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AN ECONOMIC ANALYSIS OF NITROGEN LEACHING CAUSED BY AGRICULTURAL ACTIVITIES

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ABSTRACT

The article summarizes preliminary results from a current research project based mainly on conditions valid for Sweden. Intensive nitrogen fertilization, deficient handling of farm manure, intensive tilling of the soil and some other circumstances associated with agricultural practice can increase water pollution by nitrogenous compounds. This article analyzes the reasons why farmers practise production methods can lead to an increased water pollution. Moreover, control measures are discussed which can be utilized to reduce this pollution. The suitability of the control measures is assessed from the standpoint of the aims of the various interested parts.

A series of different measures must be adopted in order to check agricultural water-pollution. Some of these measures can be effected by providing advisory services to farmers. Compulsory, specific measures are necessary in other cases. These latter control measures can be confined in Sweden to very small acreages. A higher payment for quality for potatoes and certain other products, whose quality is adversely affected by increased nitrogen fertilization, constitutes another suitable control measure. When international prices for agricultural products are lower than domestic prices, a charge ought to be imposed on commercial fertilizer. On the basis of a choice of a suitable combination of control measures, there would be a small cost for eliminating that part of agricultural water-pollution which can lead to health and environmental hazards.

Consumption of commercial fertilizer is very low in developing countries. World food production as a whole would rise more rapidly if a portion of the consumption of commercial fertilizer in industrialized countries were transferred to developing countries. Such a transfer would improve the food supply in developing countries and the environment in industrialized countries.

INTRODUCTION

The use of nitrogen fertilizer in industrialized countries has grown rapidly. At the same time, the area of arable land and the number of people occupied in farming have decreased in most of these countries. On the other hand, the consumption of nitrogen fertilizer is still very low in the developing countries (Table 1). There are many in-

Table 1. **Consumption of fertilizer nitrogen, amount of arable land and number of people occupied in farming. The trend in some countries during the 1960s. (Eriksson & Carlsson, 1973; FAO Fertilizer Programme, 1974)**

	Consumption of fertilizer N ($kg\ ha^{-1}$)		Arable land ($\cdot 10^6$ ha)		People employed in farming ($\cdot 10^6$)	
	1960	1970	1960	1970	1960	1970
Sweden	32	68	3.6	3.0	0.4	0.2
West Germany	47	89	13.1	12.8	3.3	1.8
Netherlands	84	190	1.0	0.9	0.5	0.3
Ethiopia	$<$0.01	0.2		12.9		
Nigeria	0.04	0.3		21.8		

dications that the trends shown in Table 1 will continue in the foreseeable future. The fertilizer industry forecasts a 25 % rise in Swedish consumption of nitrogen for agriculture by 1985 (Supranytt, 1975). According to the law of diminishing returns, world production of foodstuffs would rise more rapidly if this increased use of nitrogen took place in the developing countries instead.

The reason for the greater use of fertilizer at the expense of arable land and labour is illustrated in Fig. 1. This figure is based on data from Sweden only, but all Western industrialized countries display a similar trend. The figure shows that wages have risen very quickly, whereas the prices of nitrogen fertilizer and machinery have risen only slightly. The price of farm products has risen somewhat more rapidly than that of nitrogen. These changes in price relations have made it profitable for farmers to reduce the labour input, invest in more machinery and buy more fertilizer. Further, small agricultural production units, where mechanization is difficult, have become unprofitable and this has led their owners to abandon farming. Nevertheless, the total level of production has been maintained through increased production on the remaining farms.

If the labour input, with its rising costs, had not been partly replaced by the increased use of fertilizer, etc., foodstuff prices would have risen almost as rapidly as wage levels. As it is, they have risen at a much slower rate, thus increasing our purchasing power for other goods and services. The increased production of such goods and services was made possible partly by reducing farm labour.

The wider use of nitrogen fertilizer is, unfortunately, not entirely free from risk. On some soils, intensive use of N-fertilizer may lead to nitrate leaching, which in turn means that drinking water may become a health hazard and that lakes and watercourses may become filled up with vegetation. It is likely, however, that improperly handled manure, autumn ploughing of fields of leguminous crops and intensive tilling of the soil may lead to ecually severe nitrate leaching as that caused by intensive use of nitrogen fertilizer. One of the underlying causes of the unsuitable manure-handling or crop-growing techniques is, however, the wider use of N-fertilizer. While N-fertilizer was still a relatively expensive item in production, measures for better utilization of the farm's "indigenous nitrogen" by for example careful handling of manure were profitable. However, such measures are often

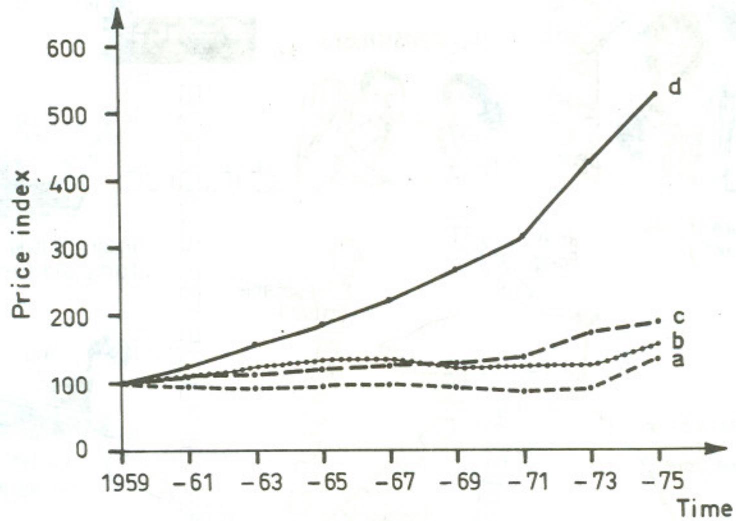

Figure 1. Relative price trend for (a) commercial nitrogen fertilizer, (b) wheat, (c) agricultural machinery, and (d) labour in Sweden, with 1959 as the base year.

labour-intensive and tend to fall into disuse as the gap between wages and nitrogen prices grows.

Table 2 indicates that agriculture is the most important human source of nitrogen transport to surface waters in Sweden. Figure 2 illustrates how water pollution can arise as a result of agricultural activity and how a series of interested parties are affected by this system. The interested parties whose environmental and health aims are affected are given in the lower part of the figure. The upper part of the figure shows farmers, food consumers and the fertilizer industry – whose monetary aims are affected by plant-nutrient management in agriculture. Interested parties outside the country are also affected by import and export activities. Various aspects of this system will be analyzed in detail below. The analysis includes an assessment of the possibility of controlling the system so as to eliminate health and environmental hazards.

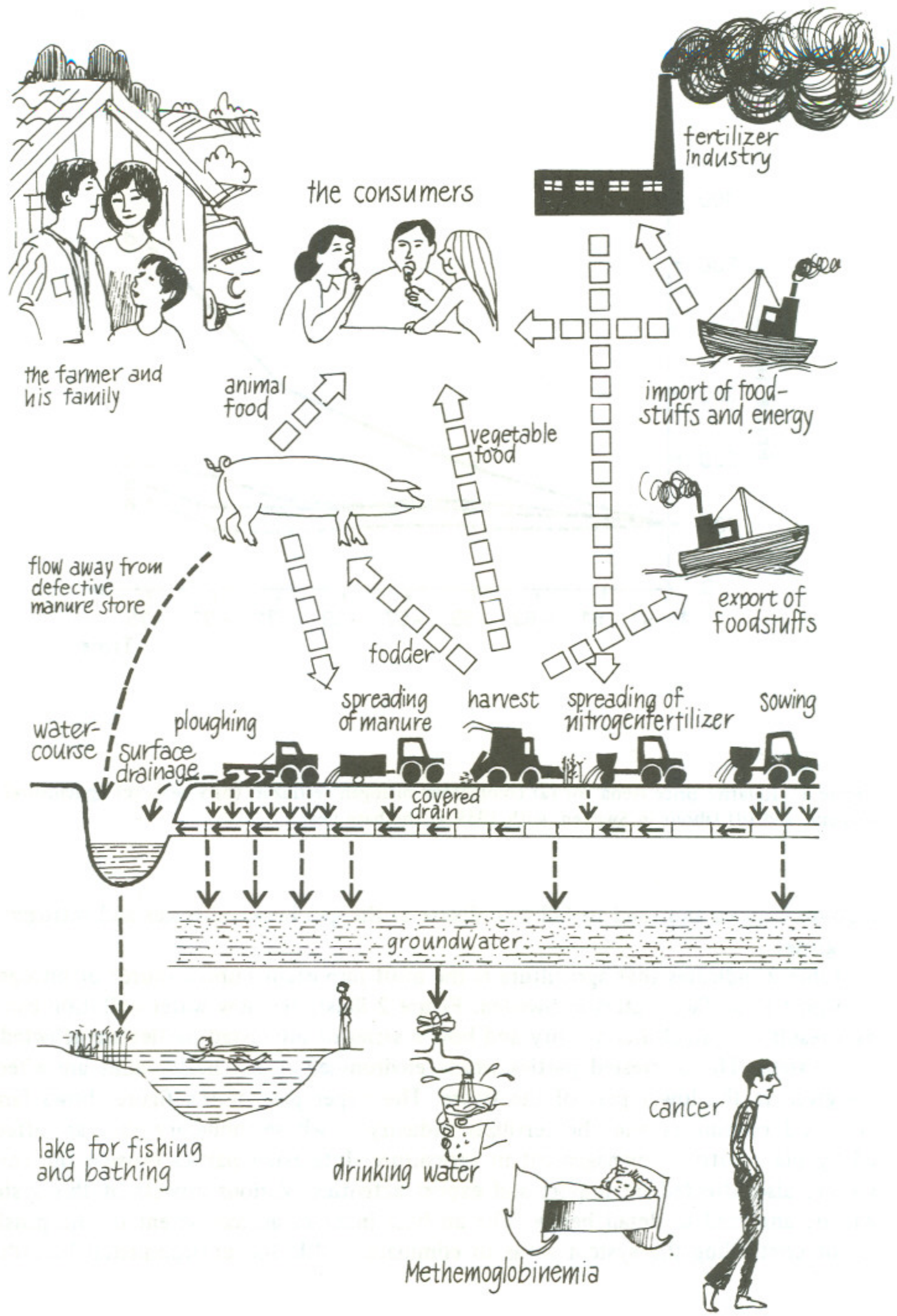

Figure 2. A schematic picture of how water pollution can arise from agricultural activity and the different interested parties affected. Bould open arrows show the flows of agricultural products and means of products. Simple arrows show the fluxes of water pollution nitrogen compounds.

Table 2. Sources of nitrogen transport to surface waters in Sweden (Landner, 1975).

Source	Amount of nitrogen (t yr^{-1})	(%)
Background	58,000	44
Forest drainage	2,000	1
Agricultural drainage	45,000	34
Municipal wastes	17,000	13
Industrial wastes	10,000	8
Total	132,000	100
Human sources	74,000	56

CAUSES OF WATER POLLUTION

When land is cultivated, the mineralization of organic nitrogen compounds increases. This leads to increased nitrate leaching. Intensive tilling of the soil, such as the tilling of fallow land, adds to the nitrate leaching. Autumn ploughing of fields where highly nitrogen-binding crops, such as peas and clover, have been grown may also cause considerable nitrate leaching. This is particularly true if a new crop is not sown until the following spring.

Unsuitable cultivation methods may also cause water erosion, i.e., the carrying away of soil to watercourses and lakes. This soil contains, among other things, nitrogen and phosphorous compounds which have an eutrophication effect in waters.

According to lysimeter tests and field experiments, nitrate leaching increases with the amount of nitrogen fertilizer used per unit area (Tables 3 and 4). These tables also show, however, that the leaching is considerable even without N-fertilization. This leaching is mainly due to mineralization of organic N-compounds.

If organic substances are spread over bare land in the autumn, a great deal of their nitrogenous content may be drained away in the form of nitrates before the next vegetation period. When manure is spread on snow-covered, frozen land, the surface drainage to watercourses may be considerable. Thus, from the water-protection angle, manure and other fertilizer should be spread in springtime just before sowing.

When manure is handled without the aid of a platform and urine tank, a great deal of the plant nutrients from the animal excreta enters the surrounding ground and may eventually find its way to watercourses, lakes, or subsoil water.

Drainage systems and subsoil water in sandy soils are more seriously affected by nitrate leaching than those found in heavier types of soil, irrespective of which of the four processes mentioned above is responsible for the inflow of nitrates (Table 3). This is probably due to two causes. One is that the transport through the soil profile of water, containing dissolved salts, is more rapid in lighter than in heavier soils. Torrential rain may therefore wash out a high proportion of the nitrates from the root zone of a sandy soil. The other reason is that denitrification conditions are better in clay soils than in lighter types of soil (Kolenbrander, 1975). Investigations in southwestern Sweden have shown that high and rising proportions of nitrates in drinking water are found exclusively in intensively cultivated and fertilized areas having permeable soils and high precipitation (Länsstyrelsen, Hallands län, 1975). According to investigations made in southern Sweden, only about 5–10 % of the municipal water reservoirs have a proportion of nitrates exceeding 30 mg NO_3 l^{-1}. In central and northern Sweden very few municipal water reservoirs show an increased proportion of nitrates (Nilsson & Rannek, 1975). Thus, it seems that a severe nitrate-leaching hazard is concentrated in a minor part of Swedish farmland.

Table 3. Nitrogen losses (kg N ha^{-1} yr^{-1}) from unfertilized soils and from soils fertilized with 100 kg N ha^{-1} yr^{-1} (1) and 120 kg N ha^{-1} yr^{-1} (2) in lysimeter experiments (Kolenbrander, 1975). The soils were of different heaviness measured as per cent particles with a diameter less than 16 μm.

Heaviness of soils	Losses when not fertilized	Additional losses when fertilized 1	Additional losses when fertilized 2
0–10	45	14	24
10–20	30	9	16
20–30	18	3	7
30–40	10	1	1

Table 4. Fertilizer nitrogen in relation to nitrate leaching in barley field experiments on clay soil in Denmark (Kjellerup, 1975).

Fertilizer applied (kg N ha^{-1})	Nitrate leaching ($kg NO_3^-$-N ha^{-1}) 1973–74	Nitrate leaching ($kg NO_3^-$-N ha^{-1}) 1974–75
0	12,5	15.0
55	13.4	17.6
110	16.0	22.4
165	19,1	31.7

ENVIRONMENTAL AND HEALTH HAZARDS

There has recently been a growing awareness not only of the importance of phosphorus but also of nitrogen in the eutrophication process in lakes and streams. It seems that nitrogen is the most limiting factor in waters which are already rich in other nutrients mostly received via waste water from communities in the neighbourhood. In less nutrient-rich waters, phosphorus and nitrogen are equally important for the process, whereas nitrogen has a smaller effect on growth in nutrient-poor waters (Forsberg, 1975).

The recreational value of lakes diminishes with an increasing eutrophication rate. Lakes vary in their sensitivity to an increased afflux of nitrogen, as also in their importance as a recreational resource. The increased afflux of nitrogen, which is a serious problem in some lakes, may therefore be only a minor one in others.

Unless converted into nitrites, nitrates in food or drinking water have no harmful effects on human beings. The conversion of nitrates into nitrites leads to a higher concentration of methemoglobin in the blood and may cause the formation of carcinogenic nitrosamines. For these reasons, nitrate is considered to be a health hazard. The higher concentration of methemoglobin has been proved to be dangerous to infants. On the other hand, it has not been proved that drinking water containing a high percentage of nitrates entails a greater cancer risk. Animal experiments and theoretical considerations, however, indicate that there may be such a hazard. Other investigations show that certain types of cancer are unduly frequent in areas with very nitrate-rich drinking water (Shuval & Gruener, 1975; Mirvish, 1975).

INTERESTED PARTIES AND THEIR AIMS

The various interested parties and some of their aims concerning the system agricultural activities/water pollution are set out in Table 5, which is based on Fig. 2.

One and the same person may be a member of two or more interested parties. Thus, for example, a farmer is also a food consumer, and the lake where he bathes and his drinking water supply can be adversely affected by his own and his neighbours' activities. Other persons, on the other hand. are members of only one group of interested parties: for example, many people are members of only the group consisting of food consumers.

PROBLEMS OF FORMULATING AIMS

The aims of farmers, food consumers and the fertilizer industry (Table 5) are mostly monetary, and are clear and easy to state. The environmental aims, on the other hand are less clear and harder to state. This is illustrated below in the case of nitrate content of drinking water. This aim is usually expressed by an upper limit of hazard, which ought not to be exceeded. This limit in Sweden is 50 mg $NO_3^- l^{-1}$. The corresponding figure in Denmark is 25, and in Czechoslovakia 15 (Nilsson & Rannek, 1975). The differences in limit values are probably due to the incomplete knowledge of the health hazard of nitrate. It is likely that new research findings will raise or lower the stated limit values. If fresh research results were to show that an increased intake of nitrate definitely raises the incidence of cancer, the limit values would be drastically lowered. It is also conceivable that new findings may show that nitrate is a smaller health hazard than is currently believed. If so, the limit values are likely to be raised.

Table 5. Parties with an interest in the system of agricultural activities/water pollution and some of their aims.

Interested parties	Aims
Farmers	Good profitability
Food consumers	Cheap foodstuffs of good quality
People with financial interests in the commercial fertilizer industry	Good profitability for sale of commercial fertilizer
People with recreational interests in lakes and watercourses, which are becoming vegetation-grown as a result of agricultural water-pollution	Conserve or restore the waters so as to make them suitable for bathing and fishing
Drinking-water consumers whose water has a high nitrate content as a result of leaching of agricultural soil	Avoid unhealthy nitrate concentration in drinking water

It is difficult to give quantitative descriptions of conditions with regard to the quality of watercourses and lakes. Conditions here have instead to be expressed in terms such as – "sport fish can live in the water"; "pike and perch, but no sport fish, can live in the water"; "carp and tench are the only fish varieties that can live in the water"; or "large algal aggregations are formed, which rot and create acute odour problems".

POSSIBLE CONTROL MEASURES

The market economy and general agricultural policy contribute towards the realization of the monetary aims. For realization of the environmental aims, special control measures are required in order to lessen agricultural water pollution by nitrogenous compounds (Table 6). Many of the measures mentioned in Table 6 also lessen water pollution caused by other nutrient salts and oxygen-consuming organic substances.

The measures which farmers can adopt, may, with some simplification, be divided into two categories. The first consists in lowering the supply of nitrogen, while the second consists in the handling of the farm's "indigenous plant-nutrients" in such a way that they are better utilized by cultivated plants and not released to the same large extent as previously into watercourses, lakes and drinking water. The farm's "indigenous plant-nutrients" may take the form of stable manure and plant residues, plus soluble plant-nutrients left in the ground after harvesting.

Table 6. **Various types of agricultural water pollution and some preventive measures which farmers and environmental protection authorities can take in order to reduce pollution.**

Type of water pollution	Preventive measures open to farmers	Control measures wich can be invoked by the environmental protection authorities
Surface runoff from fields	Avoid spreading stable manure etc. without ploughing during the autumn, and also avoid spreading on snow-covered, frozen soils	Advice, prohibitions
	Maintain permanent pastures on ground susceptible to water erosion	Advice, injunctions
Leaching out to drainage systems or groundwater	Lower dosages of nitrogen (applies to both commercial fertilizer and stable manure)	Advice, quantitative restrictions, charges on commercial-fertilizer nitrogen, increased payment for quality on certain products such as potatoes
	Spread stable manure etc. during the spring	Advice, injunctions, charges on commercial-fertilizer nitrogen
	Reduce cultivation of leguminous plants	Advice, prohibitions
	Avoid certain kinds of intensive tilling of the soil	Advice, prohibitions
	Do not remove or burn straw	Advice, prohibitions
	Sowing of protecting crop for nutrient-salt uptake after harvesting	Advice, injunctions
	Maintain permanent grass pastures	Advice, injunctions
Runoff from defaecative heaps of stable manure and from silage silos	Build manure platforms, urine tanks, etc.	Advice, injunctions, charges on commercial-fertilizer nitrogen, investment grants

COST OF THE VARIOUS CONTROL MEASURES

This paragraph deals mainly with reduced nitrogen fertilization. Figs. 3–7 show the relation between nitrogen dosage and the monetary result for some important Swedish crops. The curves represent the difference between produced crop values and nitrogen fertilizer costs. The profitability for the farmers is at its peak at the maximum point of the curve for each crop. The arrows on the nitrogen axis show the average amount of nitrogen fertilizer used in 1971 for each crop in the area where the trials were made. It can be seen that the amount of fertilizer actually applied is somewhere in the monetarily optimal interval. For most crops, however, it is to be found in the upper part of this interval.

Fig. 3 is based on aggregated results from experiments, which were carried out for a number of years on different types of soil. The relations vary considerably from one year to another and the optimal amount of nitrogen may also vary for different types of soil (Fig. 4). The large variation between different years and soils makes it impossible to calculate more exactly the monetary consequences of reducing the amount of nitrogen fertilizer.

It is evident, however, that the amounts may well be lowered to about 20–30 % below the monetarily optimal value without causing greater monetary loss than a few dollars per hectare.

If the nitrogen dosage is reduced to 50 % of the economically optimal value, the loss is 25–50 US\$ ha^{-1} for most crops. A total prohibition of all use of nitrogen fertilizer leads to very heavy economic losses.

Fig. 5 indicates that an increased payment for quality for ware potatoes would be an effective control instrument for bringing about reduced nitrogen fertilization of this crop. This is important since potatoes are often grown on light soils where leaching risks are great.

The monetary consequences of adopting measures for more effective utilization of farm manure and other "indigenous plant-nutrients" are illustrated in Fig. 6. This diagram shows the underlying principle, and the relations can vary greatly for different farms. Thus, for example, the profitability of building manure platforms and urine tanks is strongly influenced by the number of livestock and the depreciation period for buildings.

CHOICE OF CONTROL MEASURES

The choice of control measures ought to be based on the aims of the various interested parties and on the expected environmental and monetary results. This choice will be dictated by political considerations.

Table 6 shows that the environmental protection authorities can choose from among a series of control measures, which broadly fall into the following three groups:

1. Advising farmers regarding water protection
2. Compulsory, specific control-measures (prohibitions, injunctions, quantitative restrictions). These measures can in many cases be replaced by voluntary agreements with the farmers; the farmers promise to take preventive steps and the authorities to compensate the farmers.

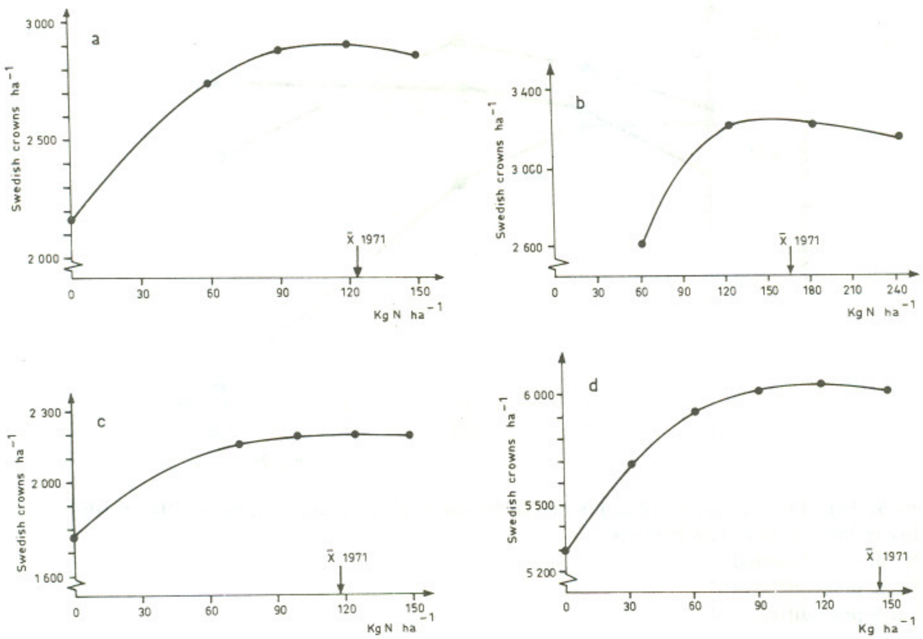

Figure 3. Profitability of nitrogen fertilization for certain crops. The curves connect points for harvest value minus cost of nitrogen fertilizer, 1974/1975 prices. Arrows denote average fertilization in 1971 for each crop. (1 Sw.Cr. = 0.25 US$)

(a) Winter wheat. Protein content taken into account in calculating harvest value.
(b) Winter rape. Oil content taken into account in calculating harvest value.
(c) Summer rape. Oil content taken into account in calculating harvest value.
(d) Sugar beet. Sugar content taken into account in calculating harvest value. Only manurial value taken into account for tops.

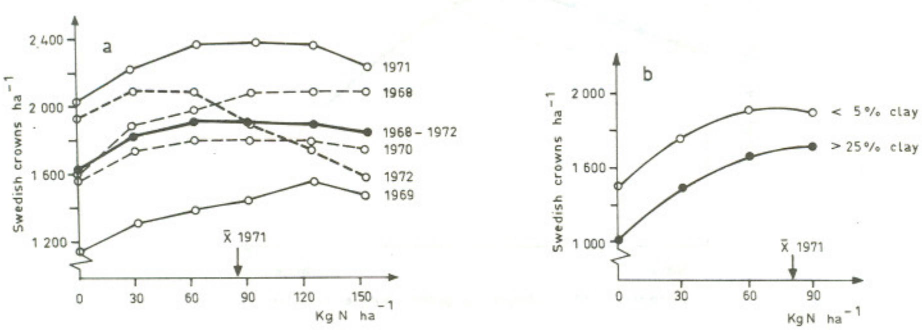

Figure 4. Variation of prfitability of nitrogen fertilization between different years (a) and between soils of different clay content (b) for spring cereals in the south of Sweden. Arrows denote average fertilization in 1971. (1 Sw.Cr. = 0.25 US$)

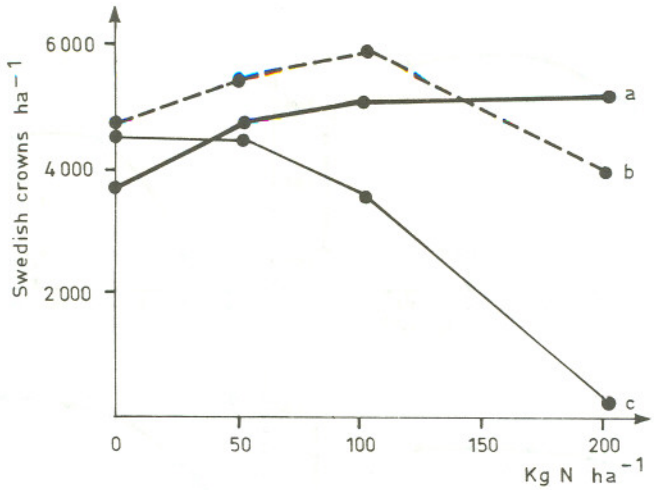

Figure 5. Effect of nitrogen fertilization on the economic result in applying price differentials for quality in the case of potato harvests:
(a) No price differential
(b) Small price differential
(c) Large price differential

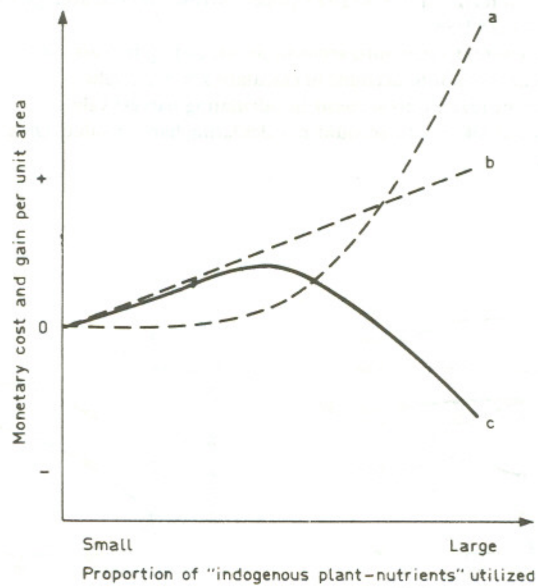

Figure 6. Qualitative diagram showing the profitability of utilizing the farm's "indigenous plant-nutrients" to varyingly effective extents. The curves show (a) cost of utilizing the plant nutrients, (b) value of utilized plant nutrients, and (c) profitability (c = b–a).

3. Price-linked control measures (charges on nitrogen fertilizer and payment for quality for certain products).

Advisory measures can be expected to constitute an effective control instrument only when the individual farmer does not lose anything by following the advice. Comprehensive water-protection measures can, however, entail great monetary sacrifice for the individual farmer (see Figs. 3–6). Simply providing advice is therefore inadequate if costly measures are required for meeting the aims of parties with environmental interests. It is, however, likely that the high amounts of nitrogen used by certain farmers of their deficient handling of farm plant-nutrients lead to business losses. In such cases, advisory help can result in both environmental and monetary gain.

By applying compulsory, specific measures, the authorities can even implement very comprehensive water-protection measures. Comprehensive water-protection measures – such as large reductions in nitrogen dosages – lead, however, to relatively large monetary costs per unit area. Therefore, in view of the aims of the parties with monetary interests, the compulsory control measures should be confined to the areas where the hazard and consequences of, for example, nitrate leaching are particularly serious.

If charges are imposed on nitrogen fertilizer, the economically optimal points are shifted in an environmentally favourable direction. Fig. 7 indicates, however, that high charges are necessary if an appreciable effect is to be attained. High charges are also necessary where improved handling of the farm's "indigenous plant-nutrients" is to be profitable. The disadvantage of charge control is that the method affects production techniques in all areas, even where reduced nitrogen fertilization is not called for by environmental considerations. It is just not possible to have different prices for commercial fertilizer in a region. Charge controls are therefore a very costly way of reducing water pollution.

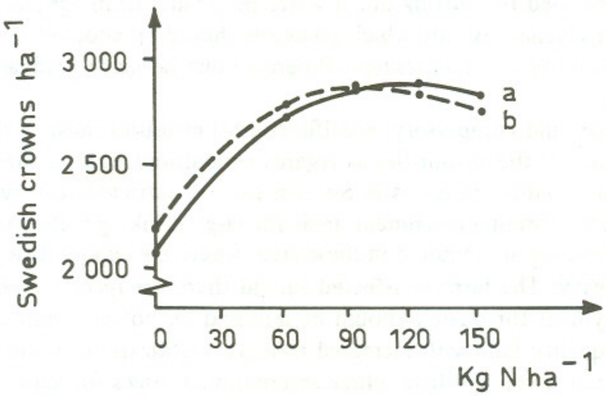

Figure 7. Profitability of nitrogen fertilization for winter wheat and effect of a charge on nitrogen fertilizer. Curve (a) shows Swedish prices in 1974/75, while (b) shows a situation where there is a 100 % increase in the price of nitrogen and a 6.5 % rise in the price of wheat. (1 Sw.Cr. = 0.25 US$)

If the international prices for agricultural products are lower than the domestic producer prices, it can be monetary profitable for the community to impose a small charge on commercial nitrogen fertilizer. Without such a charge, farmers may fertilize so intensively that the marginal increase in production will costs more in terms of commercial fertilizer than is yielded by export of the product. The charges which may be monetary justified are, however, so small that by themselves they would not appreciably diminish agricultural water-pollution. They would, however, help towards making the water-protection advisory service more effective and the specific control-measures easier to implement. Mismanagement of plant nutrients is a factor which causes the individual farmer greater loss when fertilizer prices are high.

Present knowledge of the mechanisms underlying agricultural water-pollution is relatively comprehensive. We know quite a great deal about the measures which need to be adopted for, say, reducing nitrate leaching. On the other hand, there is a general lack of knowledge about quantitative relations between water-protection measures and reduced pollution. We thus do not know the extent by which nitrogen dosages should be reduced or the handling of farm plant-nutrients improved so as to attain better quality of drinking water supplies and lakes. Water protection in agriculture must therefore be a search-learning process. The process begins with measures which appear suitable in the light of existing knowledge. The result of the measures is assessed. If it is unsatisfactory, the control measures are modified. By successive adaptation, the measures progressively become better suited to the aims of the interested parties. The measures must be adjusted when the aims of the interested parties change.

CONCLUSIONS

Reduced nitrogen fertilization with commercial fertilizer is only one of many measures which may be used for cutting down water pollutants from agriculture. It is not possible to say in advance, exactly which measures should be adopted to lessen agricultural water-pollution by a desired extent. Progress must be made gradually by a search-leaching process.

Advisory services and compulsory, specific control-measures must occupy a central place in the policies of the authorities as regards agricultural water-protection.

The compulsory control measures in Sweden can be restricted to very small areas, primarily sandy soils forming catchment areas for large drinking-water sources. Such comprehensive measures are required in these areas where the economic losses for individual farmers are heavy. The farmers affected should therefore receive monetary compensation. Higher payment for quality should be imposed on potatoes and certain other products, whose quality falls with increased nitrogen fertilization. A small charge should be imposed on commercial fertilizer where international prices for agricultural products are low.

Insofar as water-protection measures in agriculture comprise reduced nitrogen fertilization, the total food production of the country is diminished. This may appear to be a retrograde step in a starving world. The restrictions applying to Swedish agriculture would, however, reduce overall agricultural production in the nation by only a few per cent. By reducing the consumption of animal food, while at the same time increasing the consumption of vegetable food, Sweden should be able to maintain the present export of cereals in spite the reduced nitrogen fertilization; large amounts of energy and proteins are lost in live-stock production. Moreover, world food production as a whole would rise more rapidly if a portion of the commercial fertilizer consumption in Sweden and other industrialized countries were to be transferred to developing countries where nitrogen fertilization is very low (see Table 1).

In certain cases, problems of agricultural weter-pollution can be solved by extra-agricultural measures. Thus, for example, the nitrate content of drinking water can be reduced by sinking deeper wells or reducing the nitrate content in waterworks (Nilsson & Rannek, 1975). Such extra-agricultural measures are frequently the cheapest way of avoiding the health and environmental hazards which at present result from agricultural water-pollution.

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