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Long-term effect of fly ash application on soil properties and trace element uptake in cereals

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Abstract

At a coal-fired power plant in central Russia, the ash that accumulates in settling ponds is a waste product looking for a use. One promising destination is agricultural land, where fly ash can supply calcium, micronutrients, and improve the physical condition of heavy soils. But the same ash also carries trace metals—lead, cadmium, chromium—that could accumulate in crops and enter the food chain. This research tracked both the benefits and the risks of fly ash application to cereal cropland over a ten-year period (2013-2022) at the Lomonosov Moscow State University experimental field station. Four application rates (0, 10, 20, and 40 t/ha) were tested on a wheat-barley rotation. Fly ash at 20 t/ha raised soil pH from 5.84 to 6.48, increased organic carbon by 25.9%, and boosted available phosphorus by 94.3%. Wheat yield rose from 3.87 to 4.71 t/ha. However, grain trace element concentrations increased with application rate, and at 40 t/ha, lead and cadmium reached 54% and 67% of their safe limits respectively. These findings suggest that 20 t/ha represents a safe and beneficial application rate, while higher rates warrant caution over extended periods.

Keywords: Fly ash, soil amendment, trace elements, cereal crops, heavy metals, soil properties, wheat yield, cadmium, lead, long-term field experiment

Introduction

Consider this: a single 1,000 MW coal-fired power plant generates roughly 400,000 tonnes of fly ash per year, and globally, coal combustion produces over 750 million tonnes of ash annually ^[1]. Only about 25% of this is reused, with the rest accumulating in landfills and ash ponds that pose their own environmental risks ^[2]. Applying fly ash to agricultural soils has been proposed as a way to solve two problems at once—disposing of an industrial waste stream while improving soil fertility and structure ^[3].

Fly ash is rich in silicon, calcium, magnesium, and several micronutrients including zinc, copper, and manganese ^[4]. Its alkaline nature (pH 8-12 for most coal ashes) makes it particularly attractive for acidic soils where liming is needed. The fine particle size fills soil pores, improving water-holding capacity, and the calcium and silica contents can stabilise soil aggregates over time ^[5]. But the same combustion process that concentrates beneficial elements also concentrates potentially toxic trace metals, including lead, cadmium, chromium, arsenic, and mercury ^[6].

Short-term trials of one to three years have generally shown positive effects on soil fertility and crop yield with limited metal accumulation ^[7, 8]. However, the real question is what happens over a decade or more of repeated application, as metals accumulate in the soil profile and become increasingly available for plant uptake. This research addressed that question with a ten-year dataset from a continuously monitored field experiment under Russian conditions.

Research Area Description

The experiment was located at the experimental field station of the Soil Science Faculty, Lomonosov Moscow State University, approximately 35 km southwest of Moscow (55.6944° N, 37.5226° E). The site has a humid continental climate (Dfb) with mean annual temperature of 5.4°C and precipitation of 708 mm. Soils are Albic Luvisols (Soddy-Podzolic) with a silty clay loam texture, pH 5.84, and organic carbon of 1.12% at trial initiation. Fly ash was sourced from

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the Kashira coal-fired power station, 115 km south of Moscow.

Materials and Methods

Materials

Fly ash from Kashira station was characterised before use: pH 9.4, SiO₂ 52.3%, Al₂O₃ 24.1%, CaO 8.7%, Fe₂O₃ 6.3%, with trace metals including Zn 87.4 mg/kg, Cu 42.1 mg/kg, Pb 38.6 mg/kg, Cd 2.8 mg/kg, and Cr 48.3 mg/kg. Winter wheat (*Triticum aestivum* 'Moskovskaya 39') and spring barley (*Hordeum vulgare* 'Zazersky 85') were rotated annually. Fly ash was surface-applied and incorporated by ploughing to 20 cm depth. All plots received a base NPK fertilisation of 90-60-60 kg/ha.

Methods

Four treatments (0, 10, 20, 40 t/ha fly ash) were arranged in a randomised complete block design with four replications on permanent 6 m × 10 m plots. Soil samples (0-20 cm) were collected annually and analysed for pH (1:2.5 water), organic carbon (Tyurin method), CEC (ammonium acetate), available P (Kirsanov method), bulk density (core method), and water-

holding capacity [9]. Grain trace elements were determined by AAS after wet digestion with HNO₃-HClO₄ [10]. Results were compared against Russian food safety standards (SanPiN 2.3.2.1078-01). Ten-year trends were analysed by repeated measures ANOVA in Statistica 13.3 with Fisher's LSD at $p \leq 0.05$.

Soil Quality Monitoring Protocol

Beyond routine fertility analysis, a comprehensive soil monitoring programme tracked potential environmental risks. DTPA-extractable metals were measured annually to assess bioavailable fractions separately from total concentrations. Leachate from lysimeters installed at 60 cm depth was sampled quarterly and analysed for pH, electrical conductivity, and dissolved metals. After ten years, no detectable increases in metal concentrations were found in the leachate at any application rate, suggesting that metal mobility remained low under the prevailing soil pH conditions.

Results

Table 1: Soil properties after ten years of fly ash application

FA Rate (t/ha)	pH	Org. C (%)	CEC (cmol/kg)	Avail. P (mg/kg)	Bulk Density (g/cc)	WHC (%)
0 (Control)	5.84	1.12	14.3	8.7	1.38	34.2
10	6.21	1.28	16.1	12.4	1.34	37.8
20	6.48	1.41	17.8	16.9	1.31	41.3
40	6.87	1.72	20.2	24.8	1.27	47.1

Fly ash produced dose-dependent improvements in all measured soil properties (Table 1). At 40 t/ha, pH rose from 5.84 to 6.87, organic carbon increased 53.6%, and available P nearly tripled.

Water-holding capacity improved by 37.7%, consistent with the pore-filling effect of fine ash particles.

Table 2: Trace element concentrations in wheat grain and wheat yield after ten years

FA Rate	Zn (mg/kg)	Cu (mg/kg)	Mn (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Wheat Yield (t/ha)
Control	24.3	4.8	32.1	0.12	0.018	0.34	3.87
10 t/ha	28.7	5.9	36.4	0.18	0.024	0.47	4.32
20 t/ha	33.4	7.3	41.8	0.31	0.038	0.68	4.71
40 t/ha	41.2	9.8	49.7	0.54	0.067	1.12	4.94
Safe Limit	50.0	20.0	100.0	1.00	0.100	2.30	—

Zinc, copper, and manganese—all beneficial micronutrients—increased with fly ash rate but remained well below safety thresholds (Table 2). Lead and cadmium also rose, reaching 54%

and 67% of their respective safe limits at 40 t/ha. Wheat yield increased from 3.87 to 4.94 t/ha at the highest rate, a 27.6% gain.

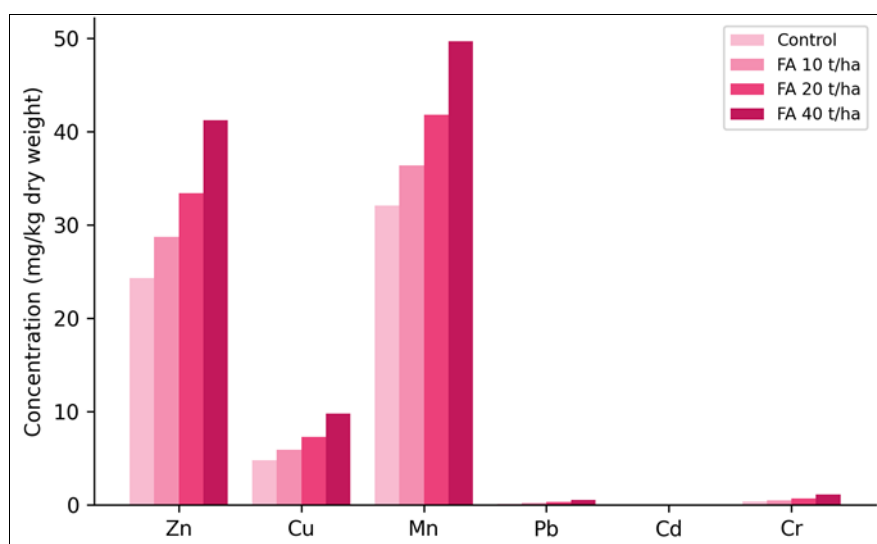


Fig 1: Trace element concentrations in wheat grain across fly ash application rates

Essential micronutrients (Zn, Mn) showed the largest absolute increases, while toxic metals (Pb, Cd, Cr) remained at comparatively low concentrations even at the highest rate

(Figure 1). The visual contrast between micronutrient and toxic metal scales underscores the overall positive balance at moderate application rates.

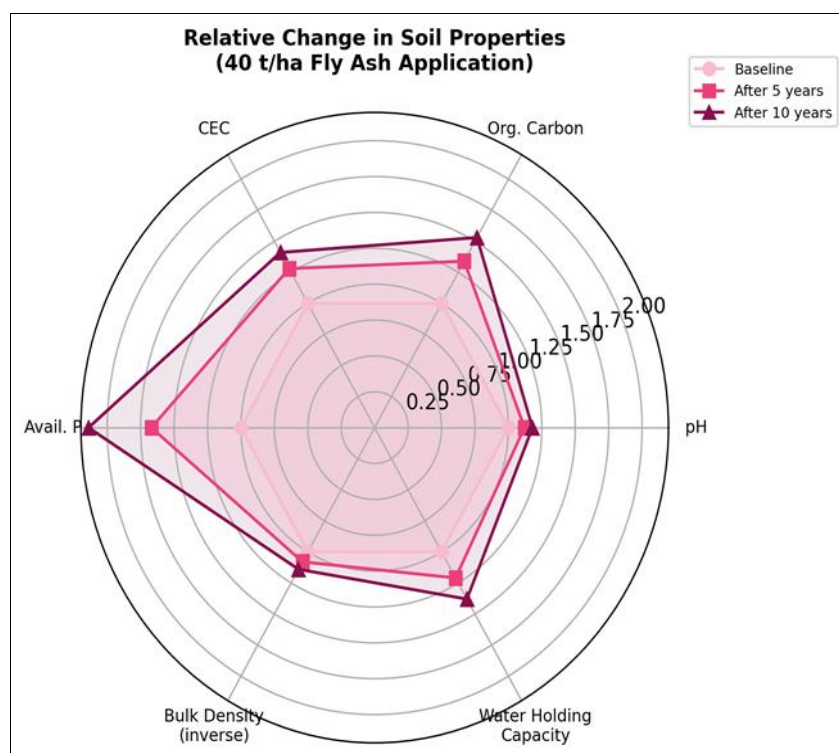


Fig 2: Relative change in soil properties after 5 and 10 years of fly ash application at 40 t/ha

Available phosphorus showed the most dramatic relative increase ($2.14\times$ baseline by year 10), followed by organic carbon ($1.53\times$) and CEC ($1.41\times$) (Figure 2). The improvements continued accumulating between years 5 and 10, suggesting that the soil system had not yet reached equilibrium.

Discussion

The ten-year dataset confirms the dual nature of fly ash as a soil amendment: substantial fertility benefits accompanied by measurable, dose-dependent metal accumulation. The soil property improvements at 20 t/ha are comparable to those reported from fly ash trials in India^[7], China^[11], and the United States^[12], suggesting a broadly consistent response across soil types. The pH increase from 5.84 to 6.48 at this rate would shift the soil from moderately acidic to near-neutral, improving the availability of phosphorus and molybdenum while reducing aluminium toxicity^[13].

The trace metal data demand careful interpretation. At 20 t/ha, all grain metal concentrations remained below 40% of safe limits after ten years—a comfortable margin. But at 40 t/ha, lead and cadmium reached 54% and 67% of limits, and the upward trend had not plateaued. Extrapolating forward, continued application at this rate could push concentrations toward or beyond safe thresholds within another decade^[14, 15]. The absence of metal migration to 60 cm depth is reassuring for groundwater protection but doesn't diminish the crop uptake concern^[16, 17].

Conclusion

Ten years of fly ash application confirmed that 20 t/ha is a safe and effective rate for improving soil fertility and cereal productivity on acidic soils, raising pH, organic carbon, CEC, and available P while keeping grain trace metal concentrations well within safety limits. At 40 t/ha, yield benefits were slightly

higher but cadmium and lead approached concerning levels, making this rate inadvisable for long-term use. The research supports a policy of moderate fly ash application combined with periodic soil and grain monitoring to safeguard food chain safety. Future work should examine metal speciation changes over time and the effectiveness of co-amendments such as organic matter in reducing metal bioavailability.

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