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LOSS OF NUTRIENTS THROUGH SOIL WATER EROSION IN CALCIC CHERNOZEM

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The application of technology for water erosion control plays an essential role in development of sustainable agricultural systems. The paper presented observes the study results from a period of six years in terms of losses of mineral nitrogen and available forms of phosphorus and potassium in the cultivation of wheat and maize on sloping terrains (on calcic chernozem soil type) under the influence of water erosion processes. The impacts of four different types of technology (conventional technology performed along the slope; conventional technology applied across the slope; surface mulching; and minimum tillage with vertical mulching) on nutrient losses were tested. On average, the annual losses of mineral nitrogen, available forms of phosphorus and potassium in wheat production along the slope utilizing conventional technology were 6.0 kg·ha^{-1}y^{-1}, 1.6 kg·ha^{-1}y^{-1}, 5.9 kg·ha^{-1}y^{-1}, and 11.3 kg·ha^{-1}y^{-1}, 2.1 kg kg·ha^{-1}y^{-1}, 10.8 kg kg·ha^{-1}y^{-1} in maize production. The lowest losses in these elements occurred with minimal employment of tillage system, as they reached values of 2.3 kg·ha^{-1}y^{-1}; 0.6 kg·ha^{-1}y^{-1}, 2.0 kg·ha^{-1}y^{-1}, respectively, in wheat production, and 1.7 kg·ha^{-1}y^{-1}, 0.3 kg·ha^{-1}y^{-1}, 1. kg·ha^{-1}y^{-1}, respectively, in maize production.

Keywords: water erosion; conventional technology; minimum tillage; available phosphorus and potassium; mineral nitrogen

This paper is an extension of work that was originally presented by Kuncheva and Dimitrov (2020).

Soil water erosion comprises three primary processes – separation, transport and deposition of soil particles. One of the results of soil water erosion is loss of nutrients with surface water runoff and eroded soil. This, along with other negative consequences of this degradation process, leads to a decrease in crop yields, loss of mineral fertilizers and environmental pollution. It is a major soil degradation cause, as it is a natural process that affects large areas (Posthumus et al., 2013). Erosion significantly reduces soil depth and increases surface runoff, leading to lower water infiltration and soil moisture (Borrelli et al., 2020). Moreover, soil organic matter and plant available nutrients are lost throughout the process of erosion, causing physical and chemical degradation (Koch et al., 2013; Bashagaluke et al., 2018). The cumulative impact of erosion results in a reduction of biomass and biodiversity of the entire ecosystem, lower plant productivity and lower yields (Borrelli et al., 2020). Considering all global dynamics scenarios, climate prognoses indicate a trend of moving toward a more vigorous hydrological cycle with potential to increase the global water erosion by 30–66%. (Borrelli et al., 2020; Eekhout and De Vente, 2022), which will only intensify the issue.

Nutrient elements (i.e., N, P, K, Ca, etc.) are displaced from the areas subjected to water erosion, with surface water runoff and with eroded soil (Meena et al., 2017). In Bulgaria, more than 100 million tons of fertile soil, 3.4 million tons of humus, 200 000 tons of nitrogen are annually removed from eroded arable lands as a result of water erosion. Tens of millions of tons of all other nutrients are also lost (Kuncheva and Dimitrov, 2020). As a consequence of soil erosion, the annual amount of fertilizers removed from agricultural soils by water erosion globally equals to US$ 34 billion for nitrogen and US$ 80 billion for phosphorus (Govers et al., 2017; Bashagaluke et al., 2018).

In natural ecosystems, the nitrogen availability represents a limiting factor for an ecosystem productivity and nitrogen cycles run with minimal losses. Nevertheless, since the usage efficiency of mineral fertilizers is low and much higher amounts (FAO, 2015) are usually utilized than necessary, much of the mineral nutrients applied are lost. This phenomenon causes numerous related negative impacts on the environment and human health, i.e., increased emissions of N_2O and NH_3, nitrogen fertilizer pollution, as well as contamination of surface and ground waters (Cameron et al., 2013). On the basis of analyses conducted by FAO (2015), the global increases in nitrogen inputs in agriculture cannot contribute to higher productivity without creating serious impacts on the environment. As a result of inefficient use of mineral phosphorus applications, it is estimated that the amount of phosphorus displaced from terrestrial ecosystems has tripled, which has a significant impact on the environment (Bertol et al., 2007). Additionally, nitrates, phosphates, etc. can generate health risk conditions, as they can play a significant role in eutrophication of water basins and contamination of drinking water (FAO, 2015).

The average Bulgarian territory altitude is 470 m. The erosion assessment of country relief suggests that

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16% of the total area has a slope of 0–3°, while the major half (55.3%) has a slope of 3–12°, and 23.9% of the area has a slope of 12–18°. In Bulgaria, 60.1% of soils have medium, strong or very strong susceptibility to erosion (over 0.03 t·ha·h·ha^{-1}·MJ^{-1}·mm^{-1}). Due to a variety of erosion parameters of natural factors in Bulgaria, it is estimated that 62% of its territory shows a potential erosion risk of 10 t·ha^{-1}y^{-1} and the potential risk exceeds 10 t·ha^{-1}y^{-1} for 43% of Bulgarian territory (Rousseva et al., 2016; Panagos et al., 2015).

Proper development of sustainable agricultural systems is dependent on soil protection from degradation processes and preservation of soil functions (Shahgholi and Moinfar, 2021; Starovoytov et al., 2017). In order to meet this goal, a variety of erosion control measures and methods are developed and implemented (Govers et al., 2017). The paper presented investigates the impacts of four tillage systems – conventional and soil protective – for cultivation of wheat and maize on sloping terrains in terms of loss of mineral N and available forms of P and K in soil due to water erosion.

Material and methods

The surveys were carried out during the period 2012–2017 on a slope of 5° (8.7%) in the experimental station for erosion control of Institute of Soil Science, Agrotechnologies and Plant Protection "Nikola Poushkarov" Sofia. This is in the northern climatic region of the Danube hilly plain, Ruse district, and is typical with a temperate-continental climate, with sharp continence compared to the rest of the territory.

The relief of Ruse region is flat to hilly. The lands with slope inclinations of 3–6° and 6–9° have the largest share in the district – 48% (this share is 28% for the entire country). Approximately 83% of Ruse district is characterized by middle erosivity of rainfalls (601–800 MJ·mm·ha^{-1}·h^{-1}·year^{-1}) (Rousseva et al., 2010). The soil type is middle eroded Calcic Chernozem (FAO, 2015). The soil-forming rock is represented by loess and sandy-clay materials with high calcium content. In accordance with the content of carbonates throughout the profile, the reaction of soils is slightly alkaline – pH 7.7–8.2.

Variants of the experiment were: a_1 – conventional tillage along the slope (for the purposes of control measurements); a_2 – conventional tillage across the slope; a_3 – conventional tillage across the slope with surface mulching; a_4 – soil protection advanced technology for minimum and unconventional soil tillage for maize and wheat cultivation, which was applied across the slope (Kuncheva and Dimitrov, 2020). Considering the wheat cultivation, the technology for advanced soil protection comprised operations such as vertical mulching with manure or compost and direct sowing, which were applied transversely of the slope. Regarding the maize cultivation for grain purposes, the technology for advanced soil protection comprised basic tillage without ploughing-loosening and operations such as vertical mulching with manure or compost, cutting with duct production simultaneously with sowing and digging, which were applied transversely of the slope (Dimitrov et al., 2017).

The volume of surface water runoff and amounts of eroded soil, macronutrient concentrations, mineral nitrogen losses, available forms of phosphorus and potassium for each erosive rainfall throughout the survey period 2012–2017 were determined utilizing stationary method (Kuncheva and Dimitrov, 2020). Data were processed using Statistica 13.1.

Results and discussion

There were recorded 25 erosive rainfalls in maize cultivation and 21 in wheat cultivation throughout the six-year survey period (Tables 1–2).

In wheat plots, the total annual soil losses in variant a_1 grown along the slope (control) ranged from 3.4 to 7.8 t·ha^{-1}y^{-1} and the surface water runoff volume was 302.4–699.7 m^3·ha^{-1}·y^{-1}. Considering the maize grown using conventional technology along the slope, the amount of eroded soil ranged from 7.6 to 15.7 t·ha^{-1}y^{-1}, and the surface water runoff volume was 530.1–1333.0 m^3·ha^{-1}·y^{-1}. In regard to wheat grown under minimum tillage with vertical mulching, the amount of eroded soil ranged from 0.53 to 1.2 t·ha^{-1}·y^{-1}, and the surface water runoff was 213.7–258.5 m^3·ha^{-1}·y^{-1}. Considering the maize cultivation under the same conditions, the amount of eroded soil ranged from 0.3 to 0.7 t·ha^{-1}·y^{-1}, and the surface water runoff was 102.2–258.1 m^3·ha^{-1}·y^{-1}. The change in the direction of cultivation led to a significant reduction in erosion (variants a_2), with soil losses between 1.9 t·ha^{-1}·y^{-1} and 4.3 t·ha^{-1}·y^{-1} for

Table 1 Total annual amounts of eroded soil and surface water runoff in wheat cultivation for period 2012–2017

Year	Total volume of surface water runoff (m^3·ha^{-1})				Total amount of eroded soil (t·ha^{-1})			
	a_1	a_2	a_3	a_4	a_1	a_2	a_3	a_4
2012	415.2	295.2	244.3	150.3	4.98	2.79	1.62	0.79
2013	302.4	213.7	180.2	108.82	3.42	1.92	1.07	0.54
2014	379.9	271.6	238.8	140.4	4.60	2.55	1.47	0.73
2015	425.0	300.8	251.4	156.4	5.05	2.83	1.58	0.79
2016	571.1	395.5	336.9	205.0	6.30	3.54	1.92	0.98
2017	699.7	499.1	413.4	258.5	7.78	4.35	2.43	1.22

ANOVA Eroded soil; p <0.00001; a_1 vs a_2, p <0.00001; a_1 vs a_3, p <0.00001; a_1 vs a_4, p <0.00001; a_2 vs a_3, p <0.00001; a_2 vs a_4, p = 0.000063; a_3 vs a_4, p = 0.186; surface water runoff; p = 0.412

Table 2 Total annual amounts of eroded soil and surface water runoff in maize cultivation for period 2012–2017

Year	Total volume of surface water runoff ($m^3 \cdot ha^{-1}$)				Total amount of eroded soil ($t \cdot ha^{-1}$)			
	a_1	a_2	a_3	a_4	a_1	a_2	a_3	a_4
2012	670.9	356.5	340.7	128.3	10.03	3.76	3.68	0.45
2013	530.1	309.8	277.8	102.2	7.61	2.88	2.65	0.34
2014	596.5	351.8	314.6	115.6	8.48	3.25	2.98	0.37
2015	848.0	472.9	427.7	160.3	11.09	4.24	3.82	0.49
2016	1079.2	629.5	544.7	204.6	13.51	5.19	4.76	0.59
2017	1333.0	781.9	694.1	258.6	15.71	6.04	5.58	0.70

ANOVA Eroded soil; p <0.00001; a_1 vs a_2, p <0.00001; a_1 vs a_3, p <0.00001; a_1 vs a_4, p <0.00001; a_2 vs a_3, p = 0.899; a_2 vs a_4, p <0.00001; a_3 vs a_4, p <0.00001; surface water runoff; p = 0.000048; a_1 vs a_2, p = 0.24; a_1 vs a_3, p = 0.00165; a_1 vs a_4, p = 0.000040; a_2 vs a_3, p = 0.228; a_2 vs a_4, p = 0.00076; a_3 vs a_4, p = 0.203

Table 3 Total annual losses of mineral nitrogen N ($N\text{-}NO_3^- + N\text{-}NH_4^+$), available forms of P_2O_5, K_2O with eroded soil and surface water runoff ($kg \cdot ha^{-1}$) in wheat experiment for the period 2012–2017

Year	Variant	Losses with eroded soil ($kg \cdot ha^{-1}$)			Losses with surface water runoff ($kg \cdot ha^{-1}$)		
		N	P	K	N	P	K
2012	a_1	0.39	1.07	6.04	3.77	0.68	5.24
	a_2	0.16	0.42	2.23	2.02	0.36	3.01
	a_3	0.22	0.77	2.33	5.20	0.38	6.06
	a_4	0.02	0.07	0.26	1.09	0.11	0.82
2013	a_1	0.65	1.25	5.07	12.54	0.57	2.83
	a_2	0.18	0.67	2.48	5.67	0.33	1.94
	a_3	0.21	0.73	2.61	5.41	0.32	2.66
	a_4	0.02	0.05	0.13	1.67	0.10	0.66
2014	a_1	0.55	1.66	4.77	12.42	0.28	9.60
	a_2	0.20	0.65	1.87	7.35	0.18	6.79
	a_3	0.34	0.94	2.06	14.80	0.22	11.92
	a_4	0.03	0.09	0.23	2.01	0.06	3.25
2015	a_1	1.03	0.79	5.41	9.58	0.79	4.22
	a_2	0.37	0.32	2.18	5.30	0.49	2.27
	a_3	0.46	0.36	3.10	6.29	0.62	3.34
	a_4	0.05	0.05	0.31	1.42	0.18	0.91
2016	a_1	1.46	1.46	4.76	9.15	1.10	5.44
	a_2	0.52	0.54	1.85	5.39	0.59	3.13
	a_3	0.61	0.56	2.01	7.49	0.58	3.44
	a_4	0.07	0.06	0.60	1.31	0.27	1.19
2017	a_1	0.72	1.40	4.79	15.35	1.32	6.75
	a_2	0.30	0.50	1.79	9.35	0.71	4.02
	a_3	0.42	0.91	2.17	9.82	0.67	5.09
	a_4	0.05	0.07	0.26	2.96	0.21	1.29

ANOVA: N losses, eroded soil p <0.0001, P losses eroded soil p <0.0001, HSD [.05] = 0.33, HSD [.01] = 0.41, K losses eroded soil p <0.0001, HSD [.05] = 0.59, HSD [.01] = 0.75, N losses water runoff p = 0.0273, HSD [.05] = 5.95, HSD [.01] = 7.54, P losses, surface water runoff p = 0.024, HSD [.05] = 0.4, HSD [.01] = 0.51, K losses, surface water runoff p = 0.0135, HSD [.05] = 3.72, HSD [.01] = 4.72

wheat and 3.3 t·ha^{-1}·y^{-1} and 6.0 t·ha^{-1}·y^{-1} for maize. Moreover, the surface application of organic materials showed also an additional effect, with the loss of soil ranging from 1.1 to 2.4 t·ha^{-1}·y^{-1} in wheat cultivation and from 2.7 to 5.6 t·ha^{-1}·y^{-1} in maize cultivation.

After measuring the volumes of surface water runoff and amounts of eroded soil, the concentration of the available forms of nitrogen-ammonium and nitrate (N-NH_4, N-NO_3) in eroded soil and nitrate (N-NO_3) in surface water runoff, as well as available forms of phosphorus and potassium, both in the liquid and in the solid runoff were determined (Tables 3–4). The sediment enrichment ratio (ER) – the ratio between content of the element in the eroded soil and in the soil on the hill – was calculated. The losses of mineral nitrogen, available forms of phosphorus and potassium were on average: 6.0 kg·ha^{-1}· y^{-1}, 1.6 kg·ha^{-1}·y^{-1}, 5.9 kg·ha^{-1}·y^{-1} in wheat control variant and 11.3 kg·ha^{-1}·y^{-1}, 2.1 kg·ha^{-1}·y^{-1}, 10.8 kg·ha^{-1}·y^{-1} in maize. The losses of these elements were the lowest when applying the minimum tillage system, as they were 2.3 kg·ha^{-1}·y^{-1}, 0.6 kg·ha^{-1}·y^{-1}, 2.0 kg·ha^{-1}·y^{-1}, respectively, in wheat cultivation and 1.7 kg·ha^{-1}·y^{-1}, 0.3 kg·ha^{-1}·y^{-1}, 1.7 kg·ha^{-1}·y^{-1}, respectively, for maize cultivation. When applying conventional technology, but transversally to the slope, the losses of available N, P and K decreased to 4.3 kg·ha^{-1}·y^{-1}, 1.1 kg·ha^{-1}·y^{-1}, 3.8 kg·ha^{-1}·y^{-1} for wheat, and 6.1 kg·ha^{-1}·y^{-1}, 3.7 kg·ha^{-1}·y^{-1}, 5.6 kg·ha^{-1}·y^{-1} for maize. The losses of mineral N and available forms of K increased in the variants with surface application of organic materials, as they reached values of 5.8 kg·ha^{-1}·y^{-1} and 3.7 kg·ha^{-1}·y^{-1}, respectively, in wheat cultivation, and 8.6 kg·ha^{-1}·y^{-1} and 7.8 kg·ha^{-1}·y^{-1}, respectively, for maize. However, the losses of available P were slightly lower on average in contrast to conventional technology applied along the slope. The losses of nutrients were the lowest in the last variant with minimum tillage and vertical mulching: 2.3 kg·ha^{-1}·y^{-1}, 0.6 kg·ha^{-1}·y^{-1}, 2.0 kg·ha^{-1}·y^{-1} for wheat, and 1.7 kg·ha^{-1}·y^{-1}, 0.3 kg·ha^{-1}·y^{-1}, 1.7 kg·ha^{-1}·y^{-1} for maize.

Table 4 Total annual losses of mineral nitrogen N ($N\text{-}NO_3^- + N\text{-}NH_4^+$), available forms of P_2O_5, K_2O with eroded soil and surface water runoff (kg·ha^{-1}) in maize experiment for the period 2012–2017

Year	Variant	Losses with eroded soil (kg·ha^{-1})			Losses with surface water runoff (kg·ha^{-1})		
		N	P	K	N	P	K
2012	a_1	0.31	0.63	3.63	17.72	0.22	2.82
	a_2	0.18	0.35	2.11	13.10	0.16	1.99
	a_3	0.15	0.25	1.76	17.41	0.18	2.79
	a_4	0.09	0.13	0.74	7.79	0.16	1.90
2013	a_1	0.11	0.34	1.95	3.16	0.32	1.39
	a_2	0.05	0.19	1.15	2.86	0.25	1.04
	a_3	0.04	0.16	1.08	3.22	0.22	1.33
	a_4	0.01	0.05	0.37	1.94	0.12	0.53
2014	a_1	0.27	0.62	2.64	8.68	1.31	3.99
	a_2	0.14	0.38	1.39	5.10	0.96	2.54
	a_3	0.14	0.28	1.08	6.70	0.98	2.25
	a_4	0.06	0.14	0.37	2.80	0.36	1.33
2015	a_1	0.34	0.69	3.98	4.95	0.25	3.16
	a_2	0.20	0.38	2.33	3.99	0.18	2.21
	a_3	0.16	0.27	1.89	5.70	0.19	2.94
	a_4	0.07	0.14	0.80	1.97	0.18	2.12
2016	a_1	0.46	1.12	3.16	6.19	0.40	3.36
	a_2	0.24	0.62	1.76	4.38	0.31	2.74
	a_3	0.16	0.57	1.07	5.58	0.44	2.65
	a_4	0.08	0.32	0.56	2.37	0.24	1.20
2017	a_1	0.35	0.56	2.01	6.95	0.67	2.81
	a_2	0.21	0.06	0.60	5.23	0.56	1.88
	a_3	0.19	1.40	4.79	6.52	0.53	2.41
	a_4	0.07	0.50	1.79	2.60	0.26	1.16

ANOVA: N losses, eroded soil $p = 0.00013$, HSD [.05] = 0.12, HSD [.01] = 0.15, P losses, eroded soil $p = 0.032$, HSD [.05] = 0.56, HSD [.01] = 0.71, K losses, eroded soil $p = 0.007$, HSD [.05] = 1.51, HSD [.01] = 1.91, N losses, surface water runoff NS, P losses, surface water NS runoff, K losses, surf. water runoff $p = 0.008$, HSD [.05] = 1.1, HSD [.01] =1.4

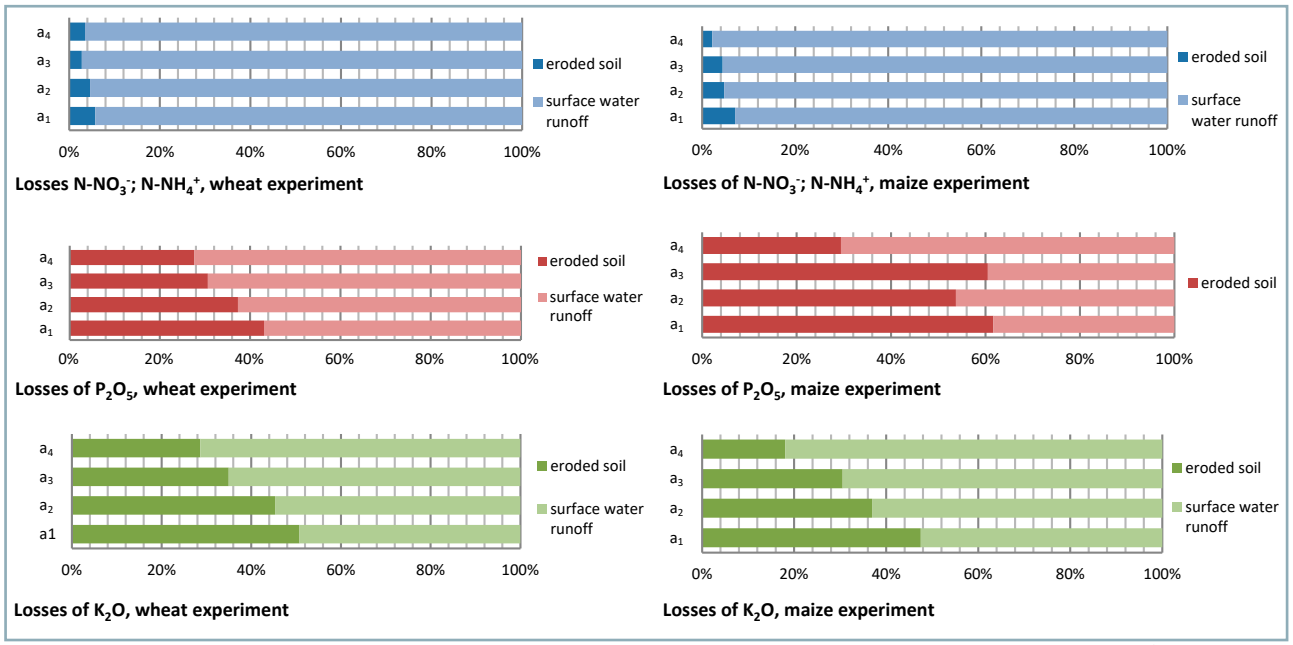


Fig. 1 Losses of available forms of N ($N\text{-}NO_3^-$; $N\text{-}NH_4^+$), P_2O_5, K_2O with eroded soil and surface water runoff (kg·ha^{-1}) annually on average for six years (2012–2017) as percentages of total losses
a_1 – conventional tillage along the slope; a_2 – conventional tillage across the slope; a_3 – conventional tillage across the slope with surface mulching; a_4 – advanced soil protection technology for minimum soil tillage

Most of the losses of mineral nitrogen occured with surface water runoff and were in nitrate form. Considering the maize control variants, approx. 90% of N losses were due to surface water runoff; utilizing the identical technology in wheat control variants, the N losses due to surface water runoff reached 93%. Conventionally grown variants of examined crops showed slightly higher losses with liquid runoff – 94–95% of total losses. Regarding the variants with application of surface mulching, 95–98% of the mineral N losses occured with water runoff. Considering the variants with minimum tillage and vertical mulching, this percentage was slightly lower (Fig. 1).

The losses of mineral N in every erosive rainfall showed a difference between two crops – it was observed lower in wheat cultivation in contrast to maize cultivation. The influence of both tillage systems and the cultivated crop was statistically significant, but the crop influence was lower. The mineral N losses reached the highest values in control variants a_1 and a_3 (Fig. 2).

Different varieties of tillage technology had an effect on N concentrations in eroded soil and in water runoff (Fig. 3, 4), which showed the highest values with application of manure or compost to the soil surface. Both factors (cultivated crop and applied technologies) had a statistically significant influence, however, the type of cultivation technology proved to have a much stronger influence. The mineral N concentrations were higher in variants a_3 and a_4. In terms of crops, they were lower in wheat cultivation.

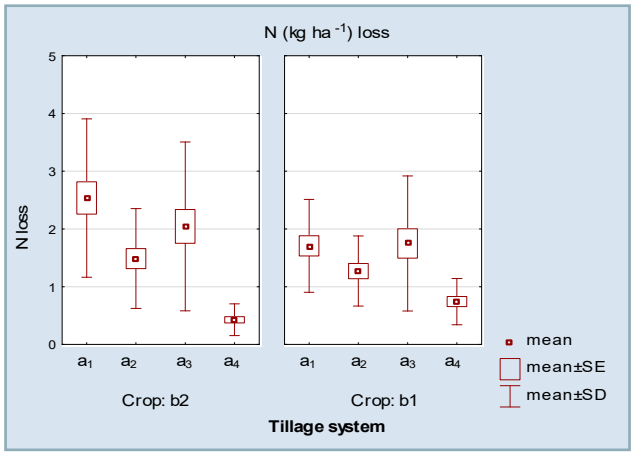


Fig. 2 Mineral N losses (kg.ha^{-1}) for four soil tillage systems (a_1–a_4), for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage $p = 0.0000$; crop $p = 0.053$

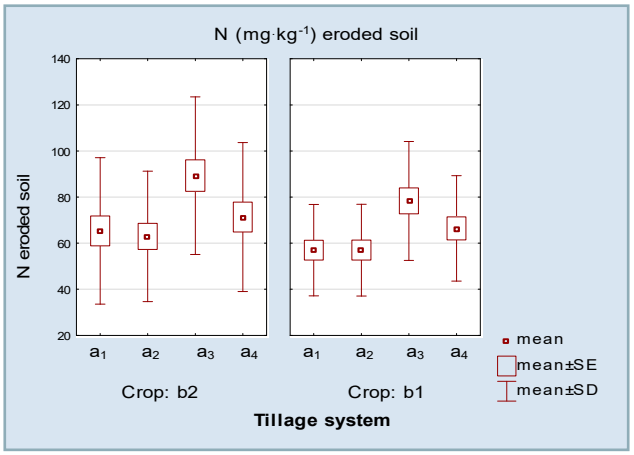


Fig. 3 Concentrations of $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ (mg.kg^{-1}) in eroded soil for four soil tillage systems (a_1–a_4), for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage $p = 0.0000$; crop $p = 0.066$

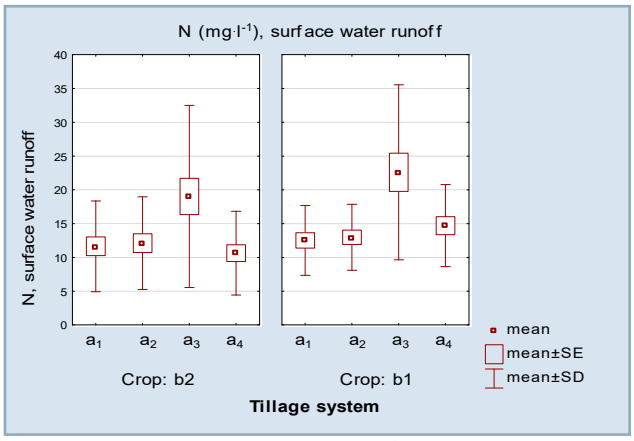


Fig. 4 Concentrations of N-NO_3^- (mg·l^{-1}) in surface water runoff for four soil tillage systems (a_1–a_4), for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage $p = 0.00000$; crop $p = 0.061$

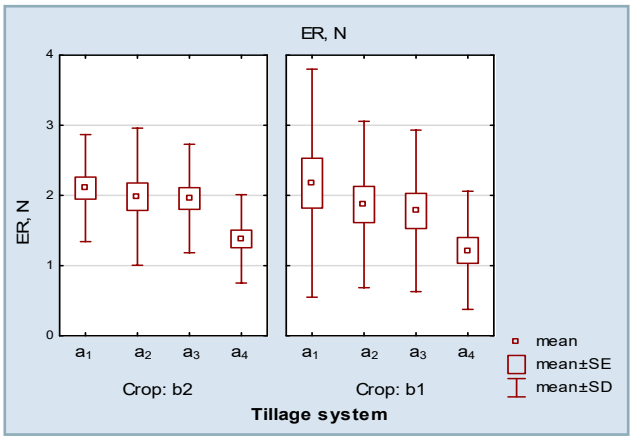


Fig. 5 Sediment enrichment ratio ER, N for four soil tillage systems (a_1–a_4), for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage $p = 0.00095$; crop NS

Sediment enrichment ratio for nitrogen was lowest for the variant with vertical mulching, because the manure was applied into the soil, not on its surface (Fig. 5).

The loss of available forms of phosphorus occurred with both surface water runoff and eroded soil (Kuncheva and Dimitrov, 2020). Regarding the wheat cultivation, approx. 50–70% of the available P loss was adsorbed onto the soil particles and the rest of this loss was due to surface water runoff. In maize cultivation on sloping terrains, 20–55% of the available P was removed with solid runoff. Considering the conventional tillage, the losses were mostly associated with eroded soil (approx. 50–60% of the total losses). On the other hand, when employing the minimum tillage, available forms of P were displaced with solid runoff – approx. 20% of the total losses on average (Fig. 1, Table 3, Table 4).

As it is evident from Figs 6–9, considering the available forms of P, higher concentrations of P_2O_5 were observed in wheat contrarily to the mineral N. This phenomenon was observed both in eroded soil and in surface water runoff. This can be explained by differences in application of fertilizers in observed crops. Similarly, to surface mulching variants, when employing the minimum tillage with vertical mulching in wheat cultivation, the available P concentrations in eroded soil showed higher values in contrast to plots treated with conventional technology. Regarding especially the minimum tillage application in wheat cultivation, mixing the phosphorus fertilizers with soil might not represent a sufficient solution, as it can cause the fertilizer to remain in the surface layer, which makes it easier to leach out. In relation to maize experiment, the last tillage variant showed no increase in the available P concentrations in eroded soil.

In spite of the higher concentrations in the liquid and solid runoff, there were observed lower P losses in wheat cultivation. Furthermore, the highest P losses occurred in the variants cultivated utilizing conventional tillage along the slope in experiments with both crops. The available P concentration in surface water runoff in wheat was higher in contrast to maize (Fig. 9), however, the ER for P was observed higher in maize (Fig. 10).

Based on the analyses of variance, the results indicate the influence of cultivated crop and tillage system on

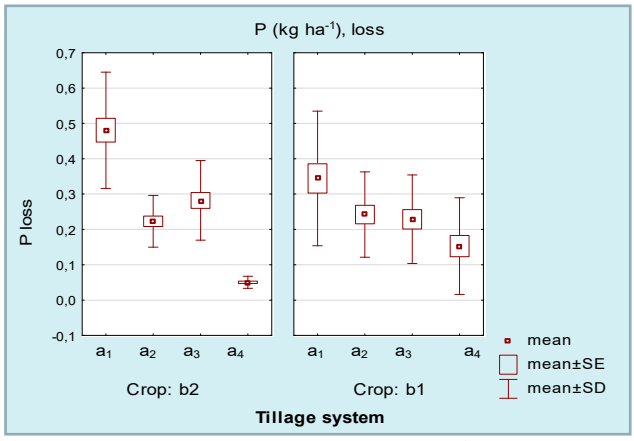


Fig. 6 Loss of available P form P_2O_5 (kg·ha^{-1}) for four tillage systems (a_1–a_4) for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage $p = 0.00011$; crop $p = 0.00345$

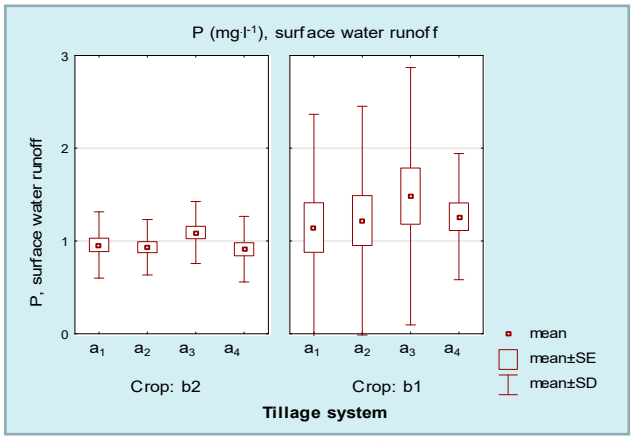


Fig. 7 Concentration of P_2O_5 (mg·l^{-1}) in surface water runoff for four tillage systems (a_1–a_4) for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage NS; crop $p = 0.0129$

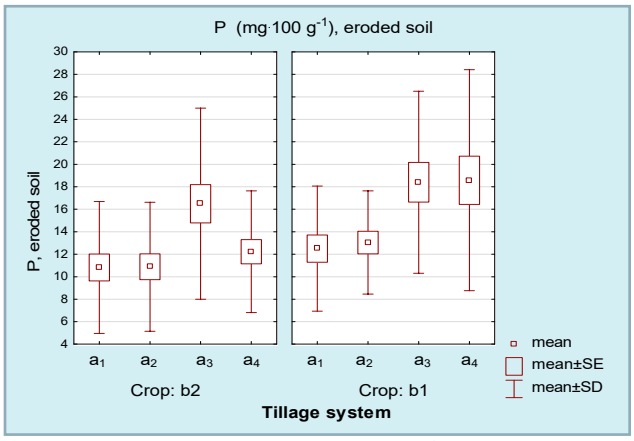


Fig. 8 Concentration of P_2O_5 (mg·100 g^{-1}) in eroded soil for four tillage systems (a_1–a_4) for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage $p = 0.00000$; crop $p = 0.003$

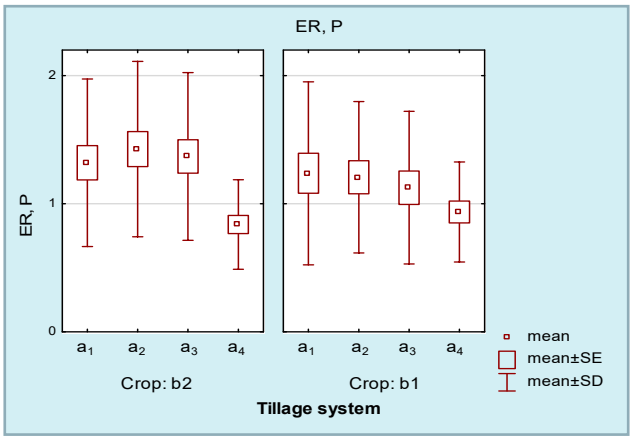


Fig. 9 ER, P (sediment enrichment ratio P_2O_5) for four tillage systems (a_1–a_4) for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage $p = 0.00198$; crop NS

the available P losses and available P concentrations in the eroded soil; the stronger influence was showed by the technology applied. The tillage system did not show a statistically significant impact on the available P concentration in the surface water runoff (Fig. 7). The same is true in terms of the impact of cultivated crop on the ER ratio for the available P (Fig. 10).

Considering the available forms of potassium in cultivation of maize for grain, its displacement was examined with both surface water runoff (approx. 50%) and eroded soil for variants with the conventional tillage employed along the slope. In case of variant with conventional tillage employed across the slope, approx. 60% of the available K was removed due to surface water runoff. In regard to the variants treated utilizing surface mulching and variants employing advanced technologies for minimum and unconventional tillage, the amount of K leached with the surface water runoff was 62–65% and 70–75%, respectively, of the total losses of available K due to erosive rainfalls occurring in 2012–2017 (Fig. 1).

The concentration of available K forms was higher in the surface water runoff in maize cultivation; on the other hand, there was observed a higher saturation of the eroded soil with this K in wheat cultivation (Fig. 11, 12).

In variants with the minimum tillage with vertical mulching applied in wheat cultivation, the available K concentrations in the eroded soil and the liquid runoff (Fig. 11, 12) were higher compared to the concentrations in variants grown with conventional technology, as well as to the variants with surface mulching (a_3). This is probably due to insufficient mixing of fertilizers with the soil in the application of minimum tillage. The influences of the crop on K losses, ER (Fig. 10, 13) and its concentration in liquid and solid runoff were not statistically significant. Nevertheless, the tillage system influence proved to be significant only in terms of the total K losses.

The results of the experiments show that the loss of nutrients due to water erosion processes depends significantly on the adopted system of tillage (Bertol et al., 2007; Muukkonen et al., 2009, Meena et al., 2017). Water erosion causes loss of nutrients and organic matter, and the

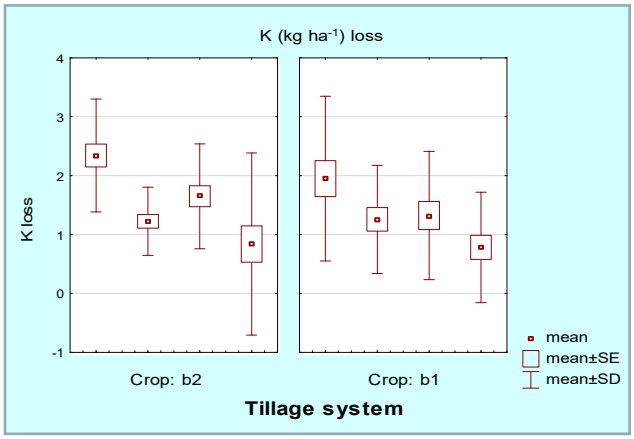


Fig. 10 Loss of available K form K_2O (kg·ha^{-1}) for four tillage systems (a_1–a_4) for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage $p = 0.00000$; crop NS

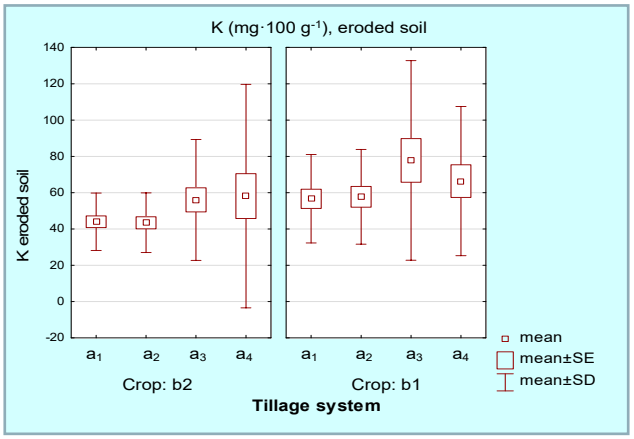


Fig. 11 K_2O concentration (mg·l^{-1}) in eroded soil for four tillage systems (a_1–a_4) for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage $p = 0.0854$; crop $p = 0.0113$

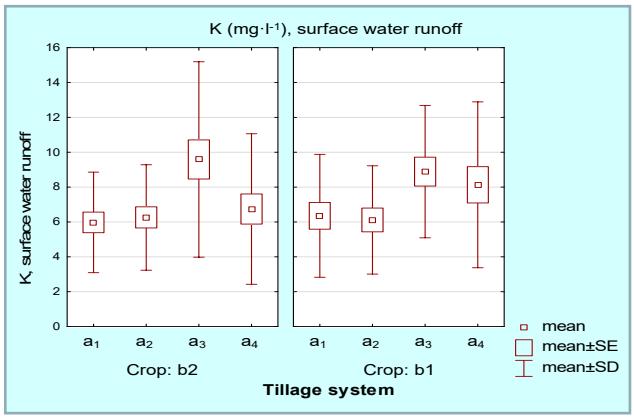


Fig. 12 K_2O concentration (mg 100 g^{-1}) in surface water runoff for four tillage systems (a_1–a_4) for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage p = 0,0005; crop NS

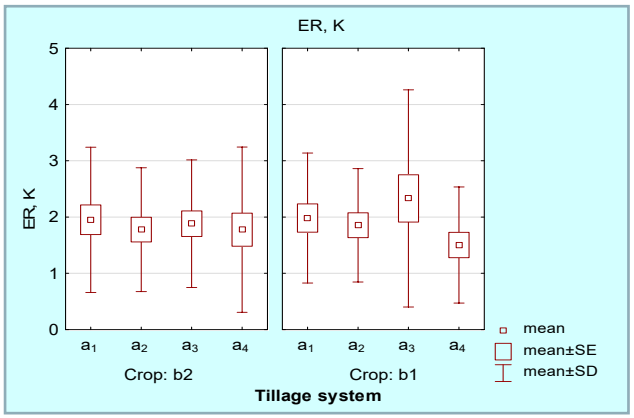


Fig. 13 ER K (sediment enrichment ratio, K_2O) for four tillage systems (a_1–a_4) for two crops (b1 – wheat, b2 – maize) throughout the period 2012–2017
ANOVA, tillage NS; crop NS

most severe is the negative impact of using conventional tillage (Bertol et al., 2007). Conservation tillage systems help to reduce soil erosion and nutrient losses to much lower levels (Meena et al., 2017; Govers et al., 2017).

Minimum tillage operations led to lower soil losses, reduced surface water runoff and macronutrient losses. On the contrary, conventional tillage applied along the slope accelerated the loss of soil and nutrients. The application of minimum tillage with vertical and surface mulching led to an increase in nutrients in eroded soil and surface water runoff, but this did not increase the loss of elements due to the higher erosion control efficiency of applied technology. The ERs were the highest for available potassium and the lowest for available phosphorus. In the case of nitrogen and phosphorus, ERs were lower in the last variants with the application of minimum tillage and vertical mulching in contrast to the other variants. This was due to the application of manure or compost in vertically made slots (intra soil), combined with minimum tillage and despite the increased amounts in the eroded soil and in the surface water runoff in these variants, the nutrient concentrations measured in the soil were higher than in variants cultivated conventionally or utilizing surface mulching.

According to Lemma et al. (2017), the nutrient loss difference between study areas was due to the different amounts of nutrients in the soils and depended less on the amount of eroded soil. In the experiments presented, the loss of nutrients depended most strongly on the loss of soil. The element concentrations in soil did not have a significant effect on N and K losses but had a significant effect on P losses. In the variants with minimum tillage and vertical mulching, high concentrations of P and K were recorded in the surface water runoff and eroded soil in wheat cultivation. This is probably due to the insufficient mixing of fertilizers when applying minimum tillage with direct sowing and their easier removal with water flow. Such a conclusion on zero tillage was also achieved by Muukkonen et al. (2009). The authors came to conclusion that zero tillage is an effective method of reducing erosion and P losses with soil particles, however, the accumulation of P in the upper soil layer and the increased risk of its leach with surface runoff decrease the environmental benefits of zero tillage. In order to prevent soil erosion and the removal of available forms of phosphorus, uniform water penetration through improved soil structure should be ensured (Muukkonen et al., 2009).

Conclusion

Employment of minimum tillage and vertical mulching (advanced technology for minimum and unconventional tillage) for cultivation of wheat and maize on sloping terrains helps to reduce soil loss and surface water runoff and preserves nutrients and soil fertility. The research presented shows that the highest losses of soil and volume of surface water runoff, as well as the largest macronutrient losses, were recorded in variants cultivated under conventional tillage technology applied along the slope.

The macronutrient concentrations in surface water runoff and eroded soil were higher when the soil surface had been treated with organic materials (manure and compost), which led to the enrichment of top surface soil layer.

Furthermore, the lower macronutrient losses in variants treated utilizing soil protection technology is a result of their erosion control efficiency, the lower amount of eroded soil and the reduced volume of surface water runoff.

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