Proc. Seminar : Production & Use of Chemical Fertilizers and Environment,
17-21 Dec. 1994, Cairo, Eds. M. M. El-Fouly and F. E. Abdalla, pp. 101 - 124 (1995)

ENVIRONMENTALLY SOUND FERTILIZER APPLICATION

A. Amberger

Institute of Plant Nutrition,
Technical University, Munich-Weihenstephan, Germany

Introduction

Inorganic and organic fertilizers applied to agricultural crops have a great beneficial potential to maximize yields, but they can contribute also to environmental pollution (air, water, soil), when applied in too high quantities, at the wrong time or with inappropriate application techniques.

The optimal amount and a modern management practice guaranty high yields and quality products and minimize possible negative effects. Food production has still priority and is the problem Nr. 1 in developing countries, however the management must be in harmony with nature avoiding over and under fertilization.

The Nobel laureate Dr. Norman E. Borlaug, made recently the following statement:

"For those of us on the food production front, let us all remember that world peace will not - and can not - be built on empty stomachs. Deny farmers access to modern factors of production - such as improved varieties, fertilizers and crop protection chemicals - and the world will be doomed - not from poisoning, as some say, but from starvation and social chaos".

Our challenge and goal as scientists are to work out concepts and strategies to promote a sustainable agricultural development through environmentally sound and balanced fertilization practices, which have to be supported strongly by economic policies.

The problems concerning a sound fertilizer application concern mainly nitrogen and phosphate, to a much less extent some other elements.

I. Nitrogen

The nitrogen dynamics in soils are complicated and very much affected by climate and soil factors as well as application techniques (Fig. 1).

On one hand, there is a positive nitrogen input into the system by symbiotic and non-symbiotic fixation and a release of available ammonium and nitrate

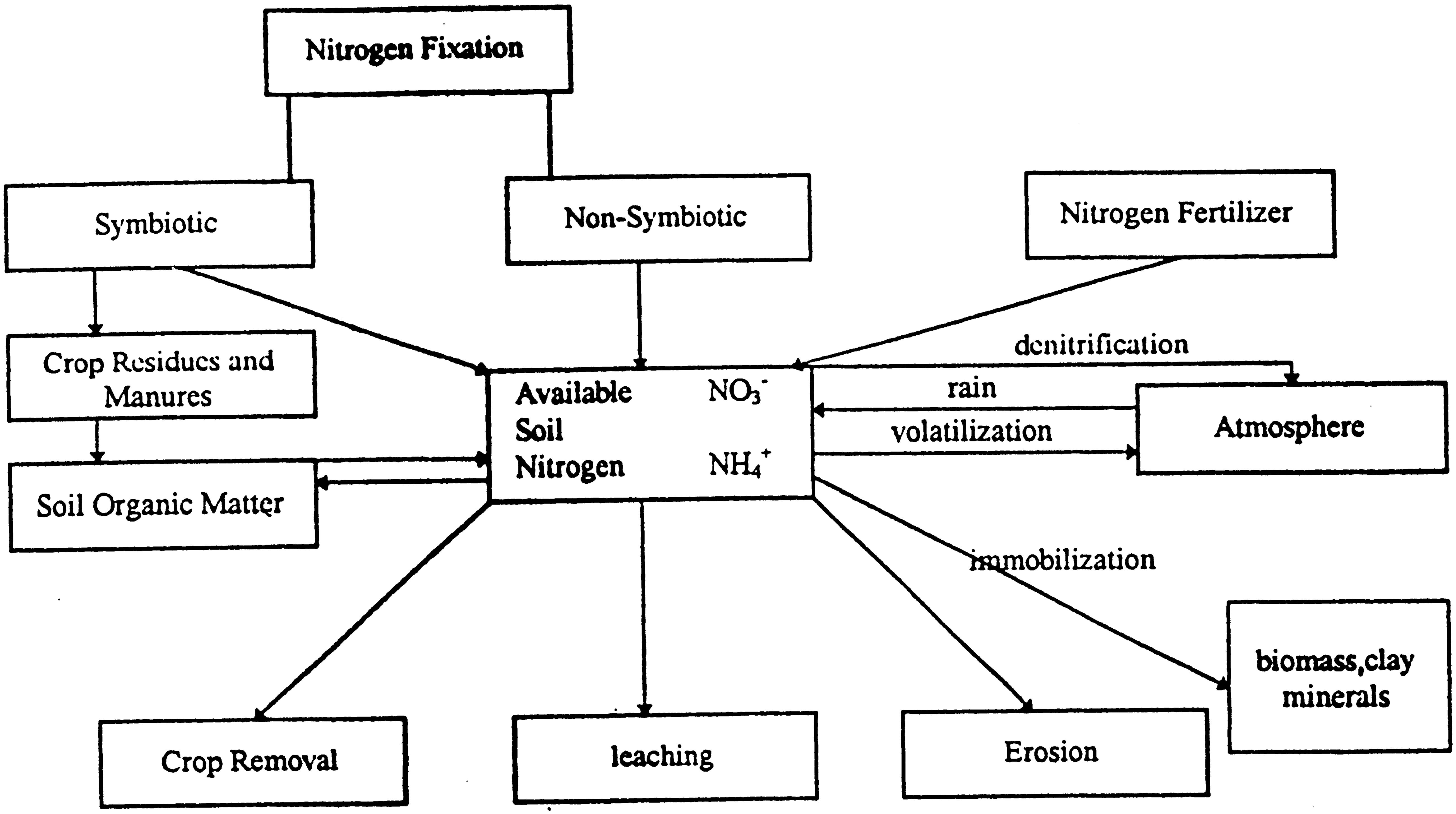


Fig. 1 ***Nitrogen sources and sinks*** *according to Hagin and Tucker, 1982 (modified).*

as a result of decomposition or mineralization process of crop residues, organic manures. soil organic matter and fertilizers. The ammonium-N can either be fixed preferentially into biomass or humic substances or between the layers of some clay minerals. This is not a real loss but a temporary immobilization. On the contrary, NH_3-volatilization or NH_4-transport by erosion into surface water means both loss and environmenal pollution.

Ammonium and nitrate can be taken up by plnats as nutrients. Ammonia released to the atmosphere both it self or converted to No_x is a matter of depositions acidifying surface water and soils (Fig. 2).

The nitrate-N is very mobile, not fixed and can easily be leached out into ground and surface water (rivers, lakes) or denitrified to N_2O, NO_2 or N_2 into the atmosphere. N_2O released to the stratosphere is capable to destroy the ozone layer. All these natural processes can hardly be controlled by farmers, meanwhile, the application of inorganic fertilizers can be optimized with minimum losses and environmental pollution. Consequently, the agricultural nitrogen cycle is by no means closed but it entails a considerable number of leaks. There are three main pathways of nitrogen losses: ammonia volatilization, denitrification, nitrate leaching and to some extent erosion (Fig. 3).

1. Ammonia volatilization

Chemical principles: Ammonium/ammonia equilibrium

NH_4^- (adsorb.) $\rightleftarrows$ NH_4^+ (solution) $\rightleftarrows$ NH_3 (solution) $\rightleftarrows$ NH_3 (gas)

$NH_4^-OH^-$ $\rightleftarrows$ $NH_3 + H_2O$

Ammonia volatlization is highly dependent on pH and temperature (Figs. 4 and 5).

Under practical conditions, it is predominately a matter of inappropriate fertilizer application. Among mineral fertilizers ammonium containing or ammonia liberating products (mainly urea, ammonium-urea solution, ammonium sulfate and ammonium sulfate nitrate) are concerned. The hydrolysis of urea takes place very quickly (2-3 days). Volatilization losses can mount up to 20-30% and even higher with broadcast application, depending on soil pH and temperature (Table 1). In recent experiments with ^{15}N urea in China on Loessbrown earth, NH_3 volatilization increased up to 50-60% with broadcasting compared with 1-2% after incorporation. In the more or less alkaline irrigation water (pH 7.5-8.0) a relative high ammonia concentration appears and, therefore, favours very much volatilization losses. Incorporation of urea into the soil, supergranules or sulfur-coated supergranules of urea, both placed at 10 cm depth minimize volatile losses (Table 2).

Table 1: NH_3-losses (%) from mineral fertilizers 5 days after surface application (Amberger, 1989 a).

Closed dynamic system, low wind flow, temperature 20° C and fertilizer doses : 100 mg N/400 g soil (50 cm^2 surface) - 3 parallels

Fertilizer	Soil silty loam	
	Niederhummel pH 7.1	*Dürnast pH 6.5*
Urea	25	20
Ammonium urea solution	20	15
Ammonium sulfate	11	1
NPK	11	0
Calcium ammonium nitrate	2	1

Table 2: Comperative effects of Basal Broadcast Urea, Split Urea (SU), Supergranules (SG) of Urea placed at 10 cm depth, Basal Broadcast Sulfur-Coated Urea (SCU) and Sulfur-Coated Supergranules of Urea (SCSG) placed at 10 cm depth on growth and nitrogen recovery by rice in the greenhouse (D.H. Parish, 1979).

Fertilizer*	Pancles (No.)	Dry matter (g/pot)		Apparent nitrogen recovery (%)
		Grain	*Total tops*	
O	27	33	99	-
BU	31	38	123	28
SU	31	47	134	48
SG	37	45	151	69
SCU	34	46	140	56
SCSG	39	52	163	89

* Fertilizer rate: 460 mg N/pot

A very serious situation arises in case of animal slurry (Fig.6) which contains 60-70% of total N in form of ammonium-N.

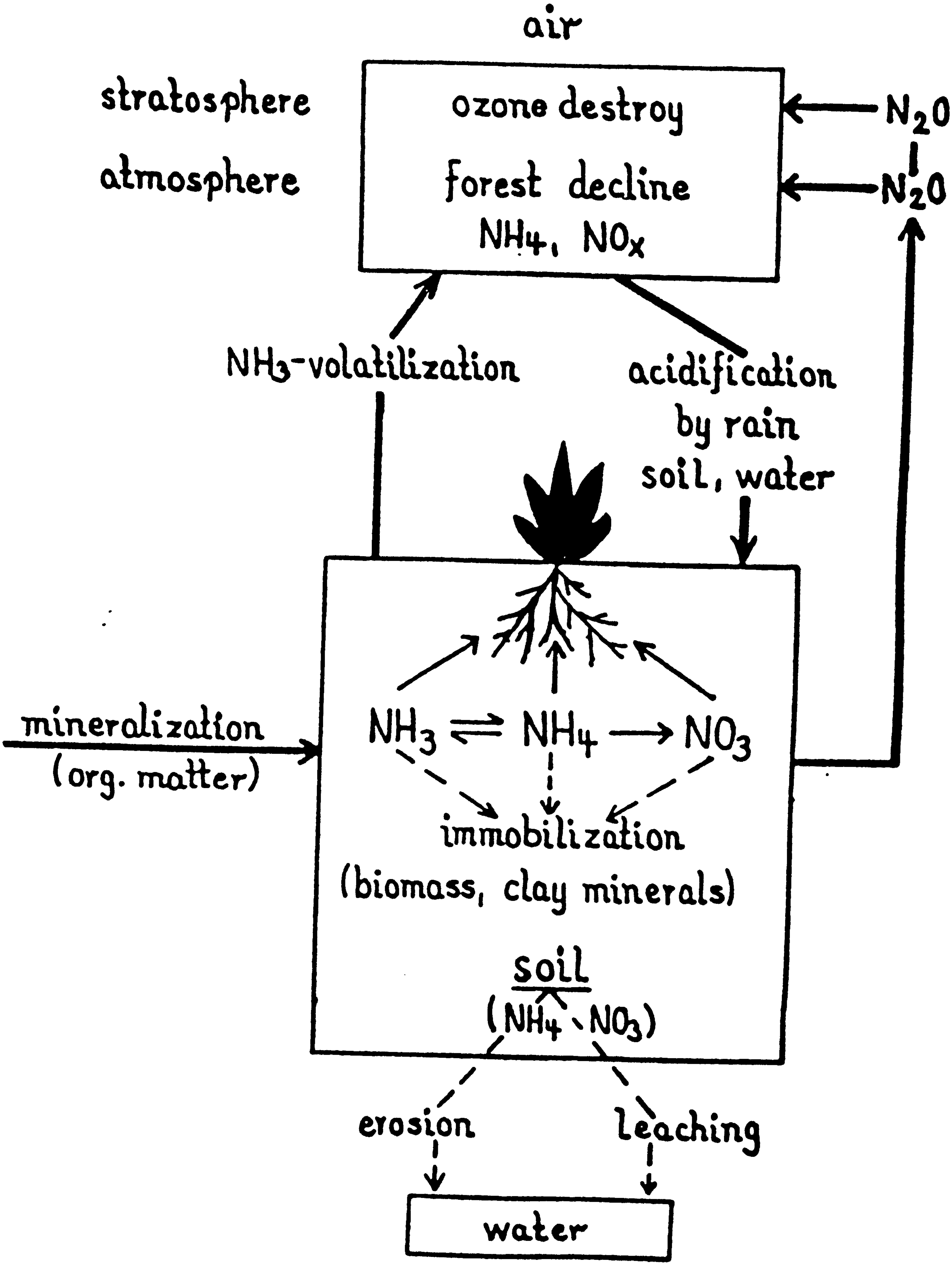


Fig. 2. Fate of ammonium and nitrate.

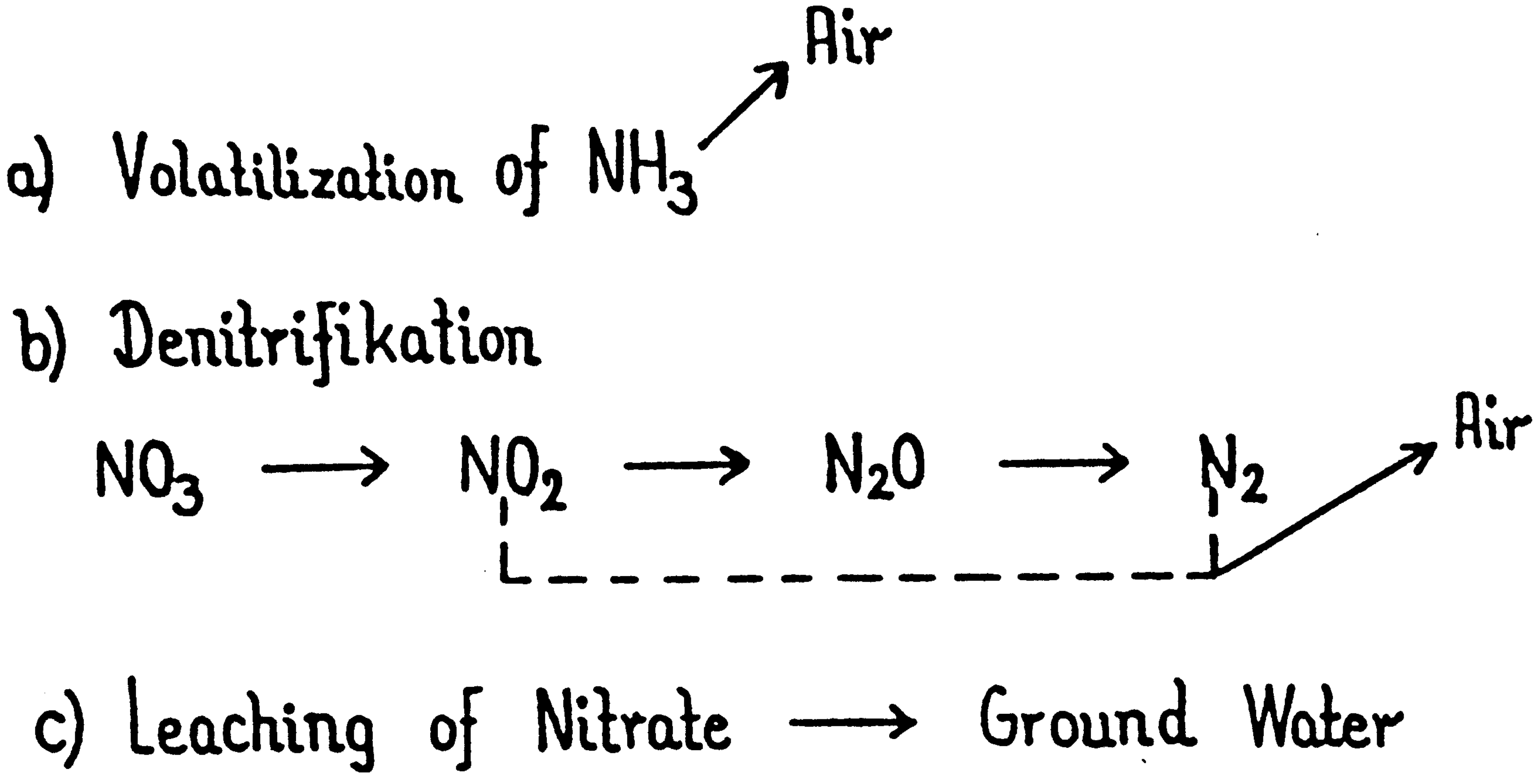


Fig. 3. Losses of N.

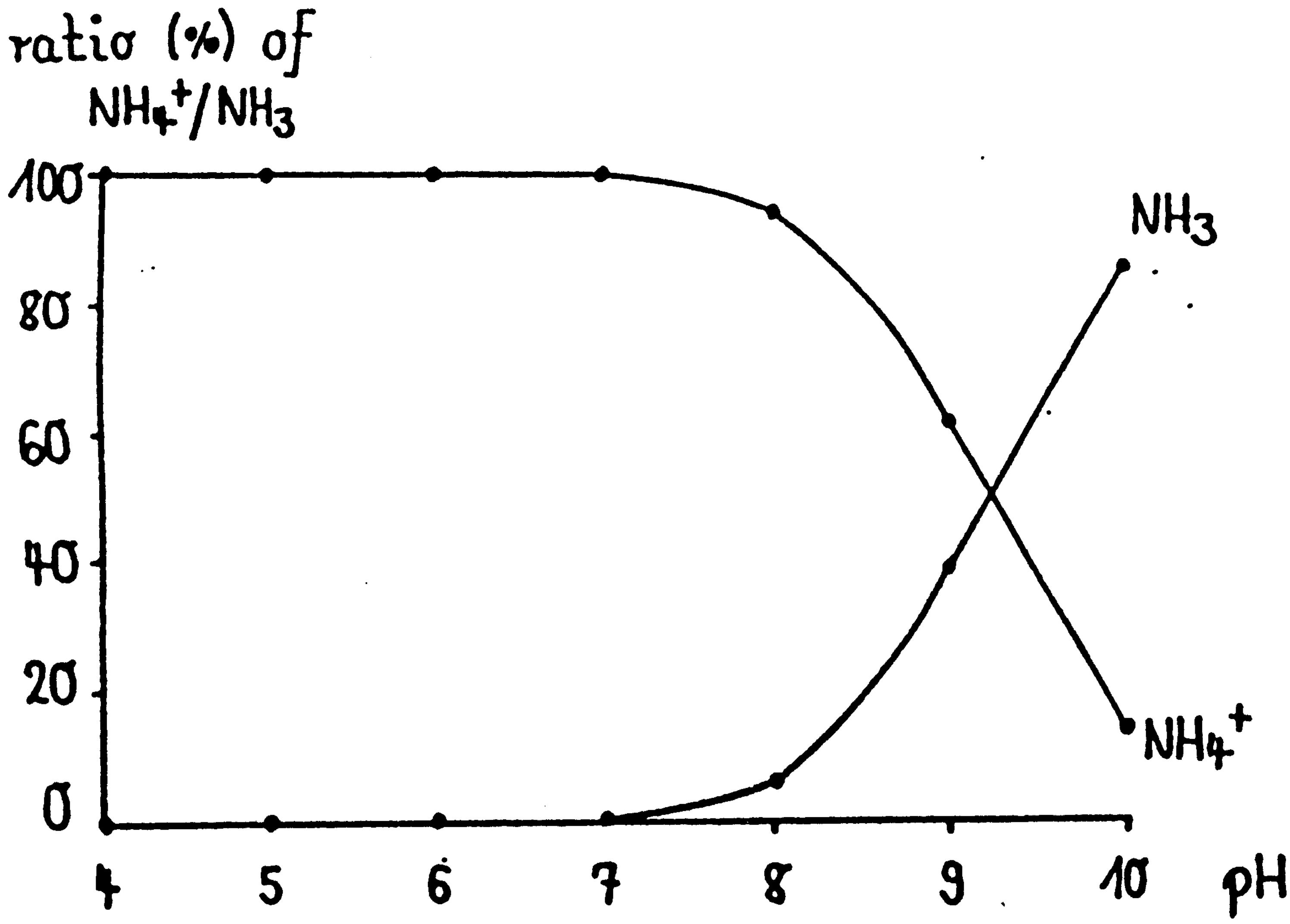


Fig. 4. Effect of pH on the relative concentration of NH_4^+ and NH_3 (Court et al. 1964).

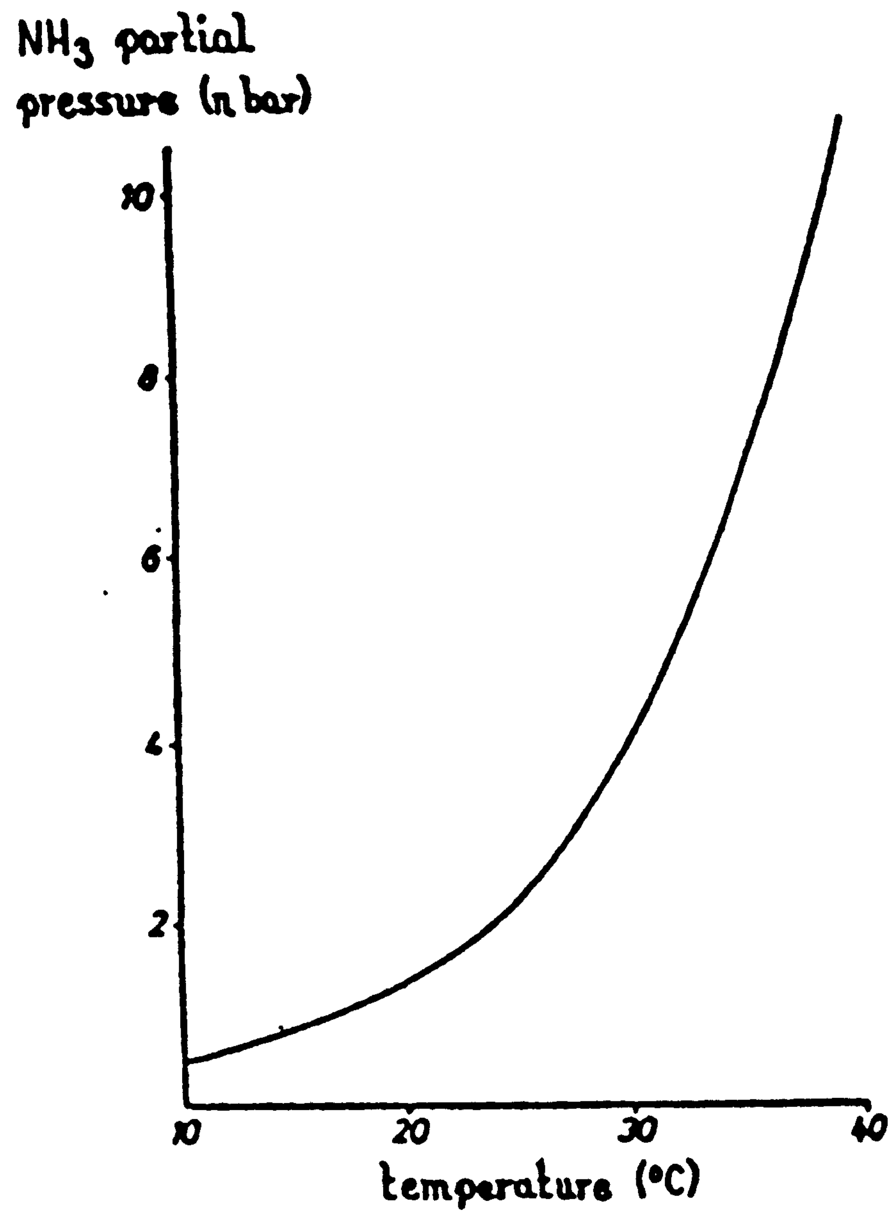


Fig. 5. Effect of temperature on partial pressure of ammonia of pH 6.8 (Farquhar et al. 1980).

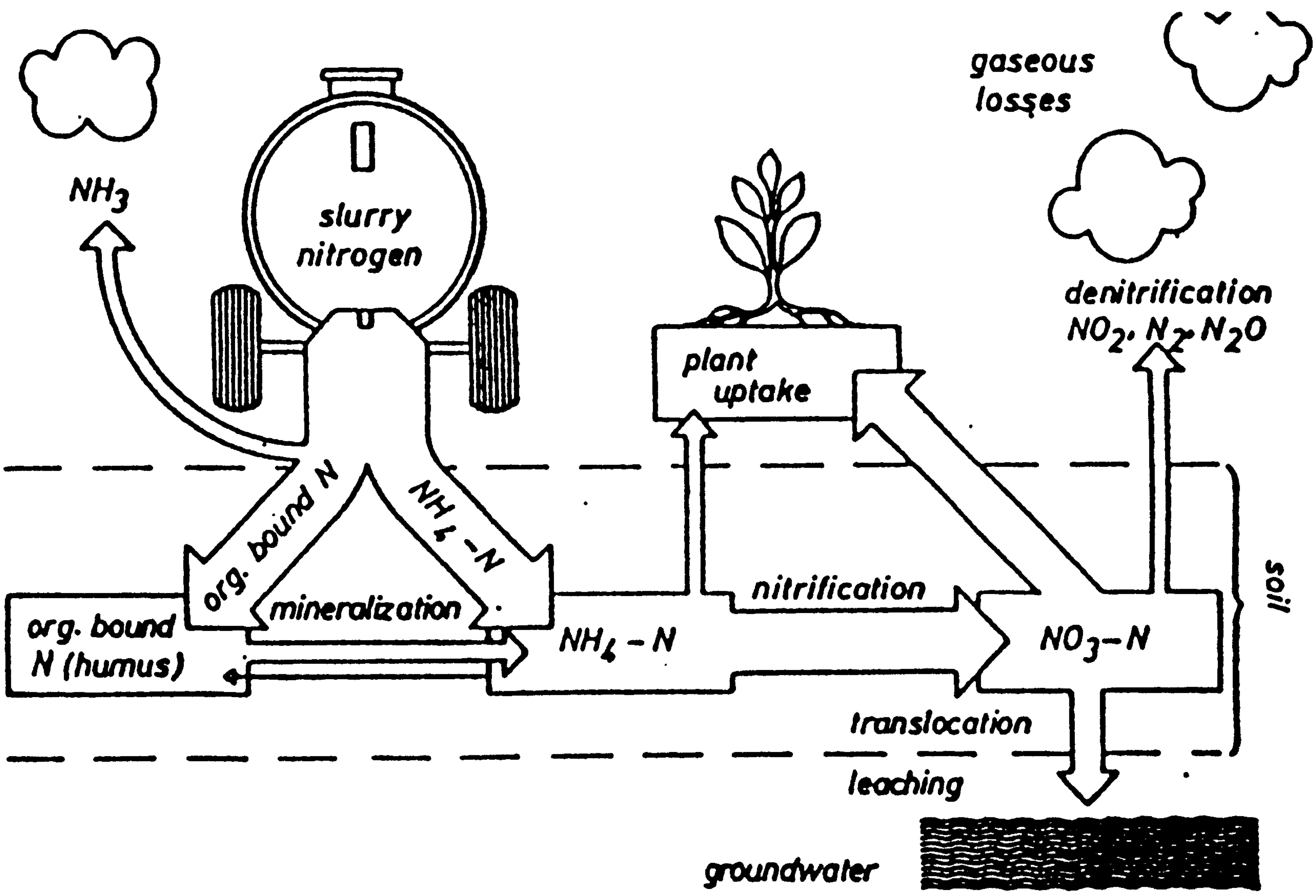


Fig. 6. Pathways of slurry nitrogen.

More than 90% of ammonia pollution of the air is caused by animal production (KTBL, 1990).

Ammonia volatilization takes place already in the first hours after spreading, and can mount up to 50% depending on air temperature and wind flow (Fig.7), soil type and structure, soil cover (stubbles of small grains, Fig.8), and also on the dry matter content of slurry - thick slurry infiltrates the soil very slowly (Fig.9) - or on grassland (Fig. 10).

For minimum losses, animal slurry has to be broadcast at low temperature or with rainy weather and incorporated immediately, possible with subsequent watering.

When slurry is applied to growing crops (e.g. small grains), the crop canopy and the reduced air flow decrease ammonia losses to about 10-15% (Huber and Amberger, 1990). In case of grassland, dilution of slurry with water is recommended.

2. Denitrification

Denitrification losses are a further problem relevant mainly in heavy soils after continuous rainfall or under flooding conditions. Estimation of losses generally ranges between 15 and 25 kg N/ha., but they can mount up to high losses, especially under rice cultivation as N_2O, assuming a high nitrate concentration in the soil, high temperature and moisture as well as high amounts of microbial decomposable carbon. These losses can only be reduced by improving soil structure with appropriate agrotechniques, and by synchronizing fertilizer and irrigation management (that means: urea incorporation into the soil prior to flooding in order to avoid ammonia and denitrification losses).

3. Leaching of nitrate

Leaching of nitrate means not only a substantial economic loss but also a hazard to ground and drinking water. It happens predominately in the fallow period and can be assessed to 50-70 kg N/ha. (Amberger, 1988) depending on site conditions and the cropping system. Under Central European conditions we get a curve like that (Fig. 11). The main determinants are the amount of unused fertilizer N in the soil after harvest and the mineralization rate during autumn. In irrigation systems it is more or less matter of the soil texture and the irrigation management. A very efficient method to avoid nitrate leaching is a permanent crop canopy throughout the year especially in the fall season.

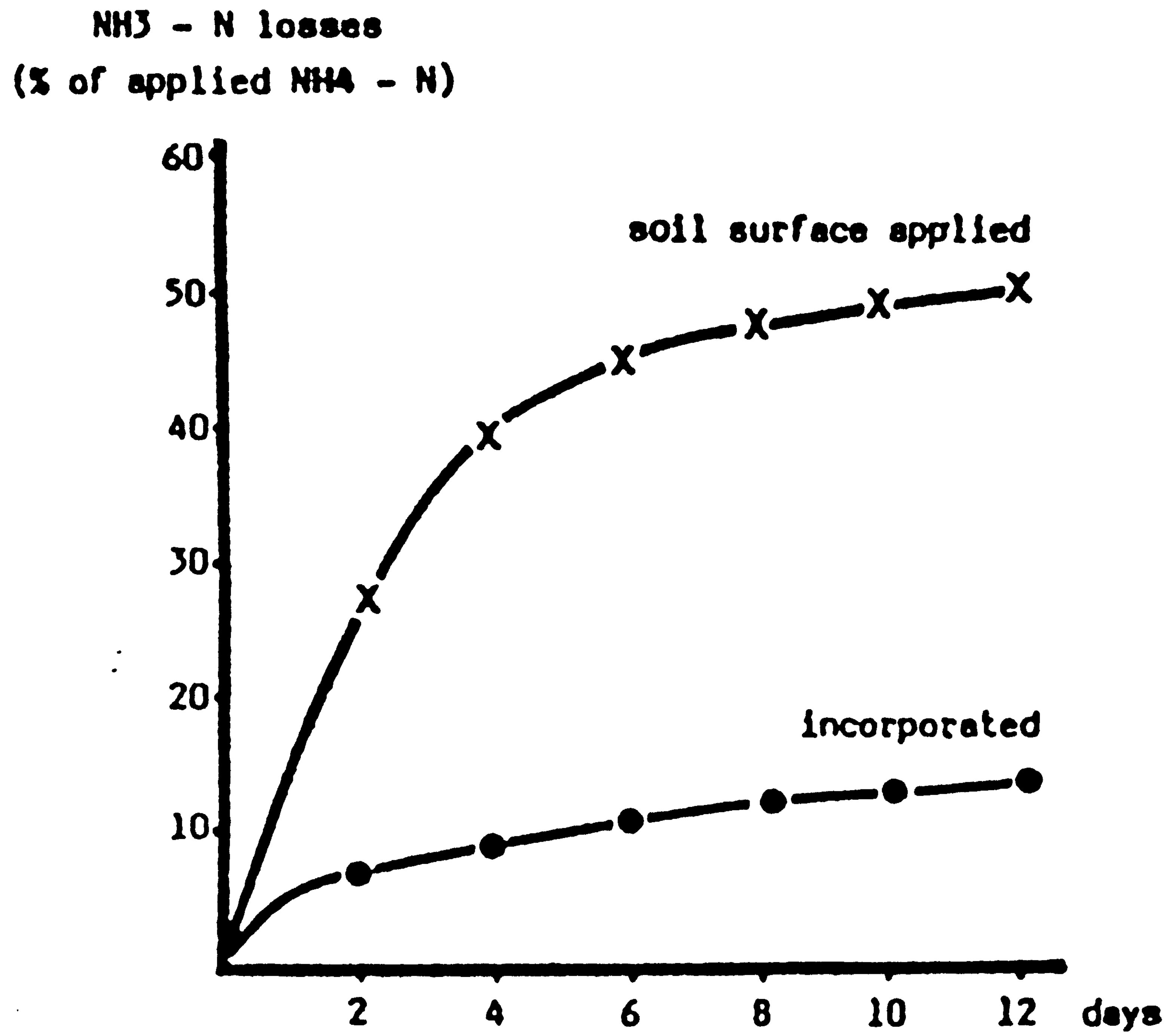


Fig. 7. Ammonia losses from cattle slurry dependent on application mode (Amberger and Huber, 1988).

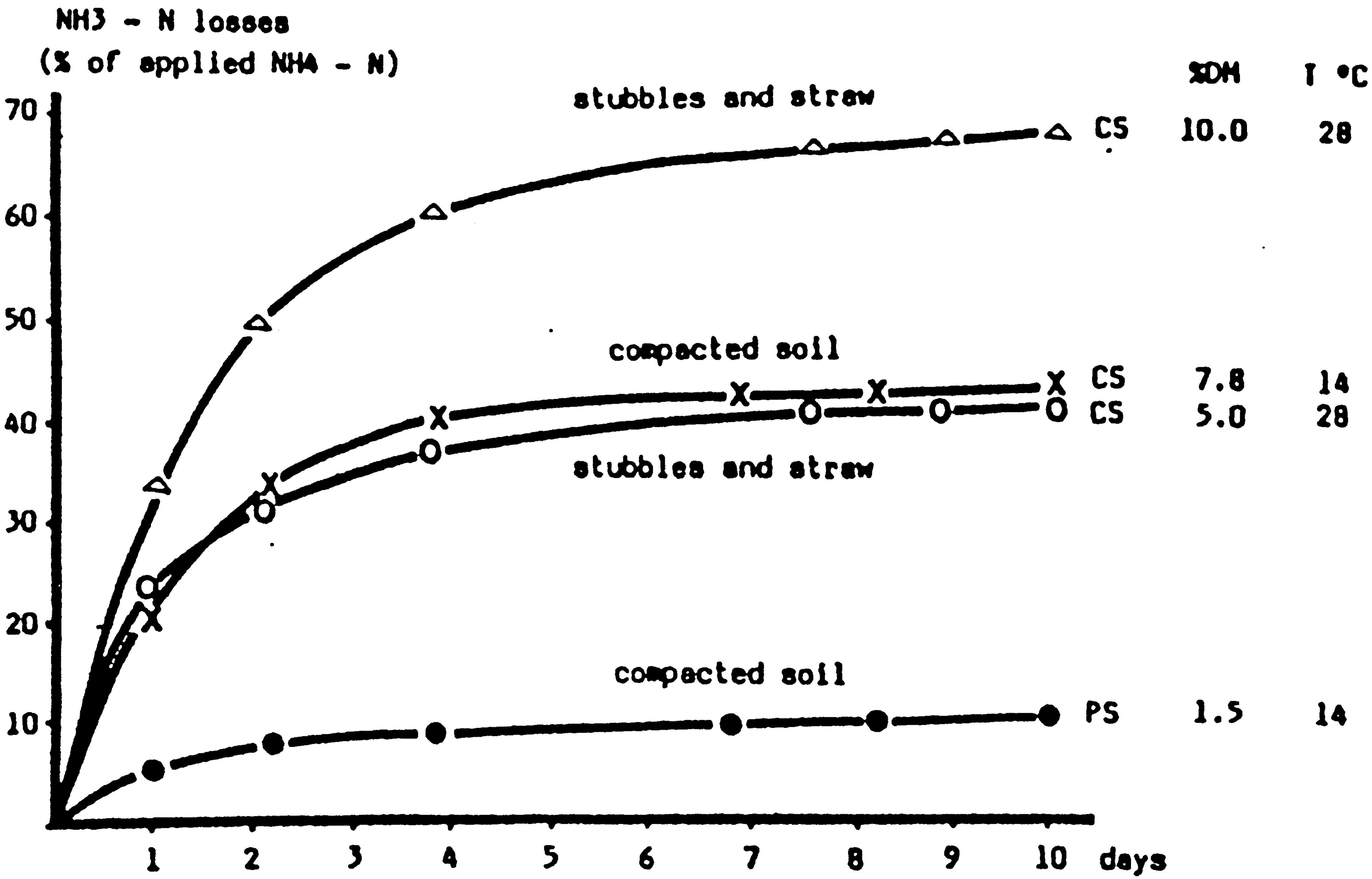


Fig. 8. Ammonia losses after surface application of cattle (CS) and pig slurry (PS) on stubbles and straw (Aug.) or compacted scil (Nov.) on silty loam (pH 6.5) (Ambergeg and Huber, 1988).

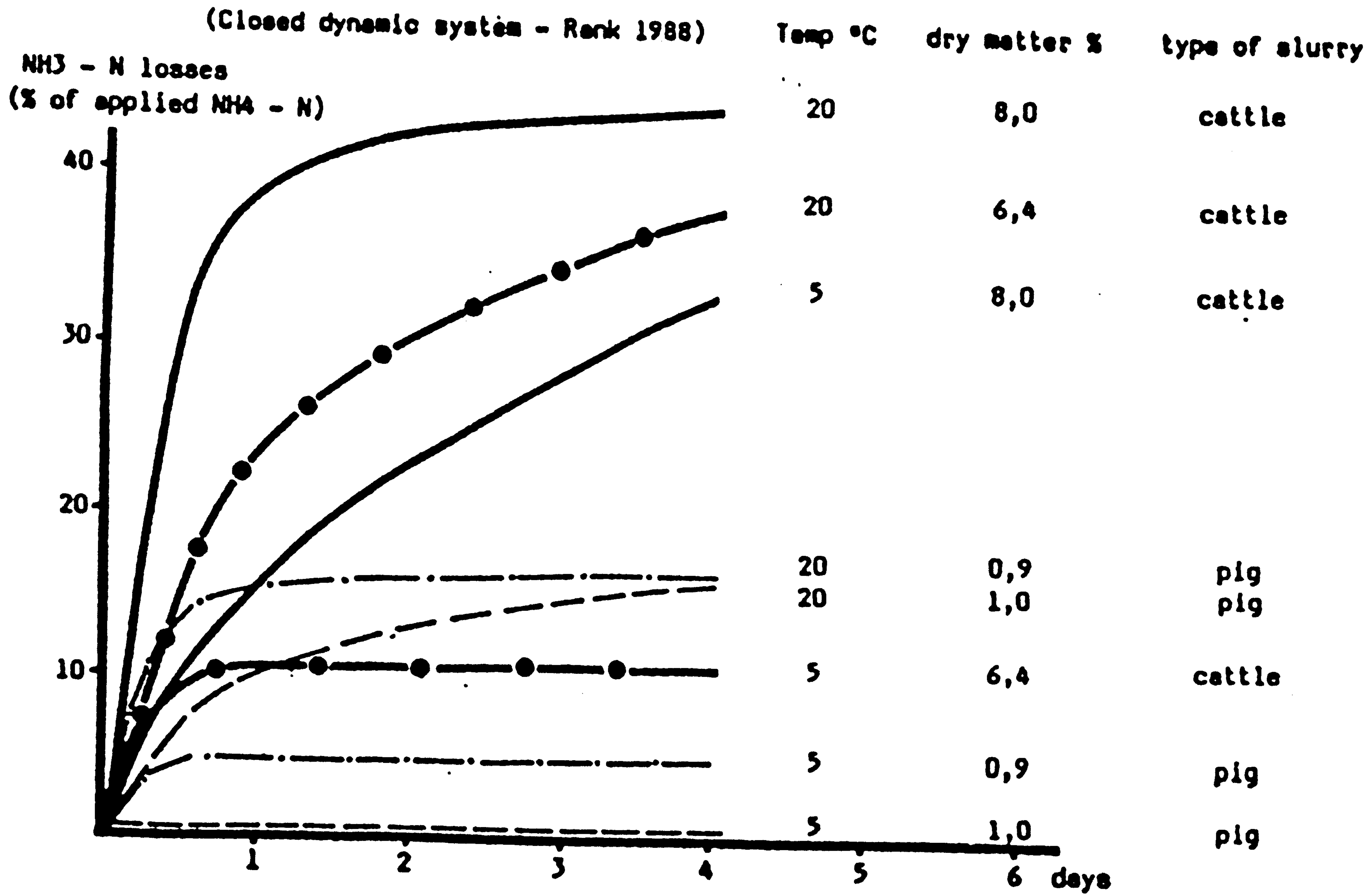


Fig. 9. Ammonia losses from slurry depending on dry matter content and temperature (Rank, 1988).

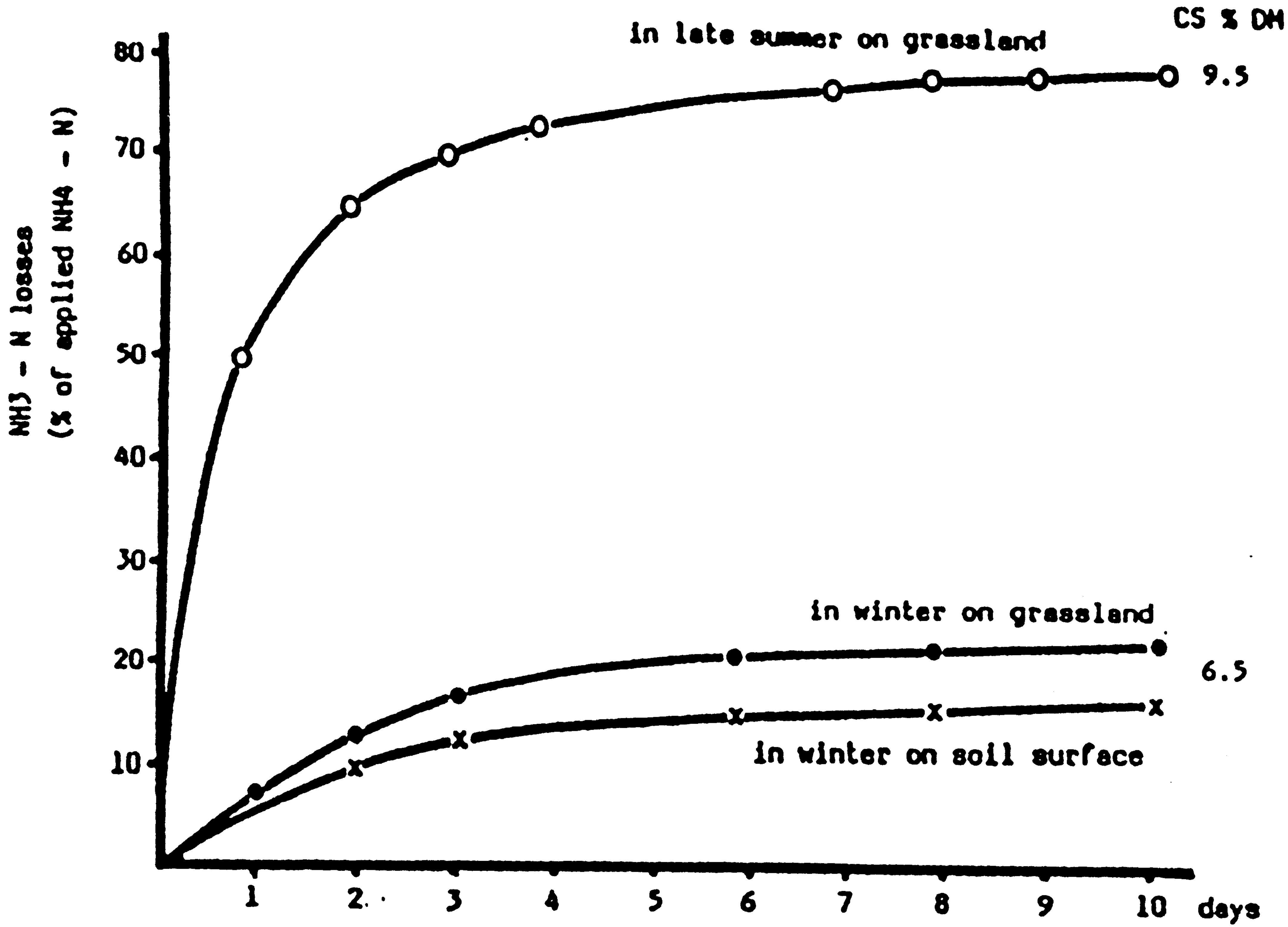


Fig. 10. NH_3 losses from cattle slurry (CS) on grassland - silty loam pH 6.5 (Windtunnel - Huber 1989).

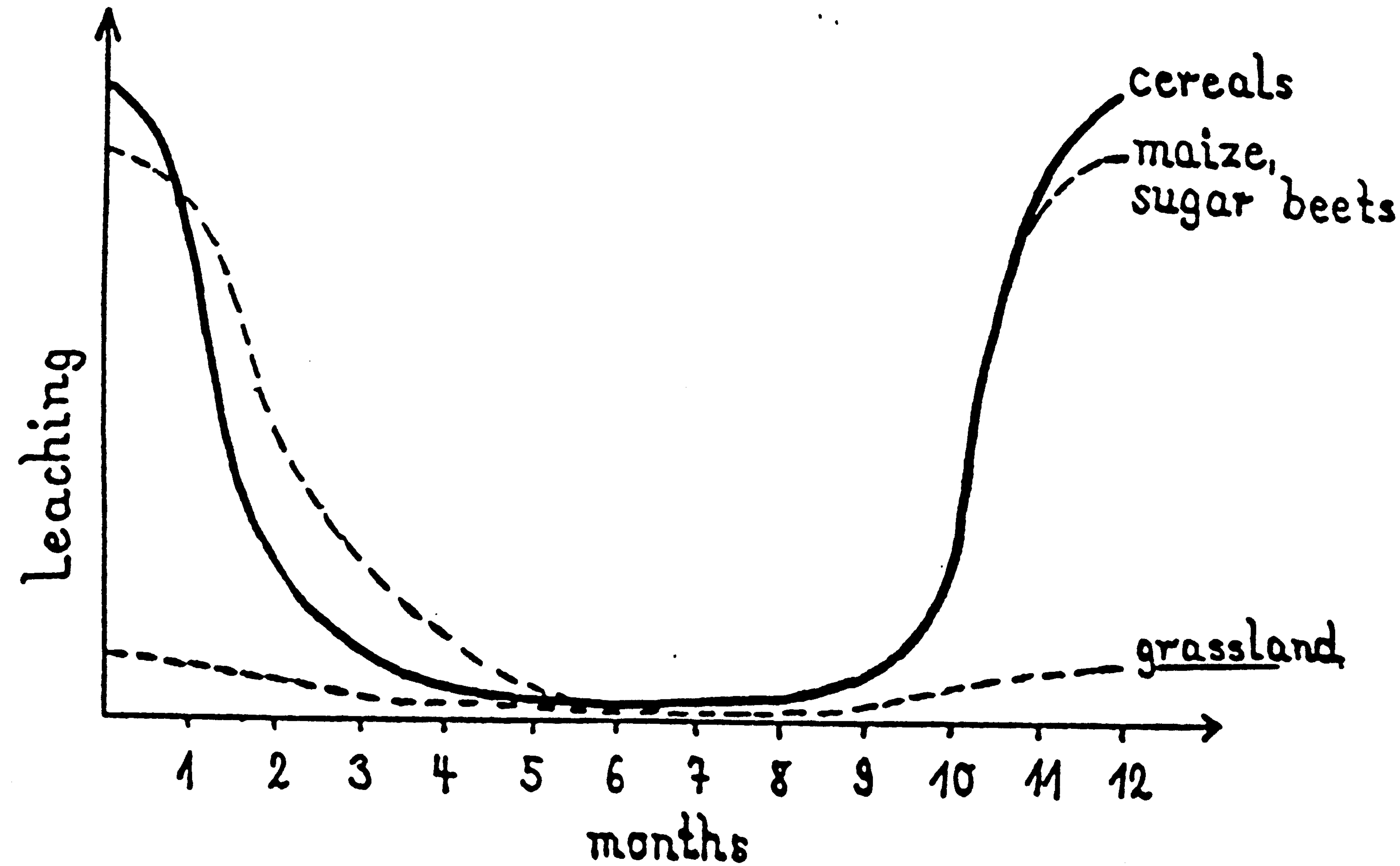


Fig. 11. Nitrate leaching.

Straw manuring is also an effective measure to preserve nitrate in the soil from being leached out (0.1 ton of straw blocks about 1 kg N). However, it has to be kept in mind that this biologically blocked nitrogen is not available to the following crop (no difference in the N uptake of rye grass ± straw, Table 3) and therefore cannot enter into the fertilizer calcultation.

Table 3: N leaching and N uptake after wheat straw manuring in pot trials silty loam, pH 6.5, N application 690 mg/pot

Time of straw and N application	N leaching mg/pot		N uptake by rye grass mg/pot	
	Without straw	*with straw*	*Without straw*	*With straw*
Control (N_o)	160	6	49	36
August	564	164	68	67
September	434	280	64	58
October	264	109	82	74
$LSD_{5\%}$	25			

Slurry or nitrogen-rich waste water immediately incorporated into the soil to avoid NH_3 losses will be nitrified already within a few weeks depending on temperature (Fig. 12); after that nitrate is ready to be leached out or denitrified. The same is the case when green manure or sugar beet leaves with a narrow C/N ratio are incorporated in early autumn (Fig. 13).

Therefore, it is recommended to combine the nitrogen-rich slurry or waste water with straw poor in nitrogen.

Among the means to control nitrate leaching and denitrification, the nitrification inhibitor dicyandiamide (DCD) as an effective instrument (Amberger, 1986 and 1988 b). It inhibits specifically the temperature dependent oxidation of ammonia to nitrate (Fig. 14),.

DCD as an additive to inorganic fertilizers like urea, ammonium sulfate or nitrate ("stabilized N-fertilizers") delays ammonia oxidation building up ammonium depot (Fig. 15) compared to calcium ammonium nitrate (CAN) for some weeks or months depending on temperature and avoiding nitrate leaching and denitrification (Fig. 15).

Exp. cond.: 300 g soil (silty loam, pH 6.5) + 60 mg NH_4-N as slurry, 60% of full water holding capacity ≙ 100 m^3 slurry/ha

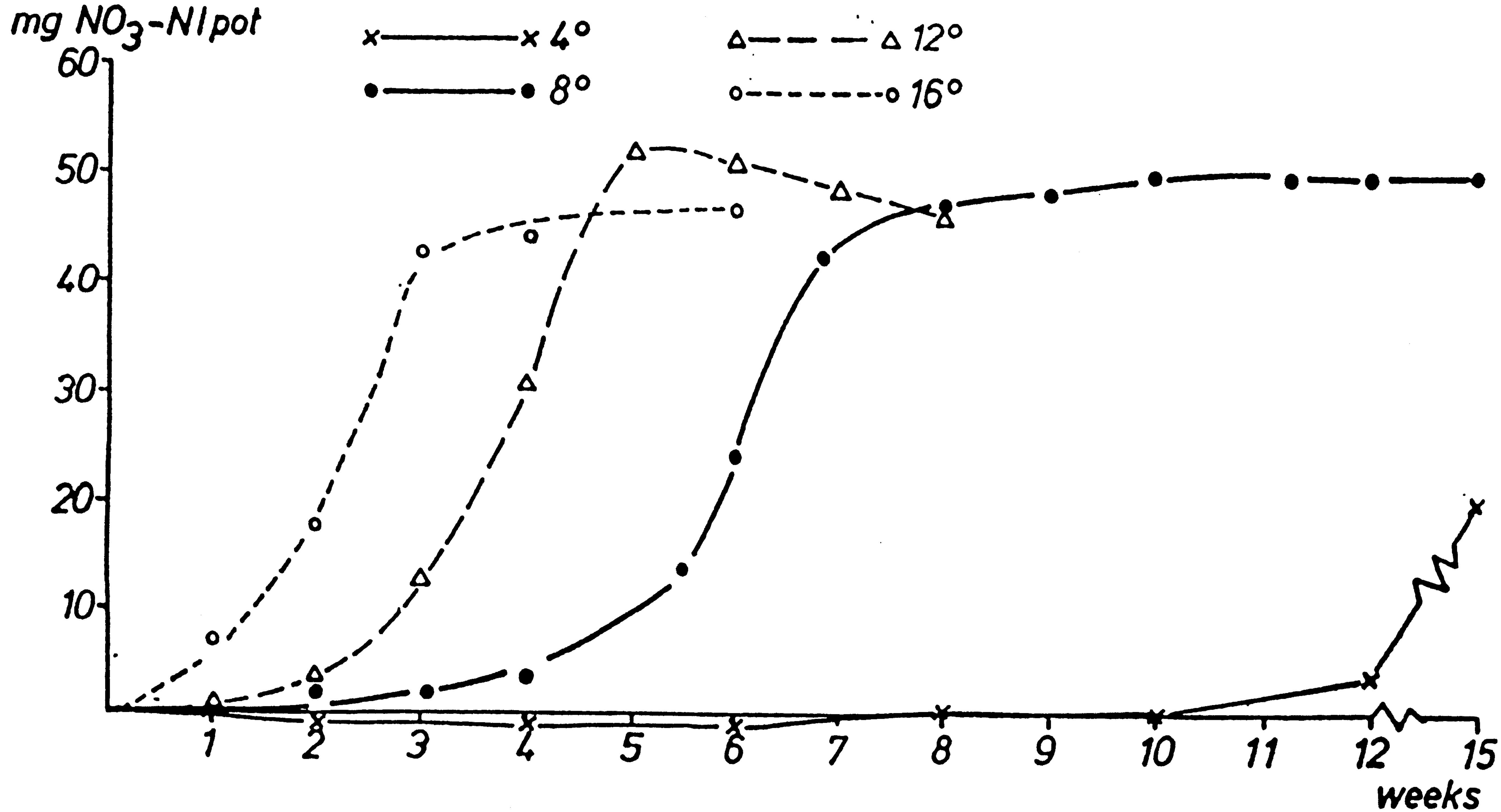


Fig. 12. Nitrification of cattle slurry as dependent on temperature (Amberger, 1984).

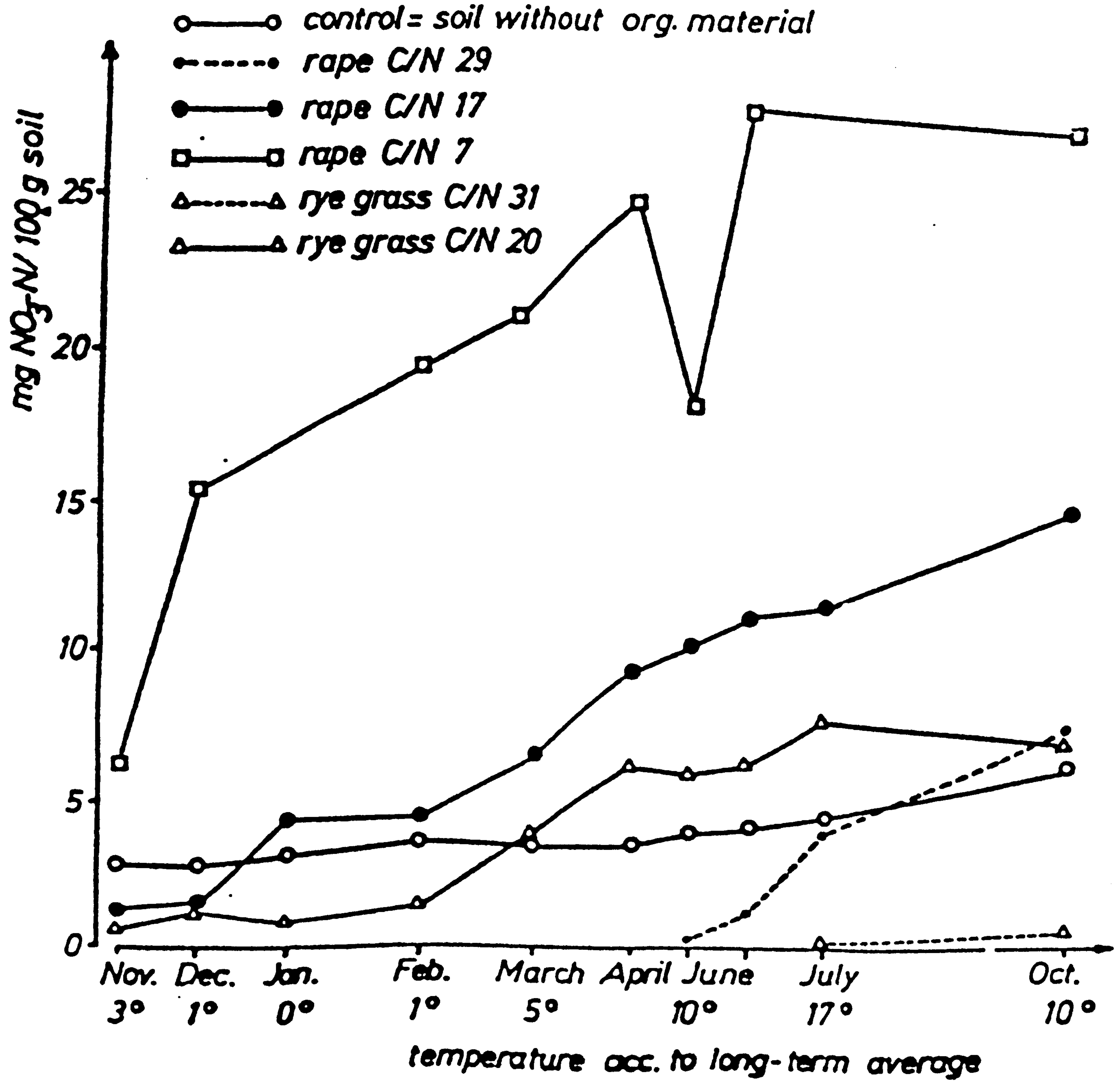


Fig. 13. N mineralization of catch crops (include. roots), incorporated in November (Vilsmeier and Gutser, 1988).

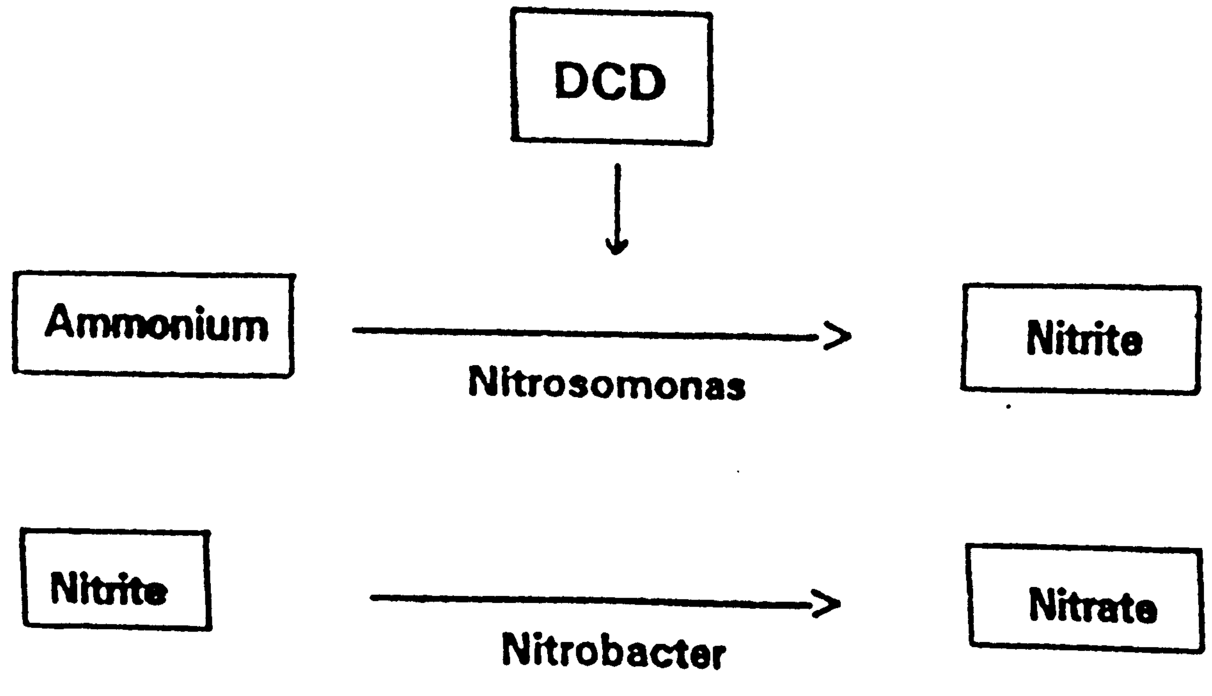


Fig. 14. Dicyandiamide (DCD) as nitrification inhibitor.

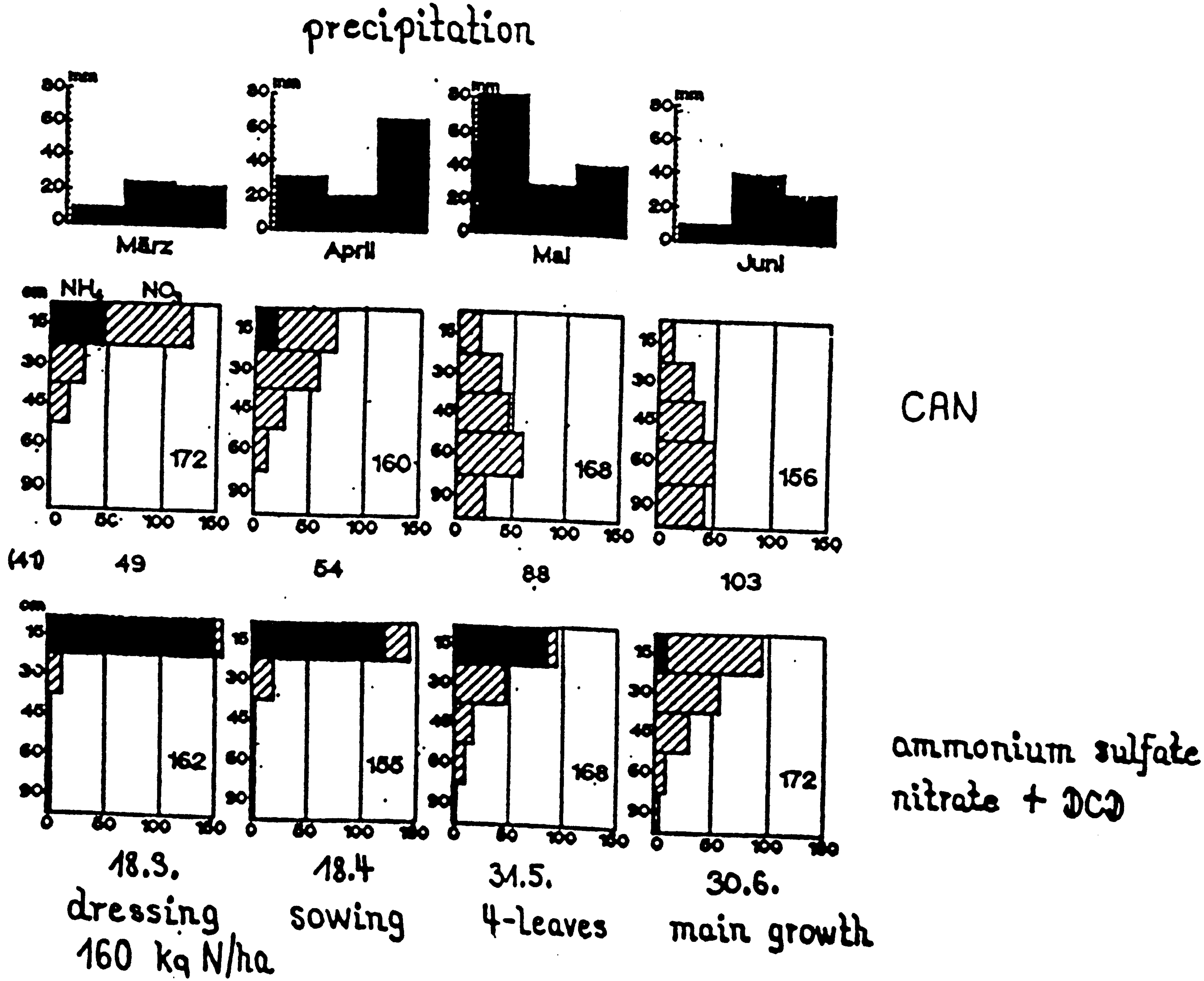


Fig. 15. Nitrate distribution in the soil profile after fertilization of sugar beets (H.J.Klasse, 1981).

DCD added to slurry or waste water applied in November prevents nitrification of slurry ammonium up to March ready for being taken up by crops (Fig. 16).

In summary, to minimize nitrogen losses through volatilization, leaching and denitrification, some agrotechniques should be applied :

- *Ammonia volatilization*
  - immediate incorporation of urea and ammonium fertilizers in the soil
  - subsequent irrigation
- *Nitrate leaching*
  - several small amounts of water applied
  - proper time and rate of fertilizer application
  - split application of fertilizers
  - fertilizers amended with nitrification inhibitors
  - deep rooting crop systems
- *Denitrification*
  - proper soil and water management
  - urea or ammonium containing fertilizers amended with nitrification inhibitors

4. Nitrogen control management

The nitrogen requirement of crops must be based on the expected yields and clear input - output calculations avoiding over - and underfertilization.

The amount of remaining nitrogen in the soil after harvest should be very low, because the unused N is a main factor of high nitrogen losses (Fig. 17). Also, nitrogen import from organic residues of plant and animal production must be considered in this calculation according to its availability (utilization of mineral nitrogen 60-70%, of organic nitrogen 30%).

II. Phosphorus

1. Erosion - Eutrophication

Phosphours is quite immobile especially in soils with neutral or high pH. It appears in more or less stable calcium phosphates. Therefore, phosphorus leaching is not a problem, however, considerable P losses can appear through water erosion, depending on topography, precipitation, soil cover and conservation practices. The losses of fertile surface soil range between 1 and 30 t/ha, equivalent to 0.8-24 kg P/ha, which enter finally surface water. A main factor of phosphorus pollution of surface water are domestic sludge and waste water which lead to eutrophication of surface water with all the consequences. About 20 years ago under European conditions, detergents made up about 40% of the total P content of water compared to only 15% coming from agriculture via erosion. But, nowadays after exclusion of total P rich detergents, the figures inversed to about 10% from detergents simultaneously increasing the relative rate of agriculture (to about 40%). From the agricultural point of view, it is necessary to minimize erosion because it is a real loss of P.

2. Cadmium content of P fertilizers

Another impact of phosphorus fertilization to the environment, in this case to the soil, is the natural Cadmium (Cd) content as impurity of P-fertilizers (Table 4). Cadmium is a real poison to human health and an undesirable element to plants which take up Cd very easily and accumulate it in the leaves.

An possible accumulatin of Cd in the soil (EC limit: 1-3 mg Cd/kg arable soil) is not so dangerous, because it will partly be leached out. However, there is a great risk potential with respect to the food chain plant - animal - human being. Therefore, the fertilizer strategy tends to avoid import and processing of phosphate rocks with high Cd contents.

Cd and other heavy metal contents can also be a problem with application of sewage sludge, which is controlled by strict new regulations (Table 5) with respect to sludge quality and the limited heavy metal content of soils.

III. Microelements

The dynamics of microelements are very similar to phosphorus. Despite of sometimes high amounts of a total element (f. i. Mn and Fe) in neutral or calcareous soils the mobility and availability to plants is very low and deficiency is becoming a constraint to crop production under these conditions.

Application of soluble microelement compounds like Fe-, Zn- or Mn sulfates to alkaline soils proved not to be very effective to crops because of rapid immobilization. Foliar sprays with chelated microelement compounds are very effective and allow accurately calculated amounts of microelements to be applied which avoid pollution of soils and water.

The only microelement which has to be considered carefully is boron, which is very often in high concentration in the irrigation water, as a consequence of B-rich detergents in domestic waste water polluting surface water used for irrigation.

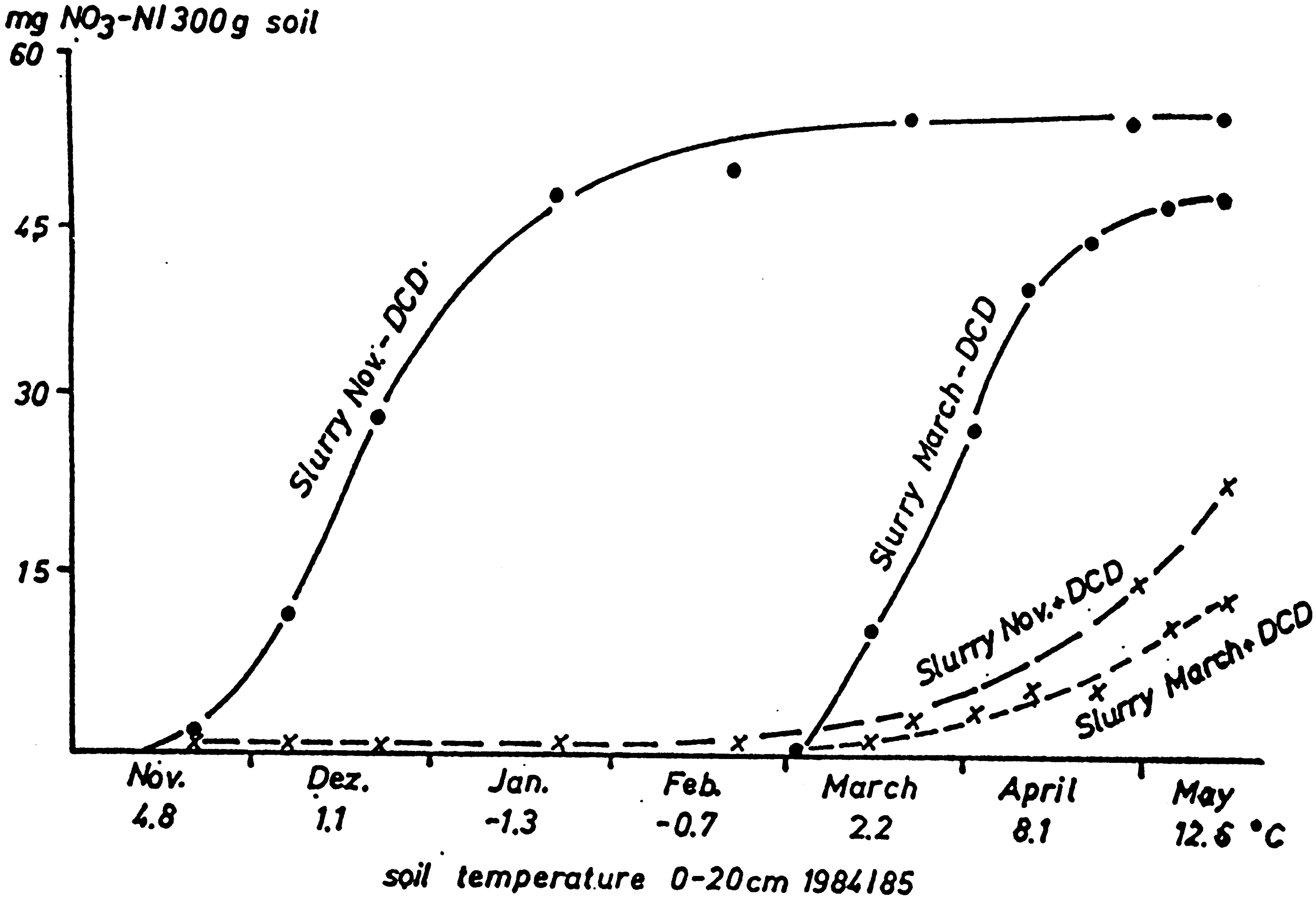
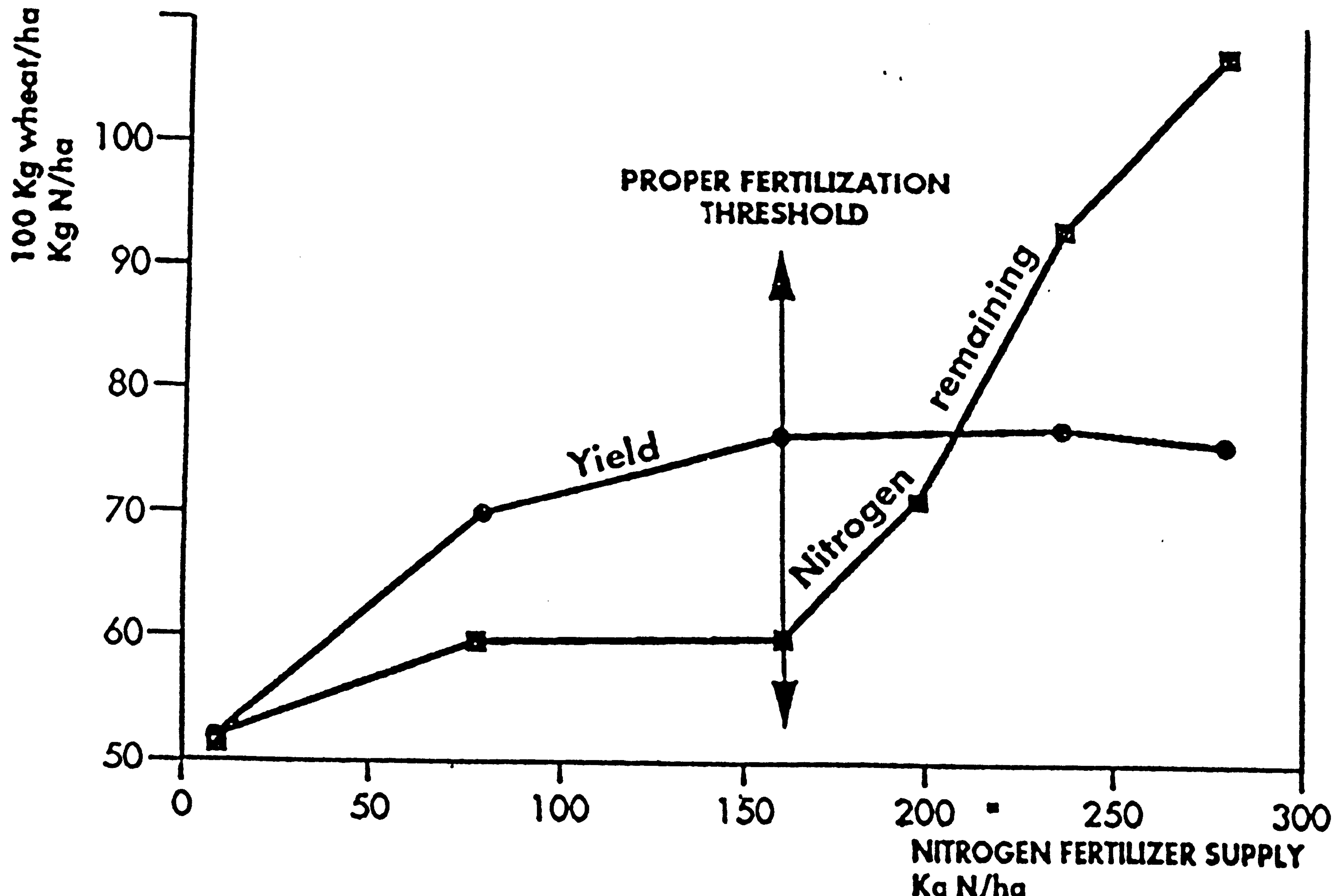


Fig.16 . Nitrification of cattle slurry (out door temperatures Novermber - May),(K. Vilsmeier and A. Amberger, 1987).



Source : INRA, Laon. In "Azote-Agriculture Environnement",
SNIE - UGCAF - UNCAA - INAC, France, November 1990.

Fig. 17. Wheat yield and pollution threshold.

Table 4: Phosphorus and cadmium contents of phosphate rocks (Norsk Hydro, 1990)

Type of rock	Phosphorus %	Cadmium	
		mg Cd/kg rock	*mg Cd/kg P*
Volcanic origin:			
Kola, USSR	17.2	0.15	0.9
Palfos, South Africa	17.2	0.15	0.9
Sedimentary origin:			
Bou Craa, Morocco	15.9	35	220
Togo	15.7	55	350
Youssofia, Morocco	14.6	40	274
Jordan	14.6	5	34
Texas Gulf, USA	14.4	40	278
Florida, USA	14.4	8	56
Negev, Irael	14.2	20	140
Khouribga, Morocco	14.2	16	113
Khneifiss, Syria	13.9	6	43
Gafsa, Tunisia	13.2	50	380

Table 5: Limited heavy metals according to sewage sludge regulation (1992)

Metal	mg/kg dry matter	
	Sludge	*Soil*
Zn	2500	300
Cr	900	100
Pb	900	100
Cu	800	100
Ni	200	50
Cd	10	3
Hg	8	2

Summary and conclusions

Environmental sound fertilization is a storng demand not only to prevent the environment (air, water, soil) from pollution through fertilization but, also to optimize the efficiency of fertilizers and to avoid economic losses.

The main problem lies in the field of N-fertilization: NH_3 volatilization, denitrification, nitrate leaching. There are appropriate agrotechniques to minimize losses and to avoid pollution.

Surface water polluted with P through erosion leads to eutrophication, which can be avoided by proper agrotechniques. Cadmium content of P fertilizers and sewage sludge and its pollution of arable soils have to be considered carefully especially with respect to food chain.

Problems with microelements are of lower importance, however, the boron content of irrigation water and the heavy metal content of sewage sludge have to be under control.

Generally, it is very important is to apply fertilizers according to real requirements of crops and to avoid over- and underfertilization. There are appropriate agrotechniques to avoid detrimental impacts of fertilizers on the environment.

References

Amberger, A. (1984): Guelleverordnung - der Weisheit letzter Schluss ? DLG-Mitteilungen 14, 800-802

Amberger, A. (1986): Potential of nitrification inhibitors in modern N-fertilizer management. Z. Pflanzenern. und Bodenkde. 149, 469-484

Amberger, A. (1988): Pflanzenernaehrung. UTB. Ulmer Stuttgart

Amberger, A. (1989 a): NH_3-Verluste aus der Anwendung organischer und anorganischer Duenger. VDLUFA-Schriftenreihe 32, 289-294

Amberger, A. (1989 b): Research on dicyandiamide as a nitrification inhibitor and future outlook. Comm. Plant Sci. and Soil Analysis 20, 1933-1955

Amberger, A. and Huber, J. (1988): Ammonia losses after animal slurry application. In: Safe and efficient slurry application. Commission of the European Communities, Liebefeld (Switzerland), 239-247

Court, M.N., Stephen, R.C.. Waid, J.S. (1964): Toicity as a cause of the inefficiency of urea as a fertilizer J Soil. Sci. 51. 42-48

Farquhar, G.D., Firth, P.M., Wetselaar, R., Weir, B. (1980): On the gaseous exchange of ammonia between leaves and the environment: Determination of the ammonia compensation point. Plant Physiol. 66, 710-714

Hagin, J. and Tucker (1982): Fertilization of dryland and irrigated soils. Springer, Berlin

Huber J. and Amberger, A. (1990): NH_3-Verluste unter verschiedenen Anbaubedingungen. VDLFA-Schriftenreihe 30. 109-115

Huber J. (1994): Untersuchungen zur Ammoniakverfluechtigung nach Guelleduengung im Windtunnel-Verfahren. Diss. TU Muenchen-Weihenstephan

Klasse, H.J. (1981): N_{min}-Gehalte im Boden nach der Duengung bzw. nach der Ernte. In: Stabilisierte Stickstoffduenger - ein Beitrag zur Minderung des Nitratproblems. Fachtagung Wuerzburg

KTBL-Symposium (1990): Ammoniak in der Umwelt. Braunschweig

Parish, D.H. (1979): Agricultural Productivity. Sustainability and Fertilizer Use. IFDC - Muscle Shoals USA

Rank, M. (1988): Untersuchungen zur Ammoniakverfluechtigung nach Guelleduengung. Diss. TU Muenchen-Weihenstephan