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Yield and quality of spring wheat grain in relation to the P status of *Luvisol* loamy sand soil and fertilization

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Studies of spring wheat yield response to fertilizers in a model field experiment with four different levels of mobile phosphorus content (P_2O_5 70–117–200–393 mg kg^{-1}) of *Luvisol* loamy sand soil contaminated with ^{137}Cs and ^{90}Sr radionuclides had been conducted in 2005–2007 in the Gomel region of Belarus. The increase of phosphorus content in the studied diapason was accompanied by the grain yield enhancement in the best fertilized treatment from 3.8 to 6.9 t ha^{-1}. The efficiency of $N_{60-90-110}$ nitrogen fertilizer and $K_2O_{90-120-180}$ potassium fertilizer positively correlated with all studied levels of phosphorus content in soil. The grain yield response per 1 kg of P_2O_5 applied was highest (10.5 kg) at the 3rd level of soil P supply and was reduced by 57% at the 4th level of phosphorus content in soil.

The protein and gluten contents of wheat grain significantly increased with the rise of N-fertilizer rates on all studied levels of soil P content. The highest protein and gluten contents in grain have been observed at the 3rd level of phosphorus supply, while the protein output per hectare continued increasing up to P content in soil ≈ P_2O_5 400 mg kg^{-1}.

The combined effect of increasing the content of mobile P in soil with balanced fertilization ($N_{90-110}P_{60}K_{120-180}$) provided the wheat grain yield increment up to 3 times simultaneously with a reduction by a factor of 2 of the radionuclides ^{137}Cs and ^{90}Sr transfer from soil to grain. The efficiency of the test fertilizers increased depending on soil supply with mobile phosphorus, resulting in a net return for food-grade grain of 89 and 227 € ha^{-1} at the 1st and the 4th levels of soil P content, respectively.

Key words: soil, phosphorus, spring wheat, yield, protein, radionuclides ^{137}Cs and ^{90}Sr

INTRODUCTION

Phosphorus is an important nutrient for growing agricultural plants. The functions of phosphorus in a plant cell are most prominent in nuclide acids which are responsible for genetic information, as well as in formation of phosphate esters related to energy metabolism (Marchner, 1993). Increasing the efficiency of P fertilizer in crop production is possible by adjusting its applications to the level of plant-available P in soil. Many methods are currently used for extracting soil samples with chemical reagents which correlate well enough with cereal yields for practical usefulness (Johnston, Salter, 2001; Svedas, Janusauskaitė, 2000; Takaheshi, Anwar, 2007; Мажвила и др., 2001; Оптимальные..., 1984; Сычев, 2000).

Agricultural soils in Belarus were originally low in plant-available phosphorus. Intensive use of commercial fertilizers and manure in the period 1970–1990 resulted in a significant, up to 3 times, increase of measured PK in soil stock, as well as a similar enhancement in crop yields. Since 1992, the use of organic and commercial fertilizers decreased on average two times, but P fertilization decreased up to 3 times. As a result, the productivity of agricultural crops has declined, and the phosphorus balance is slightly negative (Агрохимическая…, 2006). The negative balance of PK fertilization has been recently reported from many countries of Central and East Europe (Bučiene et al., 20003; D'Haene et al., 2007; Сычев, 2000; Шафран, 2006). It is important to prevent the reduction of soil fertility level, and depletion of soil P status in particular. There is a positive tendency in the consumption of fertilizers in Belarus in the last 5 years, but the efficacy of fertilization has to be increased, avoiding both under- and overfertilization. The "available" or mobile soil contents of P and K (by Kirsanov's method in 0.2 M HCl) have been measured in Belarus for a long time every 4–5 years. In general, we have a high diversity, up to 10 times, of P indexes of arable soils among the fields of different farms (Агрохимическая…, 2006). An important task is the implementation of balanced fertilization with rational rates of the expensive P fertilizer according to soil fertility tests. The fertilizer management must be improved to meet two main requirements: a better return on investment and reducing the possible negative ecological impact (Clever, Alan, 2001; Ekholm et al., 2005; Johnston, Salter, 2001).

Continuous liming of acid soils in Belarus considerably improved the availability of soil phosphorus to plants. The computer-aided recommendations had been elaborated to provide annual plant needs with consideration of phosphorus build-up requirements for a gradual increase of soil P content up to optimal levels, which were established on the basis of six long-term P fertilizer experiments and numerous short-term trials (Оптимальные..., 1984). Unfortunately in the last decade only few long-term experiments with fertilizers are still in progress. Introduction of the new varieties of agricultural crops, plant protection means, machinery, etc., forced us to reconsider the interpretation of soil fertility tests according to current conditions. It is especially important on land contaminated with radionuclides after the Chernobyl accident, where rational application of fertilizers may be the most efficient remediation action to reduce the contamination of foodstuff (Howard et al., 2004; Nisbet, 1993; Алексахин и др., 1992; Пристер и др., 2003).

The aim of this study was to quantify the relation of the yield and quality of spring wheat food-grade grain to different levels of P supply in *Luvisol* loamy sand soil contaminated with ^{137}Cs and ^{90}Sr radionuclides. The grain yield response to nitrogen, phosphorus and potassium fertilizers was studied to provide the basis for recommendations on the amount of fertilizers to apply in soil with different P indexes. The experimental data will be helpful in evaluating the fertility status of soils during soil testing.

MATERIALS AND METHODS

In a 3-year field experiment (2005–2007), the spring wheat (*Triticum aestivum*) cultivar 'Rassvet' was grown. The preceding crops in the rotation were lupine (*Lupinus angustifolins* L.) or peas (*Pisum sativum*). The experiment was carried out in the Strelichevo experimental farm, the Gomel region, Belarus, on land contaminated after the Chernobyl accident. The study was conducted on a *Luvisol* loamy sand soil which is a widespread, representative soil in the affected region (46% of arable land). The surface soil layer (0–25 cm) of the *Luvisol* loamy sand soil was characterized by a low content (14%) of fine fraction particles (< 0.01 mm). The soil has typical agrochemical properties for a medium level of fertility: organic matter 2.2%, pH (KCl) 6.2, mobile K_2O 220 mg kg^{-1} dry mass (dm), exchangeable Ca 863 mg kg^{-1} dm, Mg – 262 mg kg^{-1} dm. The deposition (mean ± SD) in soil of ^{137}Cs was 408 ± 19.8 kBq m^{-2} and of ^{90}Sr 40 ± 4.9 kBq m^{-2}, i. e. rather high.

Four blocks with a different content of mobile P in soil were prepared: I – (67–72); II – (110–124); III – (189–211) and IV – (388–398) P_2O_5 mg kg^{-1}. The first three blocks represent the main classes of soil P supply in Belarus (about 80% of arable land square). These blocks were selected as a result of a long-term residual effect of the former application of P fertilizer. Havlin et al. (1993) reported that substantial benefits from residual P can persist for 5 to 10 years or longer, influenced by the amount of residual P (Howard et al., 2004). The soil of the fourth block was additionally treated with triple superphosphate in a year before the vegetation season. Nine treatments of fertilizers in four replications had been randomly laid out on each block: 1. Control; 2. P_{60} K_{120}; 3. N_{60+30} K_{90}; 4. N_{60+30} P_{60}; 5. N_{60+30} P_{60} K_{90}; 6. N_{60+30} P_{60} K_{120}; 7. N_{60+30} P_{60} K_{180}; 8. N_{60} P_{60} K_{120}; 9. $N_{60+30+20}$ P_{60} K_{120}. The treatments include increasing rates of nitrogen (N_{60}, N_{90}, N_{110} on the background of P_{60} K_{120}) as well as increasing rates of K fertilizer (K_2O: 90, 120 and 180 kg ha^{-1} on the background of $N_{90}P_{60}$). The PK fertilizers and N_{60} were pre-plant applied before. The rates of nitrogen above 60 kg ha^{-1} were split for 2 or 3 applications at the shooting and heading stages.

The following physicochemical parameters were measured in the soil samples using conventional methods (Практикум..., 1998).

– pH was determined with a glass electrode in an aqueous suspension of 10 g of dry soil and 25 ml of 1 M KC1, shaken and left for deposition overnight. Exchangeable Ca and Mg were determined in the same solution by atomic absorption spectroscopy (AAS);

– soil organic matter was measured using 0.1 N iron ammonium sulphate titration with diphenylamine, after combustion of 1 g soil in 0.4 N chromic acid for 5 minutes;

– mobile P_2O_5 and K_2O were determined by extraction in 0.2 M HC1 at a ratio l : 5, followed by colorimetric and flame emission spectrophotometry (FES) methods, respectively.

– Grain samples from each plot were analysed for dry matter, protein and total gluten proteins (wet gluten) content (w/w %) at the laboratory by standard methods. Flour protein was determined as N ×5.7 (Лапа, Босак, 2006);

– ^{137}Cs activity concentration: plant and soil samples were homogenized, dried at room temperature and put into Marinelli beakers (1.0 l) and measured using gamma spectrometry (HP-Ge detector Canberra GC4019 in a low-background environment). The relative uncertainty of ^{137}Cs activity measurement in all samples was < 10%. Results were calculated for each soil sample both as Bq kg^{-1} and as kBq m^{-2} for the bulk density of soil 1.50 g cm^{-3} and a plough layer of 25 cm;

– ^{90}Sr activity concentration: plant and soil samples were ashed at 600 °C. The ^{90}Sr activity concentration was determined using the oxalate method with ^{90}Y separation (Cherenkov counting). The beta-activity was measured with a low level liquid scintillation counter (Canberra Tri-Carb 2750LL). Results were calculated for each soil sample both as Bq kg^{-1} and as kBq m^{-2} for the bulk density of soil 1.50 g cm^{-3} and a plough layer of 25 cm. Then the transfer coefficients of radionuclides from soil into wheat grain, Tag values (m^2 kg^{-1} × 10^{-3}) for ^{137}Cs and ^{90}Sr were calculated.

A conventional two-factorial dispersive and regression statistical analysis for the experimental data was carried out using the MS Excel program (Clever, 2001). The test of statistically significant differences at the Fisher criterion and the density of factor influence (R^2 with the probability <0.05) were used to analyse the mean differences and regression coefficients.

The meteorological conditions in 2005–2007 differed from the average long-term observation data, but these differences were favourable for plant development and yield. The vegetation seasons 2005–2006 were characterized by the wet and warm weather during May–August. The weather of the growing period in 2007 was quite different: with dry April, June and August, but very warm and wet May and July.

RESULTS AND DISCUSSION

The mean values of wheat grain yields obtained in the experiment (2005–2007) are presented in Table 1. One can see that a greater difference in yield values was provided by fertilizer treatments. The grain yields between control and $N_{110}P_{60}K_{120}$ treatment varied by a factor of 1.8 on the first level of P soil supply and by a factor of 2 on the 4th level of P supply. Slightly less differences in wheat yields – in the range of 1.6–1.8 times – were provided by contrast levels of mobile P content in soil. Anyway, the differences in grain yield capacities at all levels of mobile P content in soil are statistically significant at the probability level $P < 0.01$. The experimental data showed a sufficient wheat yield increase accompanied by a rise of mobile P content of *Luvisol* loamy sand soil in the wide P_2O_5 limits from 67–72 to 388–398 mg kg^{-1}. Studies conducted in Belarus in 1970s–1980s showed a cereal yield increase when mobile P content in *Luvisol* loamy sand soils had been raised up to P_2O_5 200–300 mg kg^{-1} (Оптимальные..., 1984). The better yield response to the increasing levels of P supply in our actual experiment could be explained by a higher level of soil fertility, higher rates of NK fertilizers as well as a higher potential yield of the tested new cultivar ('Rassvet') of spring wheat.

The grain yield response per 1 kg of the applied nutrients varied greatly, increasing according to nitrogen rates and the levels of soil P supply enhancement. There was a significant positive interaction between fertilization and the levels of soil P supply. The grain yield values were not seriously affected by the weather conditions during the trial years, so the coefficients of variation (CV%) of yields among the years were <8%. Correlation and regression data analysis showed a close relationship between wheat grain yield and mobile P content in soil (Fig. 1). The experiment has revealed that grain yields in the control (no fertilizers) treatment increased with the rise of mobile P content in soil according to the quadratic equation: y (t ha^{-1}) $= 1.51 + 0.0111x - 0.00002\,x^2$, where x is mobile P_2O_5 content in soil, mg kg^{-1}. The regression is significant at $P < 0.01$; $R^2 = 0.81$. From this regression it can be calculated that the maximum wheat yield could be expected at 278 mg kg^{-1} of P_2O_5 content in soil.

The grain yields in the $N_{110}P_{60}K_{120}$ treatment are in a close linear correlation with P soil tests ($R^2 = 0.95$ at $P < 0.01$). It is clear that the optimal level of mobile P content in soil rises according to the increasing rates of NK fertilizers.

The experiment showed (Table 2) a sufficient enhancement of wheat yield response to N fertilizer at a rate of 110 kg ha^{-1} from 12.9 to 27.7 kg of grain per 1 kg of N applied, or by a factor of 2.1 provided by the increase of mobile P_2O_5 content in soil from 67–72 to 388–398 mg kg^{-1}.

A similar increase of crop response to N fertilizer on different soils in relation to changing the PK status from lowest to highest up to 2–2.5 times had been reported by J. Johnston and Russian scientists (Johnston, Salter, 2001; Войтович и др., 2002; Державин, 1992). The enhancement of wheat grain response to K fertilizer by factors 1.7–3.0 according to an increase of mobile P content in soil from the 1st to 4th level was also observed in our experiment.

The grain yield responses to P fertilizer (means for each year of trial) are closely related to soil P content (Fig. 2).

The relationship is well fitted by a quadratic curve ($y = 2.93 + 0.0736x - 0.0002x^2$, $R^2 = 0.72$, $P < 0.01$). The calculated maximal grain response per 1 kg of P_2O_5 applied is expected when mobile P_2O_5 content in soil reaches 184 mg kg^{-1}. The further increase in mobile phosphorus concentration in soil is accompanied by a strong decline of P fertilizer efficacy. The linear negative relationship between cereal yield response to P fertilizer and P soil test indices, reported in several investigations (Johnston, Salter, 2001; Svedas, Janusauskaitė, 2000; Державин, 1992; Мажвила и др., 2001; Оптимальные..., 1984) may be explained by the narrow limits of the available P concentrations studied. In our case, the efficacy of P fertilizer within P_2O_5 content ~180–400 mg kg^{-1} may also be satisfactorily fitted by a negative linear curve. It is clear that a wide limit of the soil P tests provides a better basis for the prediction of P fertilizer efficacy.

Grain protein is an important quality factor to be considered in fertilization. It is well known that a split application of N fertilizer to cereals is a common practice in European countries, especially for spring and winter wheat in which the high grain protein contents are desired to improve baking quality (Guarda et al., 2004; Детковская, Лимантова, 1987; Лапа, Босак, 2006;

Table 1. Mean yields of spring wheat grain and responses per 1 kg of nutrients applied depending on P supply levels in Luvisol loamy sand soil (2005–2007)

Treatments	Grain yield, t ha^{-1}					Yield response, kg per 1 kg NPK				
	Levels of P_2O_5 in soil, mg kg^{-1}									
	70	117	200	393	Means	70	117	200	393	Means
Control	2.15	2.62	3.07	3.45	2.82	–	–	–	–	–
$P_{60}K_{120}$	2.38	2.90	3.35	3.86	3.12	1.3	1.5	1.6	2.3	1.7
$N_{90}K_{90}$	2.80	3.34	3.82	5.12	3.77	3.7	4.0	4.2	9.3	5.3
$N_{90}P_{60}$	2.91	3.49	3.87	4.98	3.81	5.1	5.8	5.4	10.2	6.6
$N_{90}P_{60}K_{90}$	3.21	3.91	4.45	5.39	4.24	4.4	5.4	5.8	8.1	5.9
$N_{90}P_{60}K_{120}$	3.38	4.20	4.91	6.40	4.72	4.6	5.8	6.8	10.9	7.0
$N_{90}P_{60}K_{180}$	3.68	4.45	5.04	6.63	4.95	4.7	5.5	6.0	9.6	6.4
$N_{60}P_{60}K_{120}$	3.18	4.00	4.39	5.11	4.17	4.3	5.7	5.5	6.9	5.6
$N_{110}P_{60}K_{120}$	3.80	4.49	5.06	6.90	5.07	5.7	6.5	6.9	11.9	7.7
Means	3.06	3.71	4.22	5.31		4.2	5.0	5.3	8.7	
$LSD_{0.05}$ $LSD_T = 0.212$; $LSD_P = 0.142$; $LSD_{Tx P} = 0.426$						$LSD_T = 0.41$; $LSD_P = 0.29$; $LSD_{TxP} = 0.81$				
$F_T = 106.6$; $F_P = 360.8$; $F_{TxP} = 4.0$						$F_T = 163.7$; $F_P = 370.3$; $F_{TxP} = 10.9$				

Смирнова, 2006). But the rates of N fertilizer on soils contaminated with radionuclides should be restricted to avoid an excessive accumulation of ^{137}Cs and ^{90}Sr in crops (Evans, Dekker, 1968; Nisbet, 1993; Алексахин и др., 1992). Therefore, we used only moderate rates of N fertilizer (60-90-110 kg ha^{-1}). The studies have shown that protein content in spring wheat grain was significantly increasing with the rise of N fertilizer rates at the levels of soil P content studied (Fig. 3 A).

There are contradictory opinions about the influence of P fertilization on grain protein content. The slight positive (Wibberley, 2006; Вильдфлуш и др., 2005) or negative (Детковская, Лимантова, 1987) effects of P fertilizer on grain protein content are admitted. The excess of phosphorus rarely has a direct toxic effects under agricultural conditions because phosphate ions are firmly sorbed and immobilized in soil. However, phosphorus excess can exacerbate or induce deficiencies of calcium, zinc, boron, copper, manganese and iron (Bergmann, 1992). An analysis of long-term experimental data in Russia showed a significant increase of protein content in cereal grain as a result of the application of P fertilizer well balanced with NK fertilizers (Толстоусов, 1987).

A close correlation of protein content (y, %) of spring wheat grain and mobile P concentration in soil (x, P_2O_5 mg kg^{-1}) was found in our experiment at $N_{110}P_{60}K_{120}$ treatment. This correlation is well fitted with a quadratic regression (y = 11.28 +

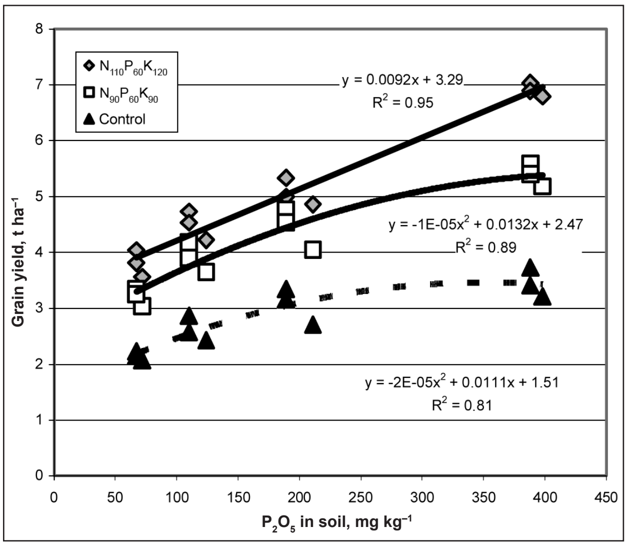

Fig. 1. Correlation between wheat grain yield and mobile phosphorus content in loamy sand soil in control and fertilized treatments during 3 years of field experiment (2005–2007)

Table 2. **Response of wheat grain yield, kg per 1 kg of N, P or K applied (mean ± SD) depending on P supply levels in *Luvisol* loamy sand soil (2005–2007)**

Nutrient	Levels of P_2O_5 in soil, mg kg^{-1}			
	67–72	110–124	189–211	388–398
N at rate 60	13.3 ± 1.69	18.3 ± 1.36	17.3 ± 1.33	20.9 ± 2.38
N at rate 90	11.1 ± 0.73	14.4 ± 0.85	17.3 ± 0.94	28.2 ± 2.41
N at rate110	12.9 ± 0.74	14.5 ± 0.69	15.5 ± 1.08	27.7 ± 0.55
P_2O_5 at rate 60	6.8 ± 1.20	9.4 ± 0.54	10.5 ± 1.64	4.5 ± 2.32
K_2O at rate 90	3.4 ± 0.96	4.6 ± 1.29	6.4 ± 0.80	5.7 ± 0.78
K_2O at rate120	3.9 ± 1.28	5.9 ± 1.02	8.6 ± 0.54	11.8 ± 0.96
K_2O at rate 180	4.3 ± 1.14	5.3 ± 0.25	6.5 ± 0.70	9.2 ± 0.49

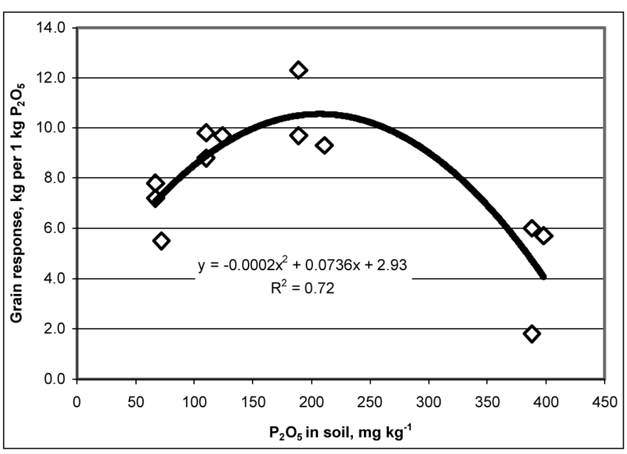

Fig. 2. Wheat grain response per 1 kg of P_2O_5 (60 kg ha^{-1}) in relation to the level of P supply in *Luvisol* loamy sand clay soil (2005–2007)

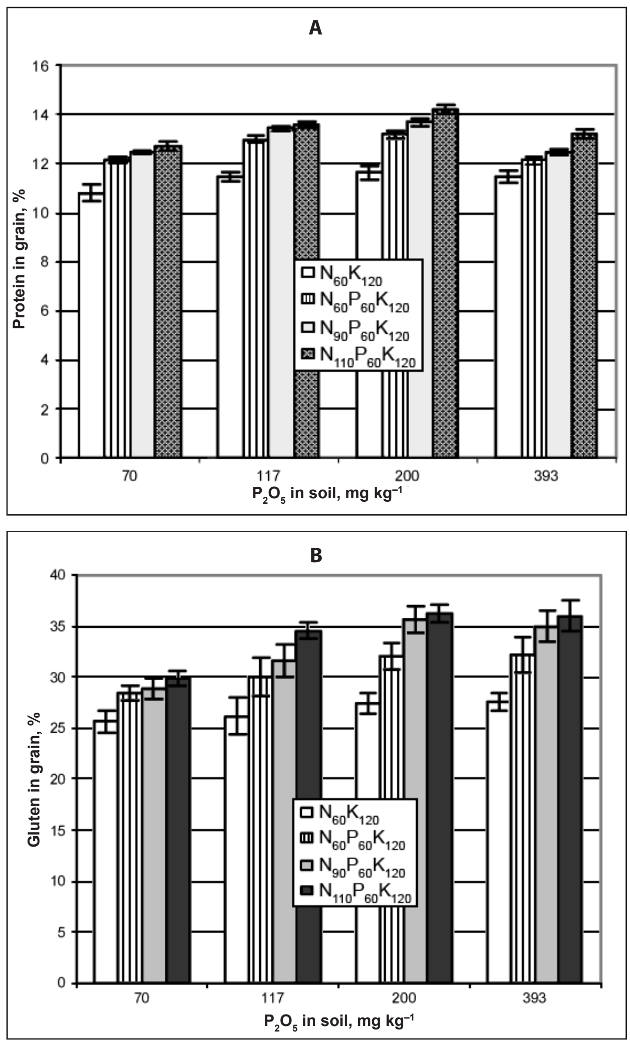

Fig. 3. The effect of increased N fertilizer rates on grain protein (A) and gluten (B) content in spring wheat in relation to mobile P content in *Luvisol* loamy sand soil (means ± SD, 2005–2007)

$+ 0.0253x - 0.00005x^2$, $R^2 = 0.90$, $P < 0.01$). This means that the maximum calculated protein content (14.5%) in wheat grain could be expected at mobile P content 253 mg kg^{-1} in soil. The further increase of soil P content will be accompanied by a reduction of grain protein content. However, protein output per hectare will sufficiently increase up to mobile P_2O_5 content in soil ~400 mg kg^{-1}.

Gluten is the main functional component of wheat, and it is the main source of viscoelastic properties in dough. The total content of gluten proteins is the main quality factor related to the market price of food-grade wheat grain in Belarus. Our results have demonstrated that gluten content in wheat flour is strongly influenced by increasing rates of N fertilizer as well as the levels of soil P supply (Fig. 3 B). The differences in gluten content among the treatments are sufficient at all studied levels of mobile P in soil. The character of the correlation of gluten content in wheat grain and mobile P concentration is similar to that of protein content due to a close correlation between these indices (Вильдфлуш, 2005; Технология …, 1996). The highest gluten content in wheat grain in $N_{110}P_{60}K_{120}$ treatment could be calculated as 35.7% at P content (P_2O_5) 231 mg kg^{-1} in soil by the equation: $y = 25.0 + 0.0925x - 0.0002x^2$, $R^2 = 0.81$, $P < 0.01$.

Balanced plant nutrition is important for the yield and quality of crop production, especially in radioactive contaminated soils. Soil fertility status exerts a considerable influence on the soil-to-plant ^{137}Cs transfer and, respectively, on the internal irradiation dose in people consuming the crop products. Fertilization and liming to improve soil fertility are the most widespread, applicable and acceptable remedial actions on radioactive contaminated agricultural lands (Howard, 2004; Nisbet, 1993; Алексахин и др., 1992). It is well known that potassium as a chemical analogue of caesium could effectively inhibit the transfer of radiocaesium from soil to plants. However, the inhibitory effect is strongly dependent on K status of soil, which will determine the effect of K fertilization as a countermeasure to reduce the ^{137}Cs concentration in crop production (Waegeneers et al., 2001; Nisbet, 1993; Алексахин и др., 1992). Potassium fertilizer could also provide a certain reduction of ^{90}Sr transfer to crop yield (Evans, Dekker, 1963; Юдинцева и др., 1983). The K status of our experimental field was close to optimal for cereal crops on loamy sand soil (mobile K_2O 220 mg kg^{-1}). We studied the inhibitory effect of increasing doses of potassium, balanced with NP fertilizers, on ^{137}Cs and ^{90}Sr transfer to wheat grain in relation to different levels of soil P supply (Fig. 4).

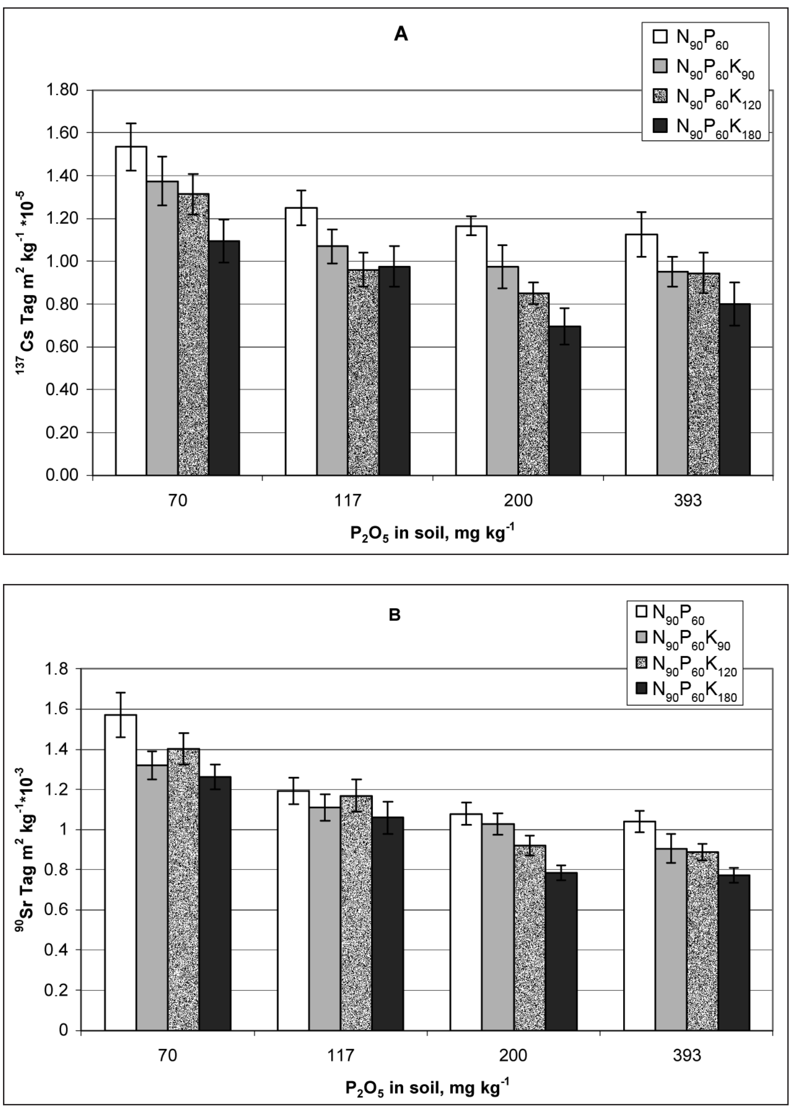

Fig. 4. Transfer Tag values (m^2 $kg^{-1} \times 10^{-5}$) for ^{137}Cs (A) and (m^2 $kg^{-1} \times 10^{-3}$) for ^{90}Sr (B) flux into spring wheat grain (mean ± SD, 2005–2007) in relation to increasing rates of K fertilizer at different levels of mobile P content in *Luvisol* loamy sand soil

The application of increasing rates of K fertilizer resulted in a significant reduction of ^{137}Cs transfer from soil to wheat grain compared to background $N_{90}P_{90}$: at the rate K_{90} by 10–16%, K_{120} by 14–27%, K_{180} by 22–40%. Reduction of ^{90}Sr transfer to grain under the influence of K fertilizer rates was comparatively less (3–28%). The inhibitory effects of K fertilizer on radionuclide transfer from soil to wheat grain were practically similar at all levels of soil P supply. We did not find a stimulating effect of increasing rates of N fertilizer on ^{137}Cs and ^{90}Sr accumulation in wheat grain because moderate N rates were used. Moreover, the so-called biological "dilution" effect of radionuclide concentration was observed due to a high wheat grain yield response to the rates of N fertilizer. A special interest was to study the relation of radionuclide transfer to mobile P content in soil.

It is known that heavy dressings of P fertilizers can prevent or reduce the uptake by plants of toxic concentrations of trace elements (Bergmann, 1992) as well as of radionuclides ^{137}Cs and ^{90}Sr (Nisbet, 1993; Проблемы…, 1996; Юдинцева и др., 1983). A significant reduction of ^{90}Sr transfer from soil to crops was admitted due to formation of insoluble strontium phosphates (Юдинцева и др., 1983). However, application of unbalanced high doses of NP fertilizers on fertile soils resulted in an enhanced ^{137}Cs accumulation in the grain and straw of cereals up to 3.2 times (Кузнецов и др., 2001). There were no clear correlation between ^{137}Cs transfer values and mobile P content in contaminated soils of Ukraine during the collection of data from short trials on farmers' fields. However, a close relation was established with the composite index evaluating the common effect on the agrochemical soil properties: pH, CEC, organic matter and K contents (Пристер и др., 2003). Usually, the agrochemical properties are closely interconnected. In our experiment, we had an opportunity to measure the effect of different concentrations of mobile P in soil on the background of the same level of other factors (Fig. 5). A close relation of Tag transfer values of ^{137}Cs and ^{90}Sr to wheat grain (y) with the increasing mobile P content in soil (x), well fitted by quadratic curves ($R^2 = 0.77, 0.91, P < 0.01$), was found. The minimum accumulation of radionuclides in wheat grain is expected at mobile P content 300–320 kg kg^{-1} in loamy sand soil.

The Tag values for ^{137}Cs were low; therefore, the grain activities varied for the treatments and P levels within 1.9–9.1 Bq kg^{-1}, which are much lower than the permitted level (PL) for food-grade grain (90 Bq kg^{-1}). The transfer of ^{90}Sr from soil to wheat grain was almost by two orders higher, and grain activities

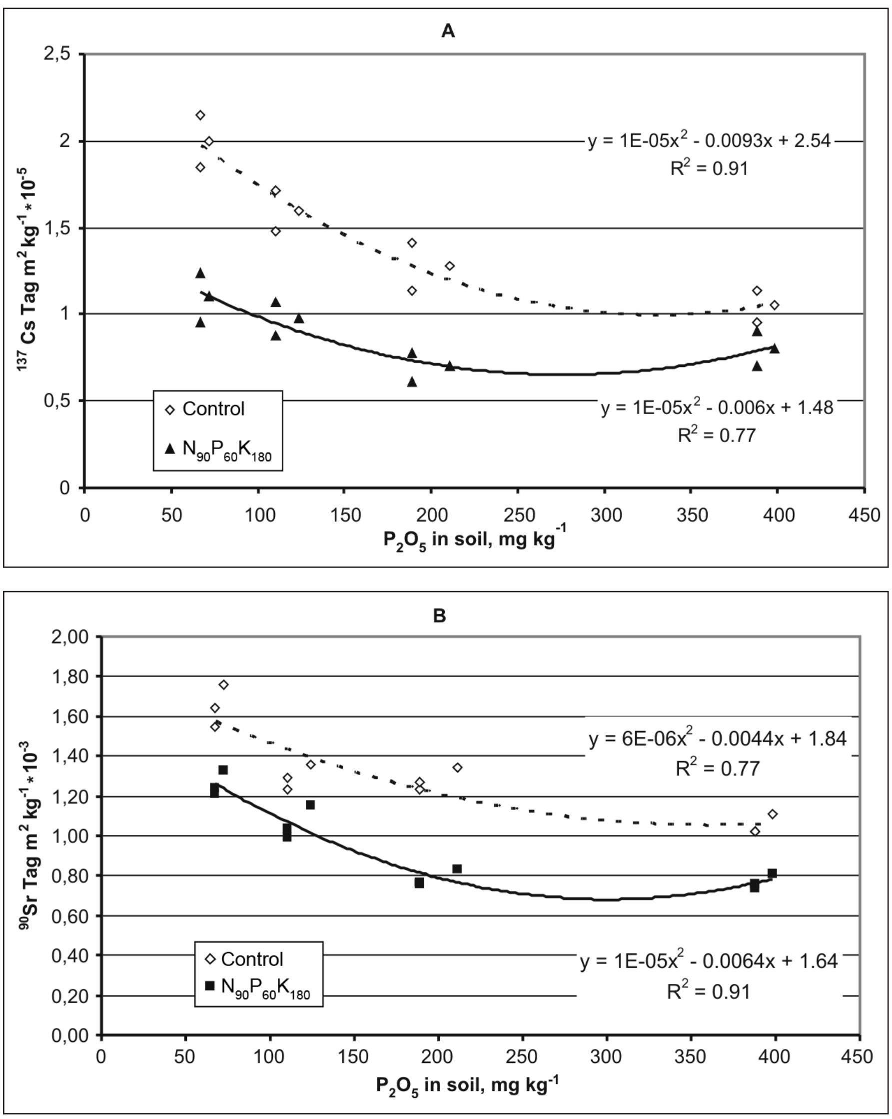

Fig. 5. Tag values (m^2 kg^{-1} × 10^{-5}) for ^{137}Cs and (m^2 kg^{-1} × 10^{-3}) ^{90}Sr flux into spring wheat grain (mean values for 2005, 2006, 2007 in control and $N_{110}P_{60}K_{180}$ treatments) in relation to different levels of mobile P content in *Luvisol* loamy sand soil

varied within 19.5–42.7 Bq kg^{-1}. The PLs for ^{90}Sr currently in force in Belarus are especially low – 11 Bq kg^{-1} for food-grade grain and 3.7 Bq kg^{-1} for bread. For this reason, the increase of mobile P content in soil up to the optimal level is very important because it allows growing food-grade wheat at ^{90}Sr deposition up to 16 kBq m^{-2}, while on soil with a poor P content only at a deposition below 11 kBq m^{-2}. About 85,000 hectares of arable lands in Belarus are contaminated with ^{90}Sr above 11 kBq m^{-2}.

For farmers in contaminated areas, it is important to be able to grow food-grade grain (instead of fodder) under the relevant PL values to maximize their income. The most economically efficient treatment was $N_{110}P_{60}K_{120}$. The profitability of the test fertilizers was increasing according to the enhancement of soil supply with mobile phosphates, resulting in a net return of 89 and 227 € ha^{-1}, respectively, for food-grade grain on the 1st and the 4th levels. Grain contaminated by ^{90}Sr above PL and sold as fodder gave a lower net return – 25 and 94 € ha^{-1}, respectively.

CONCLUSIONS

1. The rise of mobile P content in *Luvisol* loamy sand soil in the wide P_2O_5 limits from 67–72 to 388–398 mg kg^{-1} was accompanied by an increase of the grain yield of spring wheat on fertilized plots from 3.8 to 6.9 t ha^{-1}. A significant positive interaction of grain yield response to N and K fertilizers (by factors of 1.6–3.0) provided by the increasing content of mobile P in soil was found. The grain yield response per 1 kg of P_2O_5 applied was highest (10.5 kg) at the 3rd level of soil P supply ($\approx P_2O_5$ 200 mg kg^{-1}) and reduced by 57% at the 4th level of soil P content.

2. Protein content and total gluten protein content in spring wheat grain significantly increased with the rise of N fertilizer rates at all levels of soil P content. The highest protein and gluten contents in grain were found at the 3rd level of phosphate supply while protein output per hectare continued increasing up to P content in soil $\approx P_2O_5$ 400 mg kg^{-1}.

3. The application of increasing rates of K fertilizer resulted in a significant reduction of ^{137}Cs transfer from soil to wheat grain as compared to the background $N_{90}P_{90}$: at the rate K_{90} by 10–16%, K_{120} by 14–27% and K_{180} by 22–40%. Reduction of ^{90}Sr transfer to grain under the influence of K fertilizer rates has been comparatively less (3–28%). The inhibitory effects of K fertilizer on radionuclide transfer from soil to wheat grain were practically similar at all the levels of soil P supply studied.

4. The values of ^{137}Cs and ^{90}Sr transfer from soil to grain showed a close relation with mobile P content in soil, well fitted by the downward concave quadratic curves. The minimum accumulations of radionuclides in wheat grain were calculated at mobile P content P_2O_5 300–320 mg kg^{-1} in loamy sand soil.

5. The most economically efficient treatment was $N_{110}P_{60}K_{120}$. The profitability of the tested fertilizers has been increasing according to the enhancement of soil supply with mobile phosphorus, resulting in the net return of 89 and 227 € ha^{-1}, respectively, for food-grade grain on the 1st and the 4th levels. Grain contaminated with ^{90}Sr above the permitted level and sold as fodder gave a lower net return – 25 and 94 € ha^{-1}, respectively.

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VASARINIŲ KVIEČIŲ DERLIAUS IR GRŪDŲ KOKYBĖS PRIKLAUSOMUMAS NUO SMĖLINGO PRIEMOLIO IŠPLAUTŽEMIO (*LUVISOLS*) FOSFORINGUMO BEI MINERALINIO TRĘŠIMO

Santrauka

2005–2007 m. Gomelio srities (Baltarusija) smėlingo priemolio išplautžemio, užteršto ^{137}Cs ir ^{90}Sr radionuklidais, modeliniuose lauko bandymuose tirtas vasarinių kviečių derliaus priklausomumas nuo keturių dirvožemio fosforingumo, judriojo fosforo (P_2O_5 70–117–200–393 mg kg^{-1}) lygių. Jie padidino grūdų derlių nuo 3,8 iki 6,9 t ha^{-1}. Azoto ($N_{60-90-110}$) ir kalio ($K_2O_{90-120-180}$) trąšų poveikis derliui labai koreliavo su dirvožemio fosforingumu. Esant III lygio dirvožemio fosforingumui dėl 1 kg P_2O_5 gautas didžiausias derliaus priedas (10,5 kg); esant IV lygio fosforingumui šis priedas buvo 57% mažesnis.

Didėjančios azoto trąšų normos gerokai didino baltymų ir glitimo kiekį vasarinių kviečių grūduose esant visiems keturiems dirvožemio fosforingumo lygiams. Didžiausias baltymų ir glitimo kiekis grūduose buvo esant III lygio dirvožemio fosforingumui, tačiau baltymų derlius iš hektaro didėjo ir dirvožemyje esant ≈400 mg kg^{-1} judriojo P_2O_5. Dėl gerai subalansuoto tręšimo azoto ir kalio trąšomis esant nevienodam dirvožemio fosforingumui vasarinių kviečių grūdų derlius padidėjo 3 kartus, ^{137}Cs ir ^{90}Sr radionuklidų mažiau pateko iš dirvožemio į grūdus. Panaudotų trąšų pelningumas didėjo didesnio fosforingumo dirvožemiuose, o gautas maistinių grūdų pelnas, esant I lygio dirvožemio fosforingumui, buvo 89 €, esant IV lygio fosforingumui – 227 €.

Raktažodžiai: dirvožemio fosforingumas, vasariniai kviečiai, derlius, baltymai, radionuklidai ^{137}Cs ir ^{90}Sr