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Mobile Phosphorus Presence of Typical Chernozems on Fertiliser System

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Abstract. Due to the systematic utilisation of substantial amounts of phosphorus fertilisers on agricultural crops in crop rotation, the amount of available phosphate compounds increases in the soil. It ensures the maximum increase in crop yields. The study of the phosphate level in chernozem soils in various agrocenoses is really up-to-date. The gist of our research was to determine the specifics of providing mobile phosphorus in typical chernozem in field crop rotation, especially in sunflower, varying according to fertilisation systems in the forest-steppe zone of Ukraine. The assessment of mobile phosphorus content was conducted using the Chirikov method, which involves extracting mobile phosphorus compounds from the soil using a solution containing acetic acid (CH_3COOH) at a concentration of 0.5 mol dm^{-3}, with a soil–to–solution ratio of 1:25. Phosphorus was determined with the spectrophotocolorimetric method, which is based on the colour intensity of the phosphorus-molybdenum complex.

Our investigations showed that the typical low-humus chernozems have considerable reservoirs of potentially exploitable phosphorus for plant nourishment. We established that the mineral and organic-mineral fertilisation system leads to a greater use of mobile phosphorus with agricultural crops of crop rotation resulting in the formation of elevated phosphate content in the chernozem soil. By the end of the second rotation, the organic-mineral fertilisation system variant displayed the greatest concentration of mobile phosphorus within the 0–25 cm soil depth, marking a surge of 15.6 mg kg^{-1} compared to the unfertilised variant. In the period of sunflower germination, the content of mobile phosphates increased in the soil layers at depths of 0–25 cm and 25–50 cm in the variant of the mineral fertilisation system on 17.6 and 22.2 mg kg^{-1} of soil compared to the alternative without the fertiliser.

In the sunflower's ripening period, the mobile phosphorus concentration in the soil at 0–25 cm depth increased significantly in the variant of organic-mineral fertilisation system by 12.0 mg kg^{-1} and mineral fertilisation by 14.7 mg kg^{-1} of soil if compared with the variant lacking the fertiliser. In the variant of the mineral fertilisation system, the amount of mobile phosphorus increased in the 0–30 cm soil depth by 18.7 mg kg^{-1} of soil in two crop rotations compared to the beginning of the first crop rotation.

Key words: sunflower, fertilisation system, crop rotation, soil, phosphorus.

Introduction

Phosphorus (P) stands as a key nutrient element for plants. Although the total phosphorus content may be substantial, only a part of it is accessible for absorption by plants (Khristenko, 2015). However, given the limited global reservoir of phosphorite used in the phosphate fertiliser production and the high costs associated with it, its use should be judiciously managed. Moreover, excessive application of phosphorus fertilisers, leading to elevated levels of plant-available phosphorus, may yield minimal to no additional benefits (Syers et al., 2008; Hryhoriv et al., 2022a). Over the long term, the utilisation of optimal fertilisation systems results in a gradual and eventual stabilisation of the agrochemical state. In the chernozem zone, the combined factors of soil

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fertility and fertiliser provision play a crucial role in determining phosphorus availability to plants (Rieznik *et al.,* 2021; Baluk *et al.,* 2018). Due to the centuries of human heedless agriculture, the chernozem soils are exhausted and phosphorus has to be added (Hospodarenko *et al.,* 2022).

The problem of phosphorus in agriculture is quite relevant even today. The level of phosphates in soils stands as a crucial determinant of their fertility (Vasbieva et al., 2021; Nosko, 2017; Miroshnychenko et al., 2021). The optimisation of phosphorus application by plants to achieve high yields relies on factors such as soil reserves, mobility, and various conditions affecting absorption (Hryhoriv et al., 2022b; Tkachenko et al., 2023). The evidence demonstrating changes in phosphorus content in typical chernozem soils over years of fertiliser application serves as the foundational premise for the efficient utilisation of fertilisers in the Ukrainian forest-steppe region (Voitovyk *et al.,* 2023a, 2023b). The inherent capacity of this type of soil to supply plants with phosphorus serves as the foundational basis for developing fresh guidelines aimed at the prudent application of expensive phosphorus fertilisers for the region. The gist of our research was to determine the specifics of providing mobile phosphorus in typical chernozem of field crop rotation and especially in sunflower agrocenosis, depending on fertilisation systems in the forest-steppe of Ukraine.

Our research aimed to characterise the phosphate status of typical chernozem soils, identifying trends of alteration influenced by organic, mineral, and organic-mineral fertilisation systems. Additionally, we evaluated phosphate content in agrocenoses across various fertilisation systems within a 5-field crop rotation.

Materials and Methods

The study was conducted between 2012 and 2021 at the experimental field of the National Agrarian University in Bila Tserkva. The soil type studied is a deep low-humus chernozem. The content of humus is 3.7–3.9%, hydrolysed nitrogen is 110 mg kg^{-1} of soil, mobile plant available phosphorus and exchangeable potassium becomes 120–110 mg kg^{-1} of soil. The soil acidity is near to neutral (pH is 6.0–6.4), the sum of absorbed alkaline was on – 23.8–27.2 mg 100 g^{-1} of soil. The soil's density was 1.16–1.25 g cm^{-3}, and the total porosity is 52–55%.

The climate is temperately continental. The average air temperature is 20 °C. The average temperature in January ranges between 7–8 °C, with the lowest recorded temperature reaching minus 20.5 °C. The active temperatures total sum is 2800–3000 ^{o}C (5072–5432 °F). The annual rainfall amount is 500–550 mm, with a significant amount of precipitation from April to September.

The experiment was on crop rotation with crops such as: alfalfa – winter wheat – sugar beets, sunflower – buckwheat – barley + alfalfa. Sunflower was the test crop.

The scheme of the experiment provided for the study of the following variants: without fertilisers (WF). In the Organic system (O), 8.0 tonnes of cattle manure per hectare of crop rotation area and 3.0 tonnes of non-harvested crop residue, in the form of green manure, are used. The total amount of the organic matter was $N_{45}P_{30}K_{60}$. The amount of organic fertilisers applied is established according to the need to maintain a favourable humus (Moiseichenko & Yeshenko, 1994).

In the Organic-mineral system (OM), priority is given to organic fertilisers for soil fertility restoration. This system involves the application of 8.0 tonnes of cattle manure per hectare of crop rotation area along with 3.5 tonnes of green manure +110 kg mineral fertilisers that was $N_{27}P_{38}K_{45}$.

The Mineral system (M) entails the use of 8.0 tonnes of cattle manure and 222 kg ($N_{68}P_{72}K_{82}$) of mineral fertilisers per ha within the crop rotation zone. The sum of nutrient elements became $N_{113}P_{92}K_{130}$ kg.

Fertiliser calculations were derived from the initial quantity of readily available nutrients in the soil, alongside tailored to the specific requirements of the plants. The cattle manure served as the organic fertiliser, with an average nutrient content of nitrogen (N) at 13.0 g kg^{-1}, phosphorus (P) at 7.2 g kg^{-1}, and potassium (K) at 7.1 g kg^{-1}. In autumn, the organic fertilisers were spread across the field surface prior to deep ploughing, at a rate of 40 tonnes per hectare under sugar beet and sunflower crops.

Among the mineral fertilisers used were ammonium nitrate, simple granulated superphosphate, and potassium chloride. Mineral fertilisers were integrated into the soil during pre-sowing preparation for grain crops. In fields with sunflower and sugar beets, phosphorus-potassium fertilisers were applied in autumn. Winter cereals were fertilszed twice with nitrogen fertilisers: the first time in early spring and the second time at the onset of emergence of a plant. The experiment comprised three repetitions, systematically distributed across the area, with fertilizer variants sequentially assigned. The sown plot covered an area of 171 m^{2}, while the accounting plot spanned 112 m^{2}. Standard agricultural practices for crop cultivation in the zone were followed.

After harvesting the wheat, the leftover straw was crushed and integrated into the soil with a disc harrow. Then, the soil was readied for planting white mustard on the siderite mass+. Finally, from late September to early October, the mustard plants remaining after harvest were incorporated into the soil across all experimental variations. Soil samples were collected throughout the research years from layers ranging from 0–25 cm, 25–50 cm, 50–70 cm, to 70–100 cm in each experimental variant, using a specialised soil drill with a diameter of 5 cm. Three sampling points were selected within each variant. The collected soil samples were air-dried and passed through a 2 mm sieve to facilitate the determination and analysis of mobile phosphorus content in the soil.

The mobile phosphorus content was assessed using the Chirykov method (DSTU 4115:2002), specifically designed for chernozem soils. This method involves the mobile phosphorus compounds retrieval from the soil using a solution of acetic acid with a concentration of 0.5 mol dm^{-3}, with a soil-to-solution ratio of 1:25. Phosphorus levels were determined using a spectrophotocolorimeter based on the colour intensity of the phosphorus-molybdenum complex.

The statistical analysis of the data was performed using Statistica PL software. Two–way analysis of variance (ANOVA) and Fisher's mean distribution were used to ascertain statistical significance at $p < 0.05$. Additionally, the linear correlation coefficient was calculated at a significance level of $p < 0.05$ for all parameters under study.

Results and Discussion

Towards the conclusion of the second rotation, a trend of declining mobile phosphate content in the soil layers of 0–25 cm and 25–50 cm was observed in the variant without fertilisers (Figure 1). It's explained with the use of mobile phosphorus with crops of crop rotation and less replenishment of the soil and mineralisation of root residues and due to soil reserves. If a certain part of soil phosphorus is used by crops, the same part will increase from the soil solution (Naik *et al.,* 2020).

The consistent utilisation of substantial quantities of phosphorus fertilisers in agricultural crops in crop rotation, the amount of available phosphate compounds in the soil increases. It provides the maximum increase in the crop's harvest (Lisoval & Kovalenko, 2002).

A special place among the soil factors that affect the effectiveness of fertilisers is given to the content of mobile phosphorus because of its low dynamics and ability to accumulate for fertilisers. Along with mineral fertilisers, the increase in the phosphate savings of chernozem soils is largely influenced by organic fertilisers, which markedly elevate the concentration of mobile phosphorus in the soil (Soltangheisi *et al.,* 2020). The optimal phosphate regime of chernozem soils is formed using an organic-mineral fertilisation system (Ivanina *et. al.,* 2013; Schneider *et. al.,* 2019).

The organic fertilisation system caused insignificant increase in the mobile phosphorus concentration in the layers 0-25 cm and 25–50 cm when compared with the variant without fertilisers. The highest level of mobile phosphorus was obtained from the organic-mineral system. At the conclusion of the second rotation, at depth 0-25 cm the mobile phosphorus concentration increased by 15.6 mg kg^{-1} compared to the control variant.

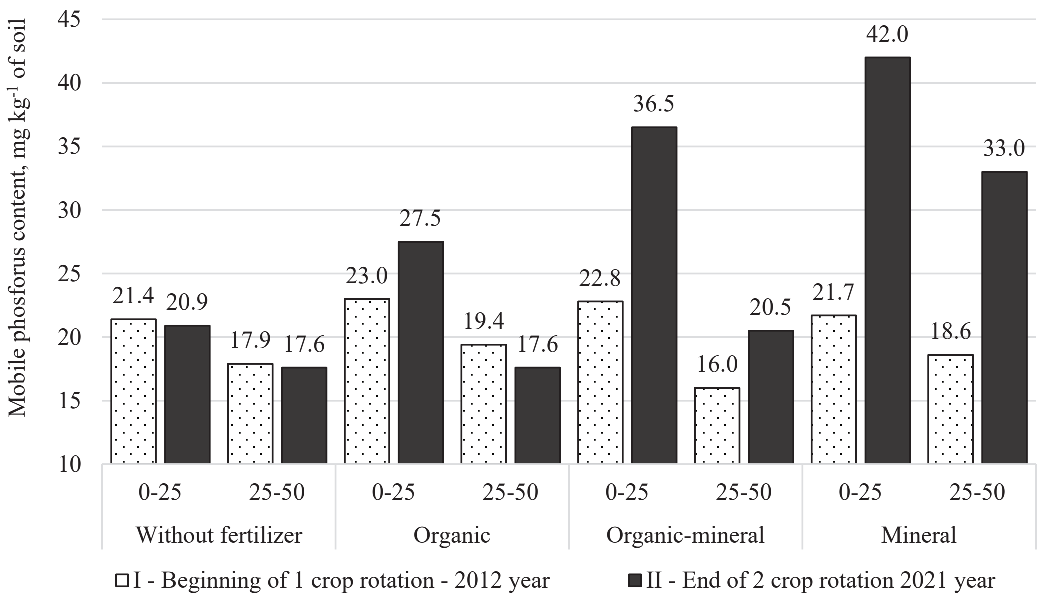
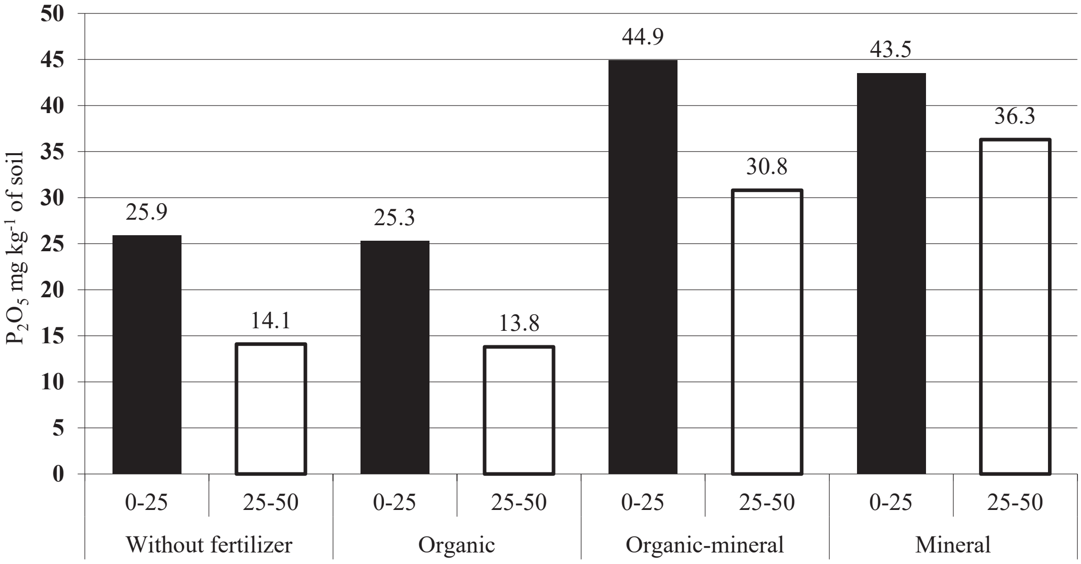


Figure 1. Mobile phosphorus content in crop rotation depending on fertilisation systems, mg kg^{-1} of soil.



LSD_{05} (0-25)=3.3 for soil layer; LSD_{05}(25-50)=2.7

Figure 2. Mobile phosphorus content in chernozem, typical for the period of sunflower germination for the 2 rotations (2012–2021), depending on the fertilisation system, mg kg^{-1} of soil.

Meanwhile, the use of a mineral fertiliser system results in a notable rise in mobile phosphorus content in the soil layer of 0–25 cm by 21.1 mg kg^{-1} compared to the variant without fertiliser. This depended on the removal of phosphates with agricultural crops and the rates of fertiliser application. As the rates of fertiliser application increase, the phosphorus content in the arable and sub–aerial soil's horizons increased.

Although the phosphorus content in the soil is determined as an important indicator of its total supply, it does not allow us to make a conclusion about the supply of this element to plants. It's necessary to know the content of mineral available forms of phosphates to plants. Mobile phosphates are represented not only by forms that can be assimilated by plants, but also by those that pass relatively quickly into the soil solution and constitute a reserve for replenishing phosphorus sources for plant nutrition. It's the most valuable. These include forms of soil phosphates that participate in the processes of phosphorus transition from solid phases to solution, and the vice versa. The mobility or ability of the solid soil's phase to release phosphorus ions into the soil solution is characterised as phosphate potential (Nosko, 2017; Kamanskyi *et al.,* 2022; Silva *et al.,* 2023).

The use of phosphorus fertilisers immediately increases their soil stores and increases the content of soluble phosphates as the concentration of phosphorus in the soil solution. If this growth is not sustained for a long period, the introduced phosphorus will turn into stable immobile compounds (Medinski *et al.,* 2018).

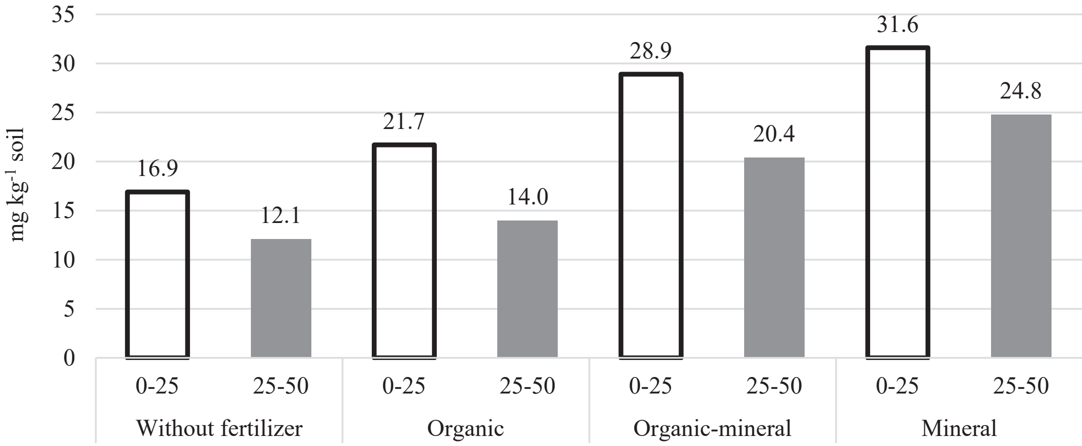
Our research has established that for the organic fertilisation system in the sunflower, the amount of mobile phosphates did not change during germination compared to the variant without fertilisers. On our variants, the temperature was caused the slow mineralisation of organic fertilisers and as a result – the entry of phosphorus into the soil (Figure 2) as reference of the literature.

The application of both organic and mineral fertilisers led to a substantial increase in phosphorus content during the sunflower germination period in the 0–25 cm soil layer, reaching 44.9 mg kg^{-1} of soil. It was 73% more than in the variant without fertilisers. Such a regularity was found for the mineral fertiliser system.

During the period of sunflower germination, the highest concentration_of mobile phosphates in soil's layer 0–25 cm and 25–50 cm was observed for the mineral fertilisation system of 43.5 and 36.3 mg kg^{-1} of soil, which is 17.6 and 22.2 mg kg^{-1} more than the control variant. And the organic-mineral variant provides high mobile phosphorus content as well.

Our research indicates a notable increase in the quantity of mobile plant-available phosphates in the variant where organic fertilisers are combined with mineral fertilisers (Voitovyk *et al.,* 2023a). It depends on biochemical, microbiological processes during the mineralisation of organic substances (Zaryshnyak *et al.,* 2015; Radchenko *et al.,* 2023).

At the conclusion of the sunflower growing season, the mobile plant available phosphates phosphorus



LSD_{05} (0-25)=5.4; LSD_{05} (25-50)=2.5

Figure 3. Mobile phosphorus content in chernozem typical for the period of sunflower maturity depending on the fertilisation system, mg kg^{-1}, soil.

level is influenced by its uptake by plants (Figure 3). In the variants of mineral and organic–mineral fertilisers, the phosphorus content did not decrease.

During the sunflower ripening period, there was a notable increase in the mobile phosphorus concentration in the 0–25 cm soil layer for the organic-mineral fertilisation system by 12.0 mg kg^{-1} and for the mineral system by 14.7 mg kg^{-1} compared to the control variant.

If the absorption of phosphorus from applied phosphate fertilisers on all backgrounds equalised on the 130–150th day, the difference in their mobility will be saved until the end of the period. To reach a certain level of phosphorus saturation, the soil receives the ability to quickly restore the balance of soluble phosphates in the soil solution, so it's characterised by greater opportunities to meet the needs of plants in phosphate nutrition (Puzniak *et al.,* 2022; Kovalenko *et al.,* 2024).

The presence of sunflower agrocenosis with mobile phosphorus is largely related to the seasonal dynamics of this element (Voitovyk *et al.,* 2023b), which depends on humidity and temperature (Centilo *et al.,* 2018). Our studies have clearly proved it.

The studies on different types of soil showed that to increase the level of mobile phosphorus by 7 mg kg^{-1} of soil, the consumption of phosphorus fertilisers increased from 34 to 123 kg ha^{-1} (Xingzhu Ma *et al.,* 2014). On Chernozem soils, to ensure an increase in the content of mobile phosphates by 1 mg kg^{-1} of soil, Kramarev (2015) recommended applying phosphorus fertilisers at rates of 40–60 kg. It exceeded the removal of this element and largely depended on the type of soil and the level of phosphorus supplied to it.

It is difficult to obtain high yields with a low level of mobile plant available phosphorus in the soil. As a result of the problems in physiological processes, it isn't possible to achieve the proper efficiency of nitrogen and potassium fertilisers. Optimising plant phosphate nutrition, creating and maintaining an optimal concentration of phosphate ions in the soil solution is recognised as the main factor for increasing soil fertility and one of the most important conditions for obtaining high and stable yields (Schröder *et al.,* 2011; Voitovyk *et al.,* 2023c). It is seen as an important task.

Phosphorus migration into the lower soil layers was observed in fertilisation systems (Table 1). Utilising a mineral fertiliser system resulted in a substantial increase of 18.7 mg kg^{-1} in mobile phosphorus concentration within the soil layer of 0–30 cm over two crop rotations. In the 30–50 cm layer, there was a slight tendency for an increase in phosphorus content in the soil. Notably, in the 50–70 cm soil layer, a significant rise of 9.9 mg kg^{-1} of soil phosphorus was observed with the mineral fertilisation system by the end of the second rotation.

This phenomenon can be attributed to the greater migratory capability of organic phosphates compared to mineral phosphorus compounds. Additionally, in the soil layer of 70–100 cm, a significant increase in phosphorus content was recorded in the organic-mineral fertilisation system variant.

The implementation of an organic-mineral fertilisation system in the 0–30 cm soil layer resulted in an increase of 17.6 mg kg^{-1} of soil in mobile phosphate content compared to the variant without fertilisers. The maximum amount of phosphorus in the mineral fertilisation system variant was observed at a depth of 50–70 cm, where the reserves of this element amounted to 22.2 mg kg^{-1} of soil. Consistent application of both organic and mineral fertilisers

Table 1

Migration of mobile phosphorus of typical chernozem depending on fertilisation systems in crop rotation, mg kg^{-1} of soil

Fertiliser System	Period of soil's samples excavation	Content of P_2O_5, mg kg^{-1} soil in the layer			
		0–30	30–50	50–70	70–100
Without fertilisers	2012	26.4	23.8	13.4	12.0
	2021	19.8	17.6	12.2	8.9
Organic	2012	27.4	20.3	13.8	14.2
	2021	32.1	22.1	16.3	15.0
Organic –Mineral	2012	26.4	19.9	16.5	15.3
	2021	39.4	22.4	19.8	17.5
Mineral	2012	27.5	20.2	12.3	11.6
	2021	46.2	26.5	22.2	13.1
LSD_{05}	2012	4.2	$F_ф<F_{05}$	2.5	1.3
	2021	$F_ф<F_{05}$	2.7	3.9	3.8

contributes to the augmentation of phosphorus levels in the deeper soil strata.

Conclusions

The phosphate saving of typical chernozem improves depending on the fertilisation system in short crop rotations. The use of mineral and organic–mineral fertilisation systems in crop rotations influences for a greater use of mobile phosphorus by agricultural crops in rotations and the formation of a typical high phosphate content in chernozem. The highest mobile phosphorus level increased significantly in the organic–mineral fertilisation system at the end of the second crop rotation, with an increase of 15.6 mg kg^{-1} soil compared with the control variant in the soil layer of 0–25 cm. During the sunflower germination period, the mobile phosphate content increased in both the 0–25 cm and 25–50 cm soil layers in the mineral fertilisation system variant, by 17.6 and 22.2 mg kg^{-1} of soil, respectively, compared to the control variant. At the time of sunflower ripening, the mobile phosphorus concentration in the soil layer of 0–25 cm increased significantly by 12.0 mg kg^{-1} in the organic-mineral fertilisation system and by 14.7 mg kg^{-1} in the mineral system compared to the control variant. Additionally, in the mineral fertilisation system, the mobile phosphorus quantity rose by 18.7 mg kg^{-1} of soil in the 0–30 cm layer over two crop rotations.

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