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Comparative assessment of pollution by the use of industrial agricultural fertilizers in four rapidly developing Asian countries

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Abstract This article describes a study of the environmental impacts of the use of industrial agricultural chemicals in four Asian countries—China, India, the Philippines and Thailand. The objective was to contribute objectively to the discussion on the extent of the problem, past and current damages to the environment to and outline possible paths to sustainable and environmentally benign agriculture. The four countries are experiencing rapid economic growth under a tremendous population growth pressure that, with the exception of China, will continue without leveling of in a foreseeable future. This requires more food production that has been accomplished by the increased use of industrial chemical fertilizers. Although the four countries uses of industrial chemicals vary, the mix of nutrients appears to be imbalanced, resulting in large nitrogen losses into the environment, especially in China. A suggested solution of the problem begins with reducing (China) or maintaining (India, the Philippines, Thailand) average nutrient application levels needed by the crops and includes optimal hybrid agriculture by using organic

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fertilizers, and fertilizers in the irrigation water already overloaded with nitrogen. There is a need to balance fertilizer N and P applications with the crop needs.

Keywords Agricultural pollution · Green Revolution · Nitrogen · Phosphorus · Fertilizer application · Organic farming · China · India · The Philippines · Thailand

1 Introduction

In the last 40 years, global agriculture has undergone dramatic changes both in the developed countries of Europe, North America, Asia and Australia, and in the developing countries throughout the world. The arable area was increased by conversion of pristine lands (prairies, forests, arid lands) to agriculture, and yields have been raised by enormous increases in the use of chemical fertilizers and pesticides, by mechanization, and, in many countries, by conversion of farming to large agricultural enterprises either by economic expansion or by nationalization. This process is known as intensification and industrialization of agriculture. In the historically short period of about 40 years, threat of famine was averted in some regions of developing countries. However, the number of hungry people in the world continues to increase, reaching almost 1 billion people in 2008 (FAO 2008). Lack of access to land and rising price of seeds and fertilizers needed under the industrial agriculture model prevent poor farmers from increasing food production in developing countries (FAO 2008).

Extensive evidence shows that intensification and industrialization of agriculture have caused damage to the environment on a global scale. Agriculture uses over 70% of the world fresh water resources, most of it for irrigation (Postel 2001). It is responsible for about a fifth of global greenhouse gas emissions (IPCC 2007), and more than 13 million hectares of tropical forests are being lost each year, mostly converted to agriculture (FAO 2006). India and China are currently the largest users of irrigation water; however, the quality of surface water resources has diminished due to eutrophication and sometimes hypereutrophic conditions (dense algal blooms), and pesticide contamination. Excessive nitrate contamination has damaged groundwater resources. Since ground and surface water resources are interconnected, high loads of nitrate in base flow are common.

Four rapidly developing countries of south and Southeast Asia, China, India, the Philippines, and Thailand, are experiencing population and economic growth, following the footsteps of the more advanced Asian countries of Japan, Korea (democratic), and Singapore. China today has the third-largest economy after the US and Japan. The Chinese economy has been until 2007 growing at an annual pace of more than 11%, compared to an average of 0–3% in most developed countries. Even in 2009 during the worldwide recession, Chinese Prime Minister predicted the growth of China's economy by 8% (Barboza 2009). China is predicted to be the largest economy in the world by 2030 (http://www.economist.com/countries/China/) based on pre-2007 predictions and perhaps even earlier based on the new post 2008–2009 economic situation. India's development is similar to that of China. China and Thailand are among the top ten countries based on economic growth; China is second and Thailand is ranked eleventh with a sustained high growth. Economic growth and the intensification of agricultural production, considering the regional exponential population increase, have rescued several hundred million people from poverty. However, China and India combined still account for 42% of the chronically hungry people in the developing world (FAO 2008). India is home to the world's largest food insecure population, with more than 200 million people who are hungry (FAO 2008). The basic demographic, land use and agriculture and chemical applications of the four investigated countries are given in Table 1.

This article assesses the environmental consequences of the use of agricultural chemicals in the four rapidly advancing countries: China, India, the Philippines, and Thailand. These countries have politically quite different systems; China has mostly a hybrid socialist/capitalist one-party system that after the economic reforms in the 1980s has been opening its economy to capitalist-free market system. In the last 40 years, after the formation of the Peoples Republic in 1949, China has undergone tremendous political

Table 1 Basic characterization of four assessed countries 2005–2007 level

Characteristic	China	India	Philippines	Thailand
Population (millions)	1,319	1,120	88.7	65.3
Annual population growth (%)	0.59	1.8	2.6	0.68
Population in agricultural sector				
(%)	61	49	37	65
(Population millions)	808	550	32.9	24
Total area (thousands km^2)	14,330	3,288	300	514
Land (thousands km^2)	9,600	2,973	298	510
Land in crops				
(thousands km^2)	1,548	1,695	107	176
(%)	16.1	57	36	34
Main crops	Rice, wheat, maize, cotton, oil seeds, tea	Rice, wheat, maize, cotton, oil seeds, tea	Rice, corn, coconut, sugarcane, banana, pineapple, mango, cassava, coffee, abaca	Rice, rubber, corn, sugarcane, coconuts, soybeans
Area irrigated				
(thousands km^2)	566	558	–	45
(%)	36.4	38		26
Area organically farmed				
(thousands km^2)	30	25	0.141	0.13
(%)	1.94	1.7	0.12	0.07
Industrial fertilizers use[a]				
(thousands tons)	494,730	18,399	745	1,788
(kg ha^{-1} year^{-1})[b]	321	108	70	101
Industrial pesticide use				
(thousands tons)	1,460	47	22.5	131
(kg ha^{-1} year^{-1})[b])	9.4	0.3	2.1	7.3

Various national and FAO (Food and Agriculture Organization of UN) open file statistics

[a] Fertilizer total as N, P_2O_5 and K_2O as of year 2005

[b] Per hectare of cultivated land. Total fertilizer is a sum of nitrogen, phosphorus and potassium

changes, and today it is a fast-growing economic giant. India has been a democracy since the end of the colonial rule in 1947, and its economy is also growing at a fast pace. US occupation of the Philippines ended in 1946, but the country had dictatorial regimes thereafter until the government of the President Aquino took power, and the democracy was installed 20 years ago. Thailand has been a constitutional monarchy.

In the last 40 years, damaging land use changes to agriculture, aquaculture and urbanization, along with enormous amounts of industrial chemicals put onto the land have changed the environment of the developing countries in the same way or more as the land development in the US and other developed countries. However, in the developed countries, rapid adverse land use changes began at the onset of industrialization 200 years ago. In the case of developing countries, urban sprawl, with interspersed small-scale industries coupled with rather inadequate facilities, extremely poor management of wastes generated (liquid, solid, or gaseous), and intensification of agriculture make these the largest and the most critical sources of diffuse pollution of land and waters, soil and vegetation contamination (Bendorichio and Jorgensen 2000; Agrawal and Trivedi 2001).

1.1 Land use conversion

Historically, agriculture has been responsible for a large part if not the most (historically over centuries) of natural land and habitat losses and fragmentation that threaten the world's forests, biodiversity, and atmospheric greenhouse gases imbalance. Matson et al. (1997), quoting Meyer and Turner (1992), estimated agricultural cultivated land expansion between 1700 and 1980 by 466%.

In India and China, agricultural land was quickly turned in production decades ago and, currently, no more suitable land is available for conversion. In China, the cropland (arable land plus permanent crops) area has actually decreased from late 1950 (pre-Great Leap Forward period) when it exceeded 2 million km^2 to today's level of 1.55 million km^2. In the 1990s, there was much discussion among scientists as to what is the crop land area in China because the numbers reported from China appeared to be underestimated by as much as 40% (Smil 1995; Fisher et al. 1998). The numbers in this article reflects the recent corrections (Liu et al. 2005). In India, agricultural land area is relatively stable, but land conversion was significant in the decades following gaining of their independence. A similar situation occurred in the Philippines where land transformation to agriculture has leveled after the 1970s. However, the government has recently initiated a program of converting coastal areas (often with mangrove wetlands) and marginal lands to agriculture, which will cause large losses of biodiversity and ecosystem services destruction. This program should be discouraged. Farmers in Thailand still practiced slush and burn land conversion practice as recently as the 1990s (Fig. 1), and conversions of coastal mangrove wetlands to aquaculture are common. Slush and burn land use transformation releases large quantities of CO_2 greenhouse gas into the atmosphere that is only partially offset by carbon sequestration by subsequent farming.

2 Agricultural sustainability and pollution

2.1 Green Revolution

The intensification of agriculture in the last 50 years by changing farming practices and by introducing agricultural chemicals—fertilizers, herbicides and insecticides dramatically

Fig. 1 Slash and burn land conversion to agriculture in Thailand in 1990s (courtesy Nitayaporn Tonmanee)

increased agricultural production and productivity in all four countries, which have been able to provide food for a much larger population. However, still about 45% of the world's undernourished people live in these four countries (FAO 2008).

The "Green Revolution" was a planned international effort funded by the Rockefeller and Ford Foundations and governments of many developing and developed countries. Late N. E. Borlaug is considered the father of the Green Revolution for which he received a Nobel Prize in 1970. The purpose of this effort was to eliminate hunger by improving crop performance. The yields were dramatically increased by:

- New crop cultivation methods
- Large applications of chemical fertilizers and pesticides
- New crop varieties that perform best with chemicals
- Irrigation
- Mechanization

The Green Revolution was made possible by the discovery of the Haber–Bosch process that produces synthetic nitrogen fertilizers from atmospheric nitrogen and hydrogen from a hydrocarbon source, mostly natural gas—methane (Smil 2001). Later inventions enabled to convert the synthetically produced ammonium to nitrate. However, producing synthetic nitrogen fertilizer by H–B process uses approximately 1.2% of the world's fossil fuel and may contribute to greenhouse gas emissions in a form of residual methane and carbon dioxide releases. In addition, agronomist developed new seeds for crops that are more efficient in the use of these synthetic fertilizers than the traditional organic fertilizers produced on the farm. In the last 40 years, the Green Revolution has increased food production per hectare several times, and worldwide caloric consumption per capita, in spite of the accelerated population growth, increased 25%. On the worldwide scale, 690 million tons of grains were produced in 1950, compared to 1.7 billion tons of grain at the end of the last century (ActionBioscience 2002). By the 1990s, almost 70% of Asian rice areas were sown with new "Green Revolution" varieties, and almost half of wheat planted in Africa, more than half in Latin America and Asia, and more than 70% of world corn

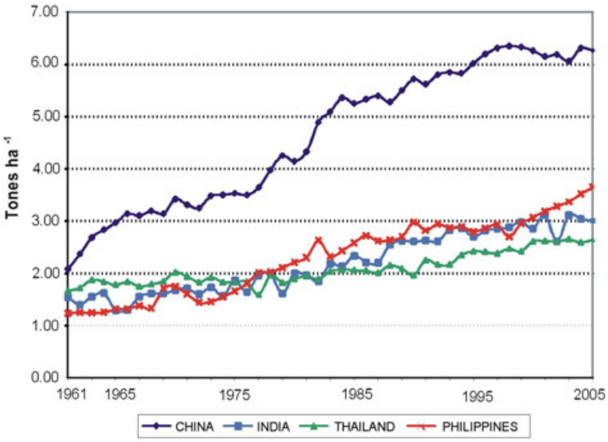

Fig. 2 Increased yields of rice in China, India, the Philippines, and Thailand plotted with the annual application rater in kg/ha (replotted from International Rice Research Institute 2007)

(Rosset et al. 2000) were of the new varieties. In the 1990s, the success of the Green Revolution in increasing food production spilled over to China, which is now the world's largest producer of food. Smil (2001) claimed that almost 40% of world population had been saved from deadly famines because of the Haber–Bosch process of synthetic nitrogen fertilizer production that enabled intensive agriculture.

Figure 2 presents the increase of rice yields in the four Southeastern Asia countries featured in this article. However, in spite of large increases in food production, world hunger still affects close to 1 billion people, 45% of people who live in the four countries studied here (FAO 2008). The Green Revolution has also brought intense negative environmental impacts that threaten the capacity to sustain further agriculture developments.

2.2 Environmental consequences of increased industrial fertilizer use

The enormous increase of the use of fertilizers in the world (see Fig. 3) did not result in the corresponding increase in yields. As Fig. 4 shows and as pointed out by other authors (Tilman et al. 2002), the yields per unit of fertilizer applied have been decreasing since the 1960s. A simple mass balance shows that not all of the increased applications of industrial fertilizers are converted into food biomass. In the National Water Quality Assessment (NAWQA) program by the US Geological Survey (1999), it was found that 20% of applied phosphorus and about 50% of applied nitrogen to land in 20 investigated watersheds in Oregon reached the receiving water streams as N and P loads. Both nutrients accumulate in soils and nitrate nitrogen concentrations increase in ground and surface water resources and coastal waters. N and P are incorporated into the plant and cereal biomass. Therefore, the decreasing yields per unit mass of fertilizer imply increasing fertilizer losses into the environment and loss of the organic matter (organic C) which retains and adsorbs NH_4^+ (ammonium) nitrogen, phosphorus, and most pesticides, often to less than one half of the original organic soil matter content (Tilman et al. 2002; Matson et al. 1998).

Until now, the four investigated countries have focused water pollution control on point sources and reduction of loads of untreated municipal sewage and industrial sources. Generally, agricultural point sources (sewage from villages and from animal operations) are untreated or poorly treated using on-site septic disposal systems. Recently, the Chinese

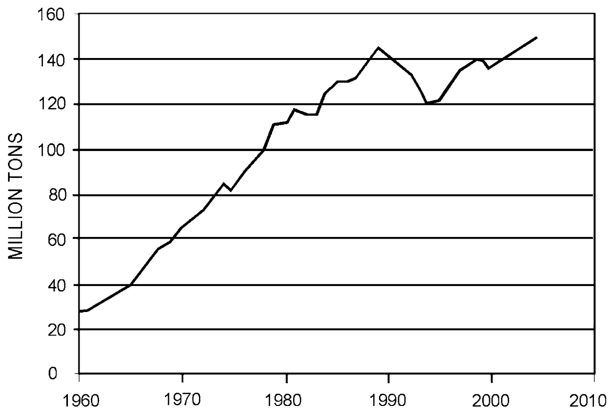

Fig. 3 World fertilizer use 1960–2004 compiled by the Earth Policy Institute from IFA and Worldwatch data

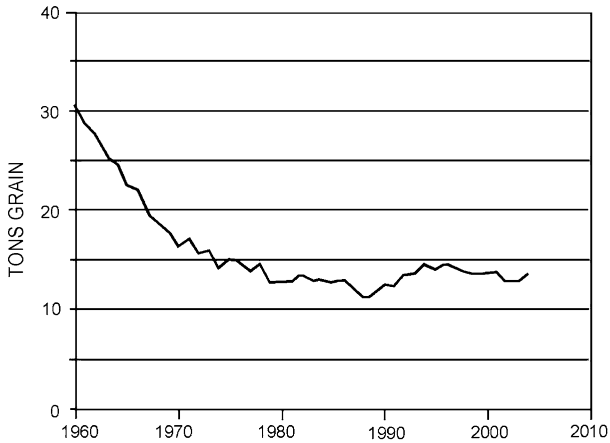

Fig. 4 Grain crop yield per unit mass of fertilizer applied compiled by Earth Policy Institute from US Department of Agriculture, IFA, and Worldwatch data

government has been providing incentives to village families in some drinking water resources protection areas to install on-site septic tank treatment systems. In Taihu (Tai Lake), Dianchi, Myiun, and other drinking water resources protection areas, some best management practices to control diffuse pollution such as constructed wetlands and stream buffer strips have been installed. On the other hand, soil conservation practices (strip cropping, no-till practices, conservation tillage, alternate meadows), with exception of terracing, that can play an important role in diffuse pollution control are not widespread.

The impact of pollution caused by the use of agricultural chemicals, primarily fertilizers, is high in China and extends nationwide (Zhu et al. 2005). More than 70% reservoirs and lakes are exhibiting various stages of excessive eutrophication. About 60% of N and P loads into Chinese surface waters originate from nonpoint sources and are derived mainly from excess fertilizer applications, which today are primarily from synthetic fertilizers. About one half of monitored groundwater sites exceeded the WHO criterion guideline for drinking water of 50 mg NO_3^- L^{-1} (CCICED 2004). Most of the water pollution in the other three countries is primarily from point sources that are largely untreated.

In India, the information and the quality of the available data is not as good as in China. However, average groundwater nitrate pollution above 50 mg NO_3^- L^{-1} has been measured in 11 states, and some very high maximal concentrations exceeding 100 mg/L were measured in 12 states (Majudmar and Gupta 2000). Although national average of synthetic fertilizer application rates in India are relatively low, around 100 kg ha^{-1} $year^{-1}$ as a total of N + P + K, in some regions N application rates are in great excess, e.g., ~250 kg N ha^{-1} $year^{-1}$ in Punjab (Pathak et al. 2006), and have been linked to nitrate pollution in the groundwater (Singh and Sekhon 1976, Singh et al. 2006). N and P pollution in Indian rivers less impacted by nonpoint (diffuse) sources is generally low and most originates from point sources. One reason for the lack of knowledge is the Indian perception that eutrophication and algae blooms do not represent water pollution (Agrawal 1999).

In the Philippines, most groundwater nitrate concentrations were measured as being less than 2 mg NO_3 L^{-1} (Bouman et al. 2002). The Philippines receive high rainfall precipitation that may provide more dilution. In Thailand, most of the surface waters have higher BOD, ammonium, suspended solids, and fecal coliform concentrations. Forty percent of surveyed surface water bodies had poor or very poor water quality. Many reservoirs are eutrophic and hypertrophic exhibited by cyanobacteria blooms (Simachaya 2002). N fertilizer consumption in Asia has grown dramatically in the last 40 years. Average fertilizer application rates in the Philippines and Thailand are relatively low compared to more industrialized countries (see Fig. 5). However, averages can be misleading since application rates vary very much among regions, crops, and farming practices, and rates are increasing rapidly in some regions of developing countries. Recent preliminary analysis in regions with high fertilizer use suggests high nitrate pollution of drinking water from artesian wells in agricultural areas in the Philippines and Thailand, often higher than the WHO safety limit of 50 NO_3 L^{-1} (Tirado 2007). It is usually believed that fertilizer use is low in the Philippines and Thailand, as represented by average estimates. There is some evidence, however, of increased use of fertilizers in highly intensified farming systems. For example, in the asparagus fields of Nakhon Pathom province, Thailand, farmers apply nitrogen fertilizers in rates close to 1,000 kg N ha^{-1} $year^{-1}$. Shockingly, only 5% of this

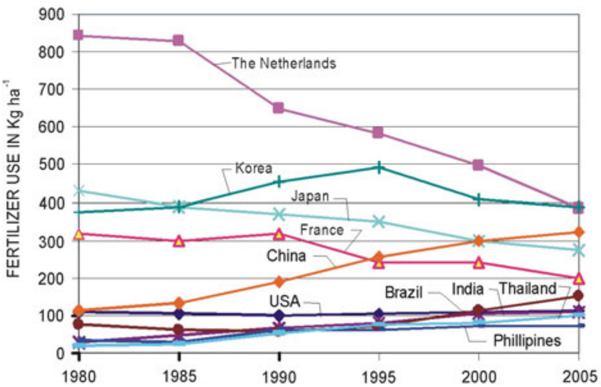

Fig. 5 Industrial annual total fertilizer applications per unit area between 1980 and 2005. Note that the trend in eight countries is converging to an optimum application rate of 100 to 150 kg of total fertilizer (N + P) per hectare. Trend of China and Brazil is increasing, while Korea's applications are high and steady. Compiled and calculated from IAIA and FAO statistical databases

nitrogen is recovered by the plant, the rest being lost to the soil, water, or air (Phupaibul et al. 2004).

When fertilizer use is decreased after its high use in the intensive agriculture, it is not accompanied by a corresponding decrease of nutrients in the receiving water bodies. Of a particulate interest is the dramatic decrease in the fertilizer applications after 1989 “velvet revolution” in the Czech Republic and political changes in the other formerly socialist countries of Eastern Europe. Therein, the government ceased subsidizing fertilizers, and the cooperatives responded by dramatic decreases of fertilizer use that, unfortunately, did not show in a corresponding rapid reduction of concentrations in surface waters. The reason is that in the preceding period the soils were overloaded by nitrogen fertilizers (Stålnacke et al. 2003; Iital et al. 2005); hence, the lag time between reduction of loads and the drop in surface water quality concentrations is long. Even more recent surveys in the Czech Republic of shallow groundwater in the watershed of the main water supply reservoir for Prague had numerous measurements of nitrate N exceeding 50 mg (NO_3^-) L^{-1} (Novotny 2009).

3 Synthesis: situation in China, India, the Philippines, and Thailand

It would be unfair to judge the use of chemicals in the four investigated countries without a worldwide context. The trends in these still-developing countries were preceded by high uses of these chemicals in other countries practicing intensive agriculture, such as the Netherlands, Germany, Japan, or democratic Korea. This combined overview can provide an insight as to where the countries may go in the future and what are the limits. Figure 5 then shows the trends in the total fertilizer unit area use in several countries. The nationwide fertilizer applications rates were calculated from the data in Tables 2 and 3. It should be noted that Tables 2 and 3 and Fig. 5 include industrial fertilizers only. Hence, these application rates are less than that the total fertilizer use in the countries with large concentrated animal herds such as the Netherlands, France, or India, where a lot of manure is disposed on land. For example, in the Netherlands, the manure application rates (Salomons and Stol 1995; Novotny 2003) ranged between 150 and 450 kg ha^{-1} $year^{-1}$.

Table 2 Total inorganic fertilizer use in ten countries (data from International Fertilizer Industry Association for China from Zhu et al. 2005; IPNI 2007)

Country	2005	2000	1995	1990	1985	1980
Total fertilizer use ($N + P_2O_5 + K_2O$) in 1,000 tones						
USA	20,090.8	19,612.7	19,266.1	18,709.4	19,688.4	20,916.8
The Netherlands	359.0	471.0	534.0	590.1	707.8	694.0
France	3,905.0	4,753.4	4,712.2	6,103.4	5,780.0	5,985.8
Japan	1,292.2	1,436.9	1,763.7	1,938.0	2,097.9	2,343.8
India	18,399.6	18,069.7	13,563.6	11,314.3	7,999.4	5,005.0
Brazil[a]	10,141.0	7,301.8	4,516.3	3,207.8	3,194.2	4,117.7
Korea[a]	712.8	783.4	979.0	957.7	836.8	825.6
The Philippines[a]	745.2	734.5	598.5	586.9	283.7	318.6
Thailand[a]	1,788.0	1,539.9	1,507.0	1,043.7	448.6	312.2
China	49,730.0	42,020.0	35,950.0	25,900	17,760.0	15,266.0[b]

[a] 2003 data have been used instead of 2005

[b] Best estimate based on several sources

Table 3 Crop land (arable land + permanent crops) in 10 countries (Source FAO Statistics, and for China Zhu et al. 2005; and Novotny et al. 2007)

Country	2005	2000	1995	1990	1985	1980
Crop land (arable land + permanent crops) in 1,000 ha						
USA	177,178	178,068	184,139	187,776	189,799	190,624
The Netherlands	941	944	916	909	855	822
France	19,635	19,582	19,493	19,190	19,242	18,872
Japan	4,692	4,830	5,038	5,243	5,379	5,461
India	169,650	169,755	169,750	169,438	169,015	168,255
Brazil[a]	66,600	65,200	65,500	57,408	53,241	52,864
Korea[a]	1,835	1,918	1,985	2,109	2,144	2,196
The Philippines[a]	10,700	10,650	9,900	9,880	9,750	9,628
Thailand[a]	17,687	19,245	20,410	20,603	19,847	18,298
China	154,872	141,100	139,400	138,400	132,000[b]	132,000[b]

[a] 2003 data have been used instead of 2005

[b] Best estimate based on several sources

Currently in China, the proportion of the industrial and organic fertilizers is about 75% inorganic and 25% organic (IPNI 2007). Hence, of the total fertilizer application rate of 426 kg ha^{-1} year^{-1} in China (based on 2005 data), 321 kg ha^{-1} year^{-1} is the application rate of industrial fertilizers and 105 is manure. The N:P ratio for manure is approximately 100:30 (Eghball and Power 1999). There seems to be a disparity of as much as 20% between various sources of information. A much larger proportion of organic fertilizers, but not exactly known how much, may be typical for India.

What is revealing in these statistics is the fact that industrial fertilizer use in India, the Philippines, and Thailand is actually on the low side when compared to the more advanced countries with intensive agriculture. It appears to be today near or below the optimum when compared to the crop requirements for the total fertilizer input (set by fertilizer manufacturers associations) being around 120–150 kg ha^{-1} year^{-1} for N and 60 kg ha^{-1} year^{-1} for P_2O_5 (see Table 4). The manufactures' application rate recommendation for developing countries is higher than that reported in the US. China's application rate of industrial fertilizers is high, approaching rapidly the level of the Netherlands, democratic Korea, and overtaking Japan's rate. What makes China and, potentially, the other three countries different from the more advanced countries is the trend which is increasing, while in the other high-use countries, with exception of Korea, the trend is decreasing. It is important that China reverses the trend, and India and Thailand

Table 4 General fertilizer applications by fertilizer industry for India recommended by the fertilizer industry (www.fertilizer.org/ifa/publicatt/bap/india.asp)

Crop	N (Kg ha^{-1})	P_2O (Kg ha^{-1})	K_2O (Kg ha^{-1})	Total (Kg ha^{-1})
Rice	120–150	60	40–60	220–270
Wheat	120	60	40–60	220–270
Maize (corn)	120	60	60	240
Pulses	10–20	30–50	20–25	60–95
Cotton	80	60	40	160

should not increase fertilizer use beyond today levels and focus on optimization, including optimum proportions of N, P, and K, and reduction of losses. The Philippines may actually be below the optimum. However, optimal loadings should be determined by agronomy scientists. Note that averages can be misleading since application rates vary very much among regions, crops, and farming practices, and rates are increasing rapidly in some regions of developing countries. In China, in high intensity agricultural areas, total fertilizer application rates exceed 1,000 kg ha^{-1} of N in a year.

The trend in the Netherlands is an example of a country with the highest agricultural productivity in cash crops (flowers), cattle, and dairy products. It was recognized that more than a decade ago the soils of the country were oversaturated with fertilizers and manure (Salomons and Stol 1995), which was causing environmental damage to water resources and potentially the Dutch population. Consequently, the Dutch government took action and instituted strict limits on the application of fertilizers on land. However, the nitrogen excess in the Netherlands is still not solved, and the country continues to have the highest intensities of nutrient surpluses across OECD countries (OECD 2008).

3.1 Imbalanced fertilizer use

In most developing countries, the bulk of fertilizers used to grow crops, fertilize orchards and flower fields comes from industrial fertilizers containing mostly urea and ammonium. The general fertilizer ratio of N:P:K recommended by agronomists and soil scientists is 100:60:40. However, the application ratio of nutrients in China in 1980 was 100:30:4 (resembling manure), improving to 100:39:24 in 2003 (National Bureau of Statistics 2006, see also Williams 2005). Thus, the mixture is deficient in phosphorus, and the growth is phosphorus limited. This results in excess nitrogen being released to the environment. Most of the nitrogen fertilizer used in China is in a form of urea or ammonium bicarbonate that can be readily decomposed to soluble ammonium ion (NH_4^+). By nitrification in aerated soils, ammonium is converted to highly soluble nitrate. Because, plant growth is related to the element that is in the shortest supply, which is P, excessive N losses into the environment are widespread in China, and on a regional scale in the other three countries. If excess N is applied, it becomes pollution. N adsorbed on soils (organic N, a part of ammonium) can move to receiving waters with eroded soils, highly mobile nitrate moves with water. Gaseous nitrous oxide (NO_x) or ammonia gas (NH_3) can volatilize from soils. These processes depend on the pH of the soil.

Information is incomplete on the additional N supplied by soy and other N fixing legumes. Worldwatch Institute (http://www.worldwatch.org/node/5442) found that until 2005 China imported 74% of its soy from abroad and was the largest importer. Both Thailand and the Philippines also import soy. India produces about 7 million tons of soy (<1/10 of US production). The natural atmospheric N fixation by plants was not included in the analyses of this article.

Figure 6 shows the food production and the total application of fertilizers in China. It is interesting to see that the line representing food production is parallel to that of P application. The slope for the N fertilizer application is greater than for food production, which indicates that P is the limiting growth nutrient and nitrogen is applied in excess on a countrywide basis. This figure also shows that until about 1981, most of the fertilizer application increase was in N forms, but there was enough P in soils to sustain the increase. The food production increase was proportional to N application. The situation has changed after 1980 when food production became limited by P and N was in excess. The excess N

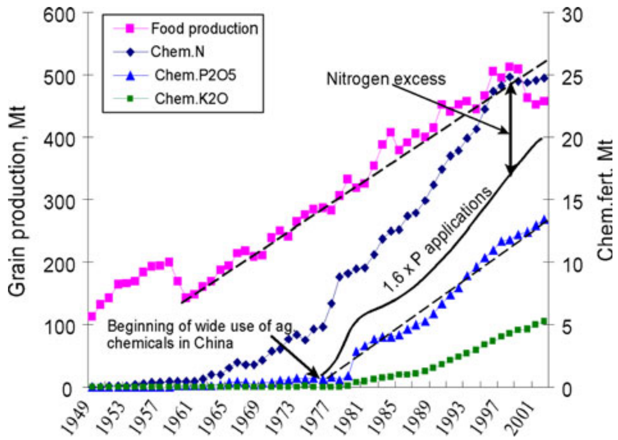

Fig. 6 Grain food production and chemical fertilizer use in China between 1949 and 2003 (modified from Zhu et al. 2005)

mostly entered the environment (ground and surface waters). Unlike N, P is a finite nutrient and is becoming limited worldwide (Barnard 2007).

The N/P/K balance must be optimized. Unbalanced use of industrial fertilizers in China and in most of Asia has been considered the biggest factor leading to widespread nutrient (phosphate, organic carbon) depletion of soils in Asia. The imbalanced high use of nitrogen is troublesome in China and impeding higher yields in the Philippines. The high yields made possible with high N applications have had the effect of removing P and K elements in the straw, stalks, and grains at harvest and depleted soils to the detriment of subsequent crops. China, India, and the Philippines have an excess of N but deficiency of P and K. Thailand is deficient in K (www.agnet.org/library/ac/1995e).

4 Is the goal of sustainability achievable?

Sustainable development has been defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al. 1987). In elaborating concepts of sustainable development, the literature has emphasized that people—including farmers and the society as whole—are participants in an ecosystem, and that they are ultimately dependent upon the renewability of the ecosystem resources and services. The conflict between the increased population and sometimes frantic effort of governments in the countries with the rapid population increase to prevent famine, feed the increasing number of people and still maintain resources for future generations, makes "sustainable development" a main focus and challenge of the twenty-first century. The science of the sustainable development in agriculture under pressure of increasing population is still developing and will require rethinking of the current paradigm of intensification of agriculture and the unrestricted and rampant urbanization. Today, in the US and other developed countries, pristine and cultivated lands are being converted to urban zones by urban sprawl. Building the new suburbs and satellite cities are proceeding at a rapid pace equaling or exceeding the conversion to agriculture centuries ago.

We have suggested that the 100 kg N ha^{-1} year^{-1} of the average industrial fertilizer application balanced between the nitrogen and phosphorus should be the first step goal to be achieved in China and Thailand. India and the Philippines should keep their total application rates at the present level but adjust the proportions between N and P. This is supported by the experience of US farmers, and the trends in some developed countries that in the past were over applying fertilizer to crop needs. Soil overloading is especially troublesome in China (as it has been in The Netherlands). The beginning point of the analysis is the mass balance of nutrients from all sources related to the recommended crop (total) nutrient requirement. These are obviously not uniform and must be locally established. The fertilizer industry has published several guidelines that generally specify the range of (balanced) fertilizer application at around 150 to more than 200 kg ha^{-1} annually, but has recommended the upper levels of N, P, and K to developing countries. For example, Table 4 shows the recommended fertilizer application for both of organic and of industrial fertilizers recommended for India.

A study conducted at the University of Missouri, synthesizing results of research on a large number of controlled experimental plots with different types of soil (Scharf et al. 2005), suggested an application rate of 100 kg N ha^{-1} year^{-1} for corn as the optimum limit. This research clearly documented that the response of the crop yield to the magnitude of the fertilizer application is not linear, and the level beyond *limiting N rate* which for the corn growing site depicted in Fig. 7 was around 120 kg N ha^{-1} year^{-1} for corn. This is represented on the figure by the dashed line. The limiting value ranged from 60 to 200, which indicates that a soil survey should precede the applications. The limiting value also depends on whether or not legumes (e.g., soy) were sown in the preceding year. Legumes (e.g., soy beans) can naturally replenish nitrogen in the soil.

A better idea about the meaning of the limiting value concept can be gained by plotting the marginal rate curve. The marginal rate is obtained by estimating the increase in the yield in kg of corn per kg of extra N applied at a given rate of N application. This concept is similar to the marginal rate of the price or cost increase in economics. It could be seen that between the application rates from 0 to 50 kg N ha^{-1} year^{-1}, the farmer is "rewarded" by a yield increase of 88 kg of corn for each extra kilogram of the N fertilizer applied. The rate at which the yield per extra unit of fertilizer begins to drop off could be

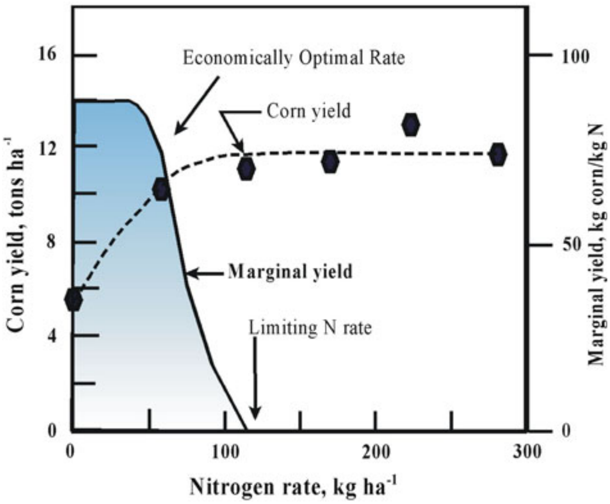

Fig. 7 Concept of the economical and environmental (sustainable) annual fertilizer application rate and effect on annual corn yield (adapted from Scharf et al. 2005)

called the *economically optimal rate*. Below that rate, it is hypothesized that the environmental impact will be minimal, because most of the nutrient applied will be converted to organic N in the corn and will be slowly released into the environment. Above the application rate of 50 kg N ha^{-1} $year^{-1}$, the marginal rate drops rapidly to zero at 120 kg N ha^{-1} $year^{-1}$, and the environmental damage (social cost) begins to increase proportionally to the excess N application. If a farmer wants to get a maximum yield at a minimum cost, he/she should not apply more than the limiting N rate because most of the excess N application over the limiting rate would end up in the environment.

4.1 Total mass balance

For a mass balance of fertilizer application, in addition to the economical and limiting rates, it is necessary to include all sources of fertilizers, not just from chemicals. For example, if the groundwater under the irrigated fields contains 10 mg/L of nitrate N, then this could represent a very significant source of N and, possibly, a mechanism for nitrogen removal from the shallow groundwater zones. If stalks of the crops are left on the field and plowed in the soil after harvest or no-till planting is used, the nutrient crop requirement can be cut approximately by half.

The following example illustrates how the goal of reaching of 120 kg ha^{-1} $year^{-1}$ of N and 60 kg ha^{-1} $year^{-1}$ of P for wheat can be determined. In this analysis, it is assumed that the field is irrigated by groundwater or surface water that contains 10 mg/L of total nitrogen and 1 mg/L phosphorus. The depth of irrigation is 600 mm of irrigation water in a season. Hence, the contributions of N and P from irrigation are 60 kg ha^{-1} $year^{-1}$ of TN and 6 kg ha^{-1} $year^{-1}$ of TP. The farmer has an option to use also organic manure or compost in which the proportion of N:P is 100:30 (Eghball and Power 1999). The calculations of the fertilizer needs for a field irrigated with groundwater and rainwater are below:

Calculation of fertilizer need for crop irrigated by groundwater with high nitrogen content

Crop wheat: irrigation	N (kg ha^{-1} $year^{-1}$)	P (kg ha^{-1} $year^{-1}$)
Optimum total application	120	60
N and P from irrigation water	−60	−6
Organic fertilizer 100 kg ha^{-1} of N + P + K	−60	−24
From inorganic fertilizer	0	30
Total	30 kg ha^{-1}	

Calculation of fertilizer need for crop without tin rain fed agriculture

Crop wheat–rain water	N (kg ha^{-1} $year^{-1}$)	P (kg ha^{-1} $year^{-1}$)
Optimum total application	120	60
N and P from rain	−6	0
Organic fertilizer 100 kg ha^{-1} of N + P + K	−60	−24
From inorganic fertilizer or credit[a]	54	36
Total	90 kg ha^{-1}	

[a] No-till planting typically requires increased application of herbicides. It can be effectively used for reducing erosion on medium slope fields, but the need for more herbicide may offset the benefits of reducing nutrient requirement

It appears that the only industrial fertilizer containing P is needed for the irrigated field. In rain fed agriculture, less nitrogen and phosphorus would be supplied by precipitation; hence, both N and P may have to be supplemented by industrial fertilizer.

This simple mass balance based on current application of organic fertilizers in China proves that the goal of reducing the application rate of industrial fertilizers below 100 kg ha^{-1} $year^{-1}$ is realistic. Furthermore, by considering the N input from irrigation water in the balance, the nitrate levels of groundwater may be reduced in the long run. However, it is obvious that such calculations are field specific, and it would be the task of the village, cooperative or district agronomist and not only of the chemicals' vendors to estimate the optimal environmentally sustainable rates and proportions between organic and inorganic fertilizers and the N and P balance to be supplied by the industrial fertilizers. Vendors have an economic interest in sales and may not have the information about the chemical in the soil and groundwater. The example also shows that in areas where high nitrate groundwater is used for irrigation, high nitrogen application of additional inorganic N-containing fertilizer would actually be counterproductive and damaging. The contaminated groundwater containing high concentrations of nitrate–N is a legacy pollution that can be turned into a resource lasting for several years and so is N and P from manure or compost. This N recycle is the basic characteristics of sustainable management that emphasizes reuse.

Is organic farming the answer? Perhaps, but the Chinese experience with the famine of the Great Leap Forward in the late 1950s, during which only organic fertilizers were used, may present psychological and economical barriers. For one, it may be labor intensive to gather organic residues and manure as well as composting to provide the optimum sustainable fertilizing quantities of N and P that would sustain current high yields on the order of Green Revolution yields. Second, some high-yield varieties of crops were developed to provide high yields when only industrial fertilizers are used and chemical companies distribute the seeds. However, the mass balance analysis presented above has shown the optimum of up to the limiting application rate satisfying fully the needs of crops can be achieved with the current applications of organic fertilizers.

It is far more preferable to use organic fertilizers supplemented with industrial chemicals that balance N, P, K, and organic C than to use monofertilizer industrial chemical compounds only. If the organic C is not provided, soil C that also nurtures a healthy soil microbiological population will be reduced. One source of nutrients and carbon is dried (pasteurized) sludge from biologic municipal wastewater treatment plants. However, the N and P content of dried sludge is not very high and is even lower in the digested sludge. For example, the commercially distributed fertilizer produced from a dried (but not digested) wastewater sludge in Milwaukee (Wisconsin, USA; http://www.milorganite.com/about/history.cfm) has a content of 6% of total N (5% water insoluble nitrogen); 2.63% available phosphate (P_2O_5), and 0.4% soluble potash (K_2O). It was found that the available N generally resembled so-called high-grade organic nitrogenous fertilizers and had superior growth results compared to manure and chemical fertilizers at the time. This material could be mixed with compost, manure, and other N-, P-, and K-containing organic residues made commercially or on the farm site, forming a mixture that could work with or even replace the inorganic fertilizers. Noting that we are actually running out of natural phosphate sources, additional needed phosphorus in a form of a mineral struvite can also be recovered from municipal wastewater (Barnard 2007). Use of raw human sewage and excreta, as was done during the Great Leap Forward and is still being done in some developing countries (e.g., Mexico), is obviously not recommended. Research must be initiated and/or expanded to find the best organic fertilizer or the best combination of organic and industrial fertilizers.

A key problem that the science of agronomy has to address is the fact the current high-yield crops have been developed for intensive agriculture and not for organic farming. "Terminator" seed production and distribution technologies by distributors of industrial fertilizers and seeds prevent farmers in the developing countries to save and use their own seeds, which makes them solely dependent on the commercial distributors. Implementation of fully organic or hybrid farming must also include investment in environmentally safe manure storage, development of timing the manure application, facilities for composting, and machinery. An interesting issue with an unknown impact is the rapidly expanding use of manure for biofuel (in solid dry form or as biogas) in rural China and elsewhere. This, however, would be competing with the farm use of manure as a fertilizer. Note that this operation removes mostly organic C and, perhaps, most N and P should remain in the solids after biogas is produced or in ash after the dry manure solids are burned.

5 Conclusions

The word "green" today is associated with development that is in harmony with the environment and does not damage ecology and public health. It is a term used worldwide for the new movement toward harmonious environmental and economical sustainability. Unfortunately, this meaning of "green" cannot be fully associated with the past practices of using agricultural chemicals in the four studied countries, notably in China.

This study pointed out that the annual industrial fertilizer application rates of around 100 kg $ha^{-1}$of total N and P in industrial fertilizers is the optimum practiced in US and also in the three countries we studied (India, the Philippines, and Thailand). It is noted that generally a uniform converging trend back toward the 100 kg ha^{-1} optimum annual industrial fertilizer application rates, apparently without a reduction of yields, is observed for the advanced countries which previously overused fertilizers. Based on the current application rates, it is recommended that China reverse its trend and India and Thailand not increase fertilizer use beyond today levels and focus on optimization, including optimum proportions of N, P, and K, and reduction of losses. The Philippines may be below the optimum.

It was also documented that farmers in the four Asian countries use imbalanced applications of nitrogen and phosphorus thereby overloading the soils with nitrogen that is then released into ground and surface water resources. This deprives soils of needed and valuable P and, consequently, the increasing yields correlate to P application which is the limiting nutrient. It was also shown that if a total nutrient balance is considered, including nutrients in the legacy ground water contamination, using high doses of N-containing fertilizers may be counterproductive and lead to further environmental deterioration. Unfortunately, farmers in the developing countries generally do not have knowledge about the chemical composition of irrigations water and rely mostly on recommendations of sales people of chemicals and seeds.

With this "optimum" as a potential goal for the four countries and other developing countries of Asia, application of best management practices and integrated fertilizer management will have to be uniformly practiced and targeted to local problems (Novotny 2007; Novotny et al. 2007). The question is whether or not the first goal of across the board 100 kg ha^{-1} $year^{-1}$ industrial fertilizer application is sustainable. This has to be answered on a local scale. The current experience in some states of the US (Wisconsin, Iowa, Michigan, and others) that both practice extensive extension services to farmers by government-paid specialists and promote widespread implementation of BMPs suggests that the answer to be affirmative.

The Green Revolution as applied to agriculture is said to save saved hundreds of million of people in developing countries from starvation (Smil 2001) but it has been done at the enormous social and environmental cost. Professor Conway (1997), President of the Rockefeller Foundation, called a decade ago for new "Doubly Green Revolution" that included developments of high yield seeds, irrigation, fertilizers on one side and need for environmental protection as an integral part of these developments on the other side. Essentially, the objectives of this new "Revolution" to further increase food production by genetically altered seeds grown with industrial chemicals and protecting environment at the same time, do not address the current food insecurity, environmental deterioration and legacy ground and surface water pollution. Blackman (2000) pointed out that a doubly green revolution will require millions of poor, small-scale farmers to adopt new agricultural practices such as agroforestry, soil conservation, implementing buffer strips, and integrated pest management. The problem is that many environmentally friendly agricultural practices differ from conventional green revolution technologies in a number of ways that make them less apt to diffuse quickly. Environmental friendly practices are knowledge intensive, not chemical intensive, and thus need support from Governments in research, development and dissemination if they are to reach the farmer effectively.

New agricultural policies in the four countries are now only evolving. Policies are built on tradition, scientific knowledge, religion (in India), and common sense derived from cognitive values of people for "good". The policies may also consider the limits given by land ownership and also different political systems that projects the authority in the four countries, ranging from the hybrid socialist/capitalist system in China to democracies in India and the Philippines, to monarchy in Thailand.

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