Article

Global pesticide use: Profile, trend, cost / benefit and more

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Abstract
In present study, the data of pesticide use, crop (the total of cereals, pulses, roots and tubers, oil crops, fibre crops, fruits, vegetables, and melons, etc.) production and the area harvested of the world and major countries for the period between 1990 and 2014 were collected, organized and summarized from FAOSTAT. First I proposed an index to measure the productive efficiency of pesticide use, cost / benefit, which refers to the amount of pesticide use to produce a certain amount of crop in a year. Theoretical relationship between crop yield and cost / benefit of pesticide use is a model with the sigmoid curve: $y = a + b / (1 + e^{c-rx})$, where y is crop yield, x is cost / benefit of pesticide use. The results showed that global cost / benefit of pesticide use (total) increased with time during 1990 to 2007, and declined since 2007. Pesticide use (total) (kg / ha) had the similar trend. Global insecticides, herbicides, and fungicides & bactericides use and cost / benefit declined with time since 2007. During 2010 and 2014, mean pesticide cost / benefit was 0.645 g pesticide use (total) / kg crop production, and mean annual pesticide use (total) was 2.784 kg /ha. Mean cost / benefit of insecticides, herbicides and fungicides & bactericides use between 2010 and 2014 were 0.051, 0.16 and 0.074 g / kg crop production, respectively, and mean annual use of insecticides, herbicides and fungicides & bactericides were 0.221, 0.69 and 0.32 kg / ha, respectively. Globally, the cost / benefit of dithiocarbamates, bipiridils, carbamates insecticides, and organo-phosphates, and the use of dithiocarbamates, bipiridils, and carbamates insecticides have significantly declined since 2007, and conversely, the cost / benefit of triazoles / diazoles and the use of triazoles / diazoles, plant growth regulators, and amides, have significantly increased since 2007. Of the major countries, the averaged annual cost / benefit of pesticide use (total) of Brazil during 2010 to 2014 was the greatest (1.883), followed by Japan (1.846), Mexico (1.678), China (1.243), Canada (0.979), USA (0.8733), France (0.708), Germany (0.673), UK (0.55), and India (0.089). The averaged annual pesticide use (total) (kg / ha) of Japan during 2010 to 2014 was the greatest (18.94), followed by China (10.45), Mexico (7.87), Brazil (6.166), Germany (5.123), France (4.859), UK (4.034), USA (3.886), and India (0.261). Profile of development, production and use of pesticides in China was discussed in detail. Various trends were analysed and a variety of valuable data were provided.

Keywords pesticide use; cost and benefit; trend analysis; bio-pesticides; world.

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1 Introduction

Global croplands are not unlimited and global population grows continually (Zhang et al., 2006; Zhang, 2008). Therefore it is necessary to take all measures to increase crop production in order to ensure food safety (Zhang et al., 2007, 2011). Reducing crop loss from pest injury is one of the major tasks to ensure crop production (Peshin et al., 2009; Peshin and Zhang, 2014).

Globally, in total of approximately 9000 species of insects and mites, 50000 species of plant pathogens, and 8000 species of weeds injure crops (Zhang et al., 2011), of which insect pests caused an estimated 14% of loss, plant pathogens caused the 13% loss, and weeds the 13% loss (Pimentel, 2009a, b). Pesticide use is necessary in crop production. It was estimated that nearly one-third of the agricultural products are produced by using pesticides (Liu et al., 2002; Zhang et al., 2011). Without pesticide use, the loss of fruits, vegetables and cereals from pest injury may reach 78%, 54% and 32%, respectively (Cai, 2008). Crop loss from pest injury declined by 35% to 42% when pesticides were used (Pimentel, 1997). Fungicides were used to 80% fruit and vegetable crops in USA. The economic value of the apple was estimated to increase 1223 million US dollars by using fungicides (Guo et al., 2007). Without pesticide use, the export of cotton, wheat and soybean in USA would decline by 27% (Zhang et al., 2011).

However, pesticide overuse and pollution have increased as well (Carson, 1962; Pimentel, 2009b; Liu et al., 2008; Zhang and Liu, 2017). A government report in 2016 stated that pesticide use of Chinese farmers reached three times the global average. In 2013, Greenpeace reported that 70% of pesticide used in China was not absorbed by plants, but instead seeped into the soil and groundwater (Fan, 2017). Chen et al. (2005) reported that pesticide poisoning caused by insecticides, rodenticides, and herbicides accounted for 7.16%, 6.47%, 3.42% of the total (Zhang et al., 2011). The major pesticides for human poisonings were highly toxic organophosphorus pesticides, which accounted for 86.02% of the total cases (Zhang et al., 2011). A study published in June 2017 found nearly 3000 children were poisoned by pesticides in eastern China’s Zhejiang province between 2006 and 2015, with most cases occurring during the farming season (Fan, 2017). Global pesticide use may have resulted in biodiversity loss (Kumar et al., 2013; Zhang et al., 2011). There are more than 20000 species of bees on Earth, which pollinate more than 90% of the world's 107 major crops. However, bee populations have significantly declined in the past years. It is reported that 75% of the honey in the world has been found to have traces of insecticides harmful to bees, particularly neonicotinoids, including acetamiprid, clothianidin, imidacloprid, thiacloprid, and thiamethoxam (Harvard School of Public Health, 2015; Sheridan et al., 2017). Neonicotinoids have been identified as a key contributor to the decline in the number of bees worldwide. Furthermore, both species and abundance of insects have declined during the past decades and pesticide use was considered as one of the major factors. Scientists in Radboud University Nijmegen and Entomological Society Krefeld have investigated insect species and abundance in more than 100 nature reserves of Western Europe since 1980s’, and found that the insect population in Orbroicher Bruch nature reserve has declined by 78%. A pitfall record indicated that there were 143 species of hoverflies in 1989 and 104 species in 2014 (Jin, 2017). In addition, pesticide use has led to various human / animal diseases, and injured human fecundity and intelligence quotient (IQ) in the past years (Chen et al., 2004; Zhang et al., 2011; Zhang, 2018).

It should be noted that pesticides refer in particular chemical pesticides in terms of environmental impact and human health, while a variety of bio-pesticides, in particular microbial pesticides (NPV, etc.), are environmentally friendly. As the substituent of chemical pesticides, bio-pesticide use is quickly increasing and they are expected to become the predominant pesticides in the future (Sanjaya et al., 2013; Darvishzadeh et al., 2014; Jafarbeigi et al., 2014; Sharifian and Darvishzadeh, 2015; Gupta et al., 2017).

In present study, I try to analyse global use of about 40 categories of pesticides, make trend and cost /

benefit analysis on global and regional pesticide use, based on the big data collected and organized from FAOSTAT databases.

2 Material and Methods

2.1 Data source

Data of pesticide use (tonnes of active ingredients), crop (the total of cereals, pulses, roots and tubers, oil crops, fibre crops, fruits, vegetables, and melons, etc.) production (tonnes) and the area harvested (ha) of the world and major countries, for the period between 1990 and 2014 (in total of 25 years) were collected, organized and analyzed from nearly four millions of data in FAOSTAT (http://www.fao.org/faostat/en/#data). More than 40 categories of pesticides were used as follows: (1) Insecticides: chlorinated hydrocarbons, organo-phosphates, carbamates insecticides, pyrethroids, botanic. produc & biologic., seed treatm insecticides, organo-phospates-SdTr In, carbamates-insect-SdTr, pyrethroids-SeedTr Ins, others-SeedTreat Ins, other insecticides. (2) Herbicides: phenoxy hormone products, triazines, amides, carbamates herbicides, dinitroanilines, urea derivates, sulfonyl ureas, bipiridils, uracil, other herbicides. (3) Fungicides & Bactericides: inorganics, dithiocarbamates, benzimidazoles, triazoles / diazoles, diazines / morpholines, botanic prod & biolog SdTrF, seed treatm fungicides, dithiocarbamates-SeedTrF, benzimidazoles-SeedTrF, Ttiazoles diazoles-SdTrF, others-SeedTreatFung, disinfectants, other fungicides. (4) Rodenticides: anticoagulants, cyanide generators, hypercalcaemics, narcotics, other rodenticides. (5) Plant Growth Regulators. (6) Mineral Oils. (7) Other Pesticides nes. (8) Pesticides (total).

In present study, all pesticide use was measured by the content of active ingredients. It is known that absolutely most pesticides were used in agricultural production. Excepting pesticide use (total), the profile of pesticide production, trade and use, etc., were collected from references (Fan, 2017; Dong, 2017; Gu, 2017).

Some data for some countries and years missed in the big data of FAOSTAT. However, I used big data analytics to collect, organize and analyse the data. With certain fault tolerance, big data analytics allows limited missing and local errors in data sets. Therefore, the results in this study will be reliable and usable.

2.2 Linear regression for trend analysis

Time series of pesticide use were generally a linear function of year. I used linear regression (Zhang et al., 2006; Zhang and Zhang, 2007; Zhang and Liu, 2017) to fit the trend for each of pesticides (Table 1): $x = a + b t$, where t is year (e.g., 2010), x is the pesticide use (tonnes of active ingredients) at t, and b is the annual growth rate of pesticide use. Linear regressions were statistically tested with F-statistic, based on r^2 for the regression. In addition, linear regression was used to other indices also. In most cases, linear regression was used as the supplement of trend analysis rather than accurate prediction.

2.3 Cost / benefit of pesticide use

2.3.1 Cost / benefit

In the past we generally use total use (tonnes / country, tonnes / province, etc.) and use strength (i.e., pesticide use) (kg / ha, etc.) to measure pesticide use and pollution in a crop, region, or country. Both of them do not take production efficiency into consideration and are incomplete indices. Here I propose an index to measure the production efficiency of pesticide use, cost / benefit. It refers to the amount of pesticide use to produce a certain amount of crop in a year, which has the scientific units as g pesticide use / kg crop production, or kg pesticide use / tonne crop production, etc. It is more reasonable than the use strength and total use in assessing production efficiency. Joint use of cost / benefit and use strength (or total use) can reflect the comprehensive impact of pesticide use in terms of production efficiency and environmental impact.

2.3.2 Theoretical relationship between crop yield and cost / benefit of pesticide use

Suppose that the other production conditions (background crop yield, pest occurrence level, etc.) are kept unchanged and the relationship between crop yield (y) and pest mortality (z) is approximately a linear equation

$$y = a + b z$$

It is known that the change of pest mortality with dosage of pesticide use (u) follows a sigmoid curve approximately

$$z = 1 / (1 + e^{k-du})$$

u is approximately supposed to be linearly correlated to cost / benefit of pesticide use, x

$$u = f + g x$$

thus we have the equation

$$y = a + b / (1 + e^{c-rx}) \qquad (1)$$

as illustrated by Fig. (4), where $c = k – d f$, $r = d g$. From eq. (1), the upper limit, i.e., max $y = a + b$ is the crop yield without any pest injury due to unlimited pesticide use, and the lower limit, i.e., min $y = a + b / (1 + e^{c})$, is the crop yield without any pesticide use. The x-axis coordinate of inflection point, $h = c / r$, is the cost / benefit in which the change of a unit of cost / benefit will lead to the maximal increase of crop yield. Therefore, there is a threshold cost / benefit, h. The marginal benefit of pesticide use will decline if pesticide use exceeds h. Eq (1) is the model for the theoretical relationship between crop yield and cost / benefit of pesticide use.

The reasonable cost / benefit will be in the interval [h, v], where v is the cost / benefit corresponding to the approximate upper limit of crop yield, e.g., 90% of ($a + b$).

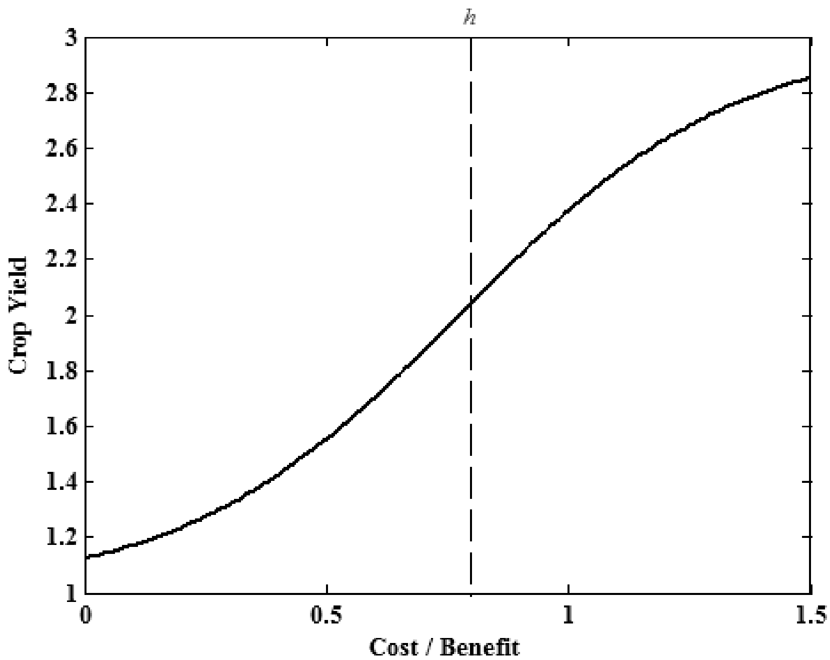

Fig. 1 An illustration of **t**heoretical relationship between crop yield and cost / benefit of pesticide use. h is the cost / benefit in which the change of an unit of cost / benefit will lead to the maximal increase of crop yield.

3 Results

3.1 Global profile and trend

3.1.1 Global pesticide use

Global pesticide use increased with time during 1990 and 2007. However, the trend changed since 2007 (Fig. 2). Therefore, two phases, 1990~2007, and 2007~2014, can be divided to analyze different trends of pesticide use in the two phases. Linear regressions of global uses for various pesticides are listed in Table 1.

It can be found that the use of pesticide (total), insecticides, herbicides, and fungicides & bactericides significantly increased with time during 1990 and 2007 (Fig. 2, Table 1). Use of pesticide (total), herbicides, and fungicides & bactericides oscillated since 2007. Insecticide use significantly declined since 2007.

The use of plant growth regulators and other pesticides nes. has continually increased since 1990.

Insecticides: the use of chlorinated hydrocarbons has continually declined since 1990. The use of carbamates insecticides increased with time during 1990 and 2007 and declined since 2007. The use of other insecticides, excepting those in Table 1, has continually increased since 1990 (Table 1).

Herbicides: the use of amides and other herbicides have continually increased since 1990. The use of triazines, urea derivates, uracil and bipiridils increased with time during 1990 and 2007, but bipiridils use declined since 2007 (Table 1).

Fungicides & Bactericides: The use of triazoles and diazoles has continually increased since 1990. Triazoles diazoles-SdTrF and disinfectants increased during 1990 and 2007, and declined since 2007. Dithiocarbamates use oscillated during 1990 and 2007, and greatly declined since 2007. The use of inorganics , benzimidazoles, dithiocarbamates-SeedTrF, and other fungicides increased during 1990 and 2007, and oscillated since 2007 (Table 1).

Rodenticides: Anticoagulants use oscillated during 1990 and 2007, and declined since 2007. The use of other rodenticides excepting those in Table 1 has continually declined since 1990 (Table 1).

Projection of pesticide use in 2018 and 2020, based on linear regressions, are listed in Table 1.

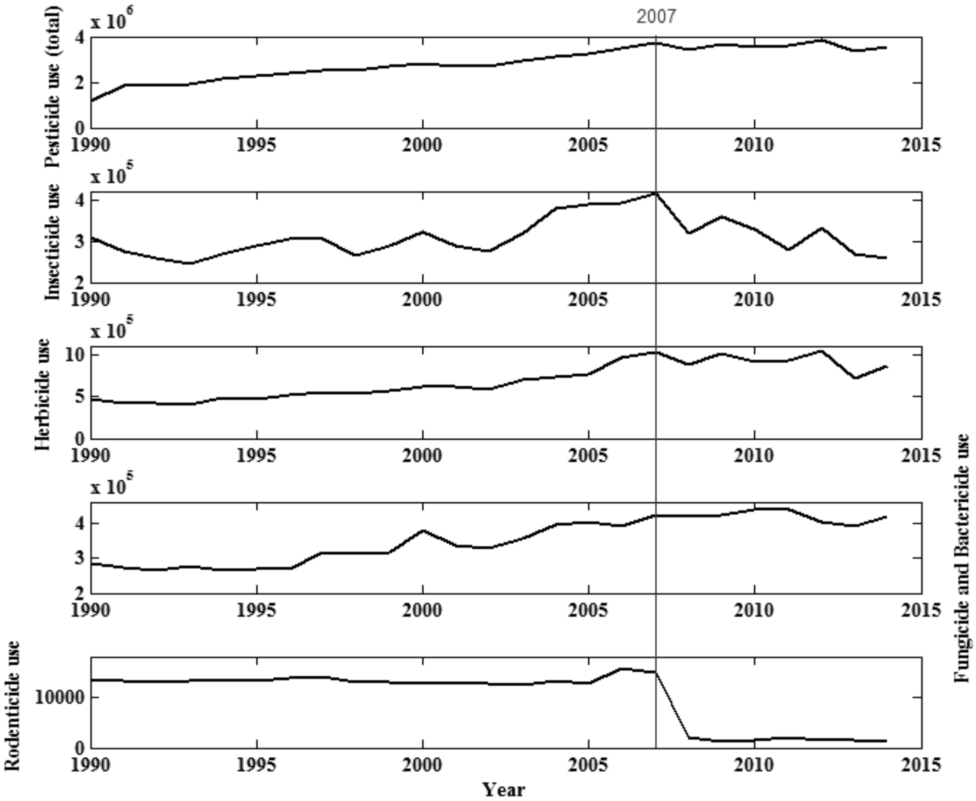

Fig. 2 Changes of global use of various pesticides (tonnes of active ingredients).

Table 1 Linear regressions and projection of global pesticide use.

Pesticide	1990~2007				2007~2014				Projection	
	a	*b*	r^2	*p*	*a*	*b*	r^2	*p*	2018	2020
Insecticides	-14404733.36	7363.15	0.6024	0.0002	35696188.67	-17595.79	0.6831	0.0114	187884.45	152692.87
Chlorinated Hydrocarbons	2861117.80	-1425.72	0.8576	0	1462496.66	-726.24	0.6246	0.0196	0	0
Organo-Phosphates	1368504.93	-660.79	0.0805	0.254	3544804.91	-1745.57	0.3982	0.0934	22244.65	18753.51
Carbamates Insecticides	-884292.30	450.32	0.2828	0.0231	7017234.37	-3484.28	0.6829	0.0114	0	0
Pyrethroids	147352.59	-70.41	0.0193	0.5824	-915816.61	459.99	0.1055	0.4325	12443.21	13363.19
Botanic.Produc&Biologic.	-37359.23	18.96	0.0807	0.2533	1621904.16	-804.25	0.0654	0.5409	0	0
Organo-phospates-SdTr In	-19967.54	10.56	0.0007	0.916	23186.93	-11.52	0.3189	0.1447	0	0
Carbamates-insect-SdTr	-22989.60	11.76	0.0046	0.7899	12599.59	-6.23	0.0488	0.599	27.45	14.99
Pyrethroids-SeedTr Ins	-15116.84	7.80	0.0022	0.8547	-599.07	0.33	0.0007	0.9496	66.87	67.53
Others-SeedTreat Ins	-146001.48	73.51	0.1151	0.1683	-54473.81	27.87	0.075	0.5115	1767.85	1823.59
Seed Treatm Insecticides	-269463.87	136.44	0.0211	0.5655	-641601.01	321.34	0.1286	0.3831	6863.11	7505.79
Other Insecticides	-4424700.47	2226.81	0.8198	0	-3040871.10	1534.34	0.7874	0.0033	55427.02	58495.7
Herbicides	-58782170.67	29713.20	0.8206	0	42705789.11	-20783.21	0.2376	0.2205	765271.33	723704.91
Phenoxy Hormone Products	-761549.99	393.82	0.055	0.3487	1270849.53	-616.98	0.0764	0.5075	25783.89	24549.93
Triazines	-404648.02	209.04	0.0283	0.5049	-669830.95	342.54	0.021	0.7324	21414.77	22099.85
Amides	-1825419.95	922.15	0.3885	0.0057	-4119363.02	2063.40	0.5737	0.0295	44578.18	48704.98
Carbamates Herbicides	-60717.02	32.65	0.0321	0.477	-20768.22	12.60	0.0011	0.9383	4658.58	4683.78
Dinitroanilines	8789.61	-1.55	0	0.9801	-187399.00	96.44	0.2	0.2666	7216.92	7409.8
Urea derivates	-702541.22	358.18	0.4113	0.0041	1312705.19	-647.44	0.4462	0.0702	6171.27	4876.39
Sulfonyl Ureas	-100595.53	50.84	0.1294	0.1426	-486651.49	243.35	0.4664	0.0619	4428.81	4915.51
Bipiridils	-2069237.50	1038.92	0.5804	0.0002	3411141.35	-1685.14	0.6739	0.0125	10528.83	7158.55
Uracil	-67997.08	34.22	0.282	0.0234	65925.42	-32.46	0.1619	0.323	421.14	356.22
Other Herbicides	-9707022.35	4894.33	0.7145	0	-41845708.44	20902.62	0.6086	0.0224	335778.72	377583.96
Fungicides & Bactericides	-18133401.93	9236.53	0.8356	0	6139742.78	-2845.29	0.1734	0.3048	397947.56	392256.98
Inorganics	-8568818.94	4318.44	0.6447	0.0001	-2256093.06	1160.76	0.0937	0.4609	86320.62	88642.14
Dithiocarbamates	-2168354.38	1101.66	0.1687	0.0905	3874969.75	-1907.40	0.7792	0.0037	25836.55	22021.75
Benzimidazoles	-591795.72	297.78	0.7275	0	396052.23	-193.79	0.1849	0.2876	4984.01	4596.43
Triazoles, Diazoles	-301881.53	153.75	0.2382	0.0399	-1884933.16	943.52	0.873	0.0007	19090.2	20977.24
Diazines, Morpholines	-304768.87	154.07	0.0773	0.2638	-5213.40	4.24	0.0004	0.9619	3342.92	3351.4
Botanic prod&biologSdTrF	-9068.17	4.55	0.2029	0.0607	-9248.62	4.62	0.1014	0.442	74.54	83.78
Dithiocarbamates-SeedTrF	-61863.11	31.10	0.3658	0.0078	-15223.12	7.80	0.0123	0.7934	517.28	532.88
Benzimidazoles-SeedTrF	-10398.94	5.24	0.1911	0.0696	-1938.33	1.00	0.0031	0.8961	79.67	81.67
Triazoles diazoles-SdTrF	-87233.56	43.79	0.6854	0	162367.29	-80.50	0.6692	0.0131	0	0
Seed Treatm Fungicides	-674845.87	338.79	0.8073	0	612241.38	-303.14	0.4088	0.0878	504.86	0
Others-SeedTreatFung	-118888.49	59.81	0.218	0.0507	41996.49	-20.61	0.3196	0.1442	405.51	364.29
Disinfectants	-540571.03	271.45	0.4421	0.0026	2688674.36	-1334.59	0.6426	0.0167	0	0
Other Fungicides	-6719966.92	3381.53	0.6753	0	-2339246.29	1189.76	0.1824	0.2912	61689.39	64068.91
Rodenticides	-70298.52	41.85	0.0744	0.2735	2300566.86	-1142.67	0.3607	0.1154	0	0
Anticoagulants	345.27	-0.08	0	0.9905	130422.82	-64.79	0.8352	0.0015	0	0
Cyanide Generators	-24486.17	12.30	0.063	0.3149	-2101.24	1.05	0.0729	0.5177	17.66	19.76
Hypercalcaemics	108.06	-0.05	0.0102	0.6895	0.00	0.00	NaN	NaN	0	0
Narcotics	-1078.73	0.54	0.0086	0.7147	-11.70	0.01	0.3185	0.1451	8.48	8.5
Other Rodenticides	68870.27	-34.15	0.2824	0.0232	91418.56	-45.27	0.5953	0.0249	63.7	0
Plant Growth Regulators	-1098747.89	558.44	0.5057	0.0009	-7045777.90	3521.42	0.5737	0.0295	60447.66	67490.5
Mineral Oils	-1190806.85	640.22	0.0949	0.2136	12897127.70	-6398.94	0.2314	0.2275	0	0
Other Pesticides nes	-131115590.06	66205.30	0.8056	0	-45941789.40	23757.18	0.8301	0.0016	2000199.84	2047714.2
Pesticides (total)	-226280630.40	114505.36	0.9402	0	28796803.29	-12537.14	0.0396	0.6365	3496854.77	3471780.49

$x = a + b\,t$, where t is year (e.g., 2010), x is the pesticide use (tonnes of active ingredients) at t, and b is the annual growth rate of pesticide use. Highlighted regressions are statistically significant at p=0.05. Red: ascending trend; blue: descending trend.

In 2014, the use of other pesticides nes. accounted for the most proportion of total pesticides (53.84%), seconded by herbicides (25.10%), and followed by fungicides & bactericides (12.06%), insecticides (7.50%), plant growth regulators (1.24%), etc (Fig. 3).

The use of insecticides in 2014: In addition to other insecticides, organo-phosphates is the most used insecticides, followed by pyrethroids, carbamates insecticides, botanic. produc & biologic., carbamates-insect-SdTr, chlorinated hydrocarbons, pyrethroids-SeedTr Ins, etc (Table 2).

The use of herbicides in 2014: In addition to other herbicides, amides is the most used herbicides, followed by phenoxy hormone products, bipiridils, triazines, urea derivates, dinitroanilines, carbamates herbicides, sulfonyl ureas, and uracil (Table 2).

The use of fungicides & bactericides in 2014: Inorganics is the most used fungicides & bactericides, followed by other fungicides, dithiocarbamates, triazoles and diazoles, benzimidazoles, diazines, morpholines seed treatm fungicides, disinfectants, etc. (Table 2).

The use of rodenticides in 2014: In addition to other rodenticides, anticoagulants are the most used rodenticides, seconded by narcotics.

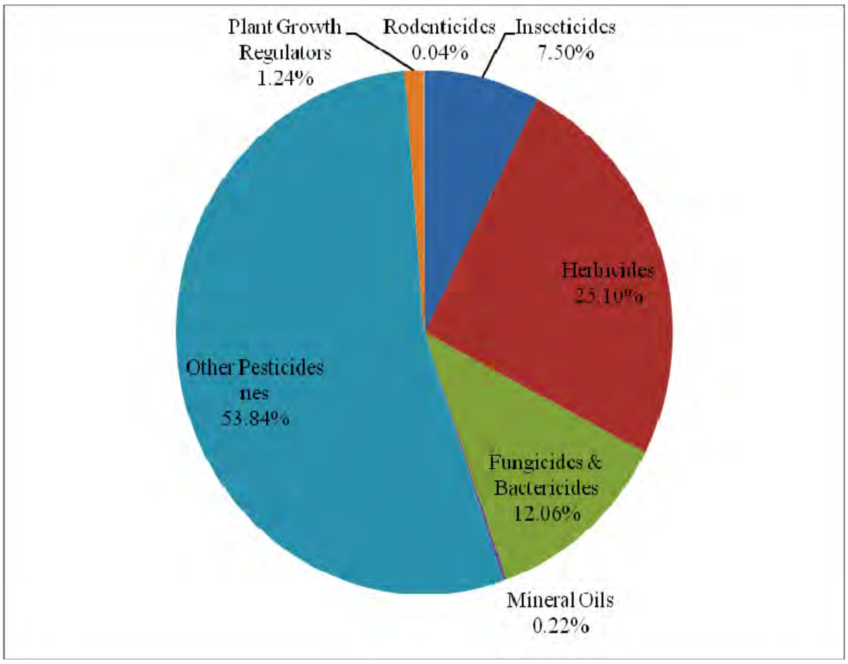

Fig. 3 Proportion of global pesticide use in 2014.

3.1.2 Cost / benefit of global pesticide use

3.1.2.1 Pesticide use (total)

Generally, pesticide cost / benefit (g pesticide use (total) / kg crop production) increased (0.0158 / yr) with time during 1990 to 2007, and declined (0.0182 / yr) since 2007 (Fig. 4, Table 3). Pesticide use (total) (kg / ha) had the similar trend as that of pesticide cost / benefit.

The linear regression models of pesticide cost / benefit for the two periods are as follows:

1990~2007: u=-30.8984+0.0158t r^2=0.7779, p=0

2007~2014: u=37.3293-0.0182t r^2=0.6104, p=0.0221

where u: pesticide cost / benefit (g pesticide use (total) / kg crop production), t: year.

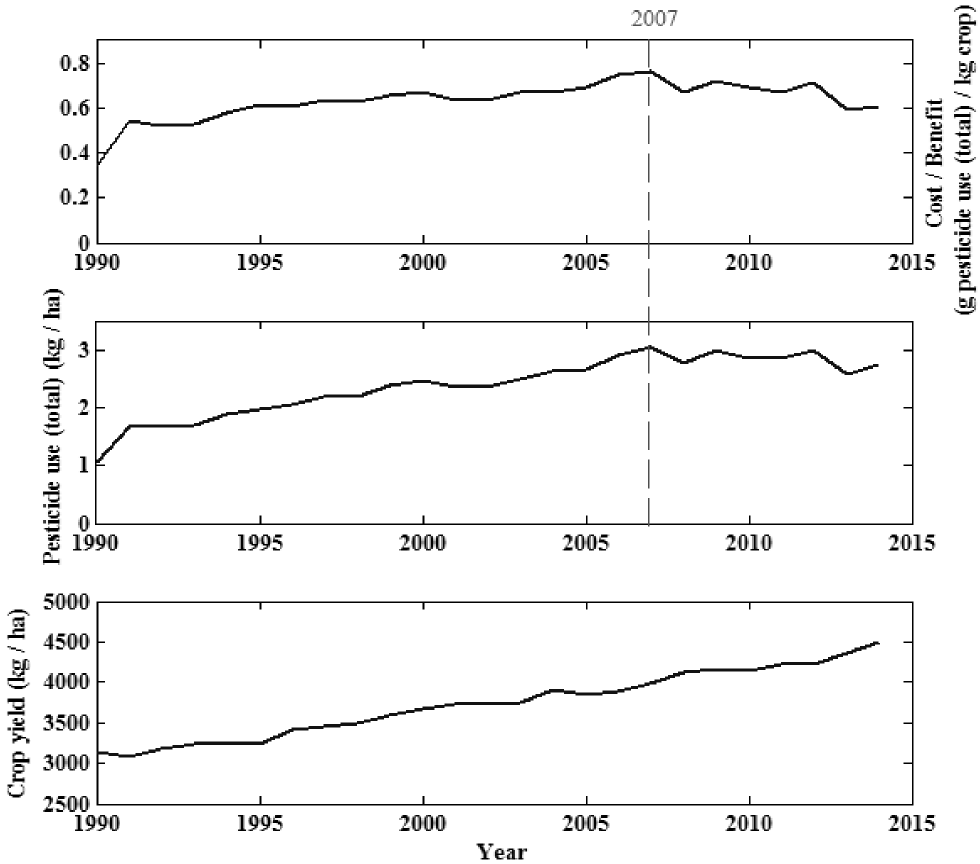

Fig. 4 Global pesticide use (total), crop yield and pesticide cost / benefit since 1990. There are three distinct phases for pesticide use (total), 1990~2007 and 2007~2014 in the period.

Table 2 Rankings of global pesticide use (tonnes of active ingredients) in 2014.

Insecticides		Herbicides		Fungicides & Bactericides		Rodenticides	
Other Insecticides	47690.4	Other Herbicides	327892.54	Inorganics	87257.16	Other Rodenticides	287.05
Organo-Phosphates	29972.53	Amides	38333.54	Other Fungicides	56527.62	Anticoagulants	13.73
Pyrethroids	8257.6	Phenoxy Hormone Products	23920.24	Dithiocarbamates	33354.76	Narcotics	0.04
Carbamates Insecticides	3914.79	Bipiridils	17242.99	Triazoles, Diazoles	15519.06	Cyanide Generators	0
Seed Treatm Insecticides	1596.49	Triazines	15158.55	Benzimidazoles	6988.88	Hypercalcaemics	0
Others-SeedTreat Ins	1349.96	Urea derivates	9493.33	Diazines, Morpholines	3192.64		
Botanic.Produc&Biologic.	491.1	Dinitroanilines	6507.89	Seed Treatm Fungicides	1754.42		
Carbamates-insect-SdTr	177.34	Carbamates Herbicides	4003.5	Disinfectants	932.4		
Chlorinated Hydrocarbons	147.51	Sulfonyl Ureas	2678.05	Others-SeedTreatFung	444.74		
Pyrethroids-SeedTr Ins	23.91	Uracil	606.01	Dithiocarbamates-SeedTrF	408.18		
				Triazoles diazoles-SdTrF	360.75		
				Botanic prod & biologSdTrF	43.68		
				Benzimidazoles-SeedTrF	23.62		

According to Table 3, mean pesticide cost / benefit (g pesticide use (total) / kg crop production) between 1990 and 2007, and between 2008 and 2014 are 0.6178 and 0.6652, respectively (for example, 0.6652 g pesticide (total) was used to produce 1 kg crop). And mean annual pesticide use (total) (kg / ha) between 1990 and 2007, and between 2008 and 2014 are 2.2063 and 2.8203, respectively.

3.1.2.2 Use of insecticides, herbicides, and fungicides & bactericides

Generally, insecticides, herbicides, and fungicides & bactericides use declined with time since 2007 (Fig. 5, Table 3). The linear regression models since 2007 are as follows:

Insecticides use: u=33.3651-0.0165t r^2=0.7263, p=0.0072
Herbicides use: u=47.8033-0.0234t r^2=0.3728, p=0.1079
Fungicides & bactericides use: u=11.2203-0.0054t r^2=0.4881, p=0.0539
where u: pesticide use (kg / ha), t: year.

Table 3 Global pesticide use and cost / benefit since 1990.

Year	Cost / Benefit (g pesticide use / kg crop production)						Pesticide Use (kg / ha)					
	Insecti.	Herbi.	Fungi.& Bacteri.	Rodenti.	Other Pest. nes	Pesti.Use (total)	Insecti.	Herbi.	Fungi. & Bacteri.	Rodenti.	Other Pest. nes	Pesti.Use (total)
1990	0.0876	0.1334	0.0817	0.0038	0.0084	0.3427	0.2743	0.4178	0.2558	0.0118	0.0264	1.0736
1991	0.0801	0.1221	0.0795	0.0038	0.2284	0.5411	0.2459	0.3749	0.2442	0.0116	0.7016	1.6618
1992	0.0718	0.1165	0.0732	0.0036	0.2286	0.5205	0.229	0.3714	0.2333	0.0116	0.7289	1.6594
1993	0.0675	0.1134	0.077	0.0037	0.2409	0.527	0.2183	0.3671	0.2492	0.0119	0.7796	1.7053
1994	0.0733	0.1323	0.0719	0.0036	0.2735	0.5804	0.2379	0.4296	0.2335	0.0117	0.8881	1.8848
1995	0.078	0.1262	0.0727	0.0036	0.3018	0.6117	0.2526	0.4085	0.2354	0.0117	0.9773	1.9807
1996	0.0775	0.1327	0.0689	0.0035	0.2961	0.6033	0.2651	0.4541	0.2357	0.0119	1.0134	2.0646
1997	0.0767	0.1361	0.0798	0.0035	0.3079	0.6323	0.2651	0.4702	0.2756	0.0122	1.0634	2.1839
1998	0.0657	0.1312	0.0777	0.0032	0.3166	0.6272	0.2302	0.4597	0.2723	0.0113	1.1091	2.1973
1999	0.0703	0.1367	0.0772	0.0031	0.3354	0.6589	0.2531	0.4923	0.2779	0.0113	1.2076	2.3725
2000	0.0766	0.1443	0.0899	0.003	0.3202	0.6685	0.2819	0.5313	0.331	0.0111	1.1785	2.4606
2001	0.0676	0.1437	0.0783	0.003	0.3141	0.6334	0.2521	0.536	0.292	0.0112	1.1716	2.3623
2002	0.0649	0.1355	0.0768	0.003	0.3264	0.6324	0.2426	0.5065	0.2872	0.0112	1.2204	2.3645
2003	0.0731	0.1609	0.081	0.0028	0.3223	0.6674	0.2741	0.603	0.3037	0.0107	1.2078	2.5012
2004	0.0817	0.1579	0.0852	0.0028	0.317	0.6707	0.319	0.6168	0.3329	0.011	1.2383	2.6197
2005	0.0831	0.1628	0.0864	0.0027	0.3302	0.6905	0.3204	0.6275	0.333	0.0105	1.273	2.6618
2006	0.0835	0.2037	0.0838	0.0034	0.3482	0.748	0.3253	0.7934	0.3264	0.0131	1.3564	2.9135
2007	0.0858	0.21	0.0873	0.003	0.3527	0.7644	0.3419	0.8366	0.3478	0.0121	1.4052	3.0454
2008	0.062	0.1721	0.0814	0.0004	0.3419	0.6685	0.2555	0.7095	0.3358	0.0017	1.4094	2.756
2009	0.0699	0.197	0.0828	0.0002	0.3496	0.7195	0.2907	0.82	0.3445	0.0009	1.455	2.9944
2010	0.0639	0.1753	0.0851	0.0003	0.3556	0.6891	0.2648	0.7265	0.3527	0.0013	1.4736	2.8554
2011	0.0517	0.1717	0.0813	0.0004	0.3454	0.6717	0.2186	0.7266	0.3439	0.0016	1.4618	2.8425
2012	0.0612	0.1921	0.0747	0.0003	0.3485	0.7089	0.2579	0.8096	0.3149	0.0011	1.4685	2.9867
2013	0.047	0.1264	0.0684	0.0003	0.329	0.5909	0.2044	0.55	0.2977	0.0012	1.4318	2.5718
2014	0.0448	0.1498	0.072	0.0002	0.3214	0.6081	0.2015	0.674	0.324	0.001	1.4458	2.7353

Cost / benefit of the use of insecticides, herbicides and fungicides & bactericides declined with time since 2007 (Fig. 5, Table 3). The linear regression models for their cost and benefit since 2007 are as follows:

Insecticides use: u=9.6458-0.0048t r^2=0.7633, p=0.0046
Herbicides use: u=16.16-0.008t r^2=0.5292, p=0.0408
Fungicides & bactericides use: u=4.8694-0.0024t r^2=0.767, p=0.0044
where u: pesticide cost / benefit (g pesticide use / kg crop production), t: year.

According to Table 3, mean cost / benefit of insecticides, herbicides and fungicides & bactericides use between 2008 and 2014 are 0.0572, 0.1692 and 0.0779 g / kg crop production, respectively. And mean annual use of insecticides, herbicides and fungicides & bactericides between 2008 and 2014 are 0.2419, 0.7166 and 0.3305 kg / ha, respectively.

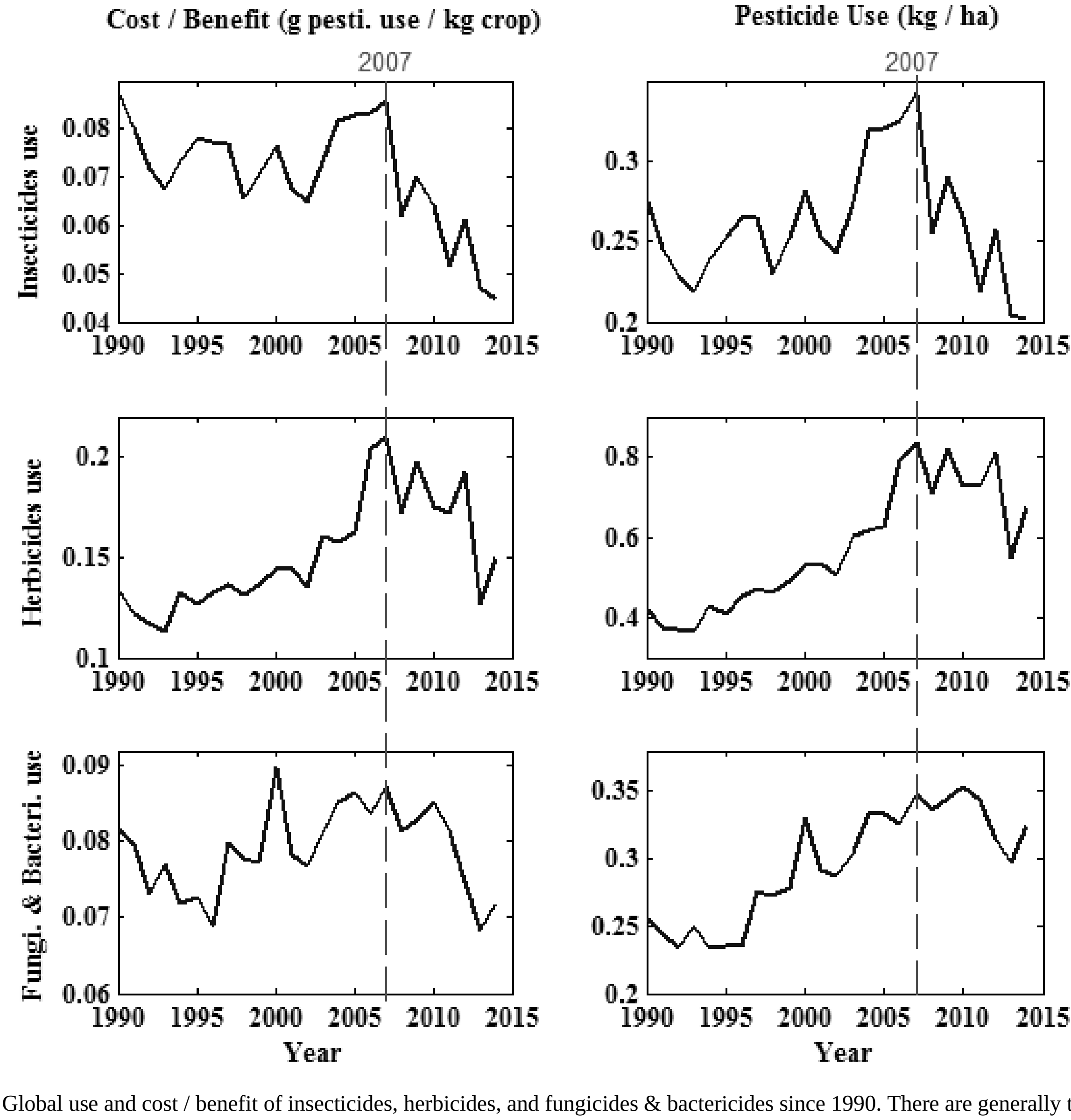

Fig. 5 Global use and cost / benefit of insecticides, herbicides, and fungicides & bactericides since 1990. There are generally two distinct phases, 1990~2007, and 2007~2014 in the period.

With 30~40% of effective use (directly act on target crops and pests), if pesticides have fully functioned without any waste, by using various accurate tools and methods, ~0.0172 to ~0.0229 g insecticides use / kg crop production, ~0.0508 to ~0.0677 g herbicides use (total) / kg crop production, ~0.0234 to ~0.0312 g fungicides & bactericides use (total) / kg crop production; or ~0.0726 to ~0.0968 kg / ha insecticides use, ~0.2149 to ~0.2866 kg / ha herbicides use, and ~0.0992 to ~0.1322 kg / ha fungicides & bactericides use, should have been the most ideal (i.e., the possible limit) indices for the three pesticides at the crop yield levels and production conditions between 2008 and 2014 (In present study, the symbol '~' without prepositive value means 'approximately' or 'around').

3.1.2.3 Use of major finer categories of pesticides

Cost / benefit and use of major finer categories of pesticides are shown in Table 4 and Table 5 respectively. According to linear regressions in the tables, the cost / benefit of dithiocarbamates, bipiridils, carbamates insecticides, and organo-phosphates, and the use of dithiocarbamates, bipiridils, and carbamates insecticides have significantly declined since 2007. Conversely, the cost / benefit of triazoles / diazoles and the use of triazoles / diazoles, plant growth regulators, and amides, have significantly increased since 2007.

3.2 Profile and trend of pesticide use in the major countries

3.2.1 Pesticide use (total)

Pesticide use (total) and cost / benefit and use of major countries are shown in Table 6. The averaged annual cost / benefit (g pesticide use (total) / kg crop production) during 2010 to 2014 of Brazil is the greatest (1.883), seconded by Japan (1.846), and followed by Mexico (1.678), China (1.243), Canada (0.979), USA (0.8733), France (0.708), Germany (0.673), which are higher than global average (0.645), excepting UK (0.55) and India (0.089). The averaged annual pesticide use (total) (kg / ha) during 2010 to 2014 of Japan is the greatest (18.94), seconded by China (10.45), and followed by Mexico (7.87), Brazil (6.166), Germany (5.123), France (4.859), UK (4.034), USA (3.886), which are higher than global average (2.784), excepting India (0.261).

Pesticide use (total) and cost / benefit and use of most of the major countries reached the maximum around 2007~2009. According to linear regressions in the table, the cost / benefit of pesticide use (total) of China and Brazil has significantly declined and France has significantly increased since 2009. The pesticide use (total) of Canada and Germany has significantly increased since 2009.

3.2.2 Use of insecticides, herbicides and fungicides & bactericides

(1) Insecticides

Insecticides cost / benefit and use of major countries are shown in Table 7. The averaged annual cost / benefit (g insecticides use / kg crop production) during 2010 to 2014 of Japan is the greatest (0.646), seconded by Mexico (0.492) and USA (0.141), higher than global average (0.051), followed by Canada (0.047), India (0.033), France (0.028), UK (0.024), and Germany (0.017). The averaged annual insecticides use (kg / ha) during 2010 to 2014 of Japan is the greatest (6.634), seconded by Mexico (2.313), and followed by Brazil (1.163), USA (0.627), higher than global average (0.221), followed by France (0.196), UK (0.174), Canada (0.125), Germany (0.124), and India (0.09).

Table 4 Global cost / benefit (g pesticide use / kg crop production) and trend of major finer categories of pesticides since 1990.

Year		Insecticides			Herbicides			Fungi. & Bacteri.			Plant Growth Regulators
		Organo-Phosphates	Pyrethroids	Carbamates Insecticides	Amides	Phenoxy Hormone Products	Bipiridils	Inorganics	Dithiocarbamates	Triazoles / Diazoles	
1990		0.0139	0.0015	0.0055	0.0011	0.0063	-	0.0057	0.0046	0.0008	0.0036
1991		0.0134	0.0013	0.0038	0.0013	0.0038	-	0.0056	0.0045	0.001	0.0038
1992		0.0136	0.0019	0.0042	0.0013	0.0047	0.0002	0.0052	0.0057	0.0012	0.0037
1993		0.014	0.0016	0.0038	0.0029	0.0057	0.0006	0.0078	0.0063	0.001	0.0033
1994		0.0136	0.0022	0.0025	0.0032	0.0096	0.0009	0.0079	0.0067	0.0011	0.0045
1995		0.0159	0.0017	0.0035	0.0058	0.0083	0.0008	0.0163	0.0083	0.0019	0.0058
1996		0.0159	0.0022	0.0032	0.0067	0.0087	0.0026	0.014	0.0087	0.0019	0.0052
1997		0.0164	0.0033	0.0032	0.0069	0.0086	0.0013	0.0109	0.0089	0.0014	0.0035
1998		0.0144	0.0021	0.0035	0.0064	0.0053	0.0012	0.0195	0.0149	0.0016	0.0035
1999		0.0134	0.0021	0.0034	0.0044	0.005	0.0014	0.0186	0.0127	0.0016	0.0037
2000		0.0098	0.002	0.0035	0.0056	0.0061	0.0014	0.0263	0.0155	0.0016	0.0042
2001		0.0058	0.0017	0.0044	0.0036	0.0041	0.001	0.0224	0.0066	0.0012	0.0038
2002		0.0033	0.0003	0.0025	0.0029	0.0024	0.0004	0.0199	0.0042	0.0007	0.0034
2003		0.0096	0.0007	0.0031	0.004	0.0106	0.0018	0.0185	0.0069	0.0009	0.0038
2004		0.0112	0.0011	0.0044	0.0049	0.0058	0.0041	0.0171	0.0073	0.0011	0.0048
2005		0.0114	0.0009	0.0038	0.0044	0.0057	0.0023	0.0155	0.007	0.0013	0.0046
2006		0.0088	0.0012	0.0046	0.0049	0.0053	0.0029	0.0149	0.0074	0.0014	0.0051
2007		0.0102	0.0018	0.0057	0.0052	0.0065	0.0058	0.0178	0.0092	0.0018	0.0053
2008		0.0065	0.0015	0.0058	0.0048	0.0058	0.0053	0.0134	0.0092	0.0021	0.0061
2009		0.0062	0.001	0.0014	0.0037	0.005	0.0046	0.0136	0.0079	0.0017	0.0041
2010		0.008	0.0015	0.0017	0.005	0.0072	0.0051	0.0127	0.0088	0.0022	0.0036
2011		0.0058	0.0015	0.0015	0.0065	0.0064	0.0046	0.0166	0.0076	0.0024	0.0075
2012		0.0065	0.0032	0.0013	0.0065	0.0068	0.0045	0.014	0.0065	0.0026	0.0084
2013		0.0055	0.0016	0.0008	0.0051	0.0042	0.0024	0.0137	0.0061	0.0024	0.0083
2014		0.0052	0.0014	0.0007	0.0066	0.0041	0.003	0.015	0.0057	0.0027	0.0074
1990	*a*	0.8097	0.0936	-0.0416	-0.3083	0.0539	-0.4343	-1.6132	-0.2596	-0.0241	-0.0964
~	*b*	-0.0004	0	0	0.0002	0	0.0002	0.0008	0.0001	0	0.0001
2007	r^2	0.3654	0.1302	0.0192	0.2108	0.0035	0.4941	0.4908	0.0478	0.0338	0.1234
	p	0.0079	0.1413	0.5839	0.0552	0.8148	0.0024	0.0012	0.3833	0.4652	0.1529
2007	*a*	0.9952	-0.1012	1.4504	-0.502	0.4892	0.8397	0.3257	1.0943	-0.2539	-1.0109
~	*b*	-0.0005	0.0001	-0.0007	0.0003	-0.0002	-0.0004	-0.0002	-0.0005	0.0001	0.0005
2014	r^2	0.5412	0.0371	0.6939	0.3618	0.2458	0.7788	0.0465	0.8946	0.7583	0.4439
	p	0.0375	0.6478	0.0102	0.1147	0.2115	0.0037	0.6079	0.0004	0.0049	0.0712

-: No available data; Linear regression: $x = a + b\,t$, where t is year (e.g., 2010), x is cost / benefit at t, and b is the annual growth rate.

Table 5 Global use (kg / ha) and trend of major finer categories of pesticides since 1990.

Year		Insecticides			Herbicides			Fungi. & Bacteri.			Plant Growth Regulators
		Organo-Phosphates	Pyrethroids	Carbamates Insecticides	Amides	Phenoxy Hormone Products	Bipiridils	Inorganics	Dithiocarbamates	Triazoles / Diazoles	
1990		0.0436	0.0047	0.0174	0.0036	0.0198	-	0.018	0.0143	0.0024	0.0113
1991		0.0412	0.0039	0.0117	0.004	0.0116	-	0.0173	0.0137	0.0032	0.0116
1992		0.0434	0.006	0.0133	0.004	0.015	0.0005	0.0166	0.0181	0.004	0.0119
1993		0.0452	0.0052	0.0122	0.0094	0.0183	0.002	0.0251	0.0205	0.0032	0.0108
1994		0.0442	0.0073	0.0082	0.0105	0.0312	0.0028	0.0255	0.0216	0.0036	0.0147
1995		0.0515	0.0056	0.0113	0.0189	0.0269	0.0028	0.0529	0.027	0.0061	0.0186
1996		0.0544	0.0075	0.0111	0.0228	0.0299	0.009	0.048	0.0299	0.0066	0.0179
1997		0.0566	0.0115	0.0109	0.0239	0.0297	0.0046	0.0375	0.0308	0.0048	0.0122
1998		0.0505	0.0073	0.0121	0.0224	0.0187	0.0043	0.0682	0.0522	0.0055	0.0123
1999		0.0481	0.0076	0.0122	0.016	0.0179	0.0049	0.0668	0.0459	0.0059	0.0133
2000		0.0362	0.0074	0.0129	0.0206	0.0226	0.0052	0.0968	0.0572	0.0058	0.0154
2001		0.0217	0.0063	0.0165	0.0133	0.0152	0.0038	0.0837	0.0245	0.0046	0.0142
2002		0.0125	0.001	0.0092	0.0107	0.0088	0.0015	0.0743	0.0158	0.0027	0.0125
2003		0.0361	0.0026	0.0117	0.0148	0.0398	0.0067	0.0692	0.0257	0.0034	0.0143
2004		0.0437	0.0044	0.0172	0.0192	0.0228	0.0162	0.0668	0.0286	0.0044	0.0189
2005		0.0438	0.0036	0.0145	0.0171	0.0221	0.0089	0.0596	0.0268	0.0051	0.0176
2006		0.0343	0.0045	0.018	0.0192	0.0206	0.0113	0.058	0.029	0.0053	0.0198
2007		0.0406	0.0071	0.0227	0.0207	0.0259	0.023	0.0709	0.0365	0.0072	0.0211
2008		0.0266	0.0063	0.0238	0.02	0.0239	0.0218	0.0551	0.0378	0.0086	0.0251
2009		0.0257	0.0041	0.0059	0.0153	0.021	0.0192	0.0567	0.0328	0.0073	0.0172
2010		0.0332	0.0063	0.0071	0.0206	0.0296	0.0211	0.0526	0.0363	0.0091	0.0149
2011		0.0244	0.0065	0.0062	0.0276	0.0273	0.0196	0.0701	0.0322	0.0103	0.0316
2012		0.0272	0.0133	0.0053	0.0276	0.0286	0.019	0.0592	0.0273	0.0111	0.0355
2013		0.0238	0.0068	0.0037	0.0224	0.0182	0.0105	0.0598	0.0265	0.0104	0.0361
2014		0.0232	0.0064	0.003	0.0297	0.0185	0.0134	0.0676	0.0259	0.012	0.0333
1990	a	1.5653	0.1763	-0.6157	-1.4581	-0.4639	-1.7967	-7.012	-1.649	-0.2189	-0.8072
~	b	-0.0008	-0.0001	0.0003	0.0007	0.0002	0.0009	0.0035	0.0008	0.0001	0.0004
2007	r^2	0.1407	0.0373	0.2184	0.3466	0.029	0.5225	0.5935	0.1319	0.1844	0.4515
	p	0.125	0.4426	0.0505	0.0102	0.4996	0.0016	0.0002	0.1385	0.0754	0.0023
2007	a	3.3813	-0.6008	5.7803	-2.8228	1.4554	3.0294	-0.5464	3.6532	-1.3117	-5.0473
~	b	-0.0017	0.0003	-0.0029	0.0014	-0.0007	-0.0015	0.0003	-0.0018	0.0007	0.0025
2014	r^2	0.4725	0.0773	0.6899	0.5042	0.1523	0.7255	0.0109	0.8383	0.8491	0.5387
	p	0.0596	0.5048	0.0107	0.0485	0.3392	0.0073	0.8053	0.0014	0.0011	0.0382

-: No available data. Linear regression: $x = a + b\,t$, where t is year (e.g., 2010), x is pesticide use at t, and b is the annual growth rate.

Table 6 Pesticide use (total), cost / benefit and trend of major countries since 1990.

Year		Cost / Benefit (g pesticide use (total) / kg crop production)											Pesticide Use (Total) (kg / ha)										
		Australia	Brazil	Canada	China	France	Germany	India	Japan	Mexico	UK	USA	Australia	Brazil	Canada	China	France	Germany	India	Japan	Mexico	UK	USA
1990		0.5971	0.484	0.4528	-	1.1502	0.5148	0.2382	-	-	0.8583	0.9933	1.131	1.1178	1.1281	0	7.185	3.5278	0.4275	-	-	6.2905	3.8596
1991		0.679	-	-	1.079	1.1852	0.563	0.2264	-	-	0.8463	1.0267	1.2166	-	-	5.0823	7.5639	3.8462	0.4062	-	-	6.2447	3.7592
1992		0.6672	-	-	1.0814	0.9236	0.5486	0.2133	-	-	0.8767	0.8914	1.3667	-	-	5.2971	6.249	3.4819	0.4068	-	-	6.6835	3.8518
1993		0.6813	-	-	1.0643	1.087	0.456	0.1923	-	-	1.0006	1.0988	1.44	-	-	5.6706	7.3345	3.1093	0.3773	-	-	7.6461	3.9309
1994		0.9178	-	0.4941	1.2246	1.1045	0.4859	0.1737	-	-	1.078	0.9161	1.33	-	1.0743	6.4544	7.2644	3.185	0.3497	-	-	8.0529	4.0216
1995		0.713	-	-	1.2699	1.0278	0.5187	0.1728	-	-	1.0347	1.1075	1.4141	-	-	7.0353	6.6961	3.5715	0.342	-	-	7.9162	4.0633
1996		0.6966	-	-	1.2236	1.0675	0.502	0.1531	-	-	0.9779	0.9761	1.5379	-	-	7.2841	7.5619	3.6992	0.3107	-	-	8.1033	4.0557
1997		0.8421	-	-	1.2866	1.1833	0.4688	0.136	-	-	0.9987	0.9687	1.6734	-	-	7.5938	8.1465	3.3983	0.291	-	-	7.646	3.9884
1998		0.8588	-	-	1.2609	1.1101	0.5149	0.1272	-	-	1.043	0.9246	1.7078	-	-	7.7171	7.9159	3.6565	0.2704	-	-	7.6074	4.0155
1999		0.7378	1.007	0.6371	1.3054	1.2147	0.4539	0.1129	-	-	1.0341	0.9694	1.51	3.0651	1.631	8.2502	8.6348	3.2933	0.2567	-	-	7.9355	4.1024
2000		0.7515	1.101	0.5932	1.2295	1.0398	0.5036	-	2.3527	1.1248	0.9334	0.9326	1.4689	3.2962	1.4297	8.0092	7.4282	3.8773	-	25.874	4.3217	7.5147	4.0899
2001		0.6519	1.1111	0.6789	1.2073	1.1406	0.4685	-	2.3539	0.9136	1.0882	0.9436	1.4512	3.5284	1.4529	7.9994	7.6816	3.6906	-	25.825	3.5658	8.0349	4.0189
2002		0.9386	1.0705	0.7049	1.199	0.8434	0.5381	-	2.1279	0.4978	0.9031	1.0168	1.2018	3.1955	1.4949	8.349	6.2737	3.8038	-	23.155	1.9827	7.2897	4.1908
2003		0.6281	1.193	0.5572	1.2306	0.9191	0.6208	0.0989	2.1856	0.6705	0.9633	0.9138	1.3612	3.6768	1.3181	8.5176	5.7622	3.9662	0.2371	22.53	2.6951	7.3688	4.0534
2004		0.8208	1.4094	0.5363	1.2209	0.7647	0.4761	0.0861	2.053	0.739	0.9545	0.8405	1.49	3.9744	1.4131	8.6979	5.7401	3.8566	0.1964	21.473	3.0787	7.3344	4.1221
2005		0.6743	1.59	0.5362	1.2505	0.8584	0.5479	0.0822	1.9763	1.5047	0.9908	0.8145	1.5015	4.2523	1.4067	9.0301	5.9393	4.0563	0.194	21.205	6.659	7.7145	3.7479
2006		1.266	1.5633	0.5604	1.3074	0.8233	0.6183	0.083	2.115	1.3811	0.7253	0.8774	1.6028	4.5589	1.4138	9.5877	5.4737	4.327	0.2036	21.945	6.0493	5.6554	3.9477
2007		-	1.8319	-	1.3316	0.9164	0.6691	0.0568	1.9295	1.7222	0.7682	0.7659	-	5.8177	-	9.9567	5.9233	4.6158	0.1449	20.835	7.8499	5.5431	3.9076
2008		-	1.7659	0.7186	1.3025	0.8339	0.6209	0.0288	1.8486	1.6022	0.6226	-	-	5.7734	1.9239	10.11	5.8622	4.779	0.0772	20.27	7.4423	4.987	-
2009		-	2.0456	0.7959	1.3098	0.6629	0.557	0.059	1.9962	1.7646	0.6533	0.6774	-	6.2789	2.0365	10.198	4.7665	4.3332	0.1564	21.1	8.4752	5.0742	3.5575
2010		-	1.9839	0.9463	1.2981	0.682	0.6531	0.0762	1.9022	1.7033	0.5255	-	-	6.4662	2.4098	10.355	4.4653	4.6684	0.2073	19.287	7.8184	3.9312	-
2011		-	1.9099	0.9517	1.2625	0.6783	0.7094	0.0995	1.7693	1.9728	0.4993	-	-	6.1929	2.4544	10.388	4.4716	5.1415	0.2783	18.338	9.3189	3.7877	-
2012		-	1.8746	1.0221	1.243	0.6959	0.7051	0.0929	1.8827	1.7281	0.6226	0.8733	-	6.217	2.6313	10.478	4.768	5.3675	0.2716	19.372	8.0467	4.0329	3.886
2013		-	1.8737	0.9195	1.2118	0.7247	0.6666	0.0773	1.8257	1.6247	0.5807	-	-	6.2475	2.7866	10.414	4.9756	5.0625	0.2298	18.64	7.5886	4.1386	-
2014		-	1.7733	1.053	1.1992	0.7606	0.6288	0.1009	1.8492	1.3588	0.521	-	-	5.7086	2.6919	10.625	5.6138	5.3768	0.3192	19.077	6.5768	4.2787	-
1990	*a*				18.826	41.08	-10.13				23.67	23.275				-678.5	233.79	-117.57				161.12	-7.94
~	*b*				0.01	-0.02	0.0053				-0.0114	-0.011				0.3431	-0.1135	0.0607				-0.0771	0.006
2009	r^2				0.5039	0.5516	0.2631				0.2455	0.4444				0.7619	0.4188	0.6391				0.1949	0.0673
	p				0.0007	0.0002	0.0207				0.0263	0.0025				0	0.002	0				0.0514	0.298
2009	*a*		101.19	-72.37	49.03	-35.75	-22.08	-11.76	50.782	145.913	21.99			206.39	-260.97		-343.66	-375.84	-50.03	653.05	666.24	182.96	
~	*b*		-0.0494	0.0364	-0.0238	0.0181	0.0113	0.0059	-0.0243	-0.0717	-0.0107			-0.0995	0.131		0.1733	0.1893	0.025	-0.3151	-0.3273	-0.0889	
2014	r^2		0.9451	0.5743	0.9839	0.8886	0.1407	0.4543	0.3488	0.4473	0.1036			0.542	0.8311		0.5812	0.7335	0.6503	0.3731	0.4473	0.1324	
	p		0.0012	0.0809	0.0001	0.0048	0.4637	0.1421	0.2171	0.1463	0.5338			0.0952	0.0114		0.078	0.0294	0.0526	0.1977	0.1464	0.4784	

-: No available data on pesticide use (total). Linear regression: $x = a + b\ t$, where t is year (e.g., 2010), x is cost / benefit or pesticide use (total) at t, and b is the annual growth rate. Linear regressions missing large amount of data are ignored. China's pesticide use (total) has continually declined since 2015 and linear regression between 2009 and 2014 was thus ignored.

Insecticides use and cost / benefit of most of the major countries reached the maximum around 2007~2009. According to linear regressions in the table, the cost / benefit of insecticides use of UK, Japan and Germany has significantly declined and France has significantly increased since 2009. The insecticides use of UK, Japan and Germany has significantly declined and France has significantly increased since 2009.

(2) Herbicides

Herbicides cost / benefit and use of major countries are shown in Table 8. The averaged annual cost / benefit (g herbicides use / kg crop production) during 2010 to 2014 of Brazil is the greatest (1.095), seconded by Canada (0.776), and followed by USA (0.548), Mexico (0.487), Japan (0.409), France (0.298), Germany (0.276), UK (0.243), which are higher than global average (0.16), and the last one is India (0.009). The averaged annual herbicides use (kg / ha) during 2010 to 2014 of Japan is the greatest (4.197), seconded by Brazil (3.585), and followed by USA (2.438), Mexico (2.282), Germany (2.103), Canada (2.056), France (2.043), UK (1.782), which are higher than global average (0.69), and the last one is India (0.027).

Table 7 Insecticides use, cost / benefit and trend of major countries since 1990.

Year		Cost /Benefit (g insecticides use / kg crop production)										Insecicides Use (kg / ha)									
		Australia	Brazil	Canada	France	Germany	India	Japan	Mexico	UK	USA	Australia	Brazil	Canada	France	Germany	India	Japan	Mexico	UK	USA
1990		0.1336	0.1791	0.0446	0.13	0.0302	0.184	-	-	0.0606	0.2135	0.2532	0.4136	0.1111	0.8118	0.2072	0.3303	-	-	0.4439	0.8295
1991		0.152	-	-	0.1223	0.026	0.1708	-	-	0.0541	0.2373	0.2723	-	-	0.7805	0.1775	0.3065	-	-	0.3989	0.8689
1992		0.1493	-	-	0.0662	0.0204	0.1557	-	-	0.0438	0.2047	0.3059	-	-	0.4479	0.1294	0.2969	-	-	0.334	0.8845
1993		0.1525	-	-	0.0639	0.0324	0.1362	-	-	0.0498	0.2556	0.3224	-	-	0.4314	0.2211	0.2673	-	-	0.3803	0.9145
1994		0.2054	-	0.058	0.0562	0.0266	0.1189	-	-	0.0563	0.2127	0.2977	-	0.126	0.3699	0.1741	0.2393	-	-	0.4203	0.9337
1995		0.1596	-	-	0.1083	0.0262	0.1129	-	-	0.0511	0.273	0.3165	-	-	0.7052	0.1802	0.2236	-	-	0.3911	1.0017
1996		0.1388	-	-	0.0829	0.0205	0.0968	-	-	0.0455	0.2514	0.3065	-	-	0.5873	0.1513	0.1965	-	-	0.3767	1.0447
1997		0.1765	-	-	0.0655	0.0202	0.0809	-	-	0.0468	0.2245	0.3508	-	-	0.4507	0.1465	0.173	-	-	0.3583	0.9242
1998		0.1993	-	-	0.0481	0.0222	0.0732	-	-	0.0416	0.1778	0.3964	-	-	0.3432	0.158	0.1555	-	-	0.3035	0.7722
1999		0.1877	0.2282	0.0325	0.0344	0.0206	0.067	-	-	0.043	0.2109	0.3841	0.6945	0.0832	0.2447	0.1494	0.1523	-	-	0.3296	0.8926
2000		0.1682	0.2225	0.0308	0.033	0.0197	-	0.8044	0.3422	0.0468	0.2174	0.3288	0.6662	0.0742	0.2355	0.1517	-	8.8467	1.3146	0.3771	0.9535
2001		0.1459	0.2185	0.0339	0.0285	0.0183	-	0.7841	0.2532	0.0519	0.1821	0.3248	0.6939	0.0727	0.1917	0.1445	-	8.6023	0.9883	0.3832	0.7754
2002		0.2101	0.2148	0.0352	0.0236	0.0221	-	0.7075	0.171	0.0443	0.2202	0.269	0.6412	0.0747	0.1756	0.156	-	7.6994	0.6809	0.3574	0.9075
2003		0.1406	0.2226	0.0446	0.0274	0.0181	-	0.7985	0.217	0.0416	0.1736	0.3047	0.6862	0.1055	0.1719	0.1159	-	8.2309	0.8724	0.3183	0.7702
2004		0.1837	0.2835	0.0322	0.0247	0.0164	0.0557	0.7227	0.2475	0.0367	0.1812	0.3335	0.7995	0.0848	0.1856	0.1327	0.1269	7.5591	1.0313	0.282	0.8887
2005		0.1509	0.2996	0.0215	0.0275	0.0145	0.05	0.7022	0.3252	0.0381	0.1294	0.3361	0.8013	0.0563	0.1902	0.1074	0.1179	7.5345	1.4391	0.2964	0.5955
2006		0.2834	0.2975	0.0197	0.0246	0.0125	0.0483	0.779	0.3115	0.0441	0.1672	0.3588	0.8677	0.0498	0.1636	0.0872	0.1185	8.0828	1.3644	0.3438	0.7522
2007		-	0.346	-	0.0249	0.0225	0.035	0.7113	0.4115	0.044	0.1502	-	1.0988	-	0.1611	0.1553	0.0893	7.6811	1.8756	0.3176	0.7665
2008		-	0.3708	0.0403	0.0133	0.0168	0.0291	0.6654	0.3668	0.0346	-	-	1.2122	0.1078	0.0936	0.1294	0.0779	7.2958	1.704	0.2772	–
2009		-	0.3728	0.0369	0.0117	0.0192	0.0067	0.7662	0.4162	0.0355	0.1192	-	1.1442	0.0943	0.0839	0.1495	0.0179	8.0991	1.999	0.2754	0.6259
2010		-	0.3849	0.0466	0.0114	0.0199	0.0282	0.7028	0.3989	0.0279	-	-	1.2546	0.1187	0.0745	0.1422	0.0766	7.1265	1.8311	0.2085	-
2011		-	0.3355	0.0485	0.0275	0.018	0.0369	0.6438	0.5125	0.0252	-	-	1.088	0.1251	0.1812	0.1304	0.1033	6.6729	2.4209	0.1912	-
2012		-	0.3092	0.0525	0.0316	0.0169	-	0.656	0.5564	0.0236	0.1409	-	1.0255	0.1351	0.2164	0.1286	-	6.7503	2.5907	0.1529	0.6268
2013		-	0.3588	0.0418	0.0361	0.0167	-	0.6068	0.5489	0.0235	-	-	1.1963	0.1265	0.2476	0.1267	-	6.1955	2.5636	0.1678	-
2014		-	0.3878	0.0477	0.0352	0.011	-	0.6227	0.4456	0.0181	-	-	1.2483	0.1219	0.2596	0.0944	-	6.4238	2.1569	0.1483	-
1990	*a*				10.5096	1.2752				1.8698	10.4778				67.5303	7.1684				13.0713	21.7551
~	*b*				-0.0052	-0.0006				-0.0009	-0.0051				-0.0336	-0.0035				-0.0064	-0.0105
2009	r^2				0.75	0.5476				0.6095	0.5274				0.7683	0.4356				0.6028	0.2724
	p				0	0.0002				0	0.0006				0	0.0015				0.0001	0.0263
2009	*a*		2.0689	-2.4542	-11.2191	2.9822		57.7623	-36.3451	5.8641			-15.106	-9.7301	-82.173	18.7328		644.3677	-179.1387	45.9351	
~	*b*		-0.0009	0.0012	0.0056	-0.0015		-0.0284	0.0183	-0.0029			0.0081	0.0049	0.0409	-0.0092		-0.3169	0.0902	-0.0227	
2014	r^2		0.0027	0.1778	0.8589	0.7623		0.8116	0.2501	0.8796			0.0275	0.4368	0.9013	0.8323		0.7698	0.2904	0.8049	
	p		0.9223	0.4051	0.0078	0.0231		0.0142	0.3124	0.0057			0.7535	0.153	0.0038	0.0112		0.0216	0.2699	0.0153	

-: No available data on insecticides use. Linear regression: $x = a + b\ t$, where t is year (e.g., 2010), x is cost / benefit or insecticides use at t, and b is the annual growth rate. Linear regressions missing large amount of data are ignored.

Herbicides use and cost / benefit of most of the major countries reached the maximum around 2007~2009. According to linear regressions in the table, the herbicides use of France and Canada has significantly increased since 2009.

Table 8 Herbicides use, cost / benefit and trend of major countries since 1990.

Year		Cost /Benefit (g herbicides use / kg crop production)										Herbicides Use (kg / ha)									
		Australia	Brazil	Canada	France	Germany	India	Japan	Mexico	UK	USA	Australia	Brazil	Canada	France	Germany	India	Japan	Mexico	UK	USA
1990		0.4123	0.2231	0.3749	0.4406	0.2623	0.0185	-	-	0.5339	0.5112	0.781	0.5152	0.9341	2.7525	1.7973	0.0332	-	-	3.9128	1.9865
1991		0.4688	-	-	0.3863	0.3129	0.0188	-	-	0.5326	0.5327	0.8401	-	-	2.4653	2.1378	0.0338	-	-	3.9294	1.9505
1992		0.4607	-	-	0.3014	0.2859	0.0224	-	-	0.5614	0.4538	0.9437	-	-	2.0394	1.8144	0.0427	-	-	4.2798	1.9608
1993		0.4705	-	-	0.3071	0.23	0.0191	-	-	0.6453	0.5405	0.9943	-	-	2.0724	1.5683	0.0375	-	-	4.9307	1.9336
1994		0.6337	-	0.3707	0.3692	0.2738	0.0193	-	-	0.7223	0.4732	0.9184	-	0.8059	2.4283	1.7944	0.0388	-	-	5.3956	2.0772
1995		0.4923	-	-	0.3355	0.2769	0.0173	-	-	0.6977	0.5472	0.9764	-	-	2.1854	1.9068	0.0342	-	-	5.3379	2.0077
1996		0.5014	-	-	0.3931	0.2621	0.0198	-	-	0.6632	0.4916	1.1071	-	-	2.785	1.9312	0.0402	-	-	5.496	2.0427
1997		0.5989	-	-	0.3619	0.2541	0.0182	-	-	0.6787	0.4753	1.1901	-	-	2.4913	1.8419	0.0389	-	-	5.196	1.9567
1998		0.5906	-	-	0.3754	0.2664	0.0194	-	-	0.7086	0.4593	1.1744	-	-	2.6769	1.8918	0.0411	-	-	5.1681	1.9949
1999		0.4746	0.5378	0.5326	0.4282	0.2393	0.0183	-	-	0.6986	0.434	0.9713	1.6368	1.3633	3.0438	1.7361	0.0416	-	-	5.3608	1.8366
2000		0.5189	0.6418	0.4818	0.3277	0.2372	-	0.334	0.3581	0.6477	0.425	1.0143	1.9215	1.1613	2.3409	1.8259	-	3.6731	1.376	5.2149	1.8638
2001		0.4501	0.6479	0.5431	0.3675	0.2094	-	0.3526	0.331	0.7564	0.4505	1.002	2.0575	1.1623	2.4751	1.6499	-	3.868	1.292	5.5847	1.9186
2002		0.6481	0.6168	0.564	0.2944	0.2239	-	0.3481	0.1881	0.6178	0.4614	0.8298	1.8411	1.1959	2.1899	1.5829	-	3.7875	0.7492	4.987	1.9016
2003		0.4337	0.7207	0.4291	0.3022	0.2681	-	0.3524	0.2788	0.6634	0.4227	0.9399	2.2211	1.0149	1.8948	1.713	-	3.6324	1.1206	5.0748	1.8748
2004		0.5667	0.8143	0.4103	0.2623	0.217	0.0184	0.3764	0.2935	0.6337	0.3812	1.0288	2.2963	1.081	1.9688	1.758	0.042	3.9373	1.2226	4.8697	1.8697
2005		0.4656	0.937	0.4183	0.3204	0.2351	0.012	0.3764	0.5563	0.6587	0.3996	1.0368	2.5059	1.0972	2.2166	1.7402	0.0283	4.0391	2.4618	5.1286	1.8389
2006		0.8742	0.9495	0.4399	0.2652	0.2737	0.0154	0.3873	0.5101	0.3953	0.4124	1.1068	2.7689	1.1099	1.7632	1.9157	0.0379	4.0181	2.2344	3.0826	1.8553
2007		-	1.1394	-	0.318	0.2819	0.0131	0.3795	0.5536	0.4183	0.3829	-	3.6185	-	2.0554	1.9446	0.0333	4.0985	2.5232	3.0181	1.9538
2008		-	1.0487	0.5611	0.2892	0.2664	0.0082	0.3731	0.4751	0.3082	-	-	3.4286	1.5021	2.0328	2.0504	0.022	4.0909	2.2071	2.4689	-
2009		-	1.2341	0.6305	0.2349	0.2149	0.0073	0.4192	0.5121	0.3217	0.3979	-	3.7881	1.6131	1.6891	1.6719	0.0195	4.4313	2.4595	2.4983	2.0894
2010		-	1.0976	0.7645	0.2493	0.2667	0.008	0.4164	0.4768	0.2339	-	-	3.5775	1.9469	1.6325	1.9065	0.0218	4.2224	2.1886	1.75	-
2011		-	1.0448	0.7701	0.3229	0.2904	0.0113	0.3899	0.5776	0.224	-	-	3.3878	1.9861	2.1289	2.1049	0.0317	4.0412	2.7281	1.6993	-
2012		-	1.1585	0.8092	0.3021	0.3078	-	0.3979	0.5591	0.2753	0.5479	-	3.8423	2.0832	2.0696	2.343	-	4.094	2.6033	1.7833	2.4379
2013		-	1.0864	0.7271	0.3025	0.2721	-	0.4143	0.4571	0.2522	-	-	3.6224	2.2034	2.077	2.0662	-	4.2295	2.1351	1.7976	-
2014		-	1.0857	0.8064	0.3126	0.2447	-	0.4265	0.3629	0.2289	-	-	3.4952	2.0613	2.3074	2.0924	-	4.3999	1.7566	1.88	-
1990	*a*				12.5864	3.9078				22.7348	16.7091				69.4234	6.016				161.9454	18.2141
~	*b*				-0.0061	-0.0018				-0.0111	-0.0081				-0.0336	-0.0021				-0.0787	-0.0081
2009	r^2				0.4315	0.1538				0.2392	0.7142				0.3052	0.0073				0.2045	0.3796
	p				0.0017	0.0872				0.0286	0				0.0115	0.7207				0.0453	0.0065
2009	*a*		39.1507	-45.583	-30.0098	-10.2236		-1.7673	47.8092	20.804			53.9185	-176.63	-248.90	-160.0335		9.0046	220.7041	166.5359	
~	*b*		-0.0189	0.023	0.0151	0.0052		0.0011	-0.0235	-0.0102			-0.025	0.0888	0.1247	0.0806		-0.0024	-0.1086	-0.0818	
2014	r^2		0.2728	0.4203	0.6064	0.0874		0.0213	0.3194	0.263			0.0734	0.6801	0.7734	0.4503		0.0008	0.325	0.2633	
	p		0.2878	0.1638	0.068	0.5694		0.7829	0.2426	0.2982			0.6034	0.0434	0.0209	0.1445		0.9577	0.2376	0.2978	

-: No available data on herbicides use. Linear regression: $x = a + b\ t$, where t is year (e.g., 2010), x is cost / benefit or herbicides use at t, and b is the annual growth rate. Linear regressions missing large amount of data are ignored.

(3) Fungicides & bactericides

Fungicides & bactericides cost / benefit and use of major countries are shown in Table 9. The averaged annual cost / benefit (g fungicides & bactericides use / kg crop production) during 2010 to 2014 of Japan is the greatest (0.773), followed by Mexico (0.698), France (0.315), Brazil (0.249), UK (0.181), Germany (0.156), which are higher than global average (0.074), and the last two are USA (0.052) and India (0.021). The averaged annual fungicides & bactericides use (kg / ha) during 2010 to 2014 of Japan is the greatest (7.934), followed by Mexico (3.275), France (2.162), UK (1.332), Germany (1.194), Brazil (0.814), which are higher than global average (0.32), and the last two are USA (0.229), and India (0.058).

Fungicides & bactericides use and cost / benefit of most of the major countries reached the maximum around 2007~2009. According to linear regressions in the table, both cost / benefit and use of fungicides & bactericides of Mexico has significantly declined since 2009.

Table 9 Fungicides & bactericides use and cost / benefit of major countries since 1990.

Year	Cost /Benefit (g fungicides & bactericides use / kg crop production)										Fungicides & Bactericides Use (kg / ha)									
	Australia	Brazil	Canada	France	Germany	India	Japan	Mexico	UK	USA	Australia	Brazil	Canada	France	Germany	India	Japan	Mexico	UK	USA
1990	0.0428	0.0818	0.1279	0.4887	0.1801	0.0346	-	-	0.1945	0.0562	0.081	0.189	0.3187	3.053	1.234	0.0621	-	-	1.4255	0.2183
1991	0.0486	-	-	0.6367	0.1718	0.0348	-	-	0.1901	0.0569	0.0872	-	-	4.0633	1.1735	0.0624	-	-	1.4025	0.2084
1992	0.0478	-	-	0.4852	0.1741	0.033	-	-	0.1952	0.0454	0.0979	-	-	3.2829	1.1047	0.063	-	-	1.4878	0.1961
1993	0.0488	-	-	0.6413	0.1388	0.0303	-	-	0.2225	0.0598	0.1032	-	-	4.3275	0.9462	0.0595	-	-	1.7005	0.2138
1994	0.0658	-	0.1032	0.6095	0.1421	0.0288	-	-	0.2113	0.0468	0.0953	-	0.2244	4.0088	0.9312	0.058	-	-	1.5781	0.2056
1995	0.0511	-	-	0.5209	0.1664	0.0272	-	-	0.2013	0.0582	0.1013	-	-	3.3938	1.1456	0.0538	-	-	1.5397	0.2134
1996	0.0459	-	-	0.5302	0.1649	0.0252	-	-	0.1882	0.0521	0.1013	-	-	3.7562	1.2147	0.0511	-	-	1.5592	0.2166
1997	0.0548	-	-	0.6903	0.1448	0.0225	-	-	0.1902	0.0536	0.1089	-	-	4.7525	1.05	0.0481	-	-	1.4562	0.2206
1998	0.0583	-	-	0.6058	0.1552	0.0255	-	-	0.1849	0.0533	0.116	-	-	4.3201	1.1023	0.0543	-	-	1.3487	0.2317
1999	0.0647	0.1592	-	0.6497	0.1402	0.0191	-	-	0.1864	0.0456	0.1325	0.4845	-	4.6183	1.0173	0.0434	-	-	1.4305	0.1931
2000	0.0539	0.1495	-	0.5613	0.1339	-	1.197	0.4246	0.1374	0.0433	0.1053	0.4477	-	4.0097	1.0306	-	13.1642	1.6311	1.1062	0.1898
2001	0.0467	0.1364	-	0.6193	0.1124	-	1.1956	0.3294	0.161	0.0437	0.104	0.4333	-	4.1708	0.8858	-	13.1174	1.2855	1.1885	0.1861
2002	0.0673	0.127	-	0.4435	0.155	-	1.0529	0.1388	0.136	0.0443	0.0861	0.379	-	3.2987	1.0954	-	11.458	0.5526	1.098	0.1824
2003	0.045	0.1266	-	0.4848	0.1716	-	1.0151	0.1747	0.1454	0.0427	0.0975	0.3902	-	3.0397	1.0965	-	10.4636	0.702	1.1124	0.1892
2004	0.0588	0.1682	-	0.3735	0.1071	0.0271	0.9389	0.198	0.1792	0.0386	0.1067	0.4744	-	2.8041	0.8674	0.0617	9.8197	0.8247	1.3771	0.1892
2005	0.0483	0.1849	-	0.394	0.1437	0.0196	0.8832	0.6232	0.1854	0.0476	0.1076	0.4944	-	2.7259	1.0636	0.0463	9.4769	2.7581	1.4434	0.2189
2006	0.0907	0.1618	-	0.4134	0.1527	0.0146	0.9352	0.5595	0.1848	0.0466	0.1148	0.4718	-	2.7484	1.069	0.0357	9.7036	2.4505	1.4412	0.2097
2007	-	0.1671	-	0.4379	0.1693	0.0277	0.8265	0.7571	0.1977	0.0408	-	0.5307	-	2.8306	1.168	0.0706	8.9245	3.451	1.4263	0.2082
2008	-	0.1857	-	0.4156	0.1538	0.0165	0.7936	0.7602	0.1787	-	-	0.6072	-	2.9217	1.1837	0.0442	8.7017	3.5313	1.4311	-
2009	-	0.2311	-	0.3386	0.1446	0.0154	0.7935	0.8363	0.1891	0.0394	-	0.7094	-	2.4343	1.1251	0.0408	8.387	4.0166	1.4691	0.2071
2010	-	0.3219	-	0.3286	0.1546	0.0183	0.7646	0.8276	0.173	-	-	1.0491	-	2.1516	1.1052	0.0498	7.7532	3.7988	1.2942	-
2011	-	0.3114	-	0.2712	0.1635	0.0234	0.7181	0.8828	0.162	-	-	1.0097	-	1.788	1.1854	0.0654	7.443	4.1699	1.2287	-
2012	-	0.2022	-	0.2982	0.1359	-	0.8095	0.6126	0.2033	0.0515	-	0.6705	-	2.0429	1.0345	-	8.3298	2.8527	1.3171	0.2291
2013	-	0.2257	-	0.3285	0.154	-	0.7893	0.6187	0.192	-	-	0.7527	-	2.2557	1.1697	-	8.0587	2.8899	1.3682	-
2014	-	0.1828	-	0.3481	0.1727	-	0.784	0.5503	0.1766	-	-	0.5886	-	2.5692	1.4769	-	8.0874	2.6634	1.4503	-
1990 *a*				23.9414	2.2892				3.0733	1.7722		-74.7405		140.6887	3.5332				18.9163	1.8024
~ *b*				-0.0117	-0.0011				-0.0014	-0.0009		0.0375		-0.0686	-0.0012				-0.0088	-0.0008
2009 r^2				0.4355	0.1051				0.1448	0.5168		0.7638		0.3263	0.0048				0.1026	0.0891
p				0.0015	0.1631				0.098	0.0008		0		0.0085	0.7705				0.1686	0.2288
2009 *a*		36.9735		-3.9573	-6.2327		-6.0021	134.4483	-1.8621			106.1197		-69.1551	-102.3679		-9.5274	624.6754	-11.1136	
~ *b*		-0.0183		0.0021	0.0032		0.0034	-0.0665	0.001			-0.0524		0.0355	0.0515		0.0087	-0.3089	0.0062	
2014 r^2		0.352		0.0192	0.2058		0.0386	0.757	0.0162			0.2697		0.0564	0.3929		0.0021	0.7472	0.0155	
p		0.2145		0.7937	0.3662		0.7091	0.0242	0.81			0.291		0.6506	0.1829		0.9317	0.0263	0.8142	

-: No available data on fungicides & bactericides use. Linear regression: $x = a + b\,t$, where t is year (e.g., 2010), x is cost / benefit or fungicides & bactericides use at t, and b is the annual growth rate. Linear regressions missing large amount of data are ignored.

3.3 Trend in China

As the world's largest country for pesticide production and use (Zhang et al., 2011), China plays an important role in reducing pesticide use and pollution. Actually, China has banned some highly toxic and residual pesticides since 2007 (Peshin et al., 2009; Peshin and Zhang, 2014). As indicated in Table 6, the cost / benefit of pesticide use of China has been declining since 2007, and overall, the use strength of pesticide (total) stabilized between 2010 and 2014.

Since 2015, China has launched zero growth action in the use of pesticides and has promoted reduction and efficiency enhancement of pesticide use. According to an investigation in 2017, the utilization rate of pesticides for the three major grain crops rice, corn and wheat was 38.8%, an increase of 2.2% over 2015, equivalent to a reduction of 30000 tons of pesticide use (Li, 2017). Consequently, the use strength of pesticide (total) declined from 2015.

3.3.1 Pesticide registrations

By the end of 2016, there were 35604 registered pesticide products and 665 registered active ingredients in China. Among them, insecticides, fungicides & bactericides, and herbicides accounted for 89.7% of the total registrations. Pesticide registrations rank first, accounting for 40% of the total registrations, with a total of 14233 registrations (1308 original pesticides), followed by fungicides & bactericides (9121 registrations, 959 original pesticides), and herbicides (8584 registrations, 1553 original pesticides) (Gu, 2017).

The registered products were mainly low-toxic pesticides (26520 registrations), accounting for 74.5% of the total; the moderate ones accounted for 16.4% (5840 registrations); the slightly-toxic pesticides accounted for 7.8% (2767 registrations). Highly toxic pesticides accounted for 1.4% only. In terms of formulations, emulsifiable concentrates accounted for 30% of the total (9414 registrations); wettable powder accounted for 21.4% (6731 registrations); suspension concentrates, water concentrates, and water dispersible granules held 3527, 2143 and 1643 registrations, respectively (Gu, 2017).

The top 20 registered pesticides of China before 2017 are listed in Table 10. With a total of 9200 registrations, rice is the hottest crop for pesticide registrations, accounting for 29.3% of the total preparations registered, followed by cotton, wheat, citrus, apple, corn, cabbage, cucumber, health insecticides, and cruciferous vegetables (Gu, 2017).

Table 10 China's top 20 registered pesticides before 2017.

	Avamectin	Imidacloprid	Beta-cypermethrin	Chlorpyrifos	Phoxim
Registrations	1642	1290	1072	1064	997
Original pesti.	31	76	31	70	17
	Glyphosate	Carbendazim	Mancozeb	Cyhalothrin	Atrazine
Registrations	956	953	877	783	776
Original pesti.	158	21	30	43	24
	Thiram	Acetochlor	Acetamiprid	Cypermethrin	Difenoconazole
Registrations	761	703	689	630	604
Original pesti.	13	33	49	30	34
	Emamectin	Tebuconazole	Bensulfuron-methyl	Nicosulfuron	Thiophanate-methyl
Registrations	586	584	566	535	504
Original pesti.	18	48	16	54	18

Source: Gu (2017).

In 2016, the registrations of the three major types of pesticides accounted for 92.4% of the newly registered in the year, and the registrations of fungicides & bactericides and herbicides exceeded that of pesticides, of which 774 were fungicides & bactericides, 749 were herbicides and 560 were insecticides. Among the new registrations, suspension concentrates accounted for 28.1% (557). Both wettable powder and water-dispersible granules accounted for 12.3% of the newly added preparations, with the registrations of 243 and 244 respectively. In total of 156 registrations were dispersible oil-based suspension concentrates, accounting for 7.9%; 154 were aqueous solutions, accounting for 7.8%, and 104 were registered as emulsions, accounting for 5.2%. Among the newly registered products in 2016, the top ten varieties were pyraclostrobin (127 registrations, 19 originals), atrazine (114 registrations), mesotrione (89 registrations), thiamethoxam (88 registrations), difenoconazole (81 registrations), azoxystrobin (81 registrations), avermectin (74 registrations), tebuconazole (74 registrations), nicosulfuron (73 registrations) and glufosinate (60 registrations). In 2016, the newly registered active ingredients were guadipyr, triflumezopyrim, flupyradifurone, *Sophora alopecuroides* alkaloids, *Metarhizium anisopliae* CQMa421, *Bacillus methylotrophicus*, terpenes, *Bacillus amyloliquefaciens*, 2,4-dichlorophenoxybutyric acid sodium butyrate, halauxifen-methyl, benzobicylon, and pyraclonil, etc.

3.3.2 Export and import

Pesticide export of China were 1.4088, 1.5994, 1.6219, 1.6417, 1.5095, 1.3725 million tonnes and pesticide import were 43.9, 53.5, 62.2, 67.2, 57.6, 39.1 thousands of tonnes for the years 2011 to 2016. In 2016, China exported over 400 varieties of pesticides, of which the top 10 were glyphosate (0.477067 million tonnes), paraquat (0.172614 million tonnes), atrazine (40.014 thousands of tonnes), chlorothalonil (26.385 thousands of tonnes), chlorpyrifos (22.215 thousands of tonnes), imidacloprid (20.345 thousands of tonnes), acephate (18.311 thousands of tonnes), carbendazim (17.527 thousands of tonnes), clethodim (10.515 thousands of tonnes), and sulfentrazone (3120 tonnes) (Gu, 2017).

In 2016, the pesticide originals of China were mainly exported to (in terms of money) USA, Brazil, India, Australia and Argentina. The preparations were mainly exported to Brazil, Australia, Thailand, Indonesia and Vietnam. In terms of quantities, China's pesticides were mainly exported to Asia (33%) and South America (28%), followed by Africa (14%), Europe (9%), North America (8%) and Oceania (8%) (Gu, 2017).

3.3.3 Profile of bio-pesticide products

At present, the annual production of bio-pesticides in China reaches 120000 tonnes and the control area reaches 26700000 ha, accounting for about 5% of the pesticide market share (Survey Platform for National Bio-pesticide Business, 2017b). More than 90 active ingredients and about 3000 products of bio-pesticides were registered, of which about 75% of the total were antibiotics products. According to the latest statistics, at present the coverage of bio-pesticides in China has reached nearly 10%. So far (December 2017), the situation of major bio-pesticides is as follows (Survey Platform for National Bio-pesticide Business, 2017a)

(1) Microbial pesticides

There are 27 active ingredients and about 300 products. The main products include

Insecticides: *Bacillus thuringiensis* (181 products), HaNPV (23 products), SlNPV and AcMNPV (4 products each), EoNPV (3 products), etc (Fig. 6).

Fungicides and bactericides: *Bacillus cereus* (23 products), *Bacillus subtilis* (17 products), Trichoderma products (5 products), *Pseudomonas fluorescens* (3 products), etc.

(2) Biochemical pesticides

There are 21 active ingredients and more than 300 products. The main products include

Plant growth regulators: ethephon (94 products), gibberellin (57 products), oligosaccharins (23 products), indole acetic acid / Indole butytic acid (18 products), triacontanol (18 products), etc.

Fungicides and Bactericides: chitosan (6 products), dioctyl divinyltriamino glycine (9 products), etc.

(3) Plant-derived pesticides

In China, there are estimated more than 10000 species of plants with insecticidal or fungicidal / bactericidal ingredients. Currently, 19 active ingredients and more than 200 products have been utilized and developed. The main products include

Insecticides: matrine (62 products), rotenone (16 products), azadirachtin (15 products), nicotine (13 products), etc.

Fungicides and bactericides: allicin (20 products), etc.

Rodenticide: tetramine (1 product).

(4) Antibiotic pesticides

There are 21 active ingredients and more than 2200 products. The main products include

Insecticides: avermectin (1367 products), emamectin benzoate (406 products), etc.

Fungicides and bactericides: validamycin (197 products), kasugamycin (73 products), polyoxin (55 products), etc.

Although bio-pesticides grow quickly in recent years, it is still 20~30% lower than that in developed countries (Survey Platform for National Bio-pesticide Business, 2017a).

From the profile above, we conclude that China's pesticide production and export / import have declined in recent years. Development and production of highly toxic and residual pesticides have reduced and more safe and efficient formulations increased in the recent years. In 2017, China has adopted a series of new measures to strengthen the management of pesticide production and use, e.g., building a national administration for pesticide management (Fan, 2017), deciding to ban all of the highly toxic pesticides in the forthcoming five years (Dong, 2017), etc. It is expected that the pesticide use in China will continually decline and 40% or more of pesticide utilization rate will be achieved by 2020 (Li, 2017).

3.4 Relationship between crop yield and cost / benefit of pesticide use

Based on the data of crop yield and global pesticide use (total) between 1990 and 2007, the observed relationship between cost / benefit of pesticide use and crop yield is indicated in Fig. 6. The fitted model (1) and fitting goodness are as follows

$$y = 3100 + 920 / (1 + e^{(27.3-42*x)})$$

r^2=0.701, p=0

It is obvious that model (1) fits the observed data well (p<0.0001).

This is a pseudo-case (i.e., dynamic production condition and multiple influential factors on crop yield) to partially verify the theoretical relationship and model (1). In model (1), I have assumed that the production conditions are constant. Thus in Fig. 6, the constant production conditions refer to the averaged production conditions between 1990 and 2007. According to Fig. 6 and model (1), the reasonable cost / benefit of pesticide use (total) is approximately between 0.62 and 0.8 for the averaged production conditions between 1990 and 2007.

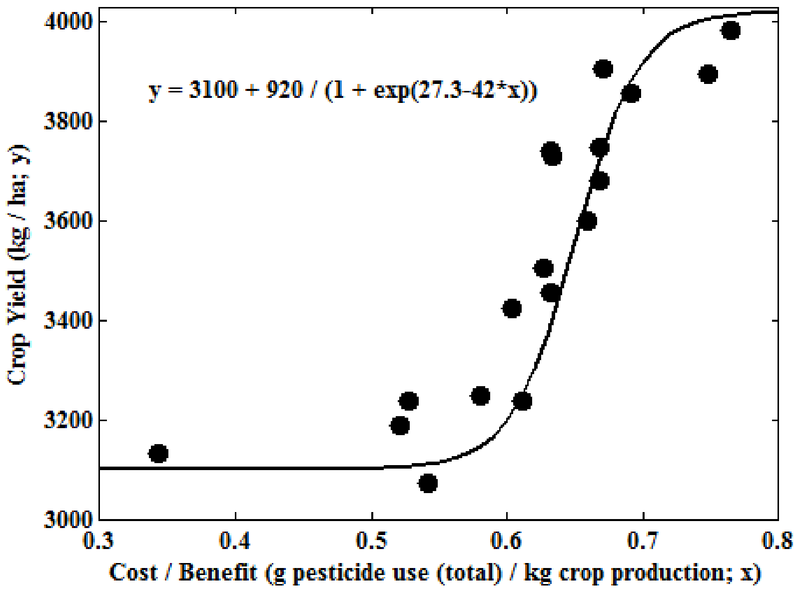

Fig. 6 Observed **(•)** and fitted (–) relationship between cost / benefit of pesticide use and crop yield (for global pesticide use (total) between 1990 and 2007).

4 Discussion

4.1 Estimated pesticide use and cost / benefit between 2017 and 2020

According to Table 3 and the trend, the estimated pesticide cost / benefit during 2017~2020 is ~0.6 g pesticide use (total) / kg crop production, and the estimated pesticide use (total) is annually ~2.7 kg / ha. It is known that only 30~40% of pesticide use is directly acted on target crops and pests (Fan, 2017). Therefore, if pesticides fully functions without any waste, by using various accurate tools and methods, ~0.18 to ~0.24 g pesticide use (total) / kg crop production, or ~0.81 to ~1.08 kg / ha of pesticide use (total) are the most ideal indices for pesticide use (total) at the present crop yield levels and production conditions.

Based on Table 4, the estimated cost / benefit (g pesticide use / kg crop production) for use of organo-phosphates, pyrethroids, carbamates insecticides, amides, phenoxy hormone products, bipiridils, inorganics, dithiocarbamates, triazoles / diazoles, and plant growth regulators during 2017~2020 are ~0.0050, ~0.0015, ~0.0007, ~0.0065, ~0.0050, ~0.0030, ~0.0130, ~0.0050, ~0.0030, and ~0.0080, respectively, and the estimated pesticide use during this period are ~0.0230, ~0.0065, ~0.0030, ~0.0250, ~0.0100, ~0.0130, ~0.0600, ~0.0250, ~0.0110, and ~0.0360 kg / ha, respectively.

From Table 6, the estimated cost / benefit (g pesticide use (total) / kg crop production) for Brazil, Canada, China, France, Germany, India, Japan, Mexico, UK, and USA during 2017~2020 are ~1.5, ~1.0, ~1.0, ~0.7, ~0.65, ~0.09, ~1.85, ~1.3, ~0.5, and ~0.8, respectively, and the estimated pesticide use (total) during this period are ~5.7, ~2.5, 9.0~10.5, ~5.0, ~5.0, ~0.25, ~18.5, ~6.5, ~4.0, and ~3.8 kg / ha, respectively.

Based on Table 7, the estimated cost / benefit (g insecticides use / kg crop production) for Brazil, Canada, France, Germany, Japan, Mexico, UK, and USA during 2017~2020 are ~0.35, ~0.045, ~0.035, ~0.01, ~0.60, ~0.40, ~0.015, and ~0.13, respectively, and the estimated insecticides use during this period are ~1.15, ~0.12, ~0.20, ~0.08, ~6.0, ~2.0, ~0.15, and ~0.60 kg / ha, respectively.

From Table 8, the estimated cost / benefit (g herbicides use / kg crop production) for Brazil, Canada, France, Germany, Japan, Mexico, UK, and USA during 2017~2020 are ~1.05, ~0.80, ~0.30, ~0.25, ~0.41, ~0.35, ~0.20, and ~0.45, respectively, and the estimated herbicides use during this period are ~3.4, ~2.1, ~2.1,

~2.1, ~4.1, ~1.6, ~1.6, and ~2.0 kg / ha, respectively.

Finally, according to Table 9 the estimated cost / benefit (g fungicides & bactericides use / kg crop production) for Brazil, France, Germany, Japan, Mexico, UK, and USA during 2017~2020 are ~0.18, ~0.3, ~0.16, ~0.78, ~0.50, ~0.16, and ~0.04, respectively, and the estimated fungicides & bactericides use during this period are ~0.55, ~2.5, ~1.2, ~8.0, ~2.5, ~1.4, and ~0.2 kg / ha, respectively.

The estimates above are combined estimation of both the past and the trend, which are not exact values and can only be used as approximate and referential data.

4.2 Insect Control and Microbial Pesticides

4.2.1 Conceptual frame of insect control

According to the criteria: (1) strength and frequency of external control; (2) environmental impact of external control: (a) environmental pollution; (b) impact on human health, and (3) sustainability, the conceptual frame of insect control is redescribed as the following

H_1: Natural Equilibrium: Without or basically without artificial forces; eternal control.

H_{11}: Natural ecosystems. For original ecosystems, insect pests are completely controlled by natural equilibrium through biodiversity, ecological food webs, etc., without artificial interferences (Jiang et al., 2015; Zhang, 2011; Zhang et al., 2014).

H_{12}: Artificially aided natural ecosystems. For the ecosystems with poorer natural equilibrium mechanisms, try to achieve ideal natural equilibrium by eternally alter the environment of the insect pest, e.g., create harbouring sites for natural enemies, improvement of irrigation facilities, etc.

H_2: Biological Control: Introduce organisms to ecosystems; semi-eternal / eternal control.

H_{21}: Release of beneficial animals. Increase the population size of a natural enemy (beneficial arthropods, etc.) by releasing more individuals of the natural enemy in agricultural ecosystems.

H_{221}: Release of pathogenic microorganisms to kill insect pests directly by living microorganisms. Spray a pathogenic microorganism to infect and kill the insect pest, and possibly trigger epidemic disease (pathogenic fungus, virus, bacteria, etc.).

H_{222}: Release of pathogenic microorganisms to kill insect pests by excreting poisonous substance. Spray the pathogenic microorganism to infect and kill an insect pest, and possibly trigger epidemic disease (Bt, etc.).

H_3: Physical / Agri. Control: Physical and some agricultural control measures; temporary control. This includes black light, magnetic control, artificial removing of insects, etc.

H_4: Chemical Control: Introduce natural or synthesized chemicals to ecosystems; temporary control.

H_{41}: Control with natural chemicals. Use the natural chemicals derived from plants, or other organisms to control insect pests. Or, use other natural products, e.g., minerals, etc., to control insect pests.

H_{42}: Control with synthesized chemicals. Use artificially synthesized chemicals, e.g., organophosphorus insecticides, etc., to control insect pests.

From H_1 to H_4, the strength and frequency of external control increase, negative environmental impact of external control increases, and sustainability declines. The conceptual frame is expected to be valuable for assessing the environmental impact and sustainability of a control measure.

4.2.2 Potentiality and exploitation of microbial pesticides

Microbial pesticides, which mainly refer to the pesticides composed of living microorganisms with insecticidal or fungicidal / bactericidal activity, are expected to be the most promising bio-pesticides in the future (Fig. 7). The substantial advantage of microbial pesticides is that they can induce epidemic diseases in insect populations. According to the modelling analysis of Zhang et al. (2011), for a NPV pesticide, triggering a sustainable epidemic disease is more effective than just using it as a one-time pesticide, and spraying time (the optimal larva instar for spraying NPV) and incubation time (incubation duration of NPV inside insect body) are more significant than NPV dosage. Therefore, how to exploit the epidemic mechanism of the disease caused by microbial pesticide and to trigger a sustainable epidemic disease is a focus for optimal use of the microbial pesticide. Insecticidal microorganisms should be further studied to (a) find new resources of insecticidal microorganisms; (b) expand insecticidal spectrum; (c) shorten the incubation duration; (d) enforce the capability for vertical transmission and horizontal transmission, and (e) enhance the environmental viability.

Fig. 7 (a) A Metarhizium pesticide. Prof YuXian Xia (twoeggz.com) and his research team have built the world's largest base for fungal pesticide production in Chongqing, China. The annual production of the Metarhizium pesticide, "a drinkable pesticide", has reached about 3000 tonnes, and after the mass production it is expected to reach 28000 tonnes/yr. (b) An insect infected and died of the fungus Metarhizium (1688.com). (c) A SlNPV insecticide. (d) A Bt insecticide (http://www.biological-control.org/biopest/biopesticide.asp).

4.3 Further discussion on cost / benefit of pesticide use

Cost / benefit and pesticide use can be jointly used to compare the relative efficiency of pesticide use between two countries if the two countries have the similar composition of pesticides to be used. Suppose the cost / benefit of the countries *A* and *B* are x_A and x_B, and the pesticide use are y_A and y_B, respectively. If $y_A/y_B>x_A/x_B$, the relative efficiency of pesticide use of *A* is considered to be greater than *B*.

It must be noted that more experimental cases are needed to verify the theoretical relationship and model (1). In such cases, pesticide use should be the only factor to determine the change of crop yield, as stressed above.

4.4 Further discussion on global pesticide development, production and use

Pesticide use in major countries, as listed above, has generally declined or oscillated since 2007~2009. Globally, pesticide use has overall declined since 2007. It is a positive sign for reducing pesticide pollution worldwide. Nevertheless, we should aware of the possible resurgence of pesticide overuse in the future. As the development of economy in developing countries, the hazard of sharp rise of pesticide use in these countries may increase in the forthcoming years. Keeping or strengthening the declining trend of pesticide use in major countries is still an arduous task. On the other hand, the same amount of pesticide use may have different pollution equivalent for different countries because the complex composition of pesticide varieties. In general, the developed countries tended to use low-toxic / low-residual pesticides, herbicides and bio-pesticides, and the developing countries tended to use highly toxic chemical pesticides. Misuse should be avoided when directly comparing environmental impacts of pesticide use between two countries.

General works to reduce pesticide use and pollution include:

(1) Develop highly efficient, low toxic and low residual pesticides, particularly bio-pesticides (Sanjaya et al., 2013; Darvishzadeh et al., 2014; Jafarbeigi et al., 2014; Sharifian and Darvishzadeh, 2015; Gupta et al., 2017). Mixture pesticides, as a resistance management strategy as well as a pollution reduction measure, can be explored also.

(2) Minimize the use of chemical pesticides (Mardani et al., 2017), increase the use of bio-pesticides, implement integrated pest management (IPM), protect natural enemies and biodiversity, and maximize the role of natural balance.

(3) Promote precision use of pesticides, reduce off-target phenomena and enhance utilization rate of pesticide use.

(4) Step up efforts to supervise, manage and standardize the production, distribution and use of pesticides.

(5) Further strengthen the legislation and regulation of pesticide production and use, for example, implement real-name registration and management of pesticide purchase and use.

(6) Strengthen the education of farmers on pesticide use, and improve their awareness and sense on environmental protection.

For a specific country or region, further guidelines can be manipulated based on both cost / benefit and use strength. For China, according to Table 6, the use strength of pesticides is strong but the cost / benefit of pesticide use is lower. Therefore, how to optimize the composition of pesticides in terms of production and use (e.g., the suggested works (1) and (2) above) is the first consideration, and to reduce pesticide use (total) by, in particular, the precision use of pesticides is another focus also.

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