Accumulation of nitrate-N in the soil profile and its implications for the environment under dryland agriculture in northern China: A review

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Fan, J., Hao, M. and Malhi, S. S. 2010. **Accumulation of nitrate-N in the soil profile and its implications for the environment under dryland agriculture in northern China: A review**. Can J. Soil Sci. **90**: 429–440. Nitrate (NO_3^-) leaching and water contamination have become a worldwide concern. In this review, some examples are presented to show the extent and magnitude of NO_3^- accumulation in the soil profiles and its potential effects on contamination of ground water and surface water under dryland farming in northern China. Climatic and management factors affecting NO_3^- leaching are also discussed. In northern China, rainfall is relatively sparse, but the high intensity of precipitation and porous soils play an important role in the accumulation of NO_3-N in soil and its subsequent leaching in the soil profile. There is a risk of nitrate accumulation and leaching when high rates of fertilizer N are applied to improve crop yields, and it becomes even worse when conventional land use is changed from cereal crops to vegetable crops and fruit orchards. Under such conditions, shallow ground water might be polluted by NO_3^-. This suggests that more attention should be paid to prevent this problem by using best management practices, especially by controlling the amount of N fertilizer input, balanced fertilization, split N application, inclusion of crops with deep taproots in the rotation and minimizing summer fallow (especially tilled) frequency.

Key words: Accumulation, contamination, dryland farming, ground water, leaching, nitrate, northern China

Fan, J., Hao, M. et Malhi, S. S. 2010. **Le point sur l'accumulation de N-nitrate dans le sol et ses conséquences pour l'environnement dans le régime d'aridoculture du nord de la Chine**. Can J. Soil Sci. **90**: 429–440. La lixiviation des nitrates (NO_3^-) et la contamination de l'eau sont des préoccupations mondiales. Dans leur article, les auteurs présentent quelques exemples illustrant l'étendue et l'ampleur de l'accumulation de NO_3^- dans le sol, ainsi que ses conséquences potentielles sur la contamination des eaux souterraines et superficielles, sous les terres arables arides du nord de la Chine. Ils abordent aussi les facteurs climatiques et agronomiques qui affectent la lixiviation du NO_3^-. Il pleut relativement peu dans le nord de la Chine, mais l'intensité des précipitations et la porosité du sol jouent un rôle important dans l'accumulation du N-NO_3 et dans sa lixiviation subséquente dans le sol. L'accumulation et la lixiviation de nitrates peuvent survenir quand on applique une grande quantité d'engrais azotés en vue d'accroître le rendement des cultures; la situation empire quand la vocation des terres passe de la céréaliculture au maraîchage et à la culture fruitière. En effet, dans de telles conditions, il peut y avoir contamination de la nappe phréatique peu profonde par le NO_3^-. On recommande de prêter une plus grande attention à la situation afin de prévenir le problème par l'adoption de meilleures pratiques culturales, notamment en régulant la quantité d'engrais azotés employée, en recourant à une fertilisation équilibrée, en divisant les applications de N, en incluant des cultures aux racines profondes dans l'assolement et en minimisant la fréquence des jachères estivales (surtout sur sol travaillé).

Mots clés: Accumulation, contamination, aridoculture, eau souterraine, lixiviation, nitrate, nord de la Chine

Nitrogen (N) is an essential plant nutrient, and it can be released into available form from the soil organic matter by mineralization. Application of N fertilizer is usually required to maximize crop yields (Edmeades 2003; Saleque et al. 2004; Wang et al. 2008). However, improper use of N fertilizer and other crop production management practices can cause nitrate (NO_3^-) leaching below the crop root zone, which may eventually contaminate ground water (Strebel et al. 1989; Aulakh and Malhi 2005). Ground water pollution by NO_3^- is a serious problem in Europe and many other developed countries (Meinardi et al. 1995; VanderVoet et al. 1996; Wilson et al. 1999). The results of field surveys have shown leaching of NO_3-N from agricultural soils to ground water (Kirchmann et al. 2002; Maeda et al. 2003), and only a few studies focused on the distribution of NO_3-N within the soil profile (Benbi et al. 1991; Malhi et al. 2002, 2009). The main causes of the increased N losses and NO_3^- contamination in ground water are input of N fertilizers and animal manures at rates much higher than crop requirements (Benbi et al. 1991; Adams et al. 1994; Rasse et al. 1999). Therefore, crop utilization efficiency of fertilizers has to be improved to reduce NO_3^- leaching losses from agricultural soils and avoid NO_3^- contamination to surface and ground waters.

In northern China, agricultural systems have been developed under arid and semi-arid climatic conditions where droughts often occur. The total dryland farming area in northern China, including 17 Provinces, is 50.5 M ha. Less than 20% of this area is irrigated. Most of the agricultural area receives an average annual rainfall from 300 to 600 mm (Xin and Wang 1998). The main agricultural practice used by farmers to maximize the use of precipitation and ensure high crop production is fertilization (Zhu and Chen 2002). Therefore, the use of N fertilizer has increased dramatically in recent years (China Agricultural Yearbook 2001; FAOSTAT 2002). A number of investigations have been conducted in northern China to study loss and accumulation of NO_3-N in the soil profiles under dryland farming systems (Yuan et al. 2000; Fan et al. 2000, 2003; Fan and Hao 2003; Gu et al. 2003; Ju et al. 2003, 2004; Liu et al. 2003, 2004; Li et al. 2003, 2005; Wu et al. 2003, 2005). However, most of the reports have been published in Chinese with a short abstract in English, and do not provide enough information to international researchers. The objective of this paper is, therefore, to review the results related to accumulation and distribution of NO_3-N in soil profiles and its implications to the environment in northern China. The locations of long-term (more than 5 yr in this study) and short-term field experiments, and field surveys included in this review paper are shown in Fig. 1. The long-term field experiments in typical cropping regions were conducted for many years on the same plots, and the detailed information is presented in Table 1. The short field experiments were generally conducted over 1 or 2 yr for typical grain crops and vegetables. For field surveys, each study was conducted in a typical soil during study periods and different land use patterns were investigated by analyzing many soil samples.

NITRATE ACCUMULATIONS IN SOIL PROFILES

Nitrate that leaches beyond the crop root zone must pass through the unsaturated soil zone before entering the ground water. A survey of NO_3^- accumulation in the unsaturated zone may provide information about the impact of different agricultural practices on NO_3^- leaching (Katupitiya et al. 1997). Results showed that NO_3-N accumulation in soil profile due to N application is becoming a serious problem in northern China (Liu et al. 1998, 2004; Yuan et al. 2000; Fan et al. 2003, 2004; Gu et al. 2003; Table 2). In an investigation on NO_3-N accumulation in 254 soil profiles under different land uses in an area near Beijing city (Liu et al. 2004), average amount of NO_3-N in the 0- to 400-cm soil profile was highest (1230 kg N ha^{-1}) in 115 commercial vegetable fields, followed closely (1148 kg N ha^{-1}) in 16 orchards. The amount of NO_3-N was reduced to 697 kg N ha^{-1} in 15 common vegetable fields, 459 kg N ha^{-1} in 93 winter wheat-summer maize rotation fields and 420 kg N ha^{-1} in eight spring corn fields. The lowest amount of NO_3-N was observed in paddy fields (average of 69 kg N ha^{-1} in seven fields). Overall, large amounts of NO_3-N were found in the 0- to 400-cm soil profiles under different land use patterns that could leach to ground water. Moreover, the area under traditional cropland, such as winter wheat, decreased, while the area under fruit orchards increased continuously in this region. Large amounts of N fertilizers being applied to apple orchards resulted in NO_3-N accumulation distinctly.

CONTROLLING NITRATE ACCUMULATION IN SOIL PROFILE

Soil

Because most soils in northern China are calcareous (with a pH of about 8) and negatively charged, NO_3^- cannot be retained by the soils. Nitrate-N leaching losses were usually less from fine-textured soils than from coarse-textured soils, because of the slower drainage of the former. In the Loess Plateau in northern China, NO_3-N was found to leach down in the planting year to about 200-cm depth in a sandy soil and to about 100-cm depth in a clay soil (Liu et al. 1998). In Shaanxi Province, Tong et al. (2005) compared NO_3-N distribution and accumulation in profiles of two soils with contrasting textures, receiving N fertilizer mostly as NO_3^-. In an Entisol (Regosol) in northern Shaanxi, due to less clay content and high porosity plus a high nitrification rate (2–5 mg kg^{-1} d^{-1}), the peak of NO_3-N concentration was observed to move down to 130-cm depth after 6 mo. But, in an Anthrosol (man-made soil) in Guanzhong Plain, due to relatively higher clay content and the presence of a clay layer at the 80- to 120-cm depth, which impeded water movement and NO_3^- leaching, 64–74% of the NO_3-N accumulated in the 0- to 100-cm depth. The results of extreme NO_3-N leaching in one growing season or year (Liu et al. 1998; Tong et al. 2005) suggest that if N fertilizers are applied in excess of crop needs for optimum growth/yield on highly porous coarse-textured soils with very rapid leaching potential, it is possible that shallow ground water in the study area (average water table about 14.2 m) may be contaminated within approximately 10 yr (detectable levels). In contrast, in the northwest dryland, because of the thickness of the loess layer ($>$100 m in many cases) and the deep ground water, one would not expect NO_3^- to leach into the ground water. For example, Fan et al. (2004) investigated NO_3-N accumulation in an apple orchard located in the Weibei upland of the Loess Plateau, and the results show a large amount of NO_3-N accumulated in the soil profile; a 403 mg N kg^{-1} peak of NO_3-N occurred in the 140- to 160-cm soil layer and most of the NO_3-N was found above 300-cm soil depth. However, on an irrigated river terrace and riverbank land in the Mizhi Town area in the Loess Plateau (Emteryd et al. 1998), NO_3-N concentrations often exceeded 50 mg N L^{-1} in shallow ground water (4–8 m).

Fig. 1. Map showing locations of long-term field experiments (✧), field surveys (●) and other short-term field experiments (Δ) conducted in northern China.

Hydrology

In the past, little attention was paid to NO_3-N leaching in northern China. Although these regions have less total rainfall than those in the south, about 70% of the annual precipitation is usually received in the 4 mo from June to September. Occasional heavy rainfall in this season not only causes N loss by surface runoff (especially in the Loess Plateau), but also transports surface NO_3^- deep into the soil profile. For example, in the Weibei dryland farming area, NO_3-N in fallow land was leached down to 600-cm depth after 16 yr fallow (Fan et al. 2005). Although no fertilizers were applied, most of the NO_3-N leached was from the N mineralization in soil, or rainfall N (Di and Cameron 2002). These findings suggest that frequent summer fallow can cause large accumulation of NO_3-N in soil and occasional heavy rains in relatively dry regions can result in downward movement of NO_3-N deep into the soil profile. To minimize NO_3-N leaching problem, it is suggested that producers should reduce or even eliminate summer fallow (especially tilled) by increasing cropping frequency using no-tillage (Campbell et al. 1984; Guillard et al. 1995; Zentner et al. 2001), proper crop rotations to include perennial grasses with deep/extensive rooting system and high N requirements (Olsen et al. 1970; Entz et al. 2001) or cover crops (Vos et al. 1998). However, quantitative information is needed on the actual contribution of increased cropping frequency using no-tillage and inclusion of deep-rooted perennial and annual crops in rotations in minimizing NO_3-N accumulation and leaching in the soil profiles.

In addition to occasional heavy rains, the usual flood irrigation on irrigated lands in northern China has also caused NO_3^- transport to deeper soil layers (Ju et al. 2003, 2004). The rainfall or irrigation immediately following the fertilizer N application was likely to increase NO_3^- leaching, not only because of possible increased by-pass flow through macropores, but also because of reduced potential for ammonia volatilization (Di and Cameron 2002). In northern and northwestern China, with calcareous soils of pH around 8.0 and the predominant use of urea and ammonium bicarbonate as mineral N fertilizers, ammonia volatilization is generally viewed as a major pathway of N loss (Zhang et al. 1992). In a long-term experiment conducted at Yangling, Shaanxi Province during 1990 to 1998, irrigated plots had more than 20 mg N kg^{-1} in the N and NK treatment in the 120–400 cm soil layers, but in rain-fed plots NO_3-N accumulation occurred between 40 and 120 cm (Fig. 2; Yuan et al. 2000). The greatest NO_3-N concentration in the soil profile occurred under irrigation conditions with unbalanced fertilization (i.e., application of N fertilizer without the use of other deficient nutrients in the soil). Irrigation in excess of crop requirements and heavy rainfall transported NO_3-N to the deep soil layer in an Ochric Aquic Cambosols (Brunisols) in northern China Plain because of the over application of N fertilizer (Zhu et al. 2005a).

Table 1. Information on five long-term experiments in northern China

Location	Crop type/land use	Soil texture	Experimental design	Annual precipitation (mm)	Reference
Changwu County, Shaanxi Province	Winter wheat	Silty clay loam	(1) 8 treatments with three replications. 120 kg N ha^{-1}, 26.2 kg P ha^{-1}, cattle manure 75 Mg ha^{-1} were applied annually.	580	Hao et al. (2005)
			(2) 14 treatments with three replications. Different fertilizers and rates were applied annually, detailed fertilizer rates are presented in Table 3. All plots were 22.2 m^2 in area, arranged in a randomized complete block design.		Fan et al. (2003)
Luanchen, Hebei Province	Wheat-maize rotation	Silty loam	14 treatments with no replications. Different fertilizers and rates were applied yearly, detailed fertilizer rates are presented in Table 3. All plots were 315 m^2 in area, arranged in a randomized complete block design.	480	Li et al. (2003)
Beijing	Wheat-maize rotation	Clay loam	7 treatments, no replications were designed for the treatments because the years could be taken as replications. 150 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, 37.5 K_2O kg ha^{-1} was applied yearly. All plots were 200 m^2 in area.	600	Zhang et al. (2004b)
Yangling County, Shaanxi Province	Wheat-maize rotation	Clay loam	4 treatments with no replications; all plots are 196 m^2. 165 N kg ha^{-1}, 132 P_2O_5 kg ha^{-1}, 66 kg K_2O ha^{-1} for winter wheat and 187 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1}, 75 K_2O kg ha^{-1} for maize were applied annually.	575	Yuan et al. (2000)
	Wheat-soybean rotation		4 treatments with no replications; all plots were 400 m^2. N 135 kg ha^{-1}, 108 P_2O_5 kg ha^{-1}, 54 kg K_2O ha^{-1} for winter wheat were applied annually and no fertilizers for soybean.		
Zhangye in Hexi Corridor of Gansu Province	Wheat-wheat-corn rotation	Sandy clay loam	8 treatments with three replications. Fertilization rate varied during the study period and applied several different times during growing seasons. All plots were 33 m^2 in area.	127	Yang et al. (2004)

In the study by Yuan et al. (2000), the total amount of NO_3-N accumulated in the 0- to 400-cm soil profile over 8 yr was much greater under irrigation (1080 kg N ha^{-1} or 135.0 kg N ha^{-1} yr^{-1}) compared with dryland conditions (660 kg N ha^{-1} or 82.5 kg N ha^{-1} yr^{-1}) (Fig. 2a and c). That is, there was on average 63.6% more NO_3-N accumulated, in addition to much deeper leaching of NO_3-N, in the soil profile under irrigation compared with rain-fed dryland farming. It is possible that leakage of NO_3-N may have occurred below the 400-cm soil depth, although no soil sampling was done below this soil layer and further research is needed to verify the exact depth and extent of NO_3-N leaching by taking very deep soil samples (Fig. 2b). The total amount of NO_3-N accumulated in the 0- to 400-cm soil profile was much greater with the N-only treatment than with the NP treatment under both irrigated (1080 kg N ha^{-1} vs. 236 kg N ha^{-1}, i.e., 236% increase) and dryland (660 kg N ha^{-1} vs. 330 kg N ha^{-1}, i.e., 100% increase) farming. This suggests a considerable annual economic loss to producers, in addition to a high potential risk of environmental pollution of water and air, most likely due to excessive flood irrigation. In summary, irrigation or heavy rainfall may promote the possibility of ground water pollution in those agricultural areas. The findings also suggest the need for future research to determine the optimum amount of irrigation to prevent any significant accumulation of NO_3-N in the soil profile, while also producing high sustainable crop yield.

Fertilizer Application

The amount of fertilizer N accumulating in soils as NO_3^- or lost through leaching over several years is determined primarily by the amount of N applied in relation to the amount of N removed by crops. Research has shown that accumulation of NO_3-N in soil is increased with increasing amounts of applied fertilizer N (Zhang et al. 2004b; Fan et al. 2003; Wu et al. 2005), but application of P fertilizer can reduce NO_3-N accumulation in soil (Yuan et al. 2000; Fan et al. 2003). Results presented in Table 3 clearly show that a balanced fertilizer N, P and K ratio is an effective method for increasing crop yields, enhancing N uptake and reducing NO_3-N leaching losses. In a Fluvo-Aquic (Gleysol) soil profile near Beijing with a winter

Table 2. Nitrate-N accumulation in the soil profile under different land use patterns in northern China

Location	Crop type/land use	Nitrate-N in 0–400 cm soil profile (kg N ha^{-1})	Rate of applied N (kg N ha^{-1} yr^{-1})	Mean annual precipitation (mm)	Reference
Guanzhong Plain, Shaanxi Province, southern edge of Chinese Loess Plateau	8 yr apple orchard	3414	900	550–600	Liu et al. (1998)
	15 yr vegetable	1362	750	550–600	
	High yield grain cropland	537	500	550–600	
	8 yr wheat-maize rotation	1076	352	550–600	Yuan et al. (2000)
Changwu County, Shaanxi Province, south central of Chinese Loess Plateau (long-term experiment, 1984–1999)	15 yr winter wheat	1199	180	580	Fan et al. (2003)
Changwu County, Shaanxi Province (typical apple orchard area in Loess Plateau)	10 yr apple orchard	1788	1000	580	Fan et al. (2004)
Arable field near Beijing (field survey)	Wheat-maize rotation	459	NA[z]	585	Liu et al. (2004)
	Protection vegetable	1230	NA	585	
	Orchard	1148	NA	585	
Luanchen, Hebei Province	5 yr wheat-maize rotation	1219	600	480	Li et al. (2003)
Guanzhong Plain, Shaanxi Province, southern edge of Chinese Loess Plateau (long-term experiment, 1990–2002)	Wheat-soybean rotation	1129	575	550–600	Gu et al. (2003)

[z]NA, fertilization information not available.

wheat–summer maize cropping system for 9 yr, Zhang et al. (2004b) reported NO_3-N accumulation in soil in the following order: N > NK > NPK > NP > Ck > PK. In Gansu Province, however, the order NPK > N > NP > CK was found in a long-term experiment, and manure application, together with N and P and/or K fertilizers decreased NO_3-N accumulation in the soil profile significantly (Yang et al. 2004, 2005). However, NO_3-N accumulation increased with increasing amount of manure applied, and the amount of accumulated nitrate in the 0- to 400-cm soil depth exceeded 1000 kg N ha^{-1} when chicken manure was applied for 15 yr in central area of Shaanxi Province (Yuan et al. 2000). In this study, 40–75% of the accumulated NO_3-N leached below 200 cm and NO_3-N concentration in water of the 50% wells exceeded 10 mg N L^{-1}.

Unbalanced fertilization with N, P and K also causes high NO_3^- accumulation in soil. With an annual application rate of 352 kg N ha^{-1} in a winter wheat–summer maize double-cropping rotation under irrigation conditions, Yuan et al. (2000) showed that the accumulated NO_3-N in the 0- to 400-cm soil profile was much lower with combined N and P fertilization (220 kg N ha^{-1}) compared with combined N and K (1171 kg N ha^{-1}) or N alone (1075 kg N ha^{-1}) treatments. The reason was that the total N uptake by crops under N and P treatment (1360 kg N ha^{-1} in 8 yr) was much higher than that under N and K (720 kg N ha^{-1} in 8 yr) or the N-only treatment (800 kg N ha^{-1} in 8 yr). A similar tendency was found in another experiment under rain-fed conditions at the same location (Yuan et al. 2000). As excessive N application (i.e., N applied in excess of crop requirements for optimum growth/yield) can lead to NO_3-N accumulation in soil, so the amount of applied N should be controlled (Zhang et al. 2005). Also, P application with N reduced NO_3-N accumulation or leaching in this region, but there was no reduction in NO_3-N amount with K application because the loess soils have sufficient K to meet crop requirements.

In a long-term experiment started in 1991 at the Yangling National Soil Fertility and Fertilizer Benefit Center located in Guanzhong Plain, soil NO_3-N accumulations were studied in 2002 in treatments where applications of 135 kg N, 47 kg P or 56 kg K ha^{-1} y^{-1} were applied in various combinations (Gu et al. 2003). Soil NO_3-N accumulation occurred in N, NK, NP and NPK treatments and the total accumulated NO_3-N followed the order: N > NK > NPK $\geq$ NP (Fig. 3a). Application of P fertilizer reduced NO_3-N in soil, and manure application decreased it further. In this study, the total amount of NO_3-N accumulated in the 0–400 cm soil profile over 12 years was 929 kg N ha^{-1} (or 94.1 kg N ha^{-1} yr^{-1}) for N only treatment, 528 kg N ha^{-1} (or 44.0 kg N ha^{-1} yr^{-1}) for NP treatment, 551 kg N ha^{-1} (or 45.9 kg N ha^{-1} yr^{-1}) for NPK treatment, and only 120 kg N ha^{-1} (or 10.0 kg N ha^{-1} yr^{-1}) for the manure-NPK treatment (Fig. 3a). This indicated 113.8% greater

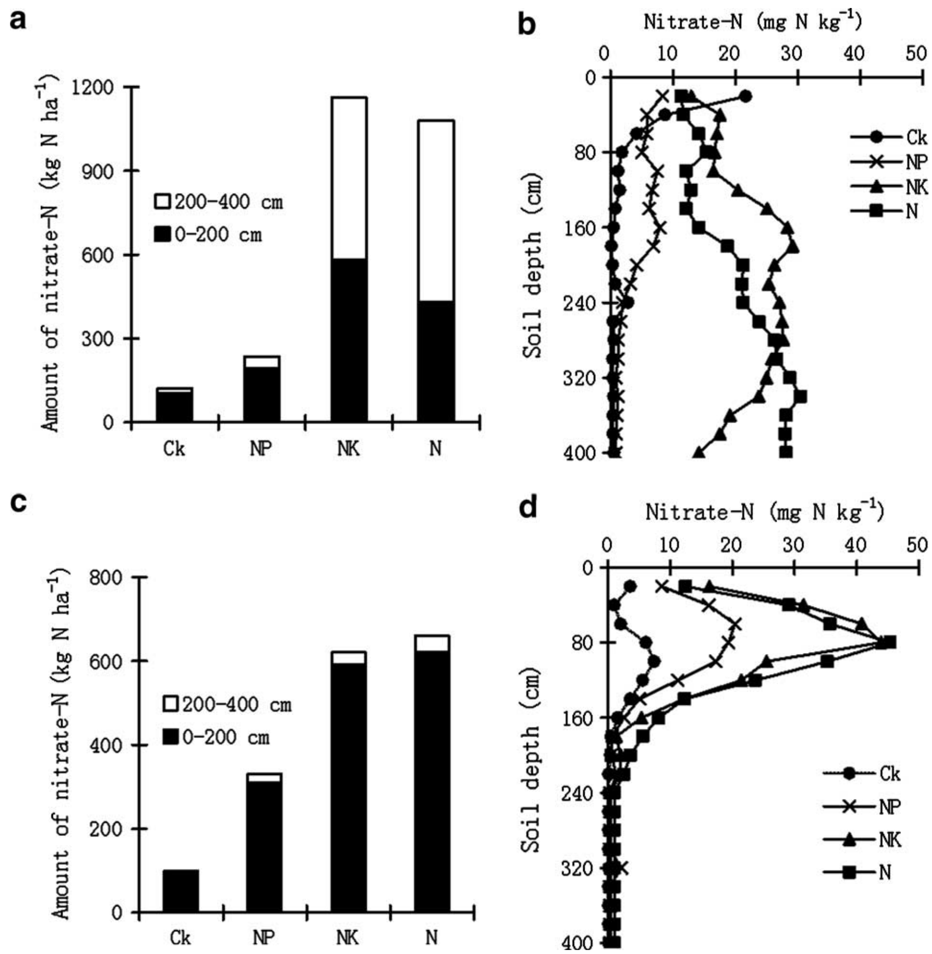

Fig. 2. Nitrate-N accumulation and distribution in the soil profile under irrigation (a and b) and dryland farming (c and d) conditions in a long-term experiment in Guanzhong Plain, Shaanxi Province, southern edge of Chinese Loess Plateau [after Yuan et al. (2000)].

accumulation of NO_3-N in the 0- to 400-cm soil profile when only N fertilizer was applied compared with when N was applied in combination with P fertilizer (NP treatment). This also suggests a reduction in build-up of NO_3-N in soil with balanced application of chemical fertilizers, and further substantial reduction in NO_3-N build-up when manure is applied together with fertilizers. The distribution of NO_3-N concentrations in the 0- to 400-cm soil profile also indicates a reduction in leaching of NO_3-N in the soil profile with combined application of NPK, and much more so when NPK was applied with manure (i.e., little or no leaching of NO_3-N with manure-NPK treatment) compared with N-only treatment, which showed major NO_3-N leaching at least up to 260-cm soil depth (Fig. 3b). These findings again suggest major annual economic losses to producers and the potential risk of environmental damage from excess application of N, but also suggest the importance of integrated use of manure with chemical NPK fertilizers (manure-NPK treatment) in minimizing the accumulation of residual NO_3-N in soil after harvest, and its subsequent leaching.

In another long-term field experiment started in 1984 in Changwu County under typical dryland farming (Hao et al. 2005), the total NO_3-N accumulation in the 0- to 400-cm soil profile was highest (Fig. 3c) and the leaching was deepest (Fig. 3d) in the N-only treatment. In this study, the total amount of NO_3-N accumulated in the 0- to 400-cm soil profile over 13 yr was 402 kg N ha^{-1} (or 30.94 kg N ha^{-1} yr^{-1}) for the N-only treatment, and only 77 kg N ha^{-1} (or 5.9 kg N ha^{-1} yr^{-1}) for the NP treatment (Fig. 3c). The total amount of accumulated NO_3-N in the 0- to 400-cm soil profile was 422% greater in the N-only treatment compared with the NP treatment. This indicates that the application of P in combination with N fertilizer substantially reduced the amount of accumulated NO_3-N, and the extent of NO_3-N leaching in the soil profile. This is an economic benefit to producers, as well as preventing environmental contamination of water and

Table 3. Effect of N, P and K fertilizer application rates on nitrate-N accumulation in the 0- to 400-cm soil depth profile at Luancheng and Changwu in northern China

Luanchen, Hebei Province[z]			Residual nitrate-N in soil (kg N ha^{-1})	Changwu, Shaanxi Province[y]		Residual nitrate-N in soil (kg N ha^{-1})
Fertilizer N, P and K rates (kg ha^{-1})				Fertilizer N and P rates (kg ha^{-1})		
N	P	K		N	P	
0	0	0	109	0	0	576
0	65	0	60	45	19.7	130
0	0	150	98	45	39.3	116
200	0	0	308	45	59	100
200	65	0	266	90	0	460
200	32.5	0	659	90	19.7	154
200	32.5	150	219	90	39.3	110
400	0	0	914	90	78.6	167
400	65	0	571	135	19.7	497
400	65	150	434	135	39.3	406
600	0	0	1219	135	59	275
600	65	0	1090	180	0	1256
600	32.5	0	1390	180	39.3	551
600	32.5	150	1300	180	78.6	349

[z]Wheat-maize rotation from 1997 to 2002 [after Li et al. (2003)].
[y]Winter wheat monoculture from 1984 to 1999 [after Fan et al. (2003)].

air. The peaks of NO_3-N concentrations in the soil profile were much deeper (100 ~ 180 cm) in the N-only treatment compared with the NP treatment (only slight accumulation in 80 ~ 120 cm layers) (Fig. 3d). That is, combined application of N with P fertilizer (NP) minimized leaching of NO_3-N in the soil profile compared with N-only treatment. In summary, balanced application of fertilizers at proper rates would reduce or even eliminate accumulation of residual NO_3-N in the soil profile and thus prevent any potential contamination of ground water.

Research has shown that manure can increase crop yield, but its over application also enhances soil NO_3-N concentration in the soil profile (Yang et al. 2004). Therefore, the amount of manure application should be controlled, because its over application can have a negative impact on the environment in the studied areas. The results from both experiments at Yangling (Gu et al. 2003) and Changwu (Hao et al. 2005) show similar results, with the highest NO_3-N accumulation occurring in the N-only treatment, and a reduction in NO_3-N accumulation shown with P application. NO_3-N accumulation was observed in the manure with chemical fertilizers treatment at Changwu, but accumulation was much lower than at Yangling. This was most likely because of the difference in the amount of manure application at Changwu, which was one-half of that at Yangling.

Cropping System

Vegetable production and fruit orchards currently represent the most intensively fertilized and cultivated production systems in northern China. The high N input makes these systems highly vulnerable to NO_3^- accumulation in the soil profile. However, apple orchards have become the major production system in the Loess Plateau where climatic conditions are completely suitable for apple tree growth. Farmers have converted their crop lands into fruit orchards, and used large quantities of fertilizers to get high yields. In return, farmers gained greater economic benefit and continued the use of high amounts of N and other fertilizers for their orchards over several years. A field survey was conducted in the Weibei dryland area in Shaanxi Province to determine NO_3-N accumulation in orchard soil profiles, and NO_3-N concentrations in the soil profiles under different ages of apple trees (Fan et al. 2004; Fig. 4). Compared with annual field crops, NO_3-N accumulation was very high in apple orchards and the depth of accumulation became greater with the increasing age of apple trees (Fan et al. 2004). For example, the total amount of NO_3-N accumulated in the 0- to 400-cm soil profile was 1496 kg N ha^{-1} in 5- to 10-yr old orchards, and 2994 kg N ha^{-1} in 15- to 30-yr-old orchards. That is a 29.4% increase in NO_3-N accumulation and an additional 60 cm of depth of NO_3-N leaching in the soil profile with increasing age of apple orchards. This suggests that if this land use is continued over many years, the NO_3-N leaching may become more severe in future (if N fertilizer rates are not controlled and balanced fertilization is not followed), in addition to annual economic loss to producers in the form of unused plant-available N.

Nitrate-N distribution in the 0- to 100-cm soil profile of commercial vegetable farms in Dingzhou city and Yongnian County of Hebei Province showed a large amount of NO_3-N accumulation in soil (Zhang et al. 2004a). The amount of accumulated NO_3-N averaged 807 kg N ha^{-1} in Dingzhou, and 430 kg N ha^{-1} in Yongnian, which was higher than that of field crops

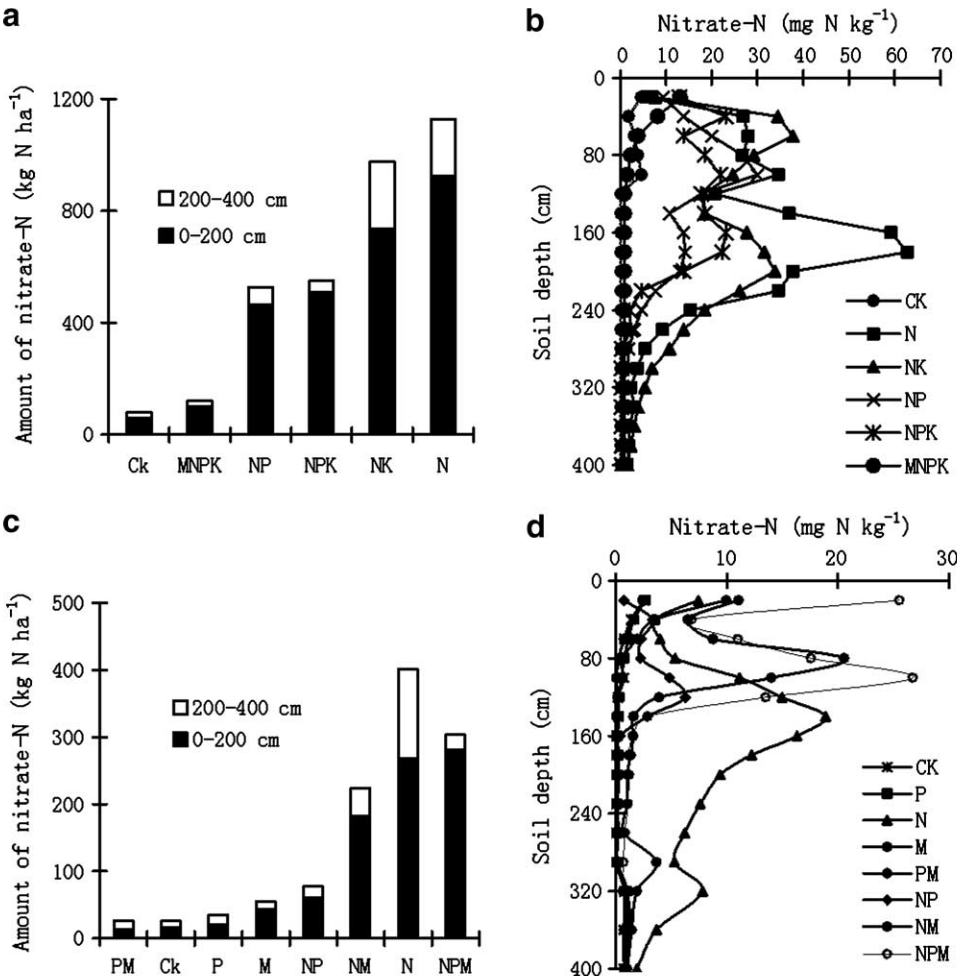

Fig. 3. Nitrate-N accumulation and distribution in the soil profile under different fertilizer and manure treatments at Yangling [a and b, after Gu et al. (2003)] and Changwu County [c and d, after Hao et al. (2005)].

(Zhang et al. 2004a). In a study on the Guanzhong Plain, the concentration of NO_3-N in the surface soil was 66.3 mg N kg^{-1}, and NO_3^- apparently migrated downward, with an average NO_3-N concentration of 27.3 mg N kg^{-1} at the 60- to 80-cm soil depth. The depth of NO_3-N leaching became greater when vegetable crops were grown for long time (Dang et al. 2004). Wang and Li (2003) reported that N can increase yield, but addition of N fertilizer to soil was the major cause of increases in NO_3-N concentration in vegetables. The total amounts of residual soil NO_3-N were 1359 kg N ha^{-1} in the vegetable fields, and 1412 kg N ha^{-1} and 1521 kg N ha^{-1} after 2 and 5 yr in plastic greenhouse fields, respectively. But it was only 245 kg N ha^{-1} in cereal crop fields. Residual NO_3-N in soils formed a serious threat to underground water in vegetable-growing areas (Wang et al. 2002). Ju et al. (2006) compared three intensive cropping systems in the Huimin County of Shandong Province, and their results show that residual soil NO_3-N after harvest was 221–275, 1173 and 613 kg N ha^{-1} in the top 90 cm of the soil profile and 213–242, 1032 and 976 kg N ha^{-1} at 90–180 cm soil depth in wheat-maize, greenhouse vegetable and orchard systems, respectively. Annual total N inputs in the greenhouses ranged from 951 to 8421 kg N ha^{-1} and were far higher than that in the wheat-maize rotations (226–1002 kg N ha^{-1}) and apple orchards (159–1507 kg N ha^{-1}). A field investigation in the Guanzhong area (near Xian city) in Shaanxi Province found that NO_3^- contamination in the edible parts of fresh vegetables was very serious (Qin et al. 2005).

In summary, the findings of these studies indicate that NO_3-N accumulation becomes worse when conventional land use is changed from annual field crops to vegetable crops and fruit orchards. Since farmers can gain greater economic returns from these systems, they will use more fertilizers, and thus incease the potential for NO_3-N contamination of soil and possibly underground water. In the Weibei dryland region, almost 40% crop land was changed to fruit orchards, and 10% of crop land was changed to vegetable crops in the Guanzhong Region because there are several big cities such as Xi'an nearby. However, it is difficult to determine the actual level of risk of this situation further deteriorating, because of lack of information on soil texture, water infiltration rate in the deep soil profile layers, etc. This kind of land use change should be controlled by government guidelines, based on research, suggesting the need for the preparation of guidelines, recommendations and policies (rules, regulations) to restrict the over-use of N fertilizers and manure, and new research on alternative crops (such as medicinal plants) compared with vegetables and fruit orchards.

ENVIRONMENTAL EFFECTS OF NITRATE ACCUMULATION

Residual Nitrate-N in Soil

Accumulated NO_3^- in soil after summer fallow could meet the N requirement for the early growing stages of wheat, and the accumulated NO_3^- provides a foundation for a high yield of winter wheat (Pen et al. 1981). Most researchers reported that residual NO_3-N in soil was an important N source for crops, and its amount was correlated with crop yield (Bundy and Malone 1988; Ferguson et al. 2002; Fan and Hao 2003). However, it should be recognized that a large amount of accumulated NO_3-N indicates that the amount of applied fertilizer N was much greater than the plant required for optimum crop yield. Therefore, the residual NO_3-N may be lost from the soil-plant systems through leaching and denitrification [including emission of nitrous oxide (N_2O) greenhouse gas (GHG); Ju et al. 2009]. Unfortunately, this problem has not yet received much attention in northern China, suggesting the need for future research.

Water Pollution

Nitrate movement in soils of the above-mentioned agricultural areas is evidently a slow process, and at least a part of the NO_3^- can be considered a permanent loss for plant use. In some flat land and irrigated areas, heavy rainfall, which often occurrs in northern China, and flooding irrigation may leach NO_3^- into shallow ground water, The NO_3-N concentrations of well water and surface water exceeded the drinking water standard of 10 mg N L^{-1} in these regions. The NO_3^- pollution of ground water and drinking water due to N fertilization in agriculture is becoming a serious problem in northern China (Chen et al. 2005; Liu et al. 2005; Zhu et al. 2005b). Results obtained by Liu et al. (1998) showed that NO_3-N concentrations exceeding 11 mg N L^{-1} were found in 20% of surface water and ground water samples in the Loess Plateau (Table 4). In another investigation conducted in 14 small cities and towns in northern China from 1993 to 1994, NO_3-N concentrations in ground water and drinking water exceeded 50 mg N L^{-1} for over half of the 69 locations investigated. In some locations, NO_3-N concentrations reached 300 mg N L^{-1} (Zhang et al. 1995). In Huimin County of Shandong Province in the North China Plain (Ju et al. 2006), NO_3-N concentrations in shallow wells (<15 m depth) in greenhouse vegetable systems ranged from 9 to 274 mg N L^{-1}, with 99% exceeding 10 mg N L^{-1}, 53% exceeding 50 mg N L^{-1}, and 26% exceeding 100 mg N L^{-1}. These findings indicate that ground water was severely contaminated by NO_3^- in cropping systems where total N inputs were much higher than crop requirements, and excessive fertilizer N inputs were about 40% of the total N inputs (Ju et al. 2006). Overall, the results on NO_3^- pollution of surface and ground water indicate that nitrates have entered the water in northern China. Although a risk map in this region can be useful for fertilization, it is difficult to prepare because of limited information and spatio-temporal variation of NO_3-N leaching.

Overall, the preceding results suggest that large amounts of accumulated NO_3-N in the soil profiles will continuously move down, and finally may contaminate shallow ground water. It is also possible that a portion of this accumulated NO_3-N under high soil water content and/or lack of oxygen in the subsoil may be denitrified to produce N_2 and/or N_2O (greenhouse gas) gases (Lemke et al. 1999; Gollany et al. 2004; Ju et al. 2009). In order to prevent water and air pollution, as well as for the long-term sustainability of productivity and the stability of economic returns, the reduction of residual NO_3-N in soil after crop harvest should be considered by using proper management of fertilizers and irrigation. For this, long-term information is required, suggesting the need for and importance of the continuation of already existing long-term studies to

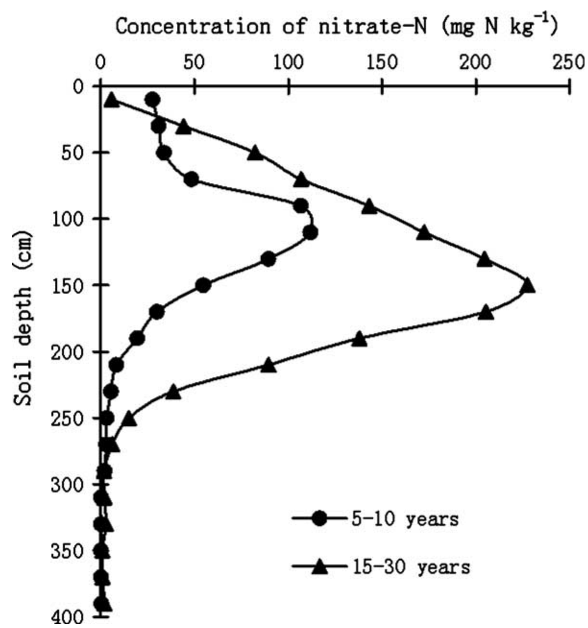

Fig. 4. Nitrate-N distribution in the soil profile under different ages of apple trees [after Fan et al. (2004)].

Table 4. Nitrate-N concentration in well water and surface water in Shaanxi Province [after Liu et al. (1998)]

			Concentration of nitrate-N (mg N L^{-1})					
			>11		5–11		<5	
Water type	Location	Number of samples	n	%	n	%	n	%
Well water	Northern	93	20	21.5	17	18.3	56	60.2
	Middle	74	22	29.7	19	25.7	33	44.6
Surface water	Shaanxi	70	11	15.7	8	11.4	51	72.9

provide vital information to validate models to predict the potential risk of NO_3-N contamination of surface and underground waters, and to assess management practices in order to minimize environmental damage.

SUMMARY OF FINDINGS, CONCLUSIONS, RESEARCH GAPS AND FUTURE RESEARCH NEEDS

Based on the published literature, the main factors involved in the accumulation and leaching of NO_3-N in the soil profile and its potential for contamination of surface and underground waters in northern China are occasional high intensity rainfalls, flood irrigation on some irrigated soils, porous, coarse-textured loess soils, excessive rates of N fertilizer application, unbalanced fertilization, over-application of manure, land use change from cereal crops requiring low levels of N fertilizer to vegetables and fruit orchards requiring high levels of fertilizer.

It is predicted that over-fertilization may become worse in the future, if fertilizer supplies and/or subsidies are not controlled, because China will have to rely heavily on N fertilizer for crop production to feed its increasing population. The implication of these findings is that a substantial increase in NO_3-N in the surface soil and subsoil layers may be a potential threat for pollution of surface water and underground water via leaching of NO_3-N over many years. Movement, transformation and the availability of accumulated NO_3-N in the soil profile to the crop have not yet studied. Therefore, attention should focus on optimizing management practices for the most efficient use of N and other nutrients in order to avoid or minimize the accumulation of NO_3-N in the soil profile.

These findings indicate substantial leaching of NO_3-N deep into the soil profiles in northern China, particularly in coarse-textured soils. This suggests the urgent need for new research in order to make use of this accumulated/leached NO_3-N effectively and efficiently by: applying proper amounts of N fertilizer using fertilizer recommendations based on soil testing and plant tissue testing; using balanced fertilization (applying all nutrients deficient in the soil); applying N using an appropriate time, method and mode [i.e., split application (Yogesh and Juo 1982)]; including in the rotation crops with large, deep roots (in order to recycle the leached NO_3-N by extracting it from lower depths and then returning the crop residues to the surface soil after harvest); reducing the frequency of summer fallow (especially tilled); and using alternative crops (such as low N requiring high cash medicinal plants) rather than vegetables and fruit orchards for sustainable land use, and environmental and economic stability.

In order to predict and evaluate the accumulation of residual NO_3-N in soil, and its subsequent leaching and downward movement in the soil profile in this region, there is an urgent need to develop models, for which long-term information obtained under field conditions is needed. The information generated from such models can be used to calculate the potential risk of NO_3-N leaching and contamination of ground water, to prepare guidelines, recommendations and policies to restrict the over-use of N fertilizer and manure, and the judicious use of fertilizers and other management practices. There is also a need to develop effective government programs to transfer these new recommendations/technologies to farmers and industry through education, presentations and the control of fertilizer distribution.

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Adams, P. L., Daniel, T. C., Edwards, D. R., Nichols, D. J., Pote, D. H. and Scott, H. D. 1994. Poultry litter and manure contributions to nitrate leaching through the vadose zone. Soil Sci. Soc. Am. J. **58**: 1206–1211.

Aulakh, M. S. and Malhi, S. S. 2005. Interactions of nitrogen with other nutrients and water: effect on crop yield and quality, nutrient use efficiency, carbon sequestration, and environmental pollution. Adv. Agron. **86**: 341–409.

Benbi, D. K., Biswas, C. R. and Kalkat, J. S. 1991. Nitrate distribution and accumulation in an Ustochrept soil profile in a long-term fertilizer experiment. Fert. Res. **28**: 173–177.

Bundy, L. G. and Malone, E. S. 1988. Effect of residual nitrate on corn response to applied nitrogen. Soil Sci. Soc. Am. J. **52**: 1377–1383.

Campbell, C. A., deJong, R. and Zentner, R. P. 1984. Effect of cropping, summer fallow and fertilizer nitrogen on nitrate-nitrogen lost by leaching on a Brown Chernozemic soil. Can. J. Soil Sci. **64**: 61–74.

Chen, J. Y, Tang, C. Y., Sakura, Y., Yu, J. J. and Fukushima, Y. 2005. Nitrate pollution from agriculture in different hydrogeological zones of the regional ground water flow system in the North China Plain. Hydrol. J. **13**: 481–492.

China Agricultural Yearbook. 2001. Editorial Committee of China agricultural yearbook. China Agricultural Publishing House, Beijing, China. 168 pp. [in Chinese].

Dang, J. X., Guo, W. L., Guo, J. W., Lv, J. L. and Wang, J. L. 2004. Study of the regularity of the salt accumulation of topsoil and NO_3-N migration in greenhouse soil and years of vegetables cultivation. Chinese Agric. Sci. Bull. **20:** 189–191 [in Chinese].

Di, H. J. and Cameron, K. C. 2002. Nitrate leaching in temperate agroecosystems, sources, factors and mitigating strategies. Nutr. Cycl. Agroecosys. **46**: 237–256.

Edmeades, D. C. 2003. The long-term effects of manures and fertilizers on soil productivity and quality: a review. Nutr. Cycl. Agroecosyst. **66**: 165–180.

Emteryd, O., Lu, D. Q. and Nykvist, N. 1998. Nitrate in soil profiles and nitrate pollution of drinking water in the Loess Region of China. Ambio **27**: 441–443.

Entz, M. H., Bullied, W. J., Foster, D. A., Gulden, R. and Vessey, K. 2001. Extraction of subsoil nitrogen by alfalfa, alfalfa-wheat, and perennial grass systems. Agron. J. **93**: 495–503.

Fan, J. and Hao, M. D. 2003. Nitrate accumulation in soil profile of dryland farmland. J. Agro-Environ. Sci. **22:** 263–266 [in Chinese].

Fan, J., Hao, M. D. and Dang, T. H. 2000. Distribution and accumulation of NO_3^--N in soil profile of long-term fertilizer experiment. Soil Environ. Sci. **9**: 23–26 [in Chinese].

Fan, J., Hao, M. D. and Shao, M. A. 2003. Nitrate accumulation in soil profile of dry land farming in Northwest China. Pedosphere **13**: 367–374.

Fan, J., Hao, M. D. and Shao, M. A. 2004. Soil desiccation and nitrate accumulation of the apple orchard on the Weibei upland. Chinese J. Appl. Ecol. **15:** 1213–1216 [in Chinese].

Fan, J., Hao, M. D., Shao, M. A. and Wang, Q. J. 2005. Nitrate accumulation and distribution in soil profiles in ecosystem of up land on the Loess Plateau. Plant Nutr. Fert. Sci. **11:** 8–12 [in Chinese].

FAOSTAT 2002. FAO statistical databases. Agriculture Data. [nline] Available: http://apps.fao.org/page/collections?subset=agriculture.

Ferguson, R. B., Hergertb, G. W., Schepersc, J. S., Gotwayd C. A., Cahoone, J. E. and Petersonf, T. A. 2002. Site-specific nitrogen management of irrigated maize, Yield and soil residual nitrate effects. Soil Sci. Soc. Am. J. **66**: 544–553.

Gollany, H. T., Molina, J. E., Clapp, C. E., Allmaras, R. R., Layese, M. F., Baker, J. M. and Cheng, H. H. 2004. N leaching and denitrification in continuous corn as related to residue management and N fertilization. Environ. Manage. **33** (Suppl. 1): S289–298.

Gu, Q. Z., Yang, X. Y., Sun, B. H. and Ma, L. J. 2003. Effect of long- term fertilization on distribution and accumulation of NO_3^--N in loess profile of dry-land. Agric. Res.Arid Areas **21:** 48–52 [in Chinese].

Guillard, K., Griffin, G. F., Allinson, D. W., Yamartino, W. R., Rafey, M. M. and Pietryzk, S. W. 1995. Nitrogen utilization of selected cropping systems in the U.S. northeast. II. Soil profile nitrate distribution and accumulation. Agron. J. **87**: 199–207.

Hao, M. D., Fan, J., Wei, X. R., Peng, L. F. and Lai, L. 2005. Effects of fertilization on soil fertility and yield of dryland wheat in the Loess Plateau. Pedosphere **15**: 189–195.

Ju, X. T., Kou, C. L., Zhang, F. S. and Christie, P. 2006. Nitrogen balance and ground water nitrate contamination, comparison among three intensive cropping systems on the North China Plain. Environ. Pollut. **143**: 117–125.

Ju, X. T., Liu, X. J. and Zhang, F. S. 2003. Accumulation and movement of NO_3-N in soil profile in winter wheat/summer maize rotation system. Acta Pedo. Sin. **40:** 538–546 [in Chinese].

Ju, X. T., Liu, X. J., Zhang, F. S. and Roelcke, M. 2004. Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China. Ambio **33**: 300–305.

Ju, X. T., Xing, G. X., Chen, X. P., Zhang, S. L., Zhang, L. J., Liu, X. J., Cui, Z. L., Yin, B., Christie, P., Zhu, Z. L. and Zhang, F. S. 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. PNAS **106**: 3041–3046.

Katupitiya, A., Eisenhauer, D. E., Ferguson, R. B., Spalding, R. F., Roeth, F. W. and Bobier, M. W. 1997. Long-term tillage and crop rotation effects on residual nitrate in the crop root zone and nitrate accumulation in the intermediate vadose zone. Trans. Am. Soc. Agric. Eng. **40**: 1321–1327.

Kirchmann, H., Johnston, A. E. and Bergstrom, L. 2002. Possibilities for reducing nitrate leaching from agricultural land. Ambio **31**: 404–408.

Lemke, R. L., Izaurralde, R. C., Nyborg, M. and Solberg, E. D. 1999. Tillage and N source influence soil-emitted nitrous oxide in the Alberta Parkland region. Can. J. Soil Sci. **79**: 15–24.

Li, W. X., Li, L., Sun, J. H., Guo, T. W., Zhang, F. S., Bao, X. G., Peng, A. and Tang, C. 2005. Effects of intercropping and nitrogen application on nitrate present in the profile of an Orthic Anthrosol in Northwest China. Agric. Ecosyst. Environ. **105**: 483–491.

Li, X. X., Hu, C. S. and Cheng, Y. S. 2003. Effects of different fertilizers on crop yields and nitrate accumulation. Agr. Res. Arid Areas **21:** 38–42 [in Chinese with English abstract].

Liu, D. Q., Tong, Y. A., Sun, B. H. and Emteryd, O. 1998. Study on effect of nitrogen fertilizer use on environmental pollution. Plant Nutr. Fert. Sci. **4:** 8–15 [in Chinese].

Liu, G. D., Wu, W. L. and Zhang, J. 2005. Regional differentiation of non-point source pollution of agriculture-derived nitrate nitrogen in ground water in Northern China. Agric. Ecosyst. Environ. **107**: 211–220.

Liu, H. B., Li, Z. H., Zhang, Y. G., Zhang, W. L. and Lin, B. 2004. Characteristics of nitrate distribution and accumulation in soil profiles under main agro-land use types in Beijing. Sci. Agric. Sin. **37:** 692–698 [in Chinese].

Liu, X. J., Ju, X. T., Zhang, F. S., Pan, J. R. and Christie, P. 2003. Nitrogen dynamics and budgets in a winter wheat–maize cropping system in the North China Plain. Field Crop Res. **83**: 111–124.

Maeda, M., Zhao, B., Ozaki, Y. and Yoneyama, T. 2003. Nitrate leaching in an Andisol treated with different types of fertilizers. Environ. Pollut. **121**: 477–487.

Malhi, S. S., Brandt, S. A., Lemke, R., Moulin, A. P. and Zentner, R. P. 2009. Effects of input level and crop diversity on soil nitrate-N, extractable P, aggregation, organic C and N, and N and P balance in the Canadian Prairie. Nutr. Cycl. Agroecosyst. **84**: 1–22.

Malhi, S. S., Brandt, S. A., Ulrich, D., Lemke, R. and Gill, K. S. 2002. Accumulation and distribution of nitrate-nitrogen and extractable phosphorus in the soil profile under various alternative cropping systems. J. Plant Nutr. **25**: 499–520.

Meinardi, C. R., Beusen, A. H. W., Bollen, M. J. S., Klepper, O. and Willems, W. J. 1995. Vulnerability to diffuse pollution and average nitrate contamination of European soils and ground water. Water Sci. Technol. **31**: 159–165.

Olsen, R. J., Hensler, R. F., Attoe, O. J., Witzel, S. A. and Peterson, L. A. 1970. Fertilizer nitrogen and crop rotation in relation to movement of nitrate nitrogen through soil profiles. Soil Sci. Soc. Am. Proc. **34**: 448–452.

Pen, L., Pen, X. L. and Lu, Z. F. 1981. The seasonal variation of soil NO_3-N and the effect of summer fallow on the fertility of loessial soil. Acta Pedolo. Sin. **18:** 212–222 [in Chinese].

Qin, Q. Y., Jia, C. Z., Qin, M., Tong, Y. A. and Qu, D. 2005. Research on vegetables nitrate accumulation under protected cultivation in Shaanxi Guanzhong area. Soil Fert. **1:** 29–31 [in Chinese].

Rasse, D. P., Ritchie, J. T., Peterson, W. R., Loudon, T. L. and Martin, E. C. 1999. Nitrogen management impacts on yield and NO_3-N leaching in inbred maize systems. J. Environ. Qual. **28**: 1365–1371.

Saleque, M. A., Abedin, M. J., Bhuiyan, N. I., Zaman, S. K. and Panaullah., G. M. 2004. Long-term effects of inorganic and organic fertilizer sources on yield and nutrient accumulation of lowland rice. Field Crop Res. **86**: 53–65.

Strebel, O., Duynisveld, W. H. M. and Bottcher, J. 1989. Nitrate pollution of groundwater in western Europe. Agric. Ecosyst. Environ. **26**: 189–214.

Tong, Y. A., Shi, W., Lu, D. Q. and Emteryd, O. 2005. Relationship between soil texture and nitrate distribution and accumulation in three types of soil profile in Shaanxi. Plant Nutr. Fert. Sci. **11:** 435–441 [in Chinese].

VanderVoet, E., Kleijn, R. and DeHaes, H. A. U. 1996. Nitrogen pollution in the European Union – origins and proposed solutions. Environ. Conserv. **23**: 120–132.

Vos, J., Van-Der-Putten, P. E. L., Hussein, M. H., Van-Dam, A. M. and Leffelaar, P. A. 1998. Field observations on nitrogen catch crops. II. Root length and root length distribution in relation to species and nitrogen supply. Plant Soil **210**: 149–155.

Wang, Z. H. and Li, S. X. 2003. Effects of N forms and rates on vegetable growth and nitrate accumulation. Pedosphere **13**: 309–316.

Wang, Z. H., Li, S. X. and Malhi, S. 2008. Effects of fertilization and other agronomic measures on nutritional quality of crops. J. Sci. Food Agric. **88**: 7–23.

Wang, Z. H., Zong, Z. Q., Li, S. X. and Chen, B. M. 2002. Nitrate accumulation in vegetables and its residual in vegetable fields. Environ. Sci. **23:** 79–83 [in Chinese].

Wilson, W. S., Ball, A. S. and Hinton, R. H. 1999. Managing risks of nitrates to humans and the environment. The Royal Society of Chemistry, Cambridge, UK. 348 pp.

Wu, J. S., Guo, S. L. and Dang, T. H. 2003. Mechanisms in the accumulation and movement of mineral N in soil profiles of farming land in a semi-arid region. Acta Ecol. Sin. **23:** 2041–2049 [in Chinese].

Wu, Y. C., Zhou, S. L., Wang, Z. M. and Luo, Y. Q. 2005. Dyanmics and residue of soil nitrate in summer maize field of North China. Acta Ecol. Sin. **25:** 1620–1625 [in Chinese].

Xin, N. Q. and Wang, L. X. 1998. Agriculture in arid regions of northern China. JiangSu Science and Technology Press, Nanjing, Jiangsu Province, China. 355 pp. [in Chinese].

Yang, S. M., Li, F. M., Malhi, S. S., Wang, P., Suo, D. R. and Wang, J. G. 2004. Long-term fertilization effects on crop yield and nitrate nitrogen accumulation in soil in Northwestern China. Agron. J. **96**: 1039–1049.

Yang, S. M., Li, F. M., Suo, D. R., Guo, T. W., Wang, J. G., Sun, B. L. and Jin, S. L. 2005. Effect of long-term fertilization on soil productivity and nitrate accumulation in Gansu Oasis. Sci. Agri. Sin. **38:** 2043–2052 [in Chinese].

Yogesh, A. and Juo, A. S. R. 1982. Leaching of fertilizer ions in a Kaolinitic Ultisol in the high rain fall tropics: Leaching of nitrate in field plots under cropping and bare fallow. Soil Sci. Soc. Am. J. **46**: 1212–1217.

Yuan, X. M., Tong, Y. A., Yang, X. Y., Li, X. L. and Zhang, F. S. 2000. Effect of phosphate application on soil nitrate nitrogen accumulation. Plant Nutr. Fert. Sci. **6**: 397–403 [in Chinese].

Zentner, R. P., Campbell, C. A., Beiderbeck, V. O., Miller, P. R., Selles, F. and Fernandez, M. R. 2001. In search of a sustainable cropping system for the semiarid Canadian prairies. J. Sust. Agric. **18**: 117–136.

Zhang, G. Y., Wang, L. Y., Wang, L., Geng, N., Sun, S. Y. and Ru, S. H. 2004a. NO_3^--N content and distribution of soil under protective vegetable culture. J. Hebei Agric. Sci. **8:** 22–25 [in Chinese].

Zhang, S. L., Cai, G. X., Wang, X. Z., Xu, Y. H., Zhu, Z. L. and Freney, J. R. 1992. Losses of urea-nitrogen applied to maize on a calcareous fluvo-aquic soil in North China Plain. Pedosphere **2**: 171–178.

Zhang, S. X., Li, X. Y., Li, X. P., Yuan, F. M., Yao, Z. H., Sun, Y. L. and Zhang, F. D. 2004b. Crop yield, N uptake and nitrates in a fluvo-aquic soil profile. Pedosphere **14**: 131–136.

Zhang, W. L., Tian, Z. X., Zhang, N. and Li, X. Q. 1995. Investigation of nitrate pollution in ground water due to nitrogen fertilization in agriculture in North China. Plant Nutr. Fert. Sci. **1:** 80–87 [in Chinese].

Zhang, Y. M., Hu, C. S., Zhang, J. B., Chen, D. L. and Li, X. X. 2005. Nitrate leaching in an irrigated wheat-maize rotation field in the North China plain. Pedosphere **15:** 196–203 [in Chinese].

Zhu, A. N., Zhang, J. B., Zhao, B. Z., Cheng, Z. H. and Li, L. P. 2005a. Water balance and nitrate leaching losses under intensive crop production with Ochric Aquic Cambosols in North China Plain. Environ. Int. **31**: 904–912.

Zhu, J. H., Li, X. L., Christie, P. and Li, J. L. 2005b. Environmental implications of low nitrogen use efficiency in excessively fertilized hot pepper (*Capsicum frutescens* L.) cropping systems. Agric. Ecosyst. Environ. **111**: 70–80.

Zhu, Z. L. and Chen, D. L. 2002. Nitrogen fertilizer use in China – Contributions to food production, impacts on the environment and best management strategies. Nutr. Cycl. Agroecosyst. **63**: 117–127.