Management of agricultural nonpoint source pollution in China: current status and challenges

Xiaoyan Wang*,**

*College of Resource, Environment & Tourism, Capital Normal University, Beijing 100037, P.R. China

**Key Laboratory of Resource, Environment & GIS, Beijing City, Beijing 100037, P.R. China

Water Science & Technology **Vol 53 No 2 pp 1–9** © IWA Publishing 2006

Abstract Water quality in China shows an overall trend of deterioration in recent years. Nonpoint source pollution from agricultural and rural regions is the leading source of water pollution. The agricultural nonpoint source pollutants are mainly from fertilization of cropland, excessive livestock and poultry breeding and undefined disposal of daily living wastes in rural areas. Agricultural nonpoint sources contribute the main source of pollution to most watersheds in China, but they are ignored in management strategy and policy. Due to the lack of full understanding of water pollution control and management and the lack of perfect water quality standard systems and practical legislative regulations, agricultural nonpoint source pollution will become one of the biggest challenges to the sustainable development of rural areas and to society as a whole. The system for agricultural nonpoint source pollution control in China should include an appropriate legislation and policy framework, financing mechanisms, monitoring system, and technical guidelines and standards. The management of agricultural nonpoint source pollution requires multidisciplinary approaches that will involve a range of government departments, institutions and the public.

Keywords Agricultural nonpoint source pollution; challenge; China; management; Miyun Reservoir

Introduction

After effective control of point sources pollution, nonpoint source pollution has become a major problem causing degradation of water quality; therefore, nonpoint source control has been increasingly discussed in some developed countries. Since the 1960s, the USA and other countries have been aware of nonpoint source pollution. Some legislation such as the Clean Water Act of 1972 and the Coastal Zone Act Reauthorization Amendments of 1990 in the USA encourage states to enact regulation of nonpoint sources (Malik *et al.*, 1994). The European Union issued the Water Framework Directive in 2000. The Directive mandates the introduction of measures to control diffuse pollution (Reeves *et al.*, 2003). Mandates or incentives have been applied to so-called "Best Management Practices" (BMP) to reduce soil erosion and other runoff, and to restrict use of fertilizer and pesticide by taxes (Helfand, 1995).

Unlike point sources, emissions from nonpoint sources are influenced by stochastic events such as temperature and precipitation. The loads are not measured with certainty but in fact represent a probability distribution around the actual discharged loads. This lack of ability to connect, scientifically, the source of effluent with its entry into a water body has made the traditional, effluent-based regulations impossible to implement (Parker, 2000). These difficulties may explain the new focus on environmental management approaches at the international and national levels (Reeves *et al.*, 2003).

China is one of the largest producers and consumers of chemical fertilizers in the world, and the excessive nutrient discharge from agricultural watersheds is considered to be an important source of nonpoint source pollution (Yan *et al.*, 1999). However, there are few researches related to these aspects in China. Research on nonpoint source pollution (NPSP) started in China in the 1980s. There has been more and more progress on

doi: 10.2166/wst.2006.033

load distribution. Compared with point sources, however, few abatement efforts have been implemented on nonpoint sources, and studies aiming at nonpoint source regulation were also rare. This paper mainly discusses the situation and difficulties in management of agricultural NPSP in China.

Current situation of NPSP in China

To support its large population, China's agriculture has one of the highest fertilizer and pesticide application rates in the world. Large amounts of fertilizer and pesticide enter surface waters with runoff, which mainly occurs in the summer months due to more run-off-producing rainstorm events in that season. Surface water inputs from direct drift, leaching and erosion are additional important sources contributing to nonpoint source pollution.

Due to the limitations of the nation's conditions, the government policies seldom involve agricultural pollution. Hence, agriculture contributes more and more pollutants to the water environment in China.

Since the 1970s, the eutrophication of major lakes and water systems in China has been getting worse rapidly. According to the monitoring data of water quality in large major rivers, lakes and reservoirs in the country in recent decades, the water quality shows an overall tendency of deterioration, and such a tendency has been kept at a relatively steady level in recent years. More than 85% of the nation's lakes are at serious eutrophication stages. Over 50% nonpoint source pollution discharges to the lakes in eastern China (Jin *et al.*, 1990).

Nearly 82% of 532 main rivers in China are contaminated by excessive nitrogen at various levels. The higher the stream order, the heavier the pollution is. The water quality in rainy seasons is worse than that in dry seasons (SEPA, 2002).

Figure 1 illustrates the water quality in typical rivers, with length over 121,000 kilometres, in the year of 2002. The proportion of grades I, II and III, which are suitable for domestic use, to the whole length is 61.4%. About 38% of the total length of rivers are so degraded (falling in the category of ultra-V) that they have lost many functions, including use for irrigation, and themselves become sources of pollution.

It is remarkable that nonpoint source pollution from agricultural and domestic wastewater aggravates rapidly, and this is the main pollution source in some regions. In Lake Taihu and Lake Dianchi, the ratios of their nonpoint sources (mainly nitrogen) to their total sources are 75% and 70%, respectively (Table 1).

Investigation has revealed that nonpoint source pollution from agricultural and rural regions is the leading source of water pollution. Due to different physical characters and social productions, there are various types of nonpoint source pollution. In general,

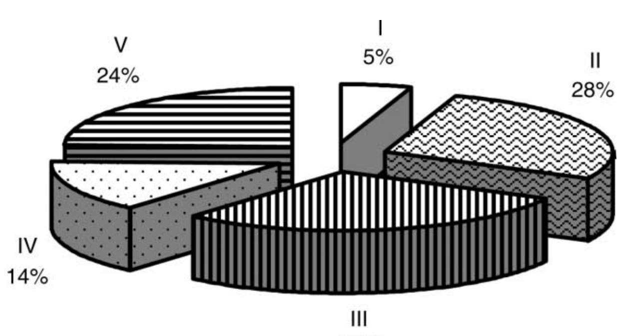

Figure 1 Water quality of typical rivers of China in the year of 2002

Table 1 Load contributions from point and nonpoint source to rivers in 2000

Pollutant	Point source		Nonpoint source		Contribution of point source (%)	Contribution of nonpoint source (%)
	discharge (Million ton)	into stream (Million ton)	discharge (Million ton)	into stream (Million ton)		
COD	18.94	12.45	75.74	8.31	60	40
NH_3-N	1.82	1.10	7.07	0.71	61	39
TN	3.81	2.10	28.64	4.24	33	67
TP	0.67	0.36	6.12	0.62	37	63

Data source from SEPA, 2002

nonpoint source pollution in China results from human activities. The lack of best management practices in agriculture and the conventional lifestyle in rural areas are two important factors contributing to the agriculture pollution. For example, improper farming practices, discharge of livestock and human wastes, and the lack of management policies on the agricultural environment are important reasons. Table 2 shows the contribution of nonpoint sources to the watershed of Lake Dianchi.

Chemicals overuse

China has the highest population in the world, but has limited arable land. In order to meet the food demands of such a huge, growing population, the agriculture has been more and more extremely intensive in using inorganic fertilizers to increase crop productivity. Rapid growth in China's per hectare chemical fertilizer application, from less than 10 kg in 1960 to more than 800 kg in 2000, is required to increase grain production, but has caused many environment problems such as groundwater pollution (Li and Zhang, 1999; Editorial Committee of Agricultural Yearbook in China, 2003). In 17 provinces, per hectare chemical fertilizer application is higher than the recommended level (225 kg) in the world.

Due to high profit from growing vegetables, fruits and flowers, farmers commonly use high rates of N and P fertilizers, about 10 times higher (average fertilizer application rate is 569–2,000 kg per hectare) than for grain crops. Increasing vegetable area with high fertilizer input is one of the biggest potential problems for eutrophication of water bodies in watersheds (Zhang *et al.*, 2004).

In addition, the average ratio of N:P:K in fertilizers in 1993 was 1:0.31:0.11, with much higher N- and P-rates than the world average (1:0.5:0.5). Large amount of N-fertilizer and poor utilization rates may lead to nitrate leaching and hence polluting groundwater. These effects were investigated in high-application regions at levels over 500 kg/hm^2 (Zhang *et al.*, 1996). The increase of P fertilizer application causes long-term accumulation of phosphorus in soils, resulting in greater overall losses of phosphorus to aquatic ecosystems.

Table 2 Nutrient load of croplands from different sources in Lake Dianchi (kg/ha) (Modified from Zhang *et al.*, 2004)

Source	1960s		1980s		Present	
	N	P_2O_5	N	P_2O_5	N	P_2O_5
Fertilizer	5	1	98	16	401	248
Manure	19	11	160	85	223	122
Village	29	8	56	15	66	18
Total	53	20	314	116	690	387

Livestock breeding

According to the State Environmental Protection Administration (SEPA) survey on pollution conditions relating to nationwide livestock and poultry breeding, in general the discharge of animal waste had approached an alarming level, while less than 10 per cent of the total breeding farms had experienced environmental impact evaluations. Animals on farms produced 1.9 billion tons of excrement during 1999, almost 2.5 times greater than the amount of solid waste discharged by China's industrial sector (Zhang, 2000). The estimated annual losses of COD, BOD and NH_3-N from manure in 2001 were 7.28 million tons, 4.99 million tons and 1.32 million tons, respectively. The COD loss from manure is near to the sum of COD from industrial and municipal wastewater. The manure loss from mid-small-size livestock farms is nearly 70% of the nation's total manure loss.

At the same time, animal breeding farms in the rural region had tried to develop into highly animal-concentrated farms. The N and P losses from such a concentrated region have reached very high levels, as much as 1,000 kg N and 600 kg P_2O_5 per hectare agricultural land, far surpassing the carrying capacity of soil to these organic nutrients (Zhang *et al.*, 2004).

The investigation of the feed, excreta, soil, surface and subsurface waters in the livestock farms in Jiangsu Province, using the case region survey and nutrient analysis approaches, showed that the discharge of liquid manure and the run-off loss of solid manure disposed on the ground were the main environment problems in livestock production. The surface run-off from the wastes of livestock production is the main route causing environmental problems (Yang *et al.*, 2001).

Rural residence

Due to the lack of sewage treatment and excessive waste accumulation in rural areas in China, especially in the transitional areas with fast urbanization, waste from daily life is discharged randomly even into rivers. TN and TP concentrations in the village runoff are nearly 10 times those from farm runoff (Wang *et al.*, 2003b; Wan *et al.*, 2000). The nonpoint source pollution from agricultural and rural areas will become one of the biggest challenges to sustainable development in China.

In short, agricultural nonpoint source pollution in China has become the predominant source to the aquatic system, especially on the seasonal climate zones in eastern and southeastern China with higher crop production and high population density. Due to diversity in physical conditions and farming practices, the pollution contribution varies (see Table 3).

The most direct and important impact of agricultural NPS on the environment is the degradation of China's drinking water resource. It is estimated that the economic loss by NPS-induced water pollution in China is $0.5 \sim 1\%$ of GDP. The impacts of NPS on soil are cumulative, persistent, and deteriorating, and consequently influence groundwater quality and food security greatly. NPS has significantly negative impacts on rural social development and upon society as a whole.

Table 3 Nonpoint source pollution from different sources in some regions in China

Region	Farm runoff (%)	Livestock (%)	Rural residence (%)	Data source
Shanghai	12.25	18.67	18.09	Zhang *et al.*, 1997
Dianchi Lake	53			Wang *et al.*, 2003a
Miyun Reservoir	30	61		Wang *et al.*, 2003b
Hangjiahu	23.62	43.8	16.07	Qian *et al.*, 2002
Taihu Lake	47.6	33.4	19	Wan *et al.*, 2000

Concerned policies and regulations in China

The maintenance of water quality has long been recognized as important for environmental and economic purposes and has prompted the introduction of statutory measures to protect the water environment. China has implemented some environmental regulations such as industrial air pollution and waste dumping. But much less attention has been paid to the environmental and health effects of farming chemicals. The environmental regulations designed for the industrial sector should be modified and enforced for the rural sector that has developed rapidly since the early 1980s. Several environmental protection laws and regulations include "Environmental Protection Law of the People's Republic of China", "Law of the People's Republic of China on Prevention and Control of Water Pollution", "Water Law of the People's Republic of China" and "Law of the People's Republic of China on Water and Soil Conservation".

At present, no legal and operational framework is established in China to control agricultural management practices, leading to high nonpoint source pollutions. Most environmental laws and regulations are constituted around point source pollution, though a few involve nonpoint source pollution but lack pertinence, feasibility and maneuverability. The direct cause is the deficiency of financial support from both the central and local governments. The total financial input to the environmental protection is less than 1% of the nation's GNP.

Another fundamental problem that remains is that many of the existing agricultural development policies are inconsistent with environmental protection policies: for the central government, it is drawing the frame of policy and legislation; whereas, the local government has no technical standards and corresponding management practice; for supervisor branches, there is lack of technical standard and system for source monitoring; for farmers, they have no technical standard to obey in fertilizer applications and cultivation practices, even in drinking water protection areas.

Other options to address nonpoint source pollution

In general, there are two main policy approaches for aquatic environmental pollution control, i.e. mandatory means and economic incentive. Many developed countries and developing countries had taken the mandatory means as the basic instrument through issuing permit licenses and implementing environmental rules or standards. Due to the inflexibility of mandatory means on environmental impact and economic efficiency, the economic means becomes a supplement, or a substitution, or combined measure for aquatic environmental pollution control. On the other hand, managers have paid more attention to public participation and education. Research and practice on agricultural pollution control have been accomplished in many western countries for a few decades. A series of effective control measurements have been designed and implemented from different viewpoints and more incentive policies are applied. Quantitative frames and evaluation policies have become an approach to get optimal schemes by integrated evaluation of environmental-economic benefit, for example, allocation of pollution load on the basis of gross load control using economic measures such as tax, subsidy and pollution trading to eliminate nonpoint source pollution (Wang, 2003).

In recent years, nonpoint source contributions have remained and have increased as a main source causing surface water pollution in China. It has been noted that the conventional command-and-control regulations are ineffective in controlling agricultural nonpoint source pollution, whereas the watershed abatement trading between point and nonpoint sources may be more cost-effective. The feasibility of point-nonpoint effluent trading in China has been discussed in detail by Zhang and Wang (2002).

Due to the vast area in China, there are huge discrepancies in regional natural conditions, agricultural production, and social and economic development. Different policies can be set for different watersheds. In a watershed with advanced development, such as Lake Taihu, the incentive approach with tax, such as tax on pollutant and chemical charges to restrain improper activities of farmers, can be practicable. In the watershed with the least advanced development, such as Lake Dianchi, the incentive approach becomes dominant, where the point source pollution has considerable portions and a tradeable market is necessary.

The hallmark advantage of economic incentive programs is, of course, their potential to minimize compliance costs by optimizing cost-effectiveness. The magnitude of cost savings depends upon factors such as differences in dischargers' marginal costs and transaction costs. In spite of limited reliable data, a preliminary analysis indicated that the proposed incentive program could provide significant cost savings compared to mandatory BMPs. At least two additional factors make incentive programs attractive. First, they are based on decentralized decision-making and preserve the flexibility of individual farmers to respond to changes in economic, environmental and technological conditions. Second, the programs encourage innovation by providing direct financial rewards for creating better and cheaper pollution control methods.

As discussed above, nonpoint emissions and abatement abilities in different watersheds may display different features, and the variance of nonpoint emissions may increase or decrease with the abatement levels. In practice, a case-by-case study is compelling and a specific model should be developed at local levels (Young & Karkoski, 2000).

In summary, in the case of diffuse sources of pollution, appropriate regulation must take account of the unobservability and unverifiability of individual emissions. Which of the methods of pollution control is appropriate depends on other factors: the information availability, type of resources to be regulated, degrees of uncertainty, social cost of damage, the number of polluters to be controlled, monitoring costs, and transaction costs. Each case must be decided on its own merit. Much remains to be done in the area of diffuse sources.

Apart from the management practice regulations and limited trading programs, the treatment of diffuse sources has remained mostly theoretical. The main problem is that the controlling prosecution has been mainly concentrated on end-control engineering projects such as establishment of sewage farm and artificially-built or reclaimed wetland at bayou or watercourse, even in the watersheds where agriculture is the leading contributor to eutrophication of water systems. To solve the problems, it was suggested that proper regulations to confine the environmentally unfriendly agricultural activities should be established and implemented in different watersheds as soon as possible. Other complex issues, such as regulation, monitoring and administration, must also be considered with care (O'Shea, 2002). Education and technical and financial assistance are effective to encourage adoptions of less polluting farm practices. Research findings indicate that the adoption of an improved management practice is most strongly influenced by producer perceptions of its effect on profitability (Feather and Cooper, 1995).

Future challenges for this problem in China

The control of diffuse pollution is an important aspect of maintaining water quality to be tackled by the regulators. No country has successfully finished this tough task. Due to the lack of full understanding of water pollution control and the lack of perfect water quality standard systems and practical legislative regulations, it is much more difficult in China because of diversity in the vast areas, inefficient management on water and land and other harassments.

- Difficulty in the technology

Non-point source emissions rely partly on some random variables such as rainfall. It is hard to identify and measure nonpoint source emissions at the source level. It is impossible to get complete information on nonpoint sources, including discharges and variations by other factors. An alternative solution is to find the effect–result relation between pollution damage and economic behavior, which is the basis of management policy (Russell and Shogren, 1993; He and Wang, 1999).

- Limitation in the national situation

Traditionally, farmers in China are not responsible for the control of pollution caused by agricultural activities. The conventional command-and-control regulation is therefore ineffective for agricultural nonpoint sources, but the economic incentive-based policies can be applied (Wang, 2003). However, there is institutional limitation to prevent environmental quality objectives from being brought into policy-making.

- Attitude of farmers

Farmers possess land but not water resources. This separation of property right leads to less initiative for farmers to reduce water pollution, whereas more care is taken of their benefits from farming (He and Wang, 1999).

- Difficulty in substitution of pesticide

Reliance on pesticides is the primary or sole means of pest control; however, it may have a number of harmful side effects. Since the mid-1970s, researchers have described unintended consequences from pesticide use in agriculture, particularly in developing countries. Several economic studies have questioned whether the current patterns of pesticide use are economically and socially efficient. Policy makers in many countries have begun to regulate pesticide use, and have taken an interest in alternative methods for controlling agricultural pests. However, it is impossible for alternative methods to replace pesticide completely (Widawsky *et al.*, 1998).

- Number of pollutants and spatial discrepancy

Numerous pollutants cause difficulty in controlling nonpoint source pollution from acquired information and reduce the level of cooperation in pollution alleviation.

Although nonpoint source pollution varies spatially and temporally a rather uniform policy and standards are performed. These controls are distinguished between the characteristics of pollutants and the characteristics of receiving waters; therefore, the impact on the local environment can be directly assessed and control can be exercised (DETR, 1997).

In short, the agricultural pollution problems were typical: a pressing pollution problem existed, the technology to control the problem was available, but the concern about costs and the administrative difficulty of creating a compliance program were stalling progress. The lack of aggressive enforcement was not simply due to a lack of legal authority, it reflected the common notion that nonpoint sources cannot be held individually accountable for specific pollution-control requirements because the sources are not only diffuse but also too many to administer individually. The same reasoning has led policymakers nationwide to an apparent impasse in the search to control nonpoint sources. The crux of this problem is finding a way to: (1) make individual farmers accountable for the pollution they generate; (2) maximize cost-effectiveness for farmers and minimize transaction costs for farmers and regulators; (3) make the control program flexible and practical for farmers to implement; and (4) simplify the administration by regulatory agencies.

Conclusions

Nonpoint source pollution from agricultural and rural regions is thought to be the leading source of water pollution and will become one of the biggest challenges to sustainable development of rural areas and upon society as a whole. The main agricultural nonpoint source pollutants are from fertilization of cropland, excessive livestock and poultry breeding and undefined disposal of daily living waste in rural areas.

There are no perfect water quality standard systems and practical legislative regulations in China to control agricultural management practices, leading to high nonpoint source pollution inputs because of the diversity of the vast areas, inefficient management of waters and lands and other harassments. The system for agricultural nonpoint source pollution control in China should include an appropriate legislative and policy framework, financing mechanisms, monitoring system, and technical guidelines and standards.

The management of agricultural nonpoint source pollution requires a multidisciplinary approach that will involve a range of government departments and institutions. The integration of water quality management on surface water and groundwater for both point and nonpoint source pollutions at the scale of watershed should be based on the full knowledge of the functions and interactions between water and the related ecological factors in the watershed.

Economic approaches will be the effective practice of nonpoint source pollution control, public participation and education, as well as an information sharing policy.

Acknowledgements

The authors are most grateful to Prof. Fujii from Kyoto University, Japan and two anonymous referees for their helpful insights, which contributed to an obvious improvement of the manuscript. Special thanks to Dr. P. Wang from UMCES, USA for correcting English writing and valuable comments. This work was jointly supported by the National Ministry of Education and Beijing Municipal Education Commission. Thanks to the Water soil Protecting Station of Miyun County for help in the fieldwork.

References

DETR (1997). *Economic Instruments for Water Pollution*. Department of the Environment Transport and the Regions, pp. 71.

Editorial Committee of Agricultural Yearbook in China (2003). *Agricultural Yearbook in China (1986–2002)*, Beijing: Chinese Agriculture Press (in Chinese).

He, P. and Wang, J.J. (1999). Current situation, puzzle and challenge of control and management on Nonpoint source pollution. *Agro-environmental Protection*, **18**(5), 235–236 (in Chinese).

Helfand, G.E. (1995). Alternative pollution standards for regulating nonpoint source pollution. *Journal of Environmental Management*, **45**(3), 231–241.

Jin, X.C., Liu, H.L., Tu, Q.Y., Zhang, Z.S. and Zhu, X. (1990). *Lake Eutrophication in China*, China Environment Science Press, Beijing, China (in Chinese).

Li, Y. and Zhang, J.B. (1999). Agricultural diffuse pollution from fertilizers and pesticides in China. *Water Science and Technology*, **39**(3), 25–32.

Malik, A.S., Larson, B.A. and Ribaudo, M. (1994). Economic incentives for agricultural nonpoint source pollution control. *Water Resources Bulletin*, **30**(3), 471–480.

O'Shea, L. (2002). An Economic Approach to Reducing Water Pollution: point and diffuse sources. *The Science of the Total Environment*, **282–283**, 49–63.

Parker, D. (2000). Controlling agricultural nonpoint water pollution: cost of implementing the Maryland Water Quality Improvement Act of 1998. *Agricultural Economics*, **24**(1), 23–31.

Feather, P.M. and Cooper, J. (1995). Voluntary Incentives for Reducing Agricultural Nonpoint Source Water Pollution. In *Agriculture Economic Research Service Agriculture Information Bulletin*, pp. 716.

Qian, X.H., Xu, J.M. and Shi, J.Ch. (2002). Comprehensive Survey and Evaluation of Agricultural Nonpoint Source Pollution in Hang-Jia-Hu Waternet Plain. *Journal of Zhejiang University*, **28**(2), 147–150 (in Chinese).

Reeves, A.D., Kirk, E.A. and Sherlock, K.L. (2003). Institutional challenges faced when tackling the issue of diffuse pollution. In *Proceedings of 7th Diffuse Pollution Conference*, Dublin, Ireland, 12, pp. 39–43.

Russell, C.S. and Shogren, J.F. (1993). *Theory, Modeling and Experience in the Management of Nonpoint-source Pollution*, Kluwer Academic Publishers, Boston.

SEPA (State Environmental Protection Administration of China) (2002). *Report on the State of the Environment in China in 2001*. Available online www.zhb.gov.cn /649368273124589568 /index.shtml (in Chinese).

Yang, J.S., Chen, D.M., Liu, G.M. and Li, H.F. (2001). Nutrient cycling and environmental effect of livestock production in case regions of Jiangsu Province. *China Environmental Science*, **21**(5), 468–471.

Young, T.F. and Karkoski, J. (2000). Green evolution: are economic incentives the next step in nonpoint source pollution control? *Water Policy*, **2**(3), 151–173.

Wan, X.H., Qiu, D. and Zhao, X.M. (2000). Analysis of Pollution Characters of the Big Animal Farms in the Taihu Area. *Agricultural Environment and Development*, **64**(2), 35–38 (in Chinese).

Wang, J.N., Ge, Ch.Zh. and Zhang, Y. (2003a). *Institution and Policy of Control of Water Pollution in China*, China Environment Science Press, Beijing, China (in Chinese).

Wang, X.Y. (2003). *Nonpoint source pollution and its management*, Ocean Press, Beijing, China (in Chinese).

Wang, X.Y., Guo, F. and Hu, Q.J. (2003b). Nonpoint source pollution loading from the watersheds of Chaohe River and Baihe River around Miyun Reservoir. *Urban Environment and Urban Ecology*, **16**(1), 31–33 (in Chinese).

Widawsky, D., Rozelle, S., Jin, S.Q. and Huang, J.K. (1998). Pesticide productivity, host-plant resistance and productivity in China. *Agricultural Economics*, **19**(1–2), 203–217.

Yan, W.J., Yin, C.Q. and Zhang, S. (1999). Nutrient budgets and biogeochemistry in an experimental agricultural watershed in Southeastern China. *Biogeochemistry*, **45**, 1–19.

Zhang, C.G. (2000). Review of the livestock revolution in China. In *Implication of Asian economic crisis for the livestock industry*, pp. 203–213.

Zhang, W. and Wang, X.J. (2002). Modeling for point-non-point source effluent trading: perspective of non-point sources regulation in China. *Sci. Total Environ*., **292**(1–3), 167–176.

Zhang, W.L., Tian, X.L., Zhang, N.X. and Li, X.Q. (1996). Nitrate pollution of groundwater in Northern China. *Agriculture, Ecosystems and Environment*, **59**(3), 223–231.

Zhang, D.D., Zhang, J.Q., Wang, Y.G. and Zhang, X.H. (1997). The Main Non-point Source Pollution in Shanghai Suburbs and Harness Countermeasure. *Environmental Science in Shanghai*, **16**(3), 1–3 (in Chinese).

Zhang, W.L., Wu, S.X., Ji, H.J. and Kolbe, H. (2004). Estimation of Agricultural Non-Point Source Pollution in China and the Alleviating Strategies I. Estimation of Agricultural Non-Point Source Pollution in China in Early 21 Century. *Scientia Agricultura Sinica*, **37**(7), 1008–1017.