International Fertilizer Industry Association

FIAT PANIS

IFA-FAO AGRICULTURE CONFERENCE

"Global Food Security and the Role of Sustainable Fertilization"

Rome, Italy, 26-28 March 2003

FERTILIZERS AND WORLD FOOD DEMAND
IMPLICATIONS FOR ENVIRONMENTAL STRESSES

David NORSE
University College London, UK

University College London, 4 Taviton Street, London WC1H 0BT, United Kingdom
Email: jarvisnors@aol.com

IFA-FAO AGRICULTURE CONFERENCE
Rome, Italy

"Fertilizers and World Food Demand - Implications for Environmental Stresses"

Paper by David Norse
University College London

Introduction

Fertilizers play a central role in a difficult trade-off between food security and environmental degradation. It is a trade-off which:

- Can be minimised but not eliminated;
- Has socio-economic as well as biophysical dimensions;
- To a greater or lesser degree applies to both organic as well as mineral fertilizers though I will concentrate on the latter.

It should also be acknowledged that fertilizer use has positive consequences for the environment notably by:

- Substituting for land thereby reducing deforestation and the loss of biodiversity;
- Preventing or limiting the nutrient mining and soil degradation which arises when crops remove more nutrients than are replaced by farmers or by natural processes.

Improved food security generally depends on three factors: greater food production; greater economic access to food through higher incomes; increased purchasing power arising from the lower food prices for the poor. All three factors are commonly dependent on increased fertilizer use. Yet it is impossible to devise crop management systems or "smart" fertilizers that do not involve losses to the environment and its degradation. Moreover, whereas in the 1970s and 80s this degradation was largely a local concern in some developed countries, notably because of the accumulation of nitrate in water wells, it is now a global issue because of the impact of fertilizers on climate change and biogeochemical cycles.

Consequently this paper has three main objectives. First, to describe and roughly quantify the main environmental stresses arising from mineral fertilizers – primarily nitrogen but also phosphate. Second, to explore these stresses in more depth at the national and regional level through an examination of the situation in China and Latin America, that is, one over user and one under user of mineral fertilizers. Finally, to consider this stress analysis in the context of food security and environmental trade-offs.

Global stresses from fertilizer use

Climate change: Agriculture currently contributes about 30% of total global emissions (and up to 80% in some countries) of the greenhouse gases (GHGs) that are the driving force for climate change (Table 1). Tropical forest clearance and land use change were the major agricultural driving forces in the past, but these are likely to play a smaller role in the future (Bruinsma, 2003). Consequently more attention is now being given to methane (CH_4) and nitrous oxide (N_2O) from crop and livestock production since agriculture is responsible for half or more of total global anthropogenic emissions of these GHGs (Table 1). Nitrogen fertilizers (both their production and use) are responsible for a large share of agriculture's contribution and hence have become significant driving forces for climate change.

Table 1: Agriculture's contribution to global greenhouse gas and ammonia emissions

Gas	Carbon dioxide	Methane	Nitrous oxide	Nitric oxides	Ammonia
Main effects	Climate change	Climate change	Climate change	Acidification	Acidification Eutrophication
Agricultural source (estimated % contribution to total global emissions)	Land use change, especially deforestation	Ruminants (15) Rice production (11) Biomass burning (7)	Livestock (incl. manure applied to farmland) (17) Mineral fertilizers (8) Biomass burning (3)	Biomass burning (13) Manure and mineral fertilizers (2)	Livestock (incl. manure applied to farmland) (44) Mineral fertilizers (17) Biomass burning (11)
Agricultural emissions as % of total anthropogenic sources	15	49	66	27	93
Expected changes in agricultural emissions to 2030	Stable or declining	from rice: stable or declining from livestock: rising by 60 %	35-60 % increase		from livestock: rising by 60 %

Main sources: IPCC (2001) (column 2); Lassey et al. (2000) (column 3); Bouwman (2001) (columns 4, 5 and 6) and FAO estimates.

The main problem is the loss of nitrous oxide (N_2O) from nitrogen fertilizers, which together with livestock production and manure use, account for about 60% of all anthropogenic emissions of this gas (Table 1). Although N_2O is generated by natural biogenic processes, this is enhanced by the addition of nitrogen fertilizers, the creation of crop residues, and nitrogen leaching and runoff. This complexity of sources is compounded by the sensitivity of N_2O formation to climate, soil type, tillage practices, and type and placement of fertilizer. Consequently precise estimates of the N fertilizer contribution are difficult because of large seasonal and annual variations in emission rates and, for example, uncertainties about the relationship between nitrogen fertilizer rates and volatilization (Bouwman, 2001). However, I believe there are strong grounds for arguing that they are not overestimates.

N_2O formation is also linked to the release of nitric oxide and ammonia, which have adverse environmental impacts at the local and regional level through the formation of acid rain and the acidification of soils and freshwater ecosystems.

FAO's fertilizer use projections to 2030 imply slower growth of nitrogen fertilizer use in most regions compared with the past (Table 2). Depending on progress in raising fertilizer use efficiency, the increase between 1997/99 and 2030 in total fertilizer use could be as low as 37 percent, entailing similar or even smaller increases in the direct and indirect N_2O emissions from fertilizer and from nitrogen leaching and runoff. However, current nitrogen fertilizer use in many developing countries is very inefficient. In China, for example, which is the world's largest consumer of nitrogen fertilizers, it is not uncommon for half to be lost by volatilisation and 5 to 10 percent by leaching (Nehru et al, 1997; Norse et al, 2001). Hence, if the higher application rates projected for the future (Table 2) result in a disproportionately greater loss of N_2O, then it is likely that there will be a significantly greater global stress coming from nitrogen fertilizer.

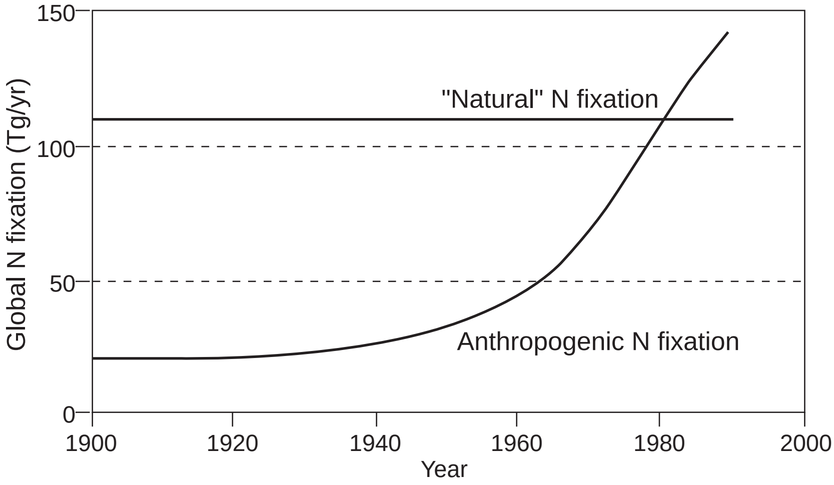
Table 2: Recent and projected fertilizer use

Region	Nutrients (million tonnes)		Average kg/ha (arable land)	
	1997/99	2030	1997/99	2030
Sub-Saharan Africa	1.1	2.6	5	9
Latin America & Caribbean	11.3	16.3	56	67
Near East/North Africa	6.1	9.1	71	99
South Asia	21.3	28.9	103	134
South Asia excluding India	4.2	6.9	113	178
East Asia	45.0	63.0	194	266
East Asia excluding China	9.4	10.3	96	92
All above	84.8	119.9	89	111
Industrial countries	45.2	58.0	60	71
Transition countries	7.6	10.1	49	58
World	137.7	188.0	92	

Source: Bruinsma, 2003

Perturbation of global biogeochemical cycles: Agriculture plays a significant role in the anthropogenic perturbation of several biogeochemical cycles, notably the nitrogen, phosphate and sulphur cycles. One of the changes in the nitrogen cycle is the emission of N_2O and other greenhouse gases discussed above, but there are other important impacts particularly the perturbation of N fixation. The manufacture of N fertilizers, the burning of fossil fuels and the cultivation of leguminous crops have resulted in anthropogenic N fixation increasingly exceeding natural N fixation since about 1980 (Figure 1). Some analysts conclude that "over the next few decades this alteration of the N fixation cycle will undoubtedly become even more severe" (Walker and Steffen, 1999). However, the FAO projections of N fertilizer use and leguminous crop cultivation all point to a slowing down in the growth of agriculture's contribution to this perturbation.

Figure 2: Agriculturally dominated changes in N fixation.



Source: Vitousek, 1994

Local and regional stresses

Water Pollution*:* Since the 1970s extensive runoff and leaching of nitrate and phosphate from soils into surface water and groundwater has become an issue in almost all industrial countries (OECD, 2001a). In France and the UK, for example, they are one of the dominant causes of water pollution. These nutrients come directly from mineral fertilizers and crop residues boosted by fertilizer use, and from eroded soil particles on which they adsorbed.

In large areas of the EU nitrate concentrations in surface and ground waters destined for human consumption are near or exceed the maximum permitted concentration of 50 mg per litre or the guide level of 25mg. This nitrate poses a risk to human health, and contributes to eutrophication of rivers, lakes and coastal waters. The bulk of the nitrate comes from mineral fertilizer and manure applied to crops and grasslands. Although the problem first arose in developed countries it is now serious in parts of China and India and a number of other developing countries, and will get worse (Zhang *et al.*, 1996).

The situation is particularly serious for the production of vegetables, because they are often grown in or close to urban areas so that there is fairly direct contamination of the drinking water sources for large numbers of people (Table 3).

The environmental problem is not limited to the nitrate content of drinking water supplies. Eutrophication because of nitrogen and phosphate enrichment of lakes, reservoirs and ponds can lead to high fish mortality and algae blooms. This is important because of the growing importance of aquaculture to food security and rural incomes in many developing countries. Algae blooms release toxins that are poisonous to fish and humans, the latter being a growing problem in some developed countries and potentially even more serious in warmer developing countries with more intense sunshine (Gross, 1998).

Table 3: Fertilizer use on vegetables in China and nitrate levels in groundwater

Location	N applied (kg/ha	N uptake (kg/ha)	NO3 in groundwater (mg/l)
Fangzhuang	1894	383	180 per year
Qiandushu	1649	433	75
Sijiqing	778	444	150
Xidian	1073	384	75
Xishuiying	5580	480	500

Source: Zhu Zhaoliang, 2000

Further intensification of fertilizer use may also add to the widespread problem of soil acidification (Scherr, 1999), that can arise with certain forms of nitrogen fertilizer and inadequate liming. However, there is an additional complication arising from the conjunction of agro-environmental problems, that is, the ammonia emissions from livestock and nitrogen fertilizers which contribute to acid rain, and add to soil acidification. This is apparent in some developed countries where serious ecosystem damage has occurred since the 1980s, and could arise in developing countries, particularly in East Asia with the rise of industrial scale pig and poultry production.

Finally, the water pollution problem unfortunately does not remain a local or national issue. Once the nitrate enters major river basins it becomes a regional issue, because it contributes eutrophication of coastal waters (van Drecht et al, 2001).

Table 4 shows the large N inputs to rivers and coastal waters, up to 80% of which come from agriculture. Nitrogen fertilizers are probably responsible for more than half of these agricultural inputs, and together with phosphate inputs from fertilizer cause serious eutrophication and algal blooms.

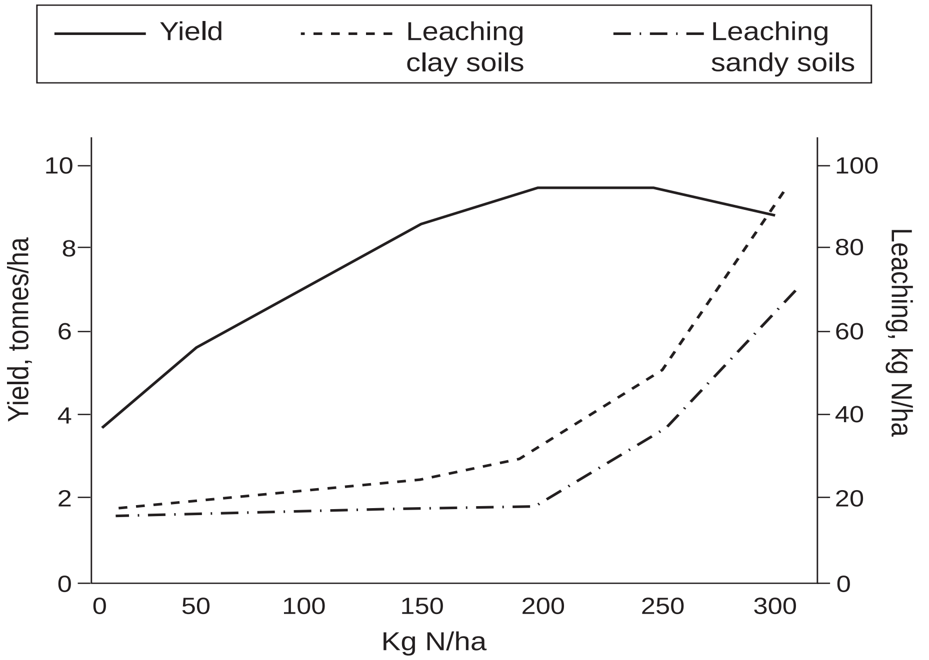
Table 4: Nitrogen inputs to rivers and coastal waters

River	N inputs to rivers		N exports to coastal waters	
	kg^{-2}year^{-1}	% agriculture	Kg^{-2}year^{-1}	% agriculture
Mississippi	7489	89	597	63
Amazon	3034	17	692	6
Nile	3601	67	268	37
Zaire	3427	18	632	9
Zambezi	3175	47	330	25
Rhine	13941	77	2795	49
Po	9060	81	1841	56
Ganges	9366	81	1269	55
Chang Jiang	11823	92	2237	83
Huang He	5159	88	214	24

Source: van Drecht et al, 2001

Nitrate losses to ground and surface waters occur primarily when application rates exceed crop nutrient uptake, with the risk depending on the crop type and yield, soil type and underlying rocks (Goulding, 2000). The risk of high nitrogen (and some phosphate) losses through leaching and runoff tends to become serious at around 150-200 kgN/ha unless there is good fertilizer management (Bockman et al, 1990; MAFF, 1999).

Figure 2: Increased N leaching risk at higher application rates



Source: Bockman et al, 1990.

One might argue therefore that the present and future risk from N pollution is not very great, because the FAO projections of fertilizer use in Table 2 suggest that for most regions the average application rates for N,P and K in the late 1990s were in the range 50-200 kg/ha, and will not exceed 266kg/ha by 2030. This implies that average application of nitrogen are unlikely to exceed 150kg/ha. However, there are large regional and crop differences in fertilizer application rates per hectare per year (Daberkov *et al.*, 1999), and large spatial and temporal differences in nutrient levels and fertilizer use efficiency on similar soil types. Hence the projected changes in average application rates given in Table 2 are not a good indicator of the risk of nitrate losses. In the U.K., for example, the present average application rate for all arable crops is about 150 kg N/ha, but the range is 25-275 kg N/ha with over 35 percent of arable land having application rates of more than 150 kg. In parts of China the situation is even more extreme with some rice farmers applying over 870 kg N/ha and vegetable growers over 1,000 kg N/ha compared with an average of 234kg.N/ha for all cropland (Table 3).

Thus, although FAO considers that there will be substantial gains in fertilizer use efficiency in coming decades and hence a relatively modest aggregate growth rate in N fertilizer demand, there could still be appreciable increases in water pollution because:

- Extensive areas in both developed and developing countries already receive large nitrogen fertilizer applications that are not commensurate with the availability of adequate soil moisture, other nutrients and management practices needed to attain high yields;
- Even modest increases in nitrogen fertilizer application could cause problems if yield growth stagnates leading to nutrient use inefficiencies and severe pollution.

Overcoming the problem will not be easy. First, these losses can occur at N application rates below the economic optimum, given that current fertilizer prices do not include the cost of environmental externalities (Pretty *et al*., 2001), so there are no specific pressures on farmers to limit them. Second, maximising the efficiency of N use is complex and difficult (Goulding, 2000). Third, it may take many years for improvements in fertilizer use efficiency to result in reductions in nitrate losses and decades for ground waters to recover from nitrate contamination.

The contrary picture – environmental stress reduction by mineral fertilizers

In contrast to the foregoing there are a number of areas where mineral fertilizer use has clear positive impacts on the environment. At the general level mineral fertilizers have made a major contribution to the land productivity gains from intensification that reduce the need to convert forest and rangeland to cropland (Table 5). The CGIAR has estimated that land saved due to yield gains over the past 30 years from CGIAR research on 7 major crops, is equivalent to 230 - 340 million ha of forest and grassland that would have been converted to cropland in the absence of those gains (Nelson and Mareida, 2001). Their estimate excludes the land savings that stemmed from research on other crops. Thus, some estimates of land savings due to all past research efforts and agricultural intensification amount to more than 400 million ha. Mineral fertilizers may have provided 30-50% of these savings, and have therefore made a major contribution to the preservation of tropical rainforests and biodiversity.

Table 5: Land savings from improved technologies and land use intensification.

	Least developed countries	World
Nelson and Mareida*	160-300	230-340
Goklany**	427	485
Avery**	339	385
CGIAR Climate Change Working Group	340	386

** for 7 major crops: barley, cassava, maize, pulses, rice, sorghum and wheat*
*** all crops including pastures*
Source: Nelson and Mareida, 2001.

Environmental stresses at the extremes of fertilizer use

Two examples will be used to illustrate the issues here:

Overuse of mineral nitrogen fertilizers in China: This is of particular concern because China is the largest producer and consumer of nitrogen fertilizer in the world. The problem is the following:

- Average application rate is about 225kg/ha cropland
- In some Provinces the average is greater than 400kg/ha
- In some vegetable areas where they grow up to five crops per year the rate is 1,000 - 5,000kg/ha/yr
- The critical application rate at which there is a high risk of large leaching and runoff losses is about 150-225kg/ha
- Much of the N is in the form of urea and bicarbonate forms which are very soluble and prone to high rates of volatilization
- Fertilizer is commonly used as a single application which increases losses to the environment
- NPK fertilizer ratios are generally out of balance – China 100:36:19, USA 100:39:45
- Hence crop utilisation efficiency is only 30-45%
- Most of the N is lost to the atmosphere and contributes to acid rain, GHGs accumulation and global warming
- A high proportion is lost to rivers, lakes and coastal waters.

The end result of these losses is that the China's nitrogen balance sheet is very unfavourable (Table 6) and the environmental consequences of this are serious locally, regionally and globally. At the local level there is the widespread incidence of high groundwater nitrate levels above accepted standards, as was discussed earlier. At the regional level there is the eutrophication of coastal waters and the rise in the incidence of red tides (algal blooms) from less than 10 per year in the 1960s to over 300 per year in the late 1990s. Finally, there is the contribution that China makes to global warming because of the loss of fertilizer N as nitrous oxide. On the basis of the gross quantities used it might be assumed that China is responsible for about one-third of global emissions. However, it is very probable that the relationship between N use and N_2O loss is non-linear although the exact form is not clear (Bouwman, 2001). Moreover, the IPCC currently assumes it is linear and sets losses at 1.25+-1.0%, though losses as a high as 14% have been recorded under tropical conditions. Given the low efficiency of fertilizer use in China and the agro-climatic conditions which favour volatilization it is possible that the N_2O losses are much greater than 1.25% and so China could be responsible for considerably more than 50% of global emissions.

Table 6 China's Nitrogen balance sheet for Chinese agriculture in 1998

Input million tonnes		Output million tonnes	
Mineral fertilizer	24.8	Harvested crops	15.3
Organic manures	4.8	Gaseous loss of fertilizer	11.2
Biological fixation	3.5	Gaseous loss of manure	0.6
Rainfall & irrigation	1.5	Leaching losses	2.0
Seeds	0.4		
Total	35.0		29.0

Source: Zhu Zhaoliang, 2000

Under use of fertilizers in Latin America: Many countries in Latin America and sub-Saharan Africa lie at the opposite extreme to China. A recent study of nutrient inputs and outputs for Latin America and the Caribbean concludes that the nutrient balance is negative for most crops and cropping systems (Wood, Sebastian and Scherr (2001). Nutrient stocks are being depleted at about 54 kg NPK per year (Table 7). The end result is not just the loss of soil fertility. The physical and biological structure of the soils will also be degraded including reduction in soil organic matter levels and hence of carbon sequestration, lower soil moisture holding capacity and greater vulnerability to erosion. It should also be note that nutrient depletion is not restricted to low input systems. Nutrition depletion also occurs in very intensive systems where the NPK balance is wrong and particularly where phosphate inputs are too low relative to N and K (Murgai, Ali, and Byerlee (2001).

Table 7 Nutrient balances in Latin America and the Caribbean

Region	Wheat	Rice	Maize	Sorghum	All crops
	kg NPK per hectare per year				
1983-85 average					
Mesoamerica	-198	-89	-17	-120	-39
Caribbean		-197	-70	-120	-67
Andean	-77	-110	-47	-32	-57
Southern Cone	-101	-46	-89	-162	-65
Regional average	-111	-62	-61	-133	-59
1993-95 average					
Mesoamerica	-199	-105	-49	-111	-43
Caribbean		-170	-33	-85	-41
Andean	-79	-73	-37	-8	-40
Southern Cone	-83	-72	-115	-161	-59
Regional average	-96	-77	-86	-108	-54

Source: Wood, Sebastian and Scherr, 2001.

Conclusion

Higher fertiliser use will continue to have both positive and negative impacts on the environment at the global and local level. On the positive side organic and mineral fertilisers will help to replace the nutrients removed by crops, and build up soil organic matter. On the negative side, the release of N_2O seems likely to be of growing global importance as a driver for climate change. Groundwater nitrate contamination will continue to be an issue in most developed countries and will increasing be a problem in developing countries. Higher fertiliser use is also likely to cause some eutrophication of lakes, reservoirs and ponds and lead to fish mortality and algal blooms. Further intensification of fertiliser use may also add to the widespread problem of soil acidification, and to other environmental stresses not considered in the paper, such as the accumulation of heavy metals in the soil, which can be locally very serious. Conversely, the lack of fertiliser in Latin America and sub-Saharan Africa is projected to add to nutrient mining[1], soil compaction and erosion problems.

On balance one might argue that the environmental stresses from fertilizer use are greater than the environmental benefits. However, the environmental stresses have to be judged against the food security benefits, and the impossibility of achieving global food security without the use of mineral fertilizers. Thus, the question of trade-offs between food security and environmental degradation must be addressed. The policy issues involved are both technological and economic. Fertilizers have been too cheap because of direct and indirect subsidies. Governments in general have addressed the former but not the latter. In particular, they have turned a blind eye to the upstream, on-farm and down stream environmental cost of fertilizer production and use. This is not acceptable if agriculture is to be sustainable. Moreover, by addressing these environmental costs, governments would be going a long way towards minimising the trade-offs between food security and the environment.

---

[1] Nutrient mining is a serious form of soil fertility decline generally arising from continuous or frequent cropping with little or no replacement of the soil nutrients removed by crops.

References

Bouwman, A.F. (2001) Global estimates of gaseous emissions from agricultural land. FAO, Rome

Bockman, O.C., Kaarstad, O., Lie, O.H. and Richards, I. (1990). *Agriculture and Fertilizers: Fertilizers in Perspective.* Norsk Hydro, Oslo.

Daberkov, S., Isherwood, K., Poulisse, J. and H. Vroomen (1999), "Fertilizer requirements in 2015 and 2030", paper presented at the IFA Agricultural Conference: "Managing Plant Nutrition towards Maximum Resource Efficiency", Barcelona, Spain.

Bruinsma, J., ed. (2003) *World agriculture: toward 2015/30. An FAO Perspective.* Earthscan, London on behalf of FAO, Rome.

Goulding, K. (2000), Nitrate leaching from arable and horticultural land. *Soil Use and Management,* 16: 145-151.

Gross, E. (1998), "Harmful Algae Blooms: A new International Programme on Global Ecology and Oceanography", Science International no. 69.

IPCC (2001), *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change,* by Watson, R. and the Core Writing Team (eds.), Cambridge University Press, Cambridge.

Lassey, K., Lowe, D. and M. Manning (2000), "The trend in atmospheric methane and implications for isotopic constraints on the global methane budget", *Global Biogeochemical Cycles* 14: 41-49.

MAFF (1999), "Tackling Nitrate from Agriculture: Strategy from Science", Ministry of Agriculture Food and Fisheries, London.

Murgai, R., Ali, M. and D. Byerlee (2001), "Productivity Growth and Sustainability in Post-Green Revolution Agriculture: The Case of the Indian and Pakistan Punjabs", The *World Bank Research Observer*, Vol. 16, no 2. Washington, D.C.

Nelson, M. and M. Mareida (2001), "Environmental Impacts of the CGIAR: An Assessment", Doc. No: SDR/TAC:IAR/01/11 presented to the Mid-Term Meeting, Durban, South Africa, May 21-25.

Nehru, V., Kraay, A., Yu Xiaoqing (1997). *China 2020.* World Bank, Washington D.C.

Norse, D., Li J., Jin L. and Z. Zhang (2001), *Environmental Costs of Rice Production in China: Lessons from Hunan and Hubei,* Aileen International Press, Bethesda.

OECD (2001), *OECD Environmental Outlook to 2020,* OECD, Paris.

Pretty, J., Brett, C, Gee, D, Hine, R., Mason, C., Morison, J., Raven, H., Rayment G., van der Bijl G. and T. Dobbs (2001), "Policy Challenges and Priorities for Internalising the Externalities of Modern Agriculture", *Journal of Environmental Planning and Management,* 44 (2): 263-283

Scherr, S. (1999), "Soil Degradation: A Threat to Developing Country Food Security by

2015?", Food, Agriculture and the Environment Discussion Paper 27, IFPRI, Washington, D.C.

Van Drecht, G., Bouwmann, A.F., Knoop, J.M. and Meinardi, C. (2001). Global Pollution of Surface Waters from Point and Nonpoint Sources of Nitrogen. *The ScientificWorld* 1 (S2), 632-641.

Walker, H. and W. Steffen (1999), *The Terrestrial Biosphere and Global Change: Implications for natural and managed ecosystems,* Cambridge University Press, Cambridge.

Wood, S., Sebastian, K. and Scherr, S.J. (2001). Agroecosystems: Pilot Analysis of Global Ecosystems. IFPRI, Washington D.C.

Zhang, W., Tian, Z., Zhang, N. and Z. Li (1996), "Nitrate pollution of groundwater in Northern China", *Agriculture, Ecosystems and Environment,* 59: 223-231.

Zhu Zhaoliang, 2000. Nitrogen Fertilization: Contribution to Development of Agriculture and Impacts on the Environment in China. Paper presented to the International Workshop on Integrated Land and Water Resources Management in the Coastal Areas of China, Nanjing, April 5-6.