)
MY	0.97	1997 [1995, 1999]	2008 [2006, 2009]	0 (10)	81 [68, 95] (6)*	0 (6)
PH	0.97	1998 [1997, 1999]	2005 [2003, 2007]	0 (10)	117 [79, 155] (18)*	30 [20, 39] (5)*
TH	0.91	2005 [2003, 2008]		66 [54, 78] (6)*	0 (7)	
VN	0.99	2012 [2010, 2013]		115 [110, 120] (3)*	0 (12)	

Values in square brackets and brackets represent 95% CI and stand error, respectively.
Asterisks indicate significance at * $p<0.05$.

Supplementary Table 2. *Data on annual harvested rice area (and percentage of global total), rice production (and percentage of global total), population, national total gross domestic product (GDP), per-capita GDP, percentage of agricultural GDP to national total GDP, and net rice export (calculated as the difference between rice export and rice import) in Cambodia (CA), Indonesia (IN), Myanmar (MY), Philippines (PH), Thailand (TH), and Vietnam (VN) during the 2017-2019 period. Sources: FAOSTAT[1], UN[29], World Bank[30].*

Country	Rice area (M ha)	% of global area	Rice production (Mt) †	% of global production	Population (million)	Total GDP (billion US$)	GDP per capita (US$)	Agriculture share of total GDP (%)	Net rice exports (Mt) †
CA	3.0	1.8	10.8	1.4	16	25	1514	22	0.8
IN	11.2	6.8	57.7	7.6	268	1059	3956	13	-1.5
MY	7.0	4.3	26.8	3.5	54	74	1373	22	2.8
PH	4.8	2.9	19.1	2.5	107	351	3287	10	-2.8
TH	10.4	6.3	31.2	4.1	69	502	7232	8	14.7
VN	7.6	4.6	43.4	5.7	96	244	2549	15	8.0
SE Asia	43.9	26.8	189.0	25	609	2254	3700	12	22.0

† Rice production and net rice exports were reported in paddy rice.

Supplementary Table 3. *The number of selected reference weather stations (RWS), associated buffer and climate zone (CZ) coverage as percentage of national harvested area for irrigated and rainfed lowland rice in six rice-producing countries in Southeast Asia: Cambodia (CA), Indonesia (IN), Myanmar (MY), Philippines (PH), Thailand (TH), and Vietnam (VN). Note that the rainfed lowland rice in Vietnam was not included in the analysis as it accounts for less than 10% of national harvested rice area*[5].

Country	Irrigated			Rainfed		
	RWS number	Buffer coverage	CZ coverage	RWS number	Buffer coverage	CZ coverage
CA	5	77	95	6	56	73
IN	31	50	99	24	24	92
MY	8	64	67	9	51	62
PH	12	59	87	10	32	74
TH	6	40	65	12	32	75
VN	7	69	81	-	-	-

Supplementary Table 4. *Time span, climatic variables, and data sources of daily weather data for six rice-producing countries in Southeast Asia: Cambodia (CA), Indonesia (IN), Myanmar (MY), Philippines (PH), Thailand (TH), and Vietnam (VN).*

Country	Time span	Climatic variables [†]	Data source
CA	2010-2019	Tmax, Tmin, and precipitation [‡]	Ministry of Water Resources and Meteorology of Cambodia (MOWRAM)
MY	2010-2019	Tmax, Tmin, and precipitation [‡]	Department of Meteorology and Hydrology of Myanmar (DMH)
IN	2000-2015	Sunshine hours, Tmax, Tmin, relative humidity, and precipitation [⸸]	Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG)
PH	2008-2017	Solar radiation, Tmax, Tmin, precipitation, vapor pressure deficit, and wind speed	Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA))
TH	2009-2018	Tmax, Tmin, and precipitation [‡, ⸸]	Thai Meteorological Department (TMD)
VN	2009-2018	Solar radiation, Tmax, Tmin, precipitation, vapor pressure deficit, and wind speed	Vietnam Institute of Meteorology, Hydrology and Climate Change (IMHEN)

[†] Tmax and Tmin represent the maximum and minimum temperature, respectively.

[‡] Other climatic variables including daily solar radiation, wind speed, and relative humidity were retrieved from the NASA-POWER Agro-climatic database[9].

[⸸] Measure daily weather data were available for 28 out of the 36 buffers in Indonesia and 15 of 18 buffers in Thailand. Hence, for the additional 11 buffers created for Thailand and Indonesia, gridded weather data from the NASA-POWER Agro-climatic database[9] were used for yield potential simulation.

Supplementary Table 5. *Time span, level of administrative unit for data, and data sources of farmer yield data for six rice-producing countries in Southeast Asia: Cambodia (CA), Indonesia (IN), Myanmar (MY), Philippines (PH), Thailand (TH), and Vietnam (VN).*

Country	Time span	Administrative unit of data	Data source
CA	2013-2017	Province	Ministry of Agriculture, Forestry and Fisheries of Cambodia (MAFF)
MY	2015-2018	Region/state	Central Statistical Organization of Myanmar (CSO)
IN	2010-2015	Regency	Central Bureau of Statistics of Indonesia (BPS)
PH	2014-2018	Province	Philippine Statistics Authority (PSA)
TH	2009-2017	Province	Ministry of Agriculture and Cooperatives of Thailand (MOAC)
VN	2007-2016	Province	General Statistics Office of Vietnam (GSO)

Supplementary Table 6. *Current (2019-2020) and future (2040) population, per-capita rice demand (in kg paddy rice), and total annual national rice demand (in Mt paddy rice) at national level in the six selected major rice-producing countries including Cambodia (CA), Indonesia, (IN), Myanmar (MY), Philippines (PH), Thailand (TH), and Vietnam (VN) and for the entire Southeast Asia (SEA).*

Country	Population (million) †		Per-capita demand (kg) ‡				Total demand (Mt) ⸸			
	Baseline (2019-2020)	Year 2040	Baseline (2019-2020)	Year 2040			Baseline (2019-2020)	Year 2040		
				IGRM	IMPACT	RECC		IGRM	IMPACT	RECC
CA	17	21	435	425	426	434	7	9	9	9
IN	271	319	209	186	208	212	57	59	66	68
MY	55	61	300	292	313	353	16	18	19	22
PH	109	136	210	203	207	213	23	28	28	29
TH	69	69	273	250	274	277	19	18	19	19
VN	98	108	347	303	325	360	34	33	35	39
SEA §	666	769	246	223	241	252	163	172	185	194

† Current (2019-2020) and future (2040) population are from the UN Population Dyanmics[29] and medium fertility variant of the UN population projections[31], respectively.

‡ Current per-capita rice demand was calculated by dividing total domestic rice consumption based on USDA[28] by current population[29]. Future per-capita rice demand was estimated based on current per-capita rice demand baseline and the projected relative change in per-capita rice demand as predicted separately by the IGRM[32], IMPACT (SSP2 scenario)[33], and RECC[34], see *Methods* for details. Per-capita rice demand in the current and in the future were expressed in paddy rice by dividing originally reported milled rice from the USDA database and the three models by the rice milling rate of 0.610, 0.635, 0.640, 0.630, 0.660, and 0.625 for CA, IN, MY, PH, TH, and VN, respectively[28].

⸸ Current national total rice demand was estimated as the average annual national rice production, imports, exports, and stock change during 2019-2020. Future national total rice demand by 2040 was estimated as the product of future population and future per-capita rice demand by 2040 for each projection.

§ Current total rice demand in Southeast Asia was estimated as the average of annual regional rice production, import, export, and stock variation during 2019-2020. Future total rice demand in Southeast Asia was estimated by multiplying the future total rice demand from the six countries by 1.05, see *Methods* for details.

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