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EXPECTED IMPACT OF PHOSPHORUS FERTILISATION ON THE EUTROPHICATION OF TERRESTRIAL ENVIRONMENT

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A b s t r a c t. The aim of this papers is to discuss the expected effect of increasing phosphorus accumulation in cultivated soils. The global consumption of phosphorus fertilisers since 1954 exceeded 1 billion tons of P_2O_5, and about a half of this amount was used in European countries. More than 95% of mined phosphate rocks are provided to food production. That resulted that the total phosphorus content in agricultural used soils was doubled or tripled in European countries up to now. A further increase of phosphorus accumulation in the cultivated soils would conduct to eutrophication of water and terrestrial ecosystems. The euthrophication of surface water is rather good known phenomena, but the euthrophication of terrestrial ecosystem need broader identification. Main sources of phosphorus in environment is food production and consumption. In agriculture, a renewed attentions is required to ensure that phosphorus in modern farming systems is managed in a manner which is sustainable from the point of view of both agriculture and environment. The mitigation of eutrophication originated from phosphorus accumulation in agricultural soils could be achieved only on scientific basis followed with country and regional abatement programs.

K e y w o r d s: phosphorus fertilisation, eutrophication, terrestrial environment.

INTRODUCTION

The Liebig rule concerning the cultivated crops could be also applied to the environmental eutrophication occurring after input of a nutrient, which is insufficient in the considered ecosystem. One would suppose that phosphorus is this very nutrient. Application of phosphorus fertilisers into agriculture resulted in increasing of yield and quality of crops. The observations made at the beginning of fertiliser use demonstrated that only a part of applied phosphorus has been taken up by crops and the remainder was bounded by the soil materials. In the consequence, the recommended fertiliser rates were higher than the amount of phosphorus removed with crops and an increasing pool of this nutrient is accumulating in the agricultural soils. Phosphorus accumulation improves the fertility and productivity of agroecosystems, but agriculture is not a closed system and a part of accumulated nutrient can disperse into other ecosystems causing there an unwanted eutrophication. Long-term applications of phosphorus fertilisers, at rates continuously in excess of crop removal, have resulted in soil phosphorus accumulation that are of environmental rather than agronomic concern [1].

The impact of phosphorus lost from agricultural sources on water eutrophication is well known. The aim on this paper is to discuss the possible consequence of phosphorus over-accumulation in agricultural soils on eutrophication of terrestrial ecosystems.

INPUTS OF PHOSPHORUS INTO ENVIRONMENT

The human industrial activity mobilises phosphorus comprised in geological deposits and disperses it into the environment. Phosphorus and its compounds have found application in black and colour metallurgy, and is component of many products such as paints, plastic and lubricants, safety matches, fumigating candles, fireworks and gun powers, zoocides, etc. Phosphorus from most of these products is practically not recycled, only in the case of Thomas basic sludge is used as phosphorus fertiliser. Adequate amounts of phosphate are added as amendments to fodder and processed food. The total amount of phosphorus in above mentioned products is not easy to be estimated, but most of it would be earlier or later dispersed into the environment and would contribute to its eutrophication. Nevertheless, the main quantities of anthropogenic mobilised phosphorus is dispersing into environment with washing agents and principally with fertilisers (Table 1).

The supposed phosphorus load added with washing agents is from 0.2 to 0.5 kg P_2O_5 per capita per year in developed countries - 0.36 kg P_2O_5 in Sweden [14]. In many countries the use of phosphate in washing agents is controlled or prohibited. The risk connected with phosphate in washings agent is multiplying by the fact that these agents are mostly drained away direct to municipal sewerage systems - the shortest way into the surface waters. The only solution to abate the inputs of phosphate from washing agents is to give up the desire to have the white whiter.

Table 1. Use of phosphate rocks in per cent of total [16]

Products or procedure	(%)
Fertilisers	90.0
Detergents	4.5
Animal feeds	3.4
Food and beverages	0.7
Metal treatment	0.6
Water treatment	0.3
Others	0.7

As it was mentioned the main phosphorus inputs into the environment is via use of fertilisers. The production of phosphorus fertilisers from phosphate rocks started in England already in 1843. Since that time phosphorus industry developed to huge enterprises in Europe and North America. The production and consumption of phosphorus fertilisers reach its apex in 1980s.

The reliable and comprehensive data describing the use of phosphorus fertilisers are available since 1954 [7]. The global consumption of these fertilisers surpassed one billion tons P_2O_5 from 1954 to 1997 (Table 2). The European countries have used nearly 50% of world consumption. About half of consumption in Europe was applied in nowadays European Union (EU15) countries. Polish agriculture participated in more than 2% of world and in about 12% of EU15 consumption. The annual world consumption of phosphorus fertilisers increased from about 15 million tons P_2O_5 in 1950s to about 40 million in 1970s and 1980s, and next was dropped due to economical annoyances in east part of Europe, particularly in the countries of former Soviet Union (Fig. 1). The last have consumed yearly more than 8 million tons P_2O_5 at the end of 1980s, two time more than USA. The use of

Table 2. Accumulated phosphorus fertiliser consumption in EU countries and Poland from 1954 to 1997

Region or country	Tg P_2O_5 (million tons)	Mg P_2O_5/ha of Al (tons/ha)
World	1.027	
Europe (with former Soviet Union)	434	
European Union countries (EU15)	205	
Belgium and Luxembourg	4.7	3.09
Germany	42.7	2.37
Finland	5.7	2.21
France	59.6	1.95
Netherland	4.1	1.83
Denmark	4.8	1.72
Italy	24.0	1.42
Sweden	4.7	1.37
Poland	**24.1**	**1.31**
Austria	3.9	1.10
United Kingdom	18.5	1.04
Ireland	5.6	0.98
Spain	18.0	0.81
Portugal	3.1	0.78
Greece	5.5	0.60
Europe in per cent of world consumption	42.3	
EU 15 in per cent of world consumption	20.0	
Poland in per cent of world consumption	2.35	
Poland in per cent of EU15 consumption	11.8	

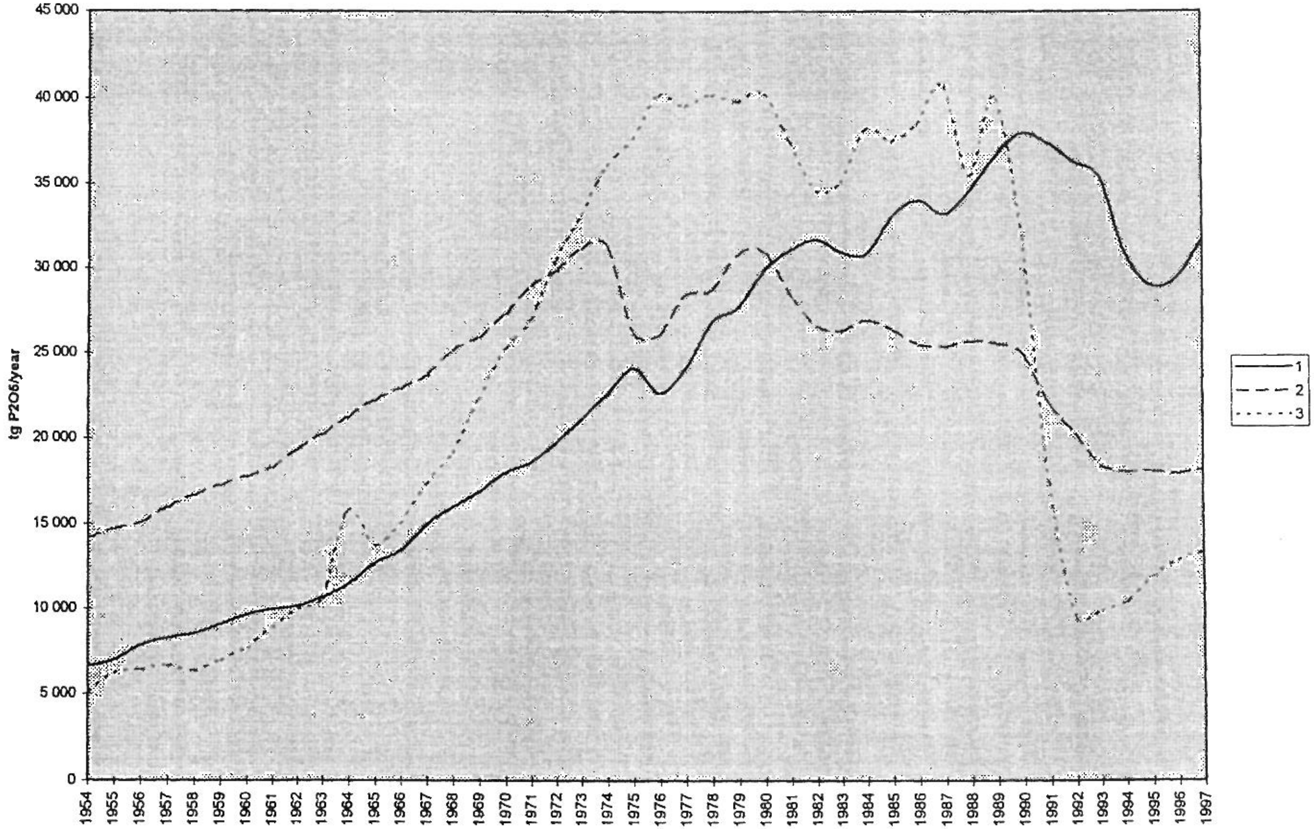

Fig. 1. Phosphorus fertilisers consumption in European Union countries (EU15) and Poland on the background of global consumption. 1 - world x1; 2 - Europe x5; 3 - Poland x42.6.

phosphorus fertilisers in EU15 was the highest in 1970s, and since is systematically dropping due to different national programmes aimed to mitigate the environmental eutrophication. The greatest decrease was observed in Germany from more than 2.2 million tons P_2O_5 in 1987 to 415 thousand tons in 1997.

The consumption of phosphorus fertilisers in Poland in 1937/1938 was 54.4 thousand tons P_2O_5 [9], and after the war was only two to four time higher up to the beginning of 1960s, when there was observed an evident increase of phosphorus fertiliser use with an apex from 1975 to 1990 - with an annual consumption about 900 thousand tons P_2O_5.

The changes in political and economical system resulted in dramatic - threefold decrease of phosphorus fertilisers use, which reached a bottom in 1992-222 thousand tons P_2O_5, and it is gently increasing now. Nevertheless, the present use is not so low as compared with the EU15 countries (Table 3). In total use, Poland is placed on sixth position. In per hectare basis on eleventh position, and in per capita basis on ninth position, using more as in the richest EU countries.

Table 3. Consumption of phosphorus fertilisers in European Union countries and in Poland in 1996/1997

Country	Gg P_2O_5 (thousand tons)	Country	kg P_2O_5/ha of Al	Country	kg P_2O_5 per capita
France	1 052	France	34.4	Ireland	35.6
Spain	560	Italy	31.2	Portugal	18.8
Italy	528	Belgium-Lux	29.4	France	18.4
Germany	415	Netherlands	28.2	Greece	15.0
United Kingdom	390	Filand	24.1	Spain	14.3
Poland	**314**	Germany	23.1	Finland	12.5
Greece	153	Ireland	22.9	Denmark	10.4
Ireland	128	United Kingdom	21.9	Italy	9.2
Portugal	75	Portugal	20.8	**Poland**	**8.1**
Finland	63	Denmark	18.9	Austria	6.8
Netherlands	62	**Poland**	**17.1**	United Kingdom	6.7
Austria	54	Greece	16.6	Sweden	5.6
Denmark	53	Austria	15.5	Germany	5.1
Sweden	49	Sweden	14.4	Belgium-Lux	4.5
Belgium-Lux	47	Spain	14.3	Netherlands	4.1

PHOSPHORUS MASS FLOW IN AGRICULTURE

In some countries, beside the main phosphorus inputs with fertilisers the imported fodder can be a significant sources of this nutrient. For example in Belgium, Denmark, Germany, and Netherland the present phosphorus inputs with imported fodder is equal or even higher than that with fertilisers. However, in the case of imported fodder, some other quantity of phosphorus fertiliser should be used in exporting countries. Most of produced fodder concentrates are amended with monocalcium phosphate to the 1.15 % P_2O_5 content in DM, which made in Sweden an inputs 5725 tons P_2O_5 annually [14].

Other sources have only a small importance. Solely, the sewage sludge rich in phosphorus appears to will have some importance in the near future. The principles of sustainable development assume a broad use of sewage sludge as a phosphorus fertiliser, assuring in such management an almost complete recycling of phosphorus from this source. Isermann [10] estimated that in Germany more than 9 kg P_2O_5/ha could be applied annually from sewage sludge, if only 80% of phosphorus contained in the waste waters would be separated. Other minor source, however reaching equally each ecosystem, is the wet and dry precipitation. In this way, about 0.7 kg P_2O_5/ha is deposited annually in the condition of West Europe - 0.25 to 0.6 kg P_2O_5/ha in Denmark and Sweden [25]. In Poland, annual total phosphorus loads in wet and dry precipitation, were higher for urban - 1.97 kg P_2O_5/ha/year than non-urban areas - 1.08 kg P_2O_5/ha/year [23].

The uptake with harvested crops is the main outputs of phosphorus from agricultural soils. However, the bulk amount of harvested phosphorus is returning with manure back into the soils, because approximately 90% of cropped products are commonly used in animal husbandry as fodder or bedding. The estimates made by means of farm gate or soil surface phosphorus balances have demonstrated that the phosphorus efficiency in national agricultural production, expressed as ratio of outputs to inputs, is generally bellow 40% in EU15 countries [Brouver et al., 1995; 10] and bellow 35% in Poland [20]. The calculated surplus of phosphorus, expressed as difference between inputs and outputs, ranged in EU countries from 8 kg P_2O_5/ha in Portugal to 92 kg P_2O_5/ha in Netherlands. In Poland, this surplus varied between 44 kg P_2O_5/ha in 1985 to 13 kg P_2O_5/ha in 1995, and 16 kg P_2O_5/ha in 1997 [20]. The phosphorus surplus in agriculture is supposed to be accumulated in soils, as phosphorus losses are negligible in balance, regardless of its negative effects in the environment. The leaching losses via drainage systems or surface runoff are generally presumed to be lesser than 1 kg P_2O_5/ha annually from mineral, and in some cases can be slightly higher from organic soils. The phosphorus losses through water and wind erosions were assessed solely in the case studies, which results are hard to extrapolate, despite of that their role will increase harmonically with the increase of total phosphorus content in soils. Many cultivated soils contains about 0.23% P_2O_5. If 1 mm soil layer is lost from a hectare of arable land, the materials removed contains more than 230 kg P_2O_5 [4]. All erosion events are irregular and short lasting, but the load of phosphorus in eroded soil material could sometime be notable and risky to the environmental quality, particularly to the surface water quality.

The path of phosphorus from agriculture via food chain in Germany (FRG) in 1986/87 [11], is a good illustration of the phosphorus fate in the environment of developed countries (Table 3). At the end, just about 10% of phosphorus inputs into the agriculture is bought by population, and only about 8% is consumed. Nevertheless, also this pool of phosphorus is dispersing into the environment. The present average daily consumption of phosphorus by a human is 1.9 g P per person and day [16], which made about 1.59 kg P_2O_5 per person annually.

ACCUMULATION OF PHOSPHORUS IN AGRICULTURAL SOILS

The main and almost sole sources of phosphorus inputs into the agricultural soils are fertilisers. Other source could be the cleaning agents (detergents) if only the sewage sludge find broader utilisation in agriculture. The average rate of phosphorus applied to agricultural soils in EU15 countries since 1954 to 1997 ranges between 0.6 to 3.1 tons P_2O_5 per hectare (Table 1). There exist no much data estimating the amount which was left in the soils. Behrendt [2] estimated that 700 to 850 kg P_2O_5/ha was accumulated in soils of province Mecklenburg-Vorpommern from East Germany since 1954 to 1994, what is much below of the accumulated amount applied in Germany since 1954 (2 370 kg P_2O_5/ha). The average total phosphorus content in soils is between 0.05 to 0.12% P_2O_5 [13], which is equal to 1.5 to 3.6 tons P_2O_5/ha in 0-20 cm layer of mineral soils.

The only controlled outputs of phosphorus from food chain are meals consumed by population and losses during food processing. The sum of both could not exceed 2-3 kg P_2O_5/capita. Greater outputs could be expected throughout losses into environment due to leaching, surface runoff and erosion. The last is the main way of losses. According to Isermann [12], total losses amounted to 3.3 kg P_2O_5/ha in Netherlands (1985/86), 6.0 kg P_2O_5/ha in FRG (1986/87), 2.3 kg P_2O_5/ha in Switzerland (1985) and 2.8 kg P_2O_5/ha in Ireland (1988) [27]. In the case of cultivated land, 75 to 90% of the phosphorus losses move with eroded soil material [21]. Generally, phosphorus losses are less than 5% of its amount applied. These losses are of little significance economically, but important ecologically in the eutrophication of surface waters. An assessment, which was based upon a detailed questionnaire sent to participating countries, shown that agriculture contributes between 24 and 71% of the total phosphorus loading to surface waters in Europe [22]. Particularly - 38% in FRG (1987), 24% in Netherland (1985) and 33% in Italy (1986) [11]. Behrendt and Bachor [3] estimated the contribution of diffuse sources to surface water pollution with phosphorus as 74% in the province Mecklenburg-Vorpommern from East Germany.

The inputs of phosphorus into Poland environment in 1997 consist of 314 000 tons P_2O_5 in form of fertilisers, about 77 000 tons with imported fodder and food together with food and fodder blending, and about 30 000 tons P_2O_5 with cleaning agents. The single monitored outputs is the load transported with riverine waters into the Baltic Sea amounted up to 30 000 tons P_2O_5/year. The remainder is left in the Poland's environment.

The inputs of phosphorus into agricultural soils is not equally distributed through particular countries. In Poland, the use of phosphorus fertilisers is several time higher in some central provinces than in east provinces (Fig. 2), it resulted in different accumulation of plant available phosphorus in soils - soil P-test (Fig. 3). Moreover, there are often some evident differences in accumulation of phosphorus in soil within farm. The highest accumulation was observed in soils of farmstead or its vicinity, were content up to 20 tons P_2O_5/ha in the form soluble in HCl (0.5 mol/dm^3) have been found [20].

DISCUSSION

Phosphorus unlike nitrogen is a conservative element in the environment. Phosphate from anthropogenic sources accumulates in the environment, mainly in agricultural soils and in the vicinity of human settlements. The inputs of phosphorus into the environment is constantly increasing causing an augmentation of its potential in particular ecosystem. Each system has a specific capacity of this potential. The exceeding of phosphorus potential could result in destroying the inner equilibrium of system. The capacity of phosphorus potential in surface water, particularly lakes is well recognised. The effects of increasing of phosphorus potential in terrestrial ecosystems is poor understood. That produce a lot of questions:

1. What is the capacity of agricultural soils to accumulate phosphate without an increased potential to disperse phosphorus into the environment?
2. What are the threshold levels of soil P above which the phosphorus losses to environment exceed agronomic benefits?

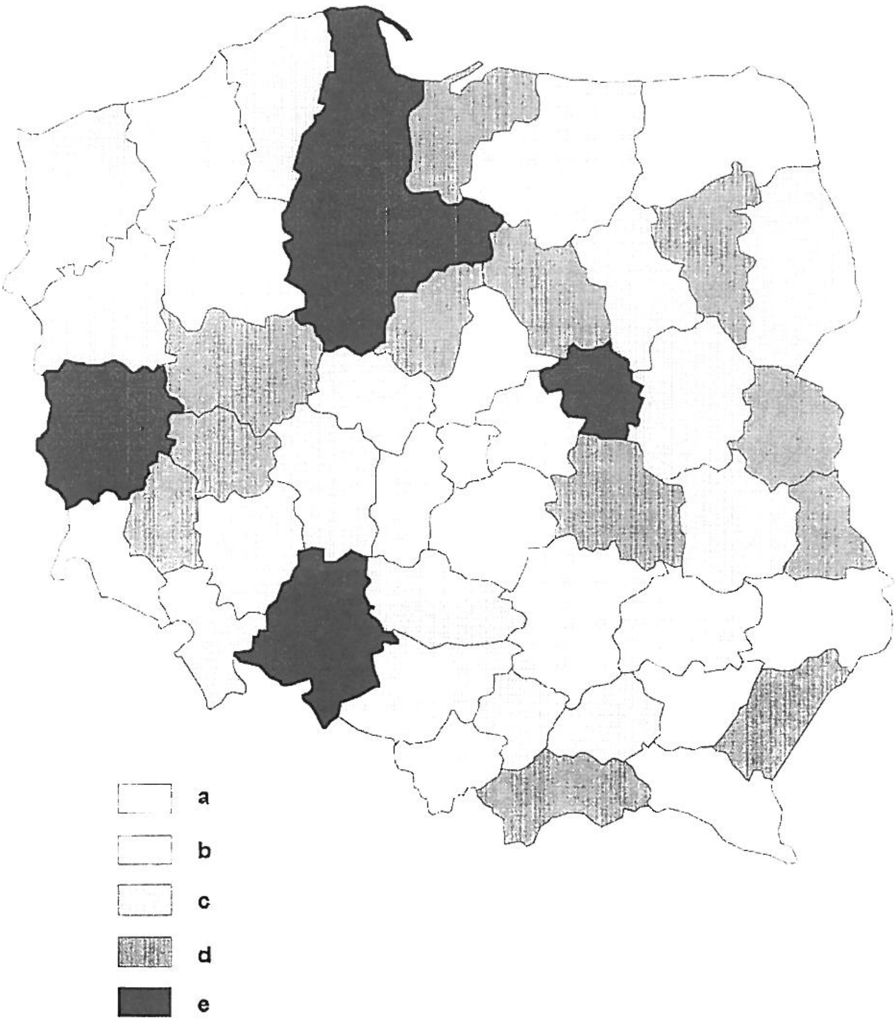

Fig. 2. Regional phosphorus fertilisers consumption in Poland (1996/1997). 1. <10 kg P_2O_5/ha; 2. 10-15 kg P_2O_5/ha; 3. 15-20 kg P_2O_5/ha; 4. 20-25 kg P_2O_5/ha; 5. >25 kg P_2O_5/ha.

3. What would be the fate of phosphorus accumulated in agricultural soils after the changes of land use such as afforestation, set-aside, renaturisation of dewatered wetlands, change to recreation objects, etc.?

4. What would be the reaction of plant communities to increased phosphorus content in soils of natural terrestrial ecosystem, including the national parks and plant reserves?

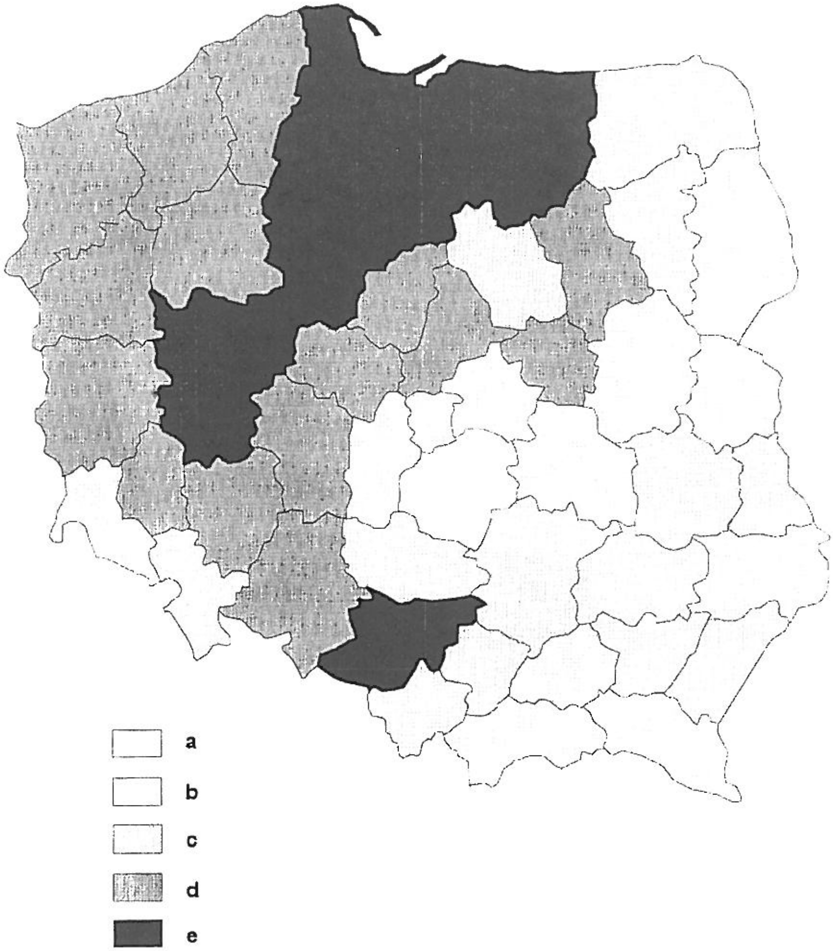

Fig. 3. Per cent of soils in Poland with high and very high P-test. 1 <15%; 2. 15-25%; 3. 25-35%; 4. 35-45%; 5. >45%.

5. What kind of actions is needed to restrict further increasing the phosphorus potential in environment?

Phosphorus does not move easily between ecosystems. Due to poor solubility of phosphate in water its amounts transported with this medium are insignificant as compared to phosphate bulk content in soils, but each quantity is of much importance to the water quality. Larger amounts of this nutrient could be moved with eroded soil material, causing the some fatal effect to water quality. The loss of agricultural phosphorus is not of economic importance to a farmer. However, it can lead to significant off-site economic impacts. Therefore, all the awareness should be concentrated on the appropriate phosphorus content in soils. The solubility of phosphate depends exponentially on its content in soil. Similarly, the amounts of eroded phosphorus depend linear on its content in soils. The crucial objective is to control this content assuring simultaneously the suitable plant grown and desired yield of crops as well as to minimise the risk of phosphorus dispersing into the environment. The agronomic objectives could be achieved using the soil P-test (Table 4). Decades of phosphorus fertilisation at rates exceeding those of crop removal have increased P-test in areas of intensive agricultural and livestock cropping. Once soil test P levels become excessive, the potential for P loss, if runoff and erosion occur, is greater than any agronomic benefits of further P applications. This is due to the dependence of P loss in runoff on surface soil P content. The agronomic concept is

Table 4. Path of phosphorus from agriculture via food chain in Germany (FRG) in 1986/87 [10,11].

	Tons P_2O_5/year	kg P_2O_5/ Al/year	kg P_2O_5/ capita	Remarks
Total P inputs into agriculture (fertilisers, imported fodder, sewage sludge)	1 000 000	84	16.4	
P; in agricultural products including:	828 000	69	13.5	Accumulation in soil
- plant products	564 000	47	9.2	588 000 t (49 kg/ha)
- animal products	264 000	22	4.3	Losses 71 700 t (6 kg/ha)
P in sold agricultural products including:	340 000	29	5.6	
- consumable	168 000	14	2.8	P recycling to agriculture with useful wastes
- non-consumable (bones etc.)	172 000	15	2.8	P recycling with fertilisers, mineral fodder
P in food destined to be sold on market	96 900	8.1	1.6	P losses during storage, transport, etc.
P in food purchased by population including:	96 900	8.1	1.6	
- consumed	81 600	6.8	1.3	P aimed to sewerage systems
- food wastes	15 300	1.3	0.3	P aimed to garbage systems

to secure sufficient supply of phosphorus to growing plants and generally the recommended rates are higher than the amount of phosphorus taken by harvested crops. The environmental concept is to maintain the phosphorus content in soils on a low level undertaking some risk of losses in yield. A compromise should be find. Both side are compatible that soils with very high P-test are unwanted. The agronoms due to excessive costs, the eniromentalist due to risk of eutrophication [6].

The contemporary fertiliser recommendation systems suggests that the applied phosphorus rate should be equal to its amount removed with crops. The main attention is paid on soils with high and very high P-test, where remarkable restrictions in phosphorus application are advocated, particularly in the case of manure, with which the applied phosphorus doses are most hard to control. Manure is the cause that recommendation based on the phosphorus field balance cannot prevent the overfertilization of some fields within a farm. To overcome this problem a recommendation systems based on phosphorus farm gate balance is developing. The phosphorus inputs into the farm with fertilisers and fodder should be equal to its amount in sold products. The recommendation systems should also regard that the vulnerability to phosphorus loss is soil and site specific. Therefore, the evaluation of P-test should consider ability of soil to erosion, slope of site, distance to the surface water bodies, etc. [15,26].

The impact of phosphorus on surface water eutrophication and the contribution of agricultural sources to it is well described [21,24]. However, there is a broad lack of information about this impact on terrestrial natural ecosystems. Fertility of many ecosystems is not desired, particularly of oligotrophic systems, where plants species demand on phosphorus is low. These species could be replaced with philophosphorus species much more dynamic and productive. Withers [28] demonstrated that attempts to regenerate a greater diversity of grassland species in areas of special scientific interest are inhibited by high soil P levels. Desirable native species are unable to compete with the vigorous growth of introduced species stimulated by the high level of available P in the soil. That could lead to decline of biodiversity and changes in plant communities. Both effects are nonwanted from many reasons. In the case of surface waters, the destructive results of eutrophication could be divided into three phases: 1. increased biomass production; 2. destabilisation of system; 3. decline of live. In terrestrial ecosystems one could expect the development of two first phases, but the development of last phase is not easy to foreseen. A factor which is complicating each forecasting is the fact that eutrophication phenomena have a certain incubation time.

Table 5. Agronomic and environmental evaluation of phosphorus soil tests

Soil test evaluation	Per cent of Polish soils in test evaluation (%)	Fertiliser recommendation in Poland	Environmental evaluation
Very low	12	Fertilise in evident excess	No risk
Low	27	Fertilise in excess	Small risk
Middle	26	Fertilise >30-50% than the amount removed with crops	Risk is increasing
High	16	Fertilise >10-30% than the amount removed with crops	Crucial risk
Very high	19	Fertilise equal to the amount removed with crops or greater	Very great risk

A genuine risk of phosphorus dispersing into environment could be expected after some changes in land use. The renaturisation of dewatered peatlands, used for many years as cultivated soils, is connected with possible mobilisation leaching of phosphate accumulated due to used fertilisers [18]. Similar risk could pose the deforestation of agricultural land with, set-aside or other use. There are few if any information dealing with the behaviour of phosphate in former agricultural soils changed to other use. One is certain, each change would increase the mobility of phosphate and it transfer to other systems.

CONCLUSIONS

There are suggestions that soils have an almost unlimited capacity to absorb and immobilize phosphorus inputs. However, only small losses are necessary to provide a potential eutrophication and it is evident that P losses from agriculture to sufficient magnitude are occurring and may be increasing in frequency. This, together with the economic necessity to make best use of a finite and increasingly more expensive input, indicates that renewed attention is required to ensure that P in modern farming systems is managed in a manner which is sustainable from the point of view of both agriculture and environment [8].

The use of phosphorus fertilisers in doses higher than the removal with crops lasts in European countries only since 40-50 years. During that time, the total phosphorus content in agricultural used soils was doubled or tripled. Such phosphorus management in agriculture cannot be continued, as a further increase of phosphorus content in the cultivated soils would not only conduct to exhausting of natural resources but also to eutrophication of water and terrestrial ecosystems.

Phosphorus is a conservative element in environment, once introduced will persist there for many human generations.

The mitigation of eutrophication originated from phosphorus fertilisers could be achieved only on scientific basis followed with country and regional abatement programs. The investigation should focus: (1) to define conceptual models of phosphorus cycling in agricultural ecosystems and to develop common methodologies for quantifying phosphorus loss from agriculture to water and other ecosystems [5]; (2) to elaborate environmental tests for soil phosphorus and to assess site vulnerability to phosphorus loss [22]; (3) to identify the effect of eutrophication of terrestrial ecosystems due to phosphorus accumulation. The abatement program should include: (1) environmentally sound fertiliser recommendation system for phosphorus; (2) levies to phosphorus fertilisers in sites vulnerable to phosphorus loss; (3) broad education activities.

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