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ASIA'S SECTORAL TRANSFORMATION, EVOLVING DIETS, AND THE CONSEQUENCES FOR CLIMATE CHANGE

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Asian Development Bank Institute

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Abstract

Established by the United Nations in 2015 with a target date of 2030, the Sustainable Development Goals (SDGs) provide a framework with specific objectives to guide global development policy. The SDGs extend and modify an earlier framework, the Millennium Development Goals (MDGs), established in 2000 with a target date of 2015. Goal 1 of the MDGs was to eradicate extreme poverty and hunger, with the specific goals of halving the proportions of both undernourished and malnourished people between 1990 and 2015. The poverty goal was met fully, ahead of schedule, and substantive progress was made toward the hunger goal due, in large part, to gains in agricultural production and productivity. Building on this progress, SDG 2 aims to "end hunger" and "achieve food security and improved nutrition," while promoting "sustainable agriculture."

Lifting millions of families from the desperate cycle of hunger and poverty also had consequences for the environment. Roughly 72% of the world's freshwater supplies go to agriculture; in South Asia, agriculture uses over 90%. On-farm greenhouse gas emissions (GHGs) are growing too. Global on-farm GHG emissions grew by about 10% between 1990 and 2020, from 6.7 to 7.4 GtCO2e; in Asia, during the same period, on-farm GHG emissions grew by 27%, from 2.5 to 3.2 GtCO2e. All of this puts agriculture and food systems at odds with other SDG goals, particularly Goal 6, which calls for efforts to better manage water supplies; Goal 12, which aims to reduce agriculture's environmental footprint; and Goal 13, which calls for urgent action to combat climate change.

This paper looks at how past technology choices opened a pathway to prosperity in Asia that now threatens the region's natural resources and the stability of the planet's climate. Specifically, the paper focuses on the greenhouse gas emissions from two practices, the cultivation of paddy rice and the growth in livestock production, in 15 countries in South and Southeast Asia, which collectively account for more than 80% of the global emissions from each practice.

Based on country-specific habit-formation models of dietary choice estimated from a 15-country panel of annual data from 1970 to 2020, out-of-sample projections show that business-as-usual emissions from rice production and animal waste will increase by 57% and 204%, respectively, over the next three decades. The projections are robust to alternative assumptions about income growth. This illustrates how the past success of the intensive agricultural technologies, and the income gains they helped spur, has led to still-ongoing dietary transitions that will complicate and hinder future efforts to reduce on-farm emissions, as researchers and policymakers strive to foster greener technologies to reduce agriculture's environmental footprint – technologies that must also sustain continued productivity gains if all SDGs are to be met.

Keywords: agriculture, Asia, diets, economic development, frontier estimator, greenhouse gas emissions, livestock, poverty, rice, Sustainable Development Goals, technology

JEL Classification: C33, Q16, Q31, Q32, Q38, Q54

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1. INTRODUCTION

In 1950, 84% of Asia's population lived in rural areas, and most households farmed, as had generations of households before them (Grigg 1975). Hunger and poverty were commonplace, and the most intransient forms of malnutrition and poverty were rooted in the inability of households to produce enough food. In most rural communities, those who didn't work on farms often ran businesses that depended on those that did. Consequently, when crops failed due to bad weather, disease, or man-made disasters, the impacts were severe and immediate. Because all community incomes were affected, informal social safety nets, which depended on the support of neighbors and family members, collapsed (Hazell 1992; Morduch 1995; Larson, Anderson, and Varangis 2004; Dercon 2005; Skees et al. 2005; Macours 2013; Hazell and Varangis 2020).

As the 21st century enters its third decade, the face of poverty and malnutrition in Asia has changed, as has the composition of Asia's economies and communities. By historical standards, the transformation has been rapid. As late as 1988, most people in East Asia (59%) and South Asia (51%) were desperately poor, living on less than \$US2.15 a day, and had been so for decades (World Bank 2023b). Today, while the numbers are still large, the share of extremely poor households has fallen to 1.2 and 8.6 %, respectively.

Today, a significant proportion of Asia's households live in rural areas even though Asia's economies have restructured. This is because the process by which households leave agriculture and rural areas to work in other sectors and places is slow and occurs across generations, even when wage gaps are large. However, once it has begun, the process gains speed (Larson and Mundlak 1997; Gardner 2000; Butzer, Mundlak, and Larson 2003). For Asia as a whole, it wasn't until 1996 that most people (50.6%) were not employed in the agricultural sector, and not until 2019 that more people lived in urban areas than rural ones (Larson and Bloodworth 2022; FAOSTAT 2023). In 2021, Asia's agriculture sectors employed far fewer workers than they had in the past (29% of workers), and many farming households earned income off-farm (Lanjouw and Lanjouw 2001; Ma et al. 2014; Li et al. 2021). Consequently, the links among poverty, malnutrition, and agriculture are less direct. For example, while crop failures remain a source of food insecurity for the poor, the impacts reach most households through markets and prices, and are less often connected to events in their own communities (Skoet and Stamoulis 2006; Masters et al. 2013; Drammeh, Hamid, and Rohana 2019; Tacoli 2019; Yamauchi and Larson 2019; Rahman and Mishra 2020). Further, most malnutrition stems from factors other than insufficient access to calories. Recent estimates suggest that roughly 3.1 billion people in the world could not afford a healthy diet in 2021; by contrast, the estimated number of undernourished people in the world stands at 738 million, a number that is nonetheless troubling and on the rise following the global pandemic and price increases following the Russian invasion of Ukraine (Fanzo et al. 2021; Ihle et al. 2022; FAO et al. 2023).

The structural shift of labor from agriculture to other sectors, together with rising productivity in agriculture, often feeds an economic transformation that promotes economy-wide growth and reduces poverty (Irz et al. 2001; Suryahadi et al. 2006; Anríquez and López 2007; Suryahadi, Suryadarma, and Sumarto 2009; Anderson, Cockburn, and Martin 2010; Diao, Hazell, and Thurlow 2010; de Janvry and Sadoulet 2010; Christiaensen, Demery, and Kuhl 2011; Christiaensen and Martin 2018; Larson et al. 2022). This dynamic has changed Asia's economies, where real income per

capita, measured in 2015 \$US, grew by 430% between 1970 and 2022, from \$US1,378 to \$US7,302 (World Bank 2023b).

In Asia, and most of the developing world, the proximate driver of poverty reductions and nutrition improvements was a sustained period of rising incomes and abundant food supplies, a period closely linked to sustained improvements in agricultural productivity. Between 1961 and 2020, growth in agricultural output outpaced population growth significantly. Measured in terms of available calories per capita, output grew by 35% worldwide, and by an astonishing 61% in Asia, even as Asia's population increased by 176%. Growing incomes set off sustained diet transformations too, especially in low-income countries. For example, the amount of protein available for consumption per person grew by 47% worldwide and by 91% in Asia. At the same time, the amount of cropland needed to support Asia's growing population fell from 0.27 to 0.13 hectares per person (FAOSTAT 2023). Further, despite rapidly growing global demand, the international prices of staple foods, measured in real terms, were lower in 2020 than throughout the 1960s (see Annex Figure 1; World Bank 2023a).

Innovations at the International Maize and Wheat Improvement Center, the International Rice Research Institute, and national agricultural research centers that resulted in high-yielding varieties of rice and wheat were the initial catalysts for decades of agricultural productivity growth. Varietal improvements continued for wheat and rice, and breeding improvements extended productivity gains to other crops and livestock (Evenson and Gollin 2003; Evenson 2005; World Bank 2007; Hazell 2009; P. L. Pingali 2012; Estudillo and Otsuka 2013; Otsuka and Larson 2017). Capital investments in irrigation, mechanization, and communications and greater stores of human capital also sustained growth and productivity (Mundlak, Larson, and Butzer 1997; Huffman 2001; McNamara 2009; Mundlak, Butzer, and Larson 2012; Valipour 2015).

Because the new cultivars improved yields, they conserved land, a crucial quality for places like the People's Republic of China (PRC), where agricultural land was in short supply (Stevenson et al. 2013). Nevertheless, the high-yielding crops that initiated Asia's Green Revolution and the subsequent input-intensive technologies that sustained it put a heavy burden on Asia's natural resources, accounting for most of Asia's freshwater use, contributing significantly to air, soil, and water pollution, and adding to the buildup of the greenhouse gases that hasten climate change (Novotny et al. 2010; Cassou, Jaffee, and Ru 2018; Cassou et al. 2022; Larson et al. 2022). Moreover, transitions in national diets, still underway, will further burden natural resources going forward.

It is the last of these three impacts, the effects of past and current technology choices in Asia on climate change, that is the focus of this paper. Specifically, the paper looks at two practices, the cultivation of paddy rice and the growth in livestock production, that have been, and will continue to be, problems for policymakers as they grapple to rein in emissions. The paper looks at contributions of these practices to emissions in the past and projects their business-as-usual impacts going forward as trends in income growth, urbanization, and diet transitions exert added pressures. The paper considers policies and alternative technologies aimed at limiting on-farm emissions without reversing hard-won gains in poverty reduction. The paper explores how the past success of the Green Revolution technologies, and the income gains they helped spur, has led to still-ongoing dietary transitions that will complicate and hinder future efforts to reduce on-farm emissions. The empirical sections of the paper focus on 15 countries in South and Southeast Asia at varying stages of dietary transitions, which share a cultural connection to rice as a dietary staple.

2. PRODUCTIVITY GROWTH, INCOME GROWTH, AND RESTRUCTURED ECONOMIES

For centuries, rice has been the central staple crop and a cultural touchstone for the 15 countries listed in Table 1, which are the focus of this paper (Chang and Bunting 1976). Together, the countries produced 87% of the world's rice crop in 2020. They are also large countries with rapidly growing economies and account for nearly half (49% in 2020) of the world's population.

The table lists real GDP per capita data for selected years, as well as the income classification used by the World Bank starting in 1987, the first year the classification system was used. Collectively, the combined economies of the 15 countries grew by 409% between 1987 and 2020.

Table 1: Real GDP per Capita and World Bank Income Classification	ns
for Selected Years	

											Period
	Group	Income	Group	Income	Group	Income	Group	Income	Class	Income	Change
	19	987	19	990	20	000	2	010	2	020	1987–2020
Bangladesh	L	456	L	482	L	634	L	1,037	LM	1,903	317%
Cambodia	L	327	L	344	L	488	L	888	LM	1,403	328%
PRC	L	778	L	891	LM	2,191	UM	5,603	UM	10,258	1,219%
India	L	475	L	545	L	771	LM	1,263	LM	1,833	286%
Indonesia	L	1,205	L	1,434	L	1,845	LM	2,696	LM	3,780	214%
Japan	н	24,513	Н	28,460	н	31,440	н	32,933	н	34,837	42%
Korea, DPR		945	LM	890	L	600	L	640	L	579	-39%
Korea, Rep. of	UM	7,186	UM	9,100	UM	17,072	н	25,837	н	31,367	336%
Lao PDR	L	571	L	626	L	905	LM	1,566	LM	2,603	356%
Malaysia	LM	3,595	LM	4,260	UM	6,462	UM	8,101	UM	10,364	188%
Myanmar	L	185	L	176	L	325	L	909	LM	1,394	653%
Philippines	LM	1,597	LM	1,740	LM	1,832	LM	2,416	LM	3,196	100%
Sri Lanka	L	1,173	L	1,256	LM	1,919	LM	2,892	LM	4,092	249%
Thailand	LM	1,917	LM	2,573	LM	3,511	UM	5,082	UM	6,042	215%
Viet Nam	L	500	L	541	L	951	LM	1,659	LM	2,675	435%

Note: L, LM, UM, and H stand for low income, low-middle income, upper-middle income, and high income, respectively. Source: World Bank (2023b), FAOSTAT (2023).

During that time, all countries moved to higher income groupings, except for Japan, which was already classified as high-income in 1987. The World Bank's classification for Malaysia had changed from lower-middle to upper-middle income by 2000, and for Thailand between 2000 and 2010. Though not shown, Indonesia was classified as upper-middle income in 2019 and again in 2021. The PRC's classification changed from low-income to lower-middle income between 1990 and 2000, and to upper-middle income by 2010. Of the 15 countries, only the Democratic People's Republic of Korea remained classified as low-income in 2020.

From 1961 to 2020, the combined agricultural sectors of the 15 countries grew robustly. Average rice yields more than doubled, moving from 1.85 to 4.93 tons per hectare between 1961 and 2020, while wheat yields increased sixfold, moving from 0.69 to 4.41 tons per hectare (FAOSTAT 2023). Labor productivity grew as well. From 1990, the first year for which comparable data are available, to 2020, the average value added per worker in agriculture more than doubled in nearly all but the wealthiest of the 15 countries (Table 2). In Viet Nam, labor productivity grew threefold; in the PRC, it grew fivefold. Between 1970 and 2020, the combined agricultural GDP of the study countries increased sixfold, from \$US22.8 to 138.0 (2015) trillion (FAOSTAT 2023; WBDI 2023).

	1990s	2000s	2010s	2020s
Japan	16,722	20,460	20,467	18,037
Korea, Rep.	8,766	12,806	19,517	19,200
Malaysia	10,133	12,385	14,318	16,104
PRC	1,227	1,915	4,300	6,373
Philippines	1,776	2,256	2,881	3,470
Indonesia	1,614	1,845	2,857	3,546
Sri Lanka	1,411	1,708	2,708	3,113
Thailand	1,340	2,052	2,671	3,002
India	1,067	1,175	1,790	2,229
Lao PDR	814	1,063	1,444	1,654
Viet Nam	665	1,012	1,423	2,129
Cambodia	629	853	1,415	1,462
Bangladesh	539	751	1,096	1,334
Korea, DPR	448	474	517	498

Source: FAOSTAT (2023) and ILO (2023). Note: Data unavailable for Myanmar.

As productivity increased, agricultural workers left to take jobs in other parts of the economy where wages were higher, and agriculture's share of the labor force fell (Figure 1). This sectoral restructuring of the labor market fueled growth economy-wide and helped boost average incomes both within and outside agriculture.



Figure 1: Share of Labor Force in Agriculture, Averages by Decade

Source: FAOSTAT (2023) and ILO (2023). Data unavailable for Myanmar.

Agriculture continued to grow, albeit with fewer workers, but other sectors grew faster, and agriculture's share of the economies fell. The sectoral shift in labor also prompted internal migration as households left rural areas to work in cities and suburbs. Consequently, the share of the population in the 15 study countries living in rural areas has fallen for decades (Figure 2). This, in combination with slowing birth rates, means that the number of people living in rural areas has begun to fall (Figure 3). For the study countries collectively, the rural population peaked in 2001 at 2.07 billion and had fallen to 1.93 billion by 2020.

Figure 2: Rural Population and its Share of Total Population for Study Countries, 1961–2020



Source: FAOSTAT (2023).

In most countries with large agricultural sectors, economic growth is associated with a decline in agriculture's share of the labor force, as farms, on average, become larger and more capital-intense (Vermeer 1951; Gardner 2009; Eastwood, Lipton, and Newell 2010; MacDonald, Korb, and Hoppe 2013; Bartolini and Viaggi 2013). Where land and capital markets work well, the transition to larger farms staffed with fewer workers proceeds contemporaneously with shifting demographics and labor markets. However, in Asia, where farms are small, the consolidation of agricultural land has been slow, which, when combined with an aging and shrinking labor force, can undercut sectoral performance (Masters et al. 2013; Manjunatha et al. 2013; Lowder, Skoet, and Raney 2016; Wang et al. 2020; Shen, Liang, and Shi 2023). Looking ahead, farm sectors structured around small under-capitalized farms can slow the adoption of new technologies, an important pathway toward lowering on-farm greenhouse gas emissions, as discussed later (Feder and O'Mara 1981; Just and Zilberman 1983; Feder and Umali 1993; Otsuka, Liu, and Yamauchi 2016). Potentially, an equitable consolidation of managed area can occur even when the ownership of land remains fragmented, and institutional arrangements are emerging in Asia that do just that (Deininger and Feder 2001; Gao, Huang, and Rozelle 2012; Larson et al. 2022). Consequently, policies that promote the necessary institutions that promote land rental markets, consolidated management contracts, and the types of hire services can have a complementary impact on efforts to promote less-polluting technologies.

3. FALLING POVERTY RATES AND RISING FOOD DEMAND

As the Green Revolution technologies took hold, food supplies expanded steadily decade after decade. Because the new crop technologies were bred to be high yielding, the area planted to these crops did not increase significantly. For example, between 1961 and 2020, the global production of primary cereals, crops like wheat, rice, maize, and barley, more than tripled, while production in the study countries more than quadrupled. At the same time, the area planted to these crops changed little (Figure 3). Worldwide, the area planted to cereal crops increased from 648 million to 730 million hectares, an increase of 13%. For the study countries, the cereal crop area

expanded from 233 million to 271 million, an increase of just 16%. However, yields grew rapidly. Starting slightly below global cereal yields in 1961, average yields for the study countries surpassed global averages in the early 1980s. By 2020, the average cereal yields in the 15 countries had grown by 280%, increasing from 1.23 to 4.74 tons per hectare.

Figure 3: Area Harvested and Average Yields for Primary Cereals, World, and Study Area, 1961–2020



Source: FAOSTAT (2023).

As agricultural productivity and production grew, so did available food supplies. Figure 4 shows the FAO's estimates of the average number of calories available for consumption per capita per day in each of the study countries by decade between 1970 and 2020.¹ It is worth emphasizing that an inadequate intake of calories is only one form of malnutrition; however, it has been a leading cause of illness and death among the very young for decades and remains too common. Moreover, having access to an adequate supply of calories is frequently the first step in overcoming undernourishment (Martins et al. 2011; Walton and Allen 2011; Kupka, Siekmans, and Beal 2020).

In most countries, the supply of available calories grew quickly from the 1970s to the 1990s, especially in countries where caloric-measured food supplies averaged less than 2,000 calories a day – for example, in Sri Lanka, Bangladesh, and Cambodia. However, at some point in the average diets of nations, the number of calories consumed plateaus, and, thereafter, average food supplies, when described in calories, appear to change little, as in Viet Nam, Lao PDR, and the PRC, for example. Nonetheless, diets change in other ways as incomes improve. In the analytic models, the increase in animal protein consumption associated with improved incomes

¹ "Available calories" and "available protein" are estimates of food available for consumption. The measures are calculated at the national level, constructed from available data on domestic food produced, net food imports, inventory changes, and losses due to transport and processing (FAOSTAT 2023). The measures are built up from data on individual food commodities, converted to kilocalories or grams of protein based on a standard set of technical conversion factors. It is important to note that the metrics represent the potential supply of calories or protein and do not directly measure consumption. Still, the methodology is based on a food-balance accounting approach, where available food equals disappearance, that is, the sum of food consumed, and food lost to waste. Consequently, to the extent that the share of food lost to waste is small or relatively constant, the indicator can serve as a useful proxy for changes in national consumption and diets.

is emphasized, in turn, because of its impacts on climate change. Still, any simple metric of national diets obscures a complex set of relationships among rising incomes, diversified diets, and health outcomes, which have their own impacts on productivity and income (Strauss and Thomas 1998; Deaton 2003; Fogel 2004; Siddiqui et al. 2020).



Figure 4: Average Available Calories per Capita per Day, by Decade

Expressing evolving diets in per capita terms also obscures the scale of Asia's food systems and their growth. As previously mentioned, most of the world's population resides in one of 15 countries analyzed here, a population that has expanded greatly during the last 50 years. Table 3 shows the FAO's estimate of food supplies expressed in total annual calories supplied. The table illustrates the scale of the production gains needed to match consumption levels that were growing on a per capita basis as populations also grew. For example, in the PRC, where per capita caloric supplies remained stable, food supplies increased from 631 trillion calories a year to 1.65 quadrillion calories.

As previously mentioned, food imports are a component of the FAO's food availability metrics; however, for all but the wealthiest of the study countries, expanded domestic agriculture sectors accounted for nearly all the increase in food supplies. For example, between 1970 and 2012, about 98% of primary grains were domestically produced (Annex Table 1).

Because the Green Revolution innovations were primarily biological and therefore scalable, the rates of productivity growth that occurred in the most populous countries of Asia occurred in other countries too. Consequently, global food prices were kept in check (Annex Figure 1). In combination, rising incomes, ample food supplies, steady food prices, and a strengthening of safety net programs powered dramatic and transformational reductions in poverty (Table 4).

Source: FAOSTAT (2023).

	1970s	1980s	1990s	2000s	2010s	2020s
			Bil	lions		
PRC	631,300	909,631	1,157,224	1,368,266	1,525,479	1,651,943
India	458,542	611,931	809,355	976,689	1,082,702	1,219,463
Indonesia	97,929	145,092	176,409	206,636	234,422	271,192
Bangladesh	54,569	71,160	89,414	119,865	130,586	145,811
Japan	112,295	125,801	133,890	131,160	125,266	125,403
Philippines	30,736	42,719	57,415	77,299	87,600	100,570
Viet Nam	32,505	43,116	53,596	74,209	87,005	97,010
Thailand	32,871	38,395	51,775	64,307	68,850	71,448
Korea, Rep. of	39,457	44,891	49,761	54,320	59,241	62,916
Myanmar	16,415	21,578	27,403	37,151	48,062	52,366
Malaysia	11,019	14,740	20,561	26,288	29,874	32,998
Sri Lanka	10,946	13,230	14,686	16,948	18,920	20,871
Korea, DPR	12,994	14,991	17,768	18,772	19,084	19,390
Cambodia	4,261	4,898	7,693	11,050	13,311	15,019
Lao PDR	2,142	2,621	3,550	4,699	5,542	6,682

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Source: FAOSTAT (2023).

Table 4: Share of Population Living in Extreme Poverty

	1980s	1990s	2000s	2010–2015	2015–2022
Bangladesh	37.23	37.80	28.65	18.20	13.50
Cambodia					
PRC		57.20	25.53	6.47	0.50
India	53.45	47.60	36.40	20.60	13.15
Indonesia	74.25	58.26	28.98	12.75	4.81
Japan			0.50	0.35	
Korea, DPR					
Korea, Rep. of			0.20	0.30	0.20
Lao, PDR		33.45	22.45	10.90	7.10
Malaysia	2.90	1.73	1.03	0.03	-
Myanmar				6.20	2.00
Philippines			13.58	8.70	3.00
Sri Lanka	16.90	11.70	6.70	2.60	1.15
Thailand	20.35	5.85	1.27	0.12	0.02
Viet Nam		34.75	19.00	2.17	1.07

Note: The table shows the average share of the population living on less than \$US2.15, adjusted by the purchase power parity index to 2017 values. Source: World Bank (2023b).

4. DIET TRANSITIONS AND THE CONSEQUENCES FOR ON-FARM GREENHOUSE GAS EMISSIONS

Rising incomes and increased urbanization wrought changes in the composition of Asian diets as they have elsewhere, part of an archetypal relationship between income growth and evolving diets. Incomes affect at least three dimensions of diet quality: 1) the adequacy of calories and nutrients required to promote good health; 2) the immoderate intake of nutrients and food groups that lead to poor health outcomes; and

3) variation in foods and food groups (Guenther, Reedy, and Krebs-Smith 2008; Herforth and Ahmed 2015).

International experience shows that, in most places, the quality of diets improves significantly as incomes rise from low levels. Staple-heavy diets, often inadequate in calories and nutrients, give way to diverse diets, more sufficient in calories and nutrients. As a consequence, the prevalence of adverse diet-linked outcomes falls. This is especially important for children, since relatively brief periods of maternal and child malnutrition can lead to a lifelong diminishment of physical and mental capacities, which, in turn, limits educational obtainment and the accumulation of other forms of human capital (Perisse, Sizaret, and Francois 1969; Strauss and Thomas 1998; Victora et al. 2008; Siddiqui et al. 2020). Conversely, reductions in the prevalence of undernourishment boost the welfare and productivity of individuals and, in the aggregate, lead to economy-wide gains, especially when driven by improved agricultural incomes (Asenso-Okyere et al. 2011; Webb and Block 2012). As incomes continue to grow, and as urbanization gains traction, growth in dietary adequacy benefits slows and problems associated with the immoderate intake of unhealthy foods speed up, along with the prevalence of obesity, diabetes, colorectal cancer, and cardiovascular disease, among others (Popkin 2003; Popkin, Adair, and Ng 2012).

Returning to the study countries, all broadly share this common transition pathway. Especially when starting at low levels of average income, economic growth allowed many households to diversify away from staple-heavy diets centered on rice and wheat to diets that included more fresh fruit, vegetables, and protein, changes that reduced stunting and improved health outcomes, particularly when combined with effective safety-net programs (Gillespie et al. 2019; Shankar, Poole, and Bird 2019). Nevertheless, as the countries urbanized and reached middle-income status, the transition to the consumption of fats, sugars, animal protein, and processed food increased rapidly. Consequently, new public health challenges associated with obesity emerged as problems associated with hunger and undernourishment declined (Drewnowski and Popkin 2009; Tacoli 2019; Huse et al. 2022).

The transition had environmental impacts too, including changes in on-farm greenhouse gas emissions (Godfray et al. 2018). In particular, increased animal protein consumption has been a central component of Asia's changing diets. In turn, the associated increase in livestock production has been an important impact of agriculture on climate change, and it is this aspect of Asia's diet transition that is the focus of the next section. Figure 5 shows how protein consumption and the share of protein originating from animal sources evolved in the aggregate for the 15 study countries. Both metrics rose steadily as food supplies expanded, incomes grew, and households moved to urban areas.

Table 5 shows how animal protein consumption increased at the country level. Apart from Japan, where animal protein consumption was already high, and in the Democratic People's Republic of Korea, where incomes have fallen, animal protein consumption increased significantly between 1970 and 2022 in each of the study countries.

Figure 5: Per Capita Daily Protein Consumption in the Study Countries and the Share from Animal Sources, 1970–2020



Source: FAOSTAT (2023).

Table 5: Average Grams of Animal Protein	Consumed per Capita per Day,
by Decade	

Country	1970s	1980s	1990s	2000s	2010s	2020–2022
Korea, DPR	15.6	19.4	10.5	9.8	10.0	10.4
Bangladesh	6.0	5.0	5.6	7.8	10.0	11.8
India	6.2	7.8	9.2	10.4	11.6	13.9
Lao PDR	5.8	6.4	7.9	12.0	14.1	17.8
Sri Lanka	7.9	9.5	11.8	13.6	15.2	17.9
Cambodia	6.6	7.0	9.2	16.3	17.8	19.2
Indonesia	6.0	8.4	11.1	13.9	15.9	21.3
Philippines	19.7	18.6	20.5	23.5	26.7	26.1
Thailand	15.9	16.3	23.7	23.2	25.1	26.4
Viet Nam	7.8	8.5	11.2	21.2	30.2	32.4
PRC	5.8	9.3	19.7	31.0	36.9	39.6
Myanmar	7.6	8.8	7.9	18.2	33.6	41.7
Malaysia	21.1	29.4	40.9	42.2	43.3	44.3
Japan	41.6	50.8	54.9	52.2	48.3	48.6
Korea, Rep. of	13.2	22.2	32.4	39.6	42.7	49.6

Source: FAOSTAT (2023).

Among crops, emissions from rice paddies and livestock wastes are especially impactful for global warming. This is because both give rise to highly potent greenhouse gases. In the case of rice, cultivation produces two types of especially potent GHG, namely methane and nitrous oxide, with 20-year global-warming potentials that are 56 and 280 times, respectively, that of carbon dioxide (UNFCCC 1995). Animal manure and urine give rise to methane and nitrous oxide too. In addition, ruminating livestock, such as cattle, sheep, and goats, produce methane from enteric fermentation.

Reducing these emissions is important for each of the study countries as they work to meet their Nationally Determined Contributions goals under the UNFCCC's Paris Agreement (Michaelowa, Shishlov, and Brescia 2019). Collectively, actions taken by the study countries are also important for the global environment since, in 2020, 83% of GHG emissions from rice production and 81% of livestock waste emissions originated in the 15 study countries (FAOSTAT 2023).

Figure 6 shows total emissions from rice and livestock production for the study countries from 1970 to 2020. The livestock emissions include enteric fermentation emissions and emissions from manure. The figure shows that emissions from rice grew slightly between 1970 and 1989 (from 496 to 541 Mt CO2eq) but have remained steady since; the FAO estimated emissions from rice at 56,800 mt for the study countries in 2020. By contrast, emissions from livestock have grown steadily, increasing by 66% over the period. By 2020, livestock emissions had risen to 1,087 Mt CO2eq. For perspective, at 1,655 Mt, the combined annual emissions from just livestock and rice production in the 15 study countries is equivalent to the total annual emissions from many middle-sized countries, including South Africa and Türkiye (Climate Watch 2023).

Figure 6: On-Farm Emissions from Rice and Livestock Production for Study Countries, 1970–2020



Source: FAOSTAT (2023).

Tables 6 and 7 show the country composition of aggregate emissions, and both tables reveal country differences not evident in the aggregated data. In the case of rice, average emission levels have fallen in Japan and the Republic of Korea, where incomes are high, and in the Democratic People's Republic of Korea, where underlying available rice supplies have changed little since the 1970s. Offsetting these reductions were significant gains in Cambodia, the Philippines, and Sri Lanka.

Outcomes are more varied for livestock emissions. Emissions have grown in most countries during the last 20 years, increasing by more than 50% in Lao PDR, the Republic of Korea, Myanmar, and Indonesia, which were partly offset by small reductions in Cambodia, Japan, Thailand, the Philippines, and the PRC. Apart from Japan, animal protein consumption has grown in these countries, and some of the decline in domestic emissions has been offset by emissions from trading partners.

Country	1970s	1980s	1990s	2000s	2010s	2020
Lao PDR	1.75	1.80	1.65	2.07	2.48	2.26
Korea, DPR	2.98	3.22	2.93	2.86	2.55	2.34
Sri Lanka	2.14	2.38	2.38	2.59	3.13	3.19
Malaysia	3.62	3.36	3.43	3.37	3.39	3.23
Korea, Rep. of	7.11	7.27	6.55	5.86	4.73	4.27
Japan	15.70	13.10	11.80	9.81	9.17	8.51
Cambodia	5.12	6.55	8.02	10.10	12.80	12.70
Myanmar	21.10	20.40	23.90	31.60	31.10	29.20
Bangladesh	27.60	28.80	28.40	29.90	31.80	31.80
Viet Nam	25.20	28.10	33.50	36.70	38.00	35.70
Philippines	32.80	31.30	33.30	39.10	43.60	44.20
Thailand	35.20	42.30	41.50	46.00	49.20	46.60
Indonesia	49.90	57.30	66.00	69.30	66.90	63.10
India	114.00	120.00	128.00	128.00	129.00	133.00
PRC	171.00	161.00	155.00	141.00	149.00	148.00

 Table 6: Average Annual Emissions from Rice Production, Mt CO2e, by Decade

Source: FAOSTAT (2023).

Table 7: Average Annual Emissions from Livestock Production, Mt CO2e,
by Decade

-						
Country	1970s	1980s	1990s	2000s	2010s	2020s
Sri Lanka	3.47	3.87	3.33	2.08	2.18	2.22
Korea, DPR	2.11	2.91	2.31	2.31	2.43	2.45
Malaysia	2.05	2.57	2.85	3.19	3.46	3.35
Cambodia	4.45	4.26	7.01	8.06	7.63	7.18
Lao PDR	2.35	3.41	4.71	5.22	6.76	7.84
Korea, Rep. of	3.25	4.81	6.50	6.23	8.41	9.31
Japan	10.20	12.50	12.90	11.80	10.70	10.60
Thailand	21.10	22.70	21.90	16.90	15.30	13.90
Philippines	13.70	12.60	13.60	16.40	15.60	15.70
Viet Nam	10.20	13.10	17.00	22.80	23.70	24.40
Bangladesh	31.80	29.30	34.40	38.20	44.00	46.30
Myanmar	18.50	23.60	24.90	31.50	45.90	55.50
Indonesia	20.70	28.20	37.30	37.10	50.20	59.70
PRC	222.00	256.00	346.00	371.00	337.00	327.00
India	333.00	389.00	431.00	460.00	490.00	501.00

Source: FAOSTAT (2023).

5. THE MOMENTUM OF HABIT AND DEMOGRAPHICS AND THE CONSEQUENCES FOR FARMGATE EMISSIONS

In recent years, policymakers in Asia have begun to grapple with Green Revolution legacies: how to reverse the damage done to domestic and global natural resources without undermining the productive agricultural sectors still rooted in high-intensity technologies. The problem is not a static one.

Using the example of climate change, this section reports on a numerical exercise showing that population and income dynamics will make more difficult the already challenging pursuit of the twin policy goals of reducing agriculture's natural resource footprint while sustaining productivity gains in agriculture.

At the center of the exercise are empirical models of demand for rice and animal protein estimated using a 15-country panel of annual data from 1970 to 2020. Estimated models are combined with projected income gains to provide out-of-sample forecasts for per capita demand. Under the assumption of business-as-usual technology choice, the models' projections are combined with population projections to forecast the emissions associated with rice and animal protein production for each of the 15 study countries. Fixed ratios are used to provide business-as-usual forecasts for on-farm emissions over three decades.

Two features of this diet dynamic discussed earlier are important for the empirical section of this paper. The first has to do with national heterogeneity. While the dynamic impacts of income gains on the composition of diets are recognizable in nearly all settings, there is considerable cross-country variation in specific transition pathways (Wiggins and Keats 2013; Herforth and Ahmed 2015). This is consistent with the notion that diets are rooted in past household experiences, and national cultures and traditions. Second, there are stages along the diet transition during which the consumption shares of specific food groups expand quickly and thereafter decline as growth shifts to other food group are influenced by past consumption and that measured income elasticities will vary with income gains, often declining as incomes and consumption pass milestone levels. The two characteristics guide the applied empirical model discussed next.

5.1 A Habit-Formation Model

The empirical foundations for the analysis presented in this section are a series of country-specific habit-formation models. The models, estimated with country-level data, are based on conceptual models of individual utility and choice, where wealth and past consumption experiences shape consumption pathways (Constantinides 1990; Heien and Durham 1991; Naik and Moore 1996). Though most habit-model applications relate to asset pricing, the models are especially relevant to understanding diet choices, which are deeply affected by preferred cuisines. In turn, the cuisines are rooted in shared national cultures and influenced over time by improved incomes.

Figure 7 shows the pooled annual observations of calories, animal protein, and rice consumption from the study countries. Visible in the top panels of the figure are patterns, associated with calories and animal protein, in which per capita consumption grows rapidly with initial income gains, then plateaus and eventually declines at high levels of national income. The lower panel shows heterogeneous patterns. In general, rice consumption appears to increase at low levels of income but decline thereafter. This pattern has been observed in aggregate and household survey data, prompting some to describe rice as an inferior good (Ito, Peterson, and Grant 1989; Prabhu Pingali 2007).

Figure 7: Pooled Daily Availability Data from Calories, Rice, and Animal Protein, 1970–2020



This perspective of the data is consistent with earlier observations about diet transitions and guided two choices for the empirical estimation. First, panel estimators are eschewed in favor of country-specific models for rice and for animal consumption, reflecting the deep influence of national cultures on diet. Second, the standard habitformation model is adapted for estimation by a stochastic-frontier estimator to reflect the potential for the data to be constrained by a saturation boundary (Coelli et al. 2005; Kumbhakar, Parmeter, and Zelenyuk 2020).

With this in mind, the empirical models can be written as:

$$c^{R}_{it} = a^{R}_{i0} + a^{R}_{i1}c^{R}_{it-1} + a^{R}_{i2}w - u^{R}_{it} + v^{R}_{it}$$
(1)

$$c^{P}_{it} = a^{P}_{i0} + a^{P}_{i1}c^{P}_{it-1} + a^{P}_{i2}w - u^{P}_{it} + v^{P}_{it},$$
(2)

where *c* represents per capita consumption, proxied by FAO availability metrics, for country *a* in year *t*; *w* represents wealth proxied by per capita income; and superscripts *R* and *P* identify the separate models for rice and animal protein. Both consumption and income are measured in natural logs. The α s are estimated parameters that are free to vary across countries and across the two types of consumption. The gap between the consumption frontier and observed consumption is given as a composite of two error terms, *u* and *v*, which are distributed independently of each other and of consumption and wealth. The v_{it} are random errors, assumed to be *iid* $N(0, \sigma_v^2)$; the u_{it} are nonnegative random variables that account for the remaining distance between observed consumption and the consumption-saturation frontier. The u_{it} are

modeled using a half-normal distribution, $h(0, \sigma_u^2)$, a distribution common in stochastic frontier models.

Model parameters were estimated for each of the 15 study countries using annual data for the period 1970 to 2020; parameter estimates, and related test statistics, are given in Tables 8 and 9. Both sets of results are consistent with the conceptual model.

In the case of rice, the estimated habit (lag c) coefficients in Table 8 fall between zero and 1 and are statistically distinguishable from zero. All are above 0.55, and most are greater than 0.80, which is consistent with the importance of rice in the culture and cuisines of the sample countries. The coefficients on income (w) are generally positive and statistically significant, an outcome that is inconsistent with the notion that rice is an inferior good in most sample countries. Nevertheless, there are exceptions. For the estimated Democratic People's Republic of Korea model, where real incomes have fallen, the coefficient is negative, statistically significant, and its absolute value is quantitatively large in comparison to the other estimated income elasticities. The estimated elasticity is also statistically negative for the Republic of Korea, although much smaller quantitatively. For Japan, Malysia, and Thailand, the estimated coefficients are indistinguishable from zero. One implication is that, for these three countries, habit-based consumption, rather than contemporaneous-income effects, largely explains observed consumption levels. Further, when habit elasticities are less than one, rice consumption per capita will decline over time unless boosted by income growth, a boost that declines as income elasticities fall once high levels of income are obtained.

	Coefficient	Std. Err.	P> z	Coefficient	Std. Err.	P> z	Coefficient	Std. Err.	P> z	
	Bar	ngladesh		Car	nbodia			PRC		
lag c	0.55	0.11	0.00	0.84	0.08	0.00	0.86	0.07	0.00	
w	0.20	0.05	0.00	0.06	0.03	0.05	0.02	0.01	0.08	
constant	0.99	0.30	0.00	0.44	0.29	0.13	0.47	0.25	0.06	
$\ln \sigma_v^2$	-5.59	0.20	0.00	-5.31	0.20	0.00	-5.36	0.20	0.00	
$\ln \sigma_u^2$	-15.67	408.04	0.97	-14.68	164.74	0.93	-15.08	165.05	0.93	
		India		Ind	onesia			Japan		
lag c	0.74	0.09	0.00	0.82	0.08	0.00	0.90	0.06	0.00	
w	0.08	0.03	0.01	0.05	0.03	0.11	0.00	0.03	0.93	
constant	0.64	0.27	0.02	0.57	0.28	0.04	0.41	0.55	0.45	
$\ln \sigma_v^2$	-5.61	0.20	0.00	-5.30	0.20	0.00	-5.63	0.20	0.00	
$\ln \sigma_u^2$	-15.13	304.29	0.96	-14.88	154.57	0.92	-15.47	205.60	0.94	
	Ko	rea, DPR		Korea, Rep. of			Lao, PDR			
lag c	0.71	0.10	0.00	0.79	0.08	0.00	0.87	0.07	0.00	
w	-0.25	0.14	0.07	-0.04	0.02	0.03	0.04	0.02	0.02	
constant	2.97	1.23	0.02	1.35	0.52	0.01	0.42	0.28	0.13	
$\ln \sigma_v^2$	-4.55	0.41	0.00	-5.05	0.20	0.00	-5.80	0.20	0.00	
$\ln \sigma_u^2$	-5.04	1.70	0.00	-14.55	175.58	0.93	-16.18	339.43	0.96	
	М	alaysia		Myanmar			Philippines			
lag c	0.90	0.06	0.00	0.67	0.10	0.00	0.78	0.11	0.00	
w	0.01	0.02	0.67	0.09	0.03	0.00	0.25	0.12	0.03	
constant	0.39	0.38	0.32	1.12	0.38	0.00	-0.82	0.46	0.07	
$\ln \sigma_v^2$	-5.05	0.20	0.00	-5.36	0.20	0.00	-5.48	0.20	0.00	
$\ln \sigma_u^2$	-14.80	397.93	0.97	-15.58	671.58	0.98	-14.39	536.61	0.98	
	Sri Lanka		Th	Thailand			Viet Nam			
lag c	0.87	0.07	0.00	0.91	0.06	0.00	0.79	0.08	0.00	
w	0.06	0.03	0.03	0.02	0.02	0.22	0.06	0.02	0.02	
constant	0.13	0.22	0.57	0.28	0.35	0.42	0.69	0.32	0.03	
$\ln \sigma_v^2$	-5.15	0.20	0.00	-5.24	0.20	0.00	-5.26	0.20	0.00	
$\ln \sigma_u^2$	-15.33	350.00	0.97	-14.52	149.08	0.92	-15.10	359.62	0.97	

Animal protein consumption models are reported in Table 9. All habit coefficients are positive and significantly different from zero. Estimated income elasticities are all positive, apart from Japan, although they are not statistically positive for the Democratic People's Republic of Korea and Cambodia. In the case of Japan, the habit elasticity is quantitatively high at 0.95. Paired with a quantitatively small and slightly negative (-0.03) income elasticity, the estimated parameter is consistent with a per capita consumption level for animal protein that is large but declining at very high levels of income. In the case of the PRC, an animal protein model estimated in levels rather than logs performed best and is included here. As an aside, it is worth noting that the FAO's data on the PRC's daily animal protein consumption on the log of time explains 96% of the deviation in the series.

	Coefficient	Std. Err.	P> z	Coefficient	Std. Err.	P> z	Coefficient	Std. Err.	P> z		
	Ba	Ingladesh		С	ambodia			PRC			
lag c	0.91	0.05	0.00	0.93	0.09	0.00	0.85	0.04	0.00		
w	0.08	0.03	0.01	0.05	0.08	0.54	1.74	0.43	0.00		
constant	-0.25	0.12	0.03	-0.04	0.32	0.90	0.25	0.08	0.00		
$\ln \sigma_v^2$	-7.79	0.61	0.00	-4.29	0.49	0.00	-1.50	0.20	0.00		
$\ln \sigma_u^2$	-5.85	0.38	0.00	-5.07	2.74	0.06	-10.26	264.3	0.97		
		India		Ir	ndonesia			Japan			
lag c	0.92	0.06	0.00	0.84	0.09	0.00	0.95	0.04	0.00		
w	0.05	0.03	0.10	0.14	0.07	0.06	-0.03	0.01	0.06		
constant	-0.08	0.07	0.30	-0.60	0.33	0.07	0.49	0.10	0.00		
$\ln \sigma_v^2$	-9.38	1.56	0.00	-6.33	0.20	0.00	-7.82	0.20	0.00		
$\ln \sigma_u^2$	-6.44	0.44	0.00	-14.64	142.63	0.92	-15.08	100.57	0.88		
	Ko	orea, DPR		Kor	ea, Rep. of		La	ao, PDR			
lag c	0.95	0.06	0.00	0.66	0.10	0.00	0.79	0.08	0.00		
w	0.04	0.12	0.75	0.16	0.06	0.00	0.17	0.06	0.00		
constant	-0.06	0.63	0.93	-0.25	0.21	0.24	-0.66	0.22	0.00		
$\ln \sigma_v^2$	-6.30	0.47	0.00	-7.11	0.59	0.00	-5.87	0.20	0.00		
$\ln \sigma_u^2$	-4.65	0.37	0.00	-4.89	0.33	0.00	-13.67	131.57	0.92		
	Ν	/lalaysia		Myanmar			Philippines				
lag c	0.91	0.06	0.00	0.73	0.04	0.00	0.86	0.08	0.00		
w	0.02	0.03	0.42	0.25	0.04	0.00	0.06	0.04	0.15		
constant	0.13	0.22	0.54	-0.71	0.10	0.00	0.02	0.17	0.92		
$\ln \sigma_v^2$	-6.77	1.58	0.00	-7.03	0.72	0.00	-7.83	0.55	0.00		
$\ln \sigma_u^2$	-7.18	6.66	0.28	-5.80	0.70	0.00	-5.81	0.34	0.00		
	Sri Lanka			Thailand			Viet Nam				
lag c	0.60	0.08	0.00	0.75	0.07	0.00	0.83	0.00	0.00		
w	0.18	0.05	0.00	0.09	0.03	0.00	0.16	0.00	0.00		
constant	-0.28	0.17	0.09	0.11	0.10	0.26	-0.50	0.00	0.00		
$\ln \sigma_v^2$	-10.06	2.28	0.00	-6.59	0.60	0.00	-38.16	216.11	0.86		
$\ln \sigma_u^2$	-4.70	0.24	0.00	-6.89	2.20	0.00	-4.56	0.20	0.00		

Table 9: Estimation Results for Animal Protein Consumption Model, by Country

Note: Consumption and income parameters are elasticities, except for the PRC, in which the animal protein consumption variable was estimated in levels rather than logs.

5.2 Out-of-Sample Forecasts

Future emissions from rice and livestock production were forecast for the period 2021–2049 in the following way. Projected per capita incomes for each country, based on historical growth rates between 1970 and 2020, were combined with population projections reported by the FAO as inputs for out-of-sample projections using the models given in Equations 1 and 2, and the parameters reported in Table 8. Because the models contain lagged consumption levels, they were dynamically simulated. Other scenarios where economic growth rates exceeded or fell short of past performance were considered as well and are reported later.

Fixed coefficients, based on the ratio of emissions to consumption, were used to project future emissions from the projected consumption levels. Several assumptions are implicit in this approach. The first is that the underlying country-differentiated technologies that produce rice and animal protein will continue to produce related GHG emissions at the same rate going forward as they have in the past. Said differently, the GHG efficiency of the underlying production technologies is treated as fixed. This is important, since the simulations provide an estimate of the potential that alternative technologies might have for limiting emissions. It is also important to reemphasize that the metric on consumption used here is what the FAO terms "available kilograms of rice" and "available grams of animal protein." Not all available supplies are consumed as food since some food goes unconsumed and is lost to waste. This offers another avenue for policy interventions since reducing waste could slow projected rates of consumption growth. Also implicit in the approach is an assumption that the share of domestic production in domestic consumption stays fixed at current levels. For most countries this is likely in the near term, but it could change for countries that obtain higher levels of income similar to current levels in the Republic of Korea and Japan. Potentially, this matters for domestic policies as countries pursue their individual commitments to reducing their emissions. However, the first-order impacts of a growing demand for rice and animal protein on climate change stem from the technologies used to meet that demand rather than the geographic location of the emissions; that is, shifting underlying production to exporting countries has an impact on measured domestic emissions but, all other things being equal, has no impact on climate change (Larson et al. 2008; Zheng et al. 2019).

Historical and projected aggregate emissions from rice and livestock production in the 15 study countries, based on this methodology, are reported in Figure 8. The figure also shows past and the projected aggregate population numbers reported by the FAO (FAOSTAT 2023). Keep in mind that the data available for estimation ended in 2020, so data in the figure for the 2020s, 2030s, and 2040s, for all practical purposes, are out-of-sample projections.

The figure presents a future in which emissions from rice production grow slowly, in part due to an easing of population growth. By contrast, livestock emissions expand rapidly, driven primarily by income growth and diet transitions. As a consequence, the share of emissions from rice production, which was 43% of combined emissions in the 1970s, falls to 23% in the 2040s.

In the aggregate, the projected emissions are large. The forecasting exercise suggests that, without new technologies that dampen on-farm emissions or interventions that dampen the demand for animal protein or reduce food waste, annual on-farm greenhouse gas emissions in the study countries from rice and livestock production alone will climb to about 4.2 billion tCO2e, more than double 2020 levels. This is nearly equal to the total greenhouse gas emissions from Japan in 2019 (Climate Watch 2023).



Figure 8: Historical and Projected Emissions from Rice and Livestock in Study Countries

Note: The disaggregated data, historical and projected, are given in Annex Table 2.

Figure 9 shows the breakdown of projected rice emissions by country. On the whole, the projections show a steady expansion across all study countries. By the 2040s, India (24%) and the PRC (23%) together account for about half the emissions. Although the shares are much larger, they are similar to recent history: In 2020, the PRC accounted for 26% of rice production emissions and India for 23%.



Figure 9: Forecasted Greenhouse Gas Emissions from Rice Production, by Country and Decade

Note: The disaggregated data, historical and projected, are given in Annex Table 2.

Figure 10 shows that India is projected to become the source of most of the area's livestock emissions by the 2040s. At the beginning of the projection period, 2020, India already accounted for 46% of livestock emissions among the 15 study countries. With growing incomes and an increasing population, India's share expands. The PRC's share drops from 30% in 2020 to 19% in the 2040s, driven in part by a declining population. Expanded animal protein consumption in places like Viet Nam and the Philippines also accounts for significant increases in aggregate emissions.





Note: The disaggregated data, historical and projected, are given in Annex Table 2.

India's outsized role as a source of livestock GHG emissions is perhaps surprising given that per capita animal protein consumption in the country is low in comparison to its neighbors. For example, recalling Table 5, the FAO estimates that India's daily per capita animal protein availability averaged 13.9 grams, much lower than the PRC's average of 39.4 for the period 2020–2021. However, as Table 10 shows, there are significant differences in the intensity of the on-farm production processes behind animal protein supplies.

				Manure Emissions	6
Country	Intensity	Enteric Fermentation	Applied to Soils	Left in Pasture	Managed Waste
Japan	5	57%	9%	13%	21%
Malaysia	6	35%	16%	23%	26%
Korea, Rep.	9	59%	8%	13%	20%
Philippines	14	56%	6%	13%	25%
Sri Lanka	15	76%	4%	12%	9%
PRC	15	57%	8%	16%	18%
Viet Nam	19	53%	8%	13%	27%
Thailand	20	57%	7%	13%	23%
Indonesia	23	52%	11%	21%	17%
Korea, DPR	26	58%	6%	21%	14%
Cambodia	61	67%	5%	11%	17%
Myanmar	63	64%	5%	11%	19%
India	63	78%	3%	12%	7%
Lao PDR	148	64%	5%	11%	19%

Table 10: Emission Intensity and Shares of Animal Protein Emissions by Type,
by Country in 2020

Note: Intensity is measured as tCO2e of GHG emissions per ton of available animal protein. Source: FAOSTAT (2023).

The first column of Table 10 lists a simple metric of GHG production intensity: a ratio of the annual tons of CO2e GHG emissions from animal wastes divided by the tons of total annual animal protein available (tAP) that year. The range of values is quite large, ranging from 5 tCO2e/tAP in Japan to 148 tCO2e/tAP in Lao PDR. India, with its much larger population, has the second-most intense sector, at 63 tCO2e/tAP. Production intensity is much lower in the PRC (15 tCO2e/tAP), which explains why the PRC accounts for fewer emissions, despite higher animal protein consumption levels.

Part of the difference is due to the composition of the livestock inventories. The FAO estimates that most animal waste emissions stem from enteric ferritization, a process by which microorganisms in the digestive systems of ruminants, including cattle, sheep, and goats, break down the complex carbohydrates in their food. This process results in the production of methane gas, a potent greenhouse gas, as a metabolic byproduct. In 2020, the share of waste emissions attributable to enteric fertilization (78%) was higher in India than in any other study country, including the PRC (57%). The remaining (nonenteric) sources of livestock waste emissions stem from how animal manure is processed. In the case of India, most is left in pastures; little is recycled in soils or treated in waste management facilities, actions that would reduce emissions.

One final difference is worth pointing out. In some countries, livestock are used as draft animals. This is especially true in Lao PDR, and to a lesser extent in India, where buffalo have not been fully displaced by tractors. While the animals also provide milk and meat, stocks of buffalo, on a per capita basis, remain higher in these countries than elsewhere (Annex Table 3). For example, in 2002, nearly 48% of all households in Lao PDR owned one or more buffalo (Stur, Gray, and Bastin 2002). As an aside, since buffalo are used for both draft power and food, the transition from buffalo to tractors reduces emissions from livestock but does not necessarily reduce total on-farm emissions (Spugnoli and Dainelli 2013).

6. SENSITIVITY ANALYSIS

While population forecasts can be made with a relatively high degree of certainty, forecasting economic growth is a tricky business, and small deviations from past trends can produce significant accumulated effects on projected per capita income over time. To determine whether the assumed growth rates are crucial to the reported out-of-sample forecasts, the forecasting exercise was repeated under two alternative assumptions: a low-growth scenario, where forecasted per capita incomes are 10% lower than the levels assumed in the original baseline forecast, and a high-growth scenario, where per capita incomes are 10% higher.

Figure 11 reports historical and forecasted data for population and aggregate rice and livestock emissions for the 15 study countries under the two alternative income assumptions. The figure shows that the alternative income assumptions do not result in large differences. Emission levels linked to animal protein consumption, which began to rise quickly during the 2010s, rise more steeply under the high-income scenario, and less steeply under the low-income scenario, while rice emissions grow steadily under both sets of assumptions.

The results are not surprising given the modeling results, which showed that, for most countries, rice and animal protein consumption for a given period were driven by cultural habits that evolve slowly as incomes rise. Populations that are growing quickly amplify the environmental impact of these changes and declining populations mute them.



Figure 11: Alternative Scenario Results

This dynamic is also apparent in the forecasted country-level results given in Tables 11 and 12. In general, the forecasts show per capita rice consumption levels that evolve slowly over time with little sensitivity to income changes. Moreover, much of the spread in outcomes for the study countries is spatial rather than temporal; that is, cultural differences apparent at the beginning of the out-of-sample projections remain apparent through the end of the projections.

		2020s			2030s			2040s	
-	High	Baseline	Low	High	Baseline	Low	High	Baseline	Low
Bangladesh	274.83	266.86	258.40	308.83	295.72	281.87	360.04	344.74	328.58
Cambodia	254.20	250.47	246.44	271.74	262.97	253.61	304.49	293.66	282.13
PRC	130.28	129.55	128.75	143.61	141.77	139.76	163.83	161.45	158.86
India	106.01	104.40	102.66	117.29	114.14	110.76	131.79	128.17	124.28
Indonesia	189.81	187.74	185.49	207.99	203.32	198.28	230.92	225.37	219.39
Japan	73.39	73.33	73.27	70.21	70.07	69.92	69.55	69.38	69.20
Korea, DPR	102.46	107.42	113.27	104.97	113.79	124.41	109.65	119.01	130.29
Korea, Rep. of	79.17	79.82	80.55	69.54	70.70	72.00	61.77	62.85	64.06
Lao PDR	250.57	247.88	244.96	282.05	275.09	267.58	322.06	312.99	303.26
Malaysia	105.54	105.27	104.97	107.14	106.43	105.65	110.34	109.45	108.46
Myanmar	198.09	195.09	191.84	222.99	217.54	211.66	257.49	251.15	244.31
Philippines	204.71	194.05	183.16	237.08	213.94	190.99	283.97	255.13	226.65
Sri Lanka	191.78	188.54	185.05	228.83	219.84	210.32	280.78	268.02	254.58
Thailand	165.89	164.92	163.86	181.52	178.73	175.70	200.92	197.05	192.85
Viet Nam	219.97	217.19	214.16	248.81	242.76	236.24	284.48	277.25	269.46

Table 1: Forecasted Daily Rice Consumption, Kg per Capita,by Growth Scenario and Decade

Overall, the same is true of the animal protein consumption forecasts. However, for most countries, the estimated income elasticities are higher for animal protein consumption than they are for rice, so the temporal variation in the panel is more pronounced. This is especially apparent for countries where initial incomes were low, like Viet Nam and Cambodia.

		2020s			2030s			2040s	
-	High	Baseline	Low	High	Baseline	Low	High	Baseline	Low
Bangladesh	16.78	16.40	16.00	24.98	23.61	22.19	34.85	32.50	30.10
Cambodia	26.55	26.15	25.72	42.19	40.57	38.86	59.55	56.58	53.46
PRC	46.56	46.13	45.65	57.14	56.16	55.07	67.76	66.65	65.43
India	20.07	19.78	19.46	28.00	26.98	25.89	37.14	35.41	33.60
Indonesia	29.71	28.69	27.62	40.15	37.34	34.45	56.39	52.08	47.70
Japan	47.55	47.95	48.41	43.37	44.53	45.86	38.96	40.47	42.20
Korea, DPR	14.54	14.36	14.15	23.93	23.07	22.16	33.03	31.33	29.56
Korea, Rep. of	73.27	71.13	68.86	104.52	99.99	95.22	141.39	135.23	128.73
Lao PDR	22.86	21.99	21.08	31.77	29.53	27.24	44.95	41.64	38.26
Malaysia	51.91	51.53	51.10	66.50	65.23	63.86	79.10	77.20	75.14
Myanmar	61.92	58.72	55.43	101.45	92.90	84.29	171.07	156.39	141.62
Philippines	31.86	31.36	30.81	37.57	36.26	34.86	41.26	39.64	37.92
Sri Lanka	23.11	22.44	21.72	28.40	27.19	25.92	34.26	32.80	31.26
Thailand	32.05	31.47	30.85	39.56	38.32	37.00	46.27	44.79	43.20
Viet Nam	59.93	57.39	54.76	114.82	105.88	96.80	189.53	173.60	157.54

Table 2: Forecasted Daily Animal Protein Consumption, Grams per Capita,by Growth Scenario and Decade

7. SUMMARY AND CONCLUSIONS: MEETING THE SUSTAINABLE DEVELOPMENT GOALS

Established by the United Nations in 2015 with a target date of 2030, the Sustainable Development Goals (SDGs) provide a framework with specific objectives to guide global development policy. The SDGs extend and modify an earlier framework, the Millennium Development Goals (MDGs), established in 2000 with a target date of 2015. Goal 1 of the MDGs was to eradicate extreme poverty and hunger, with the specific goals of halving the proportions of both undernourished and malnourished people between 1990 and 2015. The poverty goal was met fully, ahead of schedule, and substantive progress was made toward the hunger goal due, in large part, to gains in agricultural production and productivity. Building on this progress, SDG 2 aims to "end hunger" and "achieve food security and improved nutrition," while promoting "sustainable agriculture."

Lifting millions of families from the desperate cycle of hunger and poverty had consequences for the environment, and trends already set in motion will push to expand agriculture's environmental footprint. All of this puts expanding agriculture and food systems in conflict with other SDG goals, particularly Goal 6, which calls for efforts to better manage water supplies; Goal 12, which aims to reduce agriculture's environmental footprint; and Goal 13, which calls for urgent action to combat climate change.

To a large degree, most types of agricultural pollution and most sources of on-farm emissions in the study countries can be traced to high-intensity practices ushered in during the Green Revolution. The land-saving technologies proved wildly successful in boosting food supplies and sparked a structural restructuring of Asia's economies that brought economic growth and greatly reduced poverty rates. For these reasons, support for intensive agricultural practices remained in place for decades. As evidence of the unintended environmental consequences of the technologies has mounted, governments, international organizations, and the private sector have searched for alternative farming approaches that are equally productive with fewer environmental costs. This is challenging, since past policies are deeply embedded in current food systems and in all forms of underlying physical, human, and institutional capital.

The numerical exercise presented here, which models the impacts of business-asusual growth in rice and animal protein consumption on future on-farm GHG emissions, illustrates this challenge in specific ways. In combination, the importance of past dietary choices for future dietary choices and the relatively high income elasticities associated with the demand for animal protein create a momentum toward a future where on-farm emissions grow significantly.

The empirical section of the paper provides estimates of country-specific habit models of rice and animal protein demand. The models confirm that consumption pathways are heavily influenced by past consumption choices. The results also show significant differences among countries. Both results are consistent with the notion that diets have their own momentum shaped by preferences that are deeply entwined with household traditions and national cuisines. Nonetheless, the data and the estimated models also show that animal protein consumption has increased significantly in all countries as incomes have grown, reflecting an archetypical transition in diets.

Specifically, out-of-sample projections, based on forecasted country populations and assumed rates of continued per capita income growth, suggest that business-as-usual emissions from rice production and animal waste will increase by 57% and 204%, respectively, over the next three decades. The projections are robust to alternative assumptions about income growth.

The results are worrisome. In Asia and elsewhere, policymakers are working to reduce agriculture's environmental footprint and undo the damage done by the sector to national and global natural resources. Reining in on-farm greenhouse gas emissions is an important component of efforts to achieve these policy goals. Even so, robust and productive food systems have been, and will continue to be, a foundation of shared economic prosperity. Put differently, the results from this paper illustrate the crux of a dilemma that confronts policymakers as they strive to develop and hasten the adoption of agricultural technologies that are both less polluting than current technologies and more productive.

What then are possible policy interventions? One potential point of intervention is to change the underlying relationships among income, food waste, and consumption, especially the consumption of animal protein. Research shows that the climate impacts from changing diets can be large (Carlsson-Kanyama 1998; Ivanova et al. 2020) and that many of the changes that benefit the climate also improve health outcomes (Springmann et al. 2016; de Pee et al. 2021). The research shows that cultural differences influence animal protein consumption in ways that are persistent over extended periods of income growth, and that these matter for emission levels. Consequently, changing habits can have enduring impacts. That said, while research shows that interventions can shape dietary choice, it remains an open question as to

whether policy interventions can produce impacts at scale (Joyce et al. 2012; Bauer and Reisch 2019; Murayama et al. 2023).

A second set of potential interventions are aimed at modifying the underlying technologies used to produce rice and animal protein. This is a traditional type of agricultural policy intervention that has in the past been used to fuel productivity gains, primarily through public investment in research and extension (Rosegrant and Evenson 1992; Alston and Pardey 2014; Deng et al. 2021).

To a significant degree, the public and private institutions built up over decades are currently turning their attention to alternative technologies that reduce on-farm emissions, including specific efforts to reduce the emissions from rice paddies and livestock waste. For example, in the case of rice, research shows that paddy emissions can be greatly reduced by using new cultivars, by employing alternative irrigation practices, and by better managing soil fertility (Jiang et al. 2017; Liu et al. 2019; He, Wang, and Cui 2020; Chen et al. 2021; Cheng et al. 2022). Ways of reducing livestock emissions include improving productivity to reduce herd sizes, altering animal diets to reduce emissions, better managing animal wastes, and converting animal wastes to biomethane (Garnett 2009; Chadwick et al. 2011; Gerber et al. 2013; Herrero et al. 2016; Ferreira et al. 2019; Oehmichen, Majer, and Thrän 2021; Panchasara, Samrat, and Islam 2021; Seyedin et al. 2022).

To be clear, many promising technologies have yet to be proven in the field. And, even for proven technologies, there is likely a long leadup before the technologies can be impactful. In the case of the early Green Revolution crops, the new technologies were embodied in seeds and worked well on most farms. However, the technologies disseminated over decades and are still not fully adopted by poor households in some places (Gollin, Morris, and Byerlee 2005; Larson and Otsuka 2013; Takahashi, Muraoka, and Otsuka 2020).

There are a number of obstacles that slow the adoption agricultural technologies, including uncertainty and risk, the capacity of dissemination networks, and constraints on the investments, public and private, needed to implement new innovations (Feder and Umali 1993; Sunding and Zilberman 2001; Chavas and Nauges 2020). Moreover, in Asia, the number of farmers that must adopt new on-farm technologies before the accumulative effects of the technologies are impactful are staggering; in 2016, FAO researchers estimated that South and Southeast Asia agricultural sectors included over 42 million farms (Lowder, Skoet, and Raney 2016). That said, in many of the study countries, policies are in place to promote equitable land rental markets, consolidated management contracts, and expand hire services, efforts which collectively lower small-farm technology adoption hurdles.

Importantly, Green Revolution technologies spread because they were profitable, since yield increases offset the additional costs of more intensive inputs. Of course, farmers did not face the costs of externalities, including water, soil, and air pollution, or the impacts of emitted greenhouse gases, when they chose to adopt the then-new technologies. Moreover, these harmful externalities remain largely unpriced, and, looking ahead, there is no clear mechanism to reward farmers for adopting technologies that are less polluting or release fewer greenhouse gases. Formal cap-and-trade markets that do price emissions are emerging globally, including in the PRC and Indonesia. But initial cap-and-trade programs in Asia and elsewhere have rightly focused on power sectors and forestry, and most exclude other types of projects, including agricultural ones. Further, lessons from the United Nations' Clean Development Mechanism illustrate the difficulties of finding ways to accurately measure, monitor, and implement agricultural mitigation projects (Larson, Dinar, and

Frisbie 2011; Jang et al. 2023). Consequently, the limited payments currently going to farmers for adopting emission-reducing technologies flow from global voluntary carbon markets, or from projects implemented by governments, NGOs, and international development banks, sources of funding that are insufficient to change Asia's large agricultural sectors.

To conclude, it was the absence of incentives for the adoption of resource-conserving technologies that helped propel growth in the emissions described in this study. Fortunately, policymakers are seeking solutions, and researchers have developed promising technologies that are resource-conserving. Even so, less progress has been made on finding incentives that would hasten adoption without unduly slowing the needed expansion of food systems and burdening low-income households with higher food costs. Hastening progress remains a difficult but urgent task.

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ANNEX TABLES AND FIGURES



Annex Figure 1: International Food Prices, 1960–2020

Source: World Bank (2023a).

Annex Figure 2: Wheat and Rice Yields for Study Countries, 1961–2020



Note: Yields are country averages weighted by harvested area. Source: FAOSTAT (2023).

	1970s	1980s	1990s	2000s	2010s	2020s
Bangladesh	-0.07	-0.07	-0.05	-0.06	-0.09	-0.14
Cambodia	-0.01	0.00	0.00	0.00	0.00	-0.02
PRC	-0.02	-0.03	-0.01	0.01	-0.03	-0.05
India	-0.03	-0.01	0.00	0.01	0.01	0.01
Indonesia	-0.02	-0.04	-0.06	-0.08	-0.13	-0.14
Japan	-1.18	-1.81	-2.06	-2.12	-1.96	-1.96
Korea, DPR	-0.06	-0.08	-0.14	-0.16	-0.10	-0.11
Korea, Rep. of	-0.31	-0.80	-1.55	-1.79	-2.44	-3.13
Lao PDR	0.00	0.00	0.00	0.02	0.04	0.05
Malaysia	-0.39	-0.94	-1.48	-1.88	-1.85	-2.17
Myanmar	0.00	0.00	0.00	0.00	0.01	0.03
Philippines	-0.08	-0.09	-0.14	-0.14	-0.17	-0.25
Sri Lanka	-0.05	-0.24	-0.35	-0.34	-0.30	-0.27
Thailand	0.11	0.11	-0.01	-0.02	-0.07	-0.15
Viet Nam	-0.03	-0.01	0.00	-0.03	-0.18	-0.32

Annex Table 1: Net Cereal Exports as Share of Domestic Production by Decade

Source: FAOSTAT (2023).

Annex Table 2: Historical and Projected Emissions from Rice and Livestock Production, by Country and Decade

	1970s	1980s	1990s	2000s	2010s	2020s	2030s	2040s
Bangladesh								
Rice	27,477,004	28,675,611	28,303,999	29,745,875	31,765,553	35,957,213	44,452,803	54,840,631
Livestock	31,080,658	29,905,256	34,048,956	37,608,584	43,562,640	64,330,464	102,852,216	149,753,280
Population	73,175,904	92,253,776	114,564,976	137,015,008	155,048,352	173,677,104	189,058,256	200,100,560
Cambodia								
Rice	5,313,463	6,074,214	7,923,387	9,796,219	12,648,395	14,654,719	17,171,543	20,462,193
Livestock	4,693,050	3,888,274	6,874,843	7,898,105	7,798,394	10,511,401	18,156,350	26,994,350
Population	6,552,594	7,053,359	10,254,200	12,910,494	15,098,833	17,018,248	18,570,760	19,816,464
PRC								
Rice	171,916,891	161,698,904	155,446,916	142,165,225	148,897,686	160,919,828	176,423,712	193,212,101
Livestock	221,116,720	249,142,640	337,540,160	372,856,384	340,923,296	391,467,264	479,327,744	547,106,496
Population	894,655,680	1,038,556,544	1,197,678,208	1,292,854,272	1,379,521,408	1,423,891,712	1,404,004,992	1,350,758,912
India								
Rice	113,945,421	119,345,932	126,828,911	129,270,951	128,365,528	145,479,793	173,526,687	206,030,615
Livestock	330,679,552	382,770,752	428,483,648	455,978,944	488,552,320	724,736,896	1,099,641,728	1,525,797,376
Population	610,566,336	755,640,448	936,192,384	1,125,453,696	1,297,944,320	1,436,767,104	1,551,418,112	1,640,595,712
Indonesia								
Rice	49,610,676	56,273,276	65,146,028	69,429,093	67,600,258	70,227,783	82,883,516	96,349,004
Livestock	20,691,836	27,006,510	37,152,184	36,508,764	48,419,520	75,318,144	106,940,584	156,405,024
Population	128,064,520	160,395,072	193,369,200	224,471,296	254,433,344	278,867,680	298,181,504	312,742,688
Japan								
Rice	15,822,022	13,329,384	11,948,595	9,903,025	9,261,529	8,247,230	7,507,757	6,909,677
Livestock	10,099,059	12,363,032	12,985,561	11,884,995	10,842,918	10,247,896	9,004,415	7,607,968
Population	110,868,184	120,003,456	124,887,104	127,468,464	127,440,224	122,928,232	115,979,024	107,809,560
Korea, DPR								
Rice	2,947,835	3,235,307	2,958,635	2,870,124	2,604,958	2,644,105	2,885,281	2,971,795
Livestock	2,070,788	2,846,824	2,413,925	2,275,063	2,422,451	3,241,744	5,294,841	7,078,865
Population	16,347,322	18,928,652	21,857,914	23,861,542	25,086,956	26,172,078	26,577,932	26,177,024
Korea, Rep. of								
Rice	7,097,113	7,251,642	6,657,047	5,946,460	4,844,023	3,929,490	3,398,192	2,849,475
Livestock	3,185,311	4,709,070	6,366,086	6,089,863	8,276,024	11,901,213	16,485,190	20,982,290
Population	35,163,744	40,319,696	45,024,356	47,551,968	50,235,432	51,718,580	50,731,748	47,822,588

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	1970s	1980s	1990s	2000s	2010s	2020s	2030s	2040s
Lao PDR								
Rice	1,738,984	1,822,447	1,613,259	2,047,174	2,480,456	2,827,703	3,636,823	4,531,318
Livestock	2,331,740	3,267,481	4,682,494	5,066,269	6,580,103	9,560,184	14,567,866	22,489,628
Population	2,937,464	3,616,437	4,736,836	5,733,072	6,655,238	7,680,407	8,622,769	9,442,267
Malaysia								
Rice	3,610,564	3,393,738	3,415,034	3,379,898	3,390,046	3,430,320	3,791,989	4,152,811
Livestock	2,013,384	2,529,726	2,844,425	3,130,457	3,468,058	4,288,314	6,012,087	7,573,472
Population	11,372,153	14,578,025	19,360,580	25,026,128	30,349,088	34,467,032	37,668,100	40,113,788
Myanmar								
Rice	21,266,883	20,249,306	23,233,372	30,754,026	31,565,799	33,491,730	40,212,223	47,795,576
Livestock	18,232,322	23,398,878	24,499,912	30,608,212	44,002,244	67,260,888	112,533,000	194,920,880
Population	29,743,794	35,827,916	42,042,452	47,032,564	50,847,096	54,742,988	57,847,536	59,568,624
Philippines								
Rice	32,641,128	31,471,126	32,876,410	38,638,479	43,488,625	52,589,546	68,135,016	90,828,826
Livestock	13,911,733	12,507,439	13,302,643	16,297,156	15,720,786	20,192,338	27,170,684	33,190,114
Population	41,496,712	52,901,988	67,040,932	83,764,608	100,619,312	118,233,480	135,090,144	150,977,648
Sri Lanka								
Rice	2,115,668	2,407,640	2,329,219	2,573,042	3,120,483	3,581,373	4,329,467	5,240,913
Livestock	3,464,693	3,823,570	3,515,017	2,072,458	2,187,766	2,666,684	3,337,182	3,997,298
Population	13,410,311	15,752,393	17,858,308	19,418,026	21,124,884	21,907,160	22,244,890	22,099,092
Thailand								
Rice	34,837,970	41,743,593	41,496,533	45,471,455	49,778,111	49,996,358	55,135,380	58,951,418
Livestock	21,035,034	22,565,506	22,636,464	16,595,767	15,781,526	17,698,438	22,074,116	25,016,964
Population	39,849,916	49,125,996	58,134,764	64,976,572	69,642,096	71,783,616	71,804,152	69,664,328
Viet Nam								
Rice	25,007,983	27,922,699	32,671,451	36,805,914	38,006,444	40,755,009	48,528,961	56,754,437
Livestock	10,175,200	12,553,874	16,675,960	22,162,428	23,857,598	40,406,844	79,335,880	133,119,944
Population	46,088,252	57,783,124	71,609,664	81,882,536	90,731,296	99,019,600	103,991,440	106.506.040

Annex Table 2 continued

Annex Table 3: Number of Buffalo per Capita, by Country and Decade

	1970s	1980s	1990s	2000s	2010s	2020s	Total
Cambodia	0.096	0.078	0.072	0.053	0.045	0.041	0.064
PRC	0.019	0.019	0.018	0.018	0.020	0.019	0.019
India	0.097	0.095	0.091	0.088	0.083	0.079	0.089
Indonesia	0.020	0.018	0.016	0.010	0.005	0.004	0.012
Japan	-	_	-	-	-	_	-
Korea, DPR	-	_	-	-	-	_	-
Korea, Rep.	-	-	-	-	-	-	-
Lao PDR	0.237	0.256	0.235	0.190	0.176	0.169	0.210
Malaysia	0.025	0.016	0.008	0.005	0.004	0.002	0.010
Myanmar	0.056	0.057	0.052	0.057	0.060	0.037	0.053
Philippines	0.091	0.054	0.040	0.038	0.029	0.026	0.046
Sri Lanka	0.058	0.058	0.040	0.016	0.016	0.015	0.034
Thailand	0.142	0.121	0.067	0.026	0.018	0.012	0.064
Viet Nam	0.049	0.044	0.040	0.035	0.028	0.024	0.037