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Macroplastics Quantity and Its Influence on Soil Nutrients in Typical Plastic Film Mulching Farmland in Northern Xinjiang

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Abstract: Plastic film mulching (PFM) technology plays an important role in agricultural production in "drought and cold" regions, and macroplastics pollution in farmland has become a major concern affecting the sustainable development of regional agricultural production. However, there remains a lack of research on the effects of film application and macroplastics characteristics on soil nutrients in farmland. In this study, the characteristics of plastic film application and macroplastics, and their effect on soil nutrients in typical plastic film cropland in northern Xinjiang were explored by field research and a review of the relevant literature. It was found that the average annual growth rate was higher in areas where the amount, usage intensity, and proportion of plastic film were lower. The amount of plastic film input was a key factor affecting the amount of macroplastics. The macroplastics amount of plastic film was positively correlated with soil organic carbon content and negatively correlated with soil available phosphorus; however, it had no effect on soil available potassium. It is necessary to take immediate action regarding the characteristics of plastic film application and macroplastics and the impact of macroplastics on soil nutrients, in order to establish a response to the dual challenges of food security and sustainable agricultural development in terms of plastic film pollution prevention and control measures.

Keywords: usage intensity of plastic film; loess model; plastic film covering ratio; soil available nutrients

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Citation: Jin, T.; Liu, X.; Cui, J.; Peng, J.; Liu, Q. Macroplastics Quantity and Its Influence on Soil Nutrients in Typical Plastic Film Mulching Farmland in Northern Xinjiang. *Agriculture* **2024**, *14*, 734. https://doi.org/10.3390/agriculture14050734

Received: 9 April 2024
Revised: 30 April 2024
Accepted: 4 May 2024
Published: 9 May 2024

1. Introduction

Plastic film mulching (PFM) is widely accepted as one of the important technologies used to promote the significant improvement of agricultural productivity and considerable changes in production systems, as well as to increase the adaptation area of some crops. PFM performs various functions, such as increasing the topsoil temperature, decreasing soil evaporation, inhibiting weed growth and salt accumulation, promoting earlier germination, and enhancing illumination uniformity of the crop canopy through the scattering of light [1–4]. Field experiments with large samples confirmed that the mulching technique is more effective in areas where annual precipitation is <400 mm and the >0 °C accumulated temperature is 3000–4000 °C [3]. Nationwide, PFM technology has led to a 20–35% increase in grain crop yield and a 30% increase in water use efficiency (WUE) and has played crucial roles in ensuring food security, promoting the incomes of farmers, and accelerating rural economic development of China [1,5,6]. Affected by the growth of potato, peanut, and vegetable mulching areas and the implementation of the new standard of PFM, it is predicted that in the next 20 years, the national PFM area will be maintained between 19.0 and 23.0 million hectares, with usage ranging from 1.5 to 1.9 million tons [7,8]. Meanwhile, the extensive application of PFM has brought a series of environmental pollution problems due to the lack of awareness regarding the rational use of plastic film and the absence of plastic residue recycling [7,9,10].

Numerous studies have been carried out on the application and macroplastics of PFM in typical areas [11] and in mulching farmland of different planting crops and with a different number of mulching years [12]. Previous results showed that the lower limit of macroplastics content was mainly determined by the amount of plastic film used and that the upper limit of macroplastics presence was mainly determined by the implementation of recycling measures for plastic film [8,13,14]. In addition, a large amount of plastic film remaining in farmland soil reduces soil permeability; disrupts soil structure and nutrient transfer [15–17]; and further affects the growth of crops, microorganisms, and earthworms in soil [18–20]. The direct impact of plastic film debris on soil properties, soil microorganisms, soil animals, and crops also indirectly affects a series of key soil biogeochemical processes (such as the degradation of organic matter, nutrient cycling, and greenhouse gas generation) [21,22]. Therefore, it is of great significance to study the application characteristics of plastic film, the extent of macroplastic pollution, and the overall relationship between plastic film influence on soil nutrients while ensuring agricultural production, in order to scientifically and rationally develop prevention and control measures for residual pollution from plastic film.

At present, only a limited studies have studied the effects of plastic film-derived macroplastics on soil nutrients, mainly focusing on alterations in the soil organic carbon (SOC) content and the availability of soil nitrogen and phosphorus. Some studies have shown that plastic film-derived macroplastics can associate with soil minerals or organic compounds through biological and abiotic processes, becoming protected by soil aggregates against microbial decomposition, thereby increasing the soil carbon pool [23]. This phenomenon is attributed to the lower soil organic matter (SOM) breakdown under polyethylene fragments, which is correlated with the degradation of soluble proteins and the reduction in protein bacteria abundance. Other studies showed that SOC content decreased with the quantity of macroplastics amount from plastic film [24]. In addition, studies have shown that microplastics can reduce root penetration resistance and promote root growth, thereby changing the distribution of root exudates [25]. Microplastic circles can also be formed, favoring the growth of specific microbial communities, interfering with the normal functions of microorganisms (such as phosphorus dissolution), and diminishing the interactions between plants and microorganisms [26]. These effects may result in direct or indirect impacts on soil nutrients and their availability. However, there remains a paucity of relevant studies on soil nutrients attributed to macroplastics at the farmland scale, particularly with regard to different crops, soil types, and mulch application years.

This study evaluated the characteristics of plastic film application, macroplastics, and their effects on soil nutrients in typical plastic film farmland in northern Xinjiang. We hypothesized that macroplastics may increase SOC while reducing the levels of active nutrients such as available phosphorus (AP) and potassium (AK). To test our hypothesis, we (1) explored the characteristics of plastic film application in typical plastic film cropland in northern Xinjiang, (2) investigated the characteristics of macroplastics in typical plastic film cropland in northern Xinjiang, and (3) evaluated the effects of macroplastics on SOC and available phosphorus and potassium.

2. Materials and Methods

2.1. Main Agricultural Production Data

The sown area of crops and the consumption of main agricultural energy and materials were obtained from the statistical yearbooks of typical mulching counties in northern Xinjiang from 2006 to 2021.

2.2. Macroplastics in Farmland

To quantify the amount of macroplastics in plastic film used for mulching in typical mulch farmland in northern Xinjiang, 70 survey sites in seven counties in northern Xinjiang were sampled in March 2019 (Figure 1). The sampling point interval was approximately 30 km, and for each sampling point, we selected five sample squares, 1 m × 1 m in area and 0.3 m in sampling depth. Macroplastics, defined as particles larger than 5 mm in size, were collected from the sample squares.

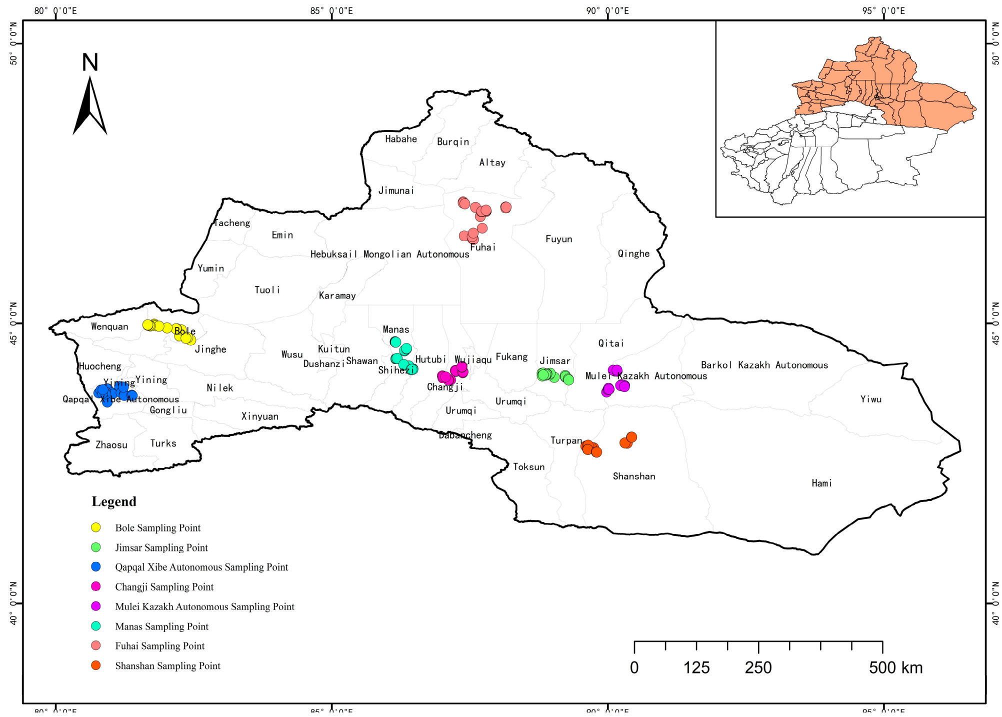

Figure 1. Locations of sampling sites.

The questionnaire mainly included information on mulched crops, the thickness of plastic film, plastic film covering ratio, years of plastic film use, and annual plastic film input.

2.3. Soil Sampling

At each sampling point, five soil samples were systematically collected from the 0–30 cm soil layer by following the prescribed W-shaped pattern (with one sample obtained at each vertex or apex of the W). Subsequently, these samples were homogenized to form a composite sample representing each soil layer within every plot. The composite samples were promptly transferred to an ice box and transported without delay to the laboratory for analysis. The determination of SOC content utilized the K_2CrO_7-H_2SO_4 oxidation method coupled with external heating. AP content was assessed through $NaHCO_3$ extraction followed by the molybdenum–antimony resistance colorimetric technique. AK content was determined via NH_4OAc extraction followed by flame photometry.

2.4. Index Calculation

The formula for calculating the usage intensity of plastic film is as follows:

$$\mathrm{IPF} = \frac{QPM}{CSA}$$

where IPF is the usage intensity of plastic film (kg·ha^{-1}), *QPM* is the amount of plastic film used (kg), and *CSA* is the sown area of crops (ha).

The calculation formula of plastic film covering ratio is as follows:

$$\mathrm{CR} = \frac{PMA}{CSA} \times 100\%$$

where CR is the plastic film covering ratio (%), *PMA* is the area covered by plastic film (ha), and *CSA* is the sown area of crops (ha).

The macroplastics amount of plastic film can be calculated as follows:

$$\mathrm{MPM} = \frac{\sum_1^n (X1 + X2 + \cdots + Xn)}{n} \times 10$$

where MPM is the macroplastics amount of plastic film (kg·ha^{-1}) and *X* is the net weight of plastic film in the survey sample (g).

The formula for calculating the averaged annual growth rate of the amount of plastic film usage, the strength of plastic film use, and the proportion of plastic film is

$$\mathrm{AAGR} = \sqrt[n]{\frac{B}{A}} - 1$$

where AAGR is the annual growth rate (%); *A* and *B* are the first and last years of statistics, respectively; and *n* is the difference between the last and first years.

2.5. Data Analysis

After preprocessing the data by using Excel 2021 (Microsoft Corporation, Redmond, DC, USA), statistical analysis and data visualization were conducted by using IBM SPSS Statistics 21 (SPSS, Inc., Chicago, IL, USA) and R 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria). Specifically, ggplot2 in R was utilized to visualize the effects of years of plastic film use and annual mulching film input on plastic film-derived macroplastics. Furthermore, ggcor in R was employed to map the application characteristics of plastic film, facilitate the pairing comparison between the amount of macroplastics and soil nutrients, and establish the relationship between the macroplastics of plastic film and soil nutrients. Additionally, the loess function within the stats package of R software was used to model the relationship between the macroplastics of plastic film and soil nutrients. ArcGIS 10.2 (Environmental Systems Research Institute, Redlands, CA, USA) was utilized to create the distribution map of the sampling points.

3. Results

3.1. Characteristics of PFM in Typical Plastic Film Mulching Farmland

The average amount of plastic film used in different areas of northern Xinjiang from 2006 to 2018 decreased in the following order: Manasi County > Changji County > Bole City > Fuhai County > Shanshan County > Jimusar County > Mulei County; their annual growth rates were between 1.0% and 40.5% (Table 1). Comparatively, the usage intensity of plastic film can intuitively reflect usage and dependency on plastic film in different regions. From 2006 to 2018, the usage intensity of plastic film in different regions of northern Xinjiang decreased as follows: Shanshan County > Manas County > Bole City > Changji City > Fuhai County > Jimusar County > Mulei County; their annual growth rates were between −1.8% and 26.6%. Additionally, the proportion of film coverage in different regions of northern Xinjiang decreased as follows: Bole City > Manas County > Changji City > Shanshan County > Fuhai County > Jimusar County > Mulei County; their annual averaged growth rates were between −4.8% and 7.0% (Table 1).

Table 1. Key parameters of plastic film mulching applications in different areas of northern Xinjiang.

Calculation of Indicators	Manas	Changji	Bole	Shanshan	Fuhai	Mori Kazak Autonomous County	Jimusaer
Plastic film application amount (t)	3294.4	3009.4	2227.7	836.2	1472.3	422.3	645.8
Averaged annual growth rate of plastic film application amount (%)	8.4	5.2	9.7	1.0	40.5	2.7	10.7
Usage intensity of plastic film (kg·ha^{-1})	4.8	3.8	4.4	6.5	2.6	0.9	1.4
Averaged annual growth rate of usage intensity of plastic film (%)	5.8	4.7	3.7	0.2	26.6	−1.8	5.5
Covering ratio (%)	83.7	65.2	89.2	61.3	56.7	17.8	27.3
Averaged annual growth rate of covering ratio (%)	1.3	2.4	2.7	2.7	7.0	−4.8	3.8

3.2. Characteristics of Macroplastics in Typical Plastic Film Mulching Farmland

The years of plastic film use and the macroplastics amount of plastic film in typical plastic film mulching farmland were investigated with different soil types and crops. As depicted in Figure 2a, with the same time of plastic film mulching usage, the averaged concentration of macroplastics from plstic film varied across different soil types, with a decreasing trend observed as follows: clay (142.32 kg·ha^{-1}) > loam (110.80 kg·ha^{-1}) > sandy soil (72.95 kg·ha^{-1}). Similarly, with the same time of film usage, the mean values of macroplastics for different crop types decreased as follows: cotton (140.54 kg·ha^{-1}) > pumpkin (117.19 kg·ha^{-1}) > sunflower (116.05 kg·ha^{-1}) > corn (109.44 kg·ha^{-1}) > watermelon (58.63 kg·ha^{-1}).

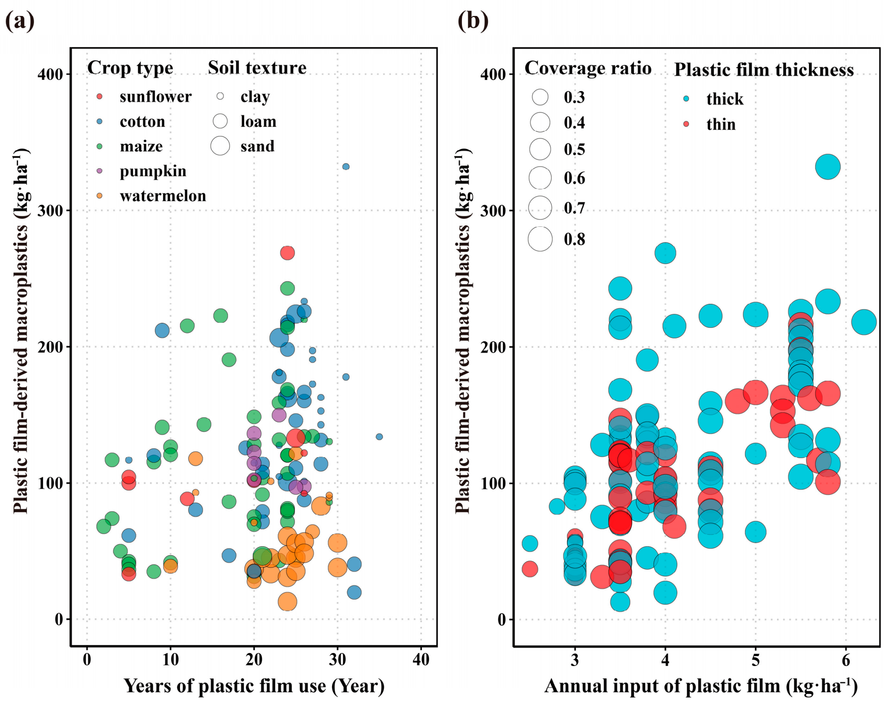

Figure 2. Effects of time of plastic film usage (**a**) and annual input of plastic film (**b**) on plastic film residual.

The annual input of plastic film and macroplastics amount of typical plastic film mulching farmland was investigated with different plastic film thicknesses and coverage ratios. As depicted in Figure 2b, at the same input level, the quantity of macroplastics amount (116.21 kg·ha^{-1})

in the farmland with thick plastic film was higher than that in the farmland with thin plastic film (100.27 kg·ha^{-1}). Moreover, under equivalent input conditions, an increase in the proportion of plastic film led to a corresponding increase in the macroplastics content of farmland, as indicated by an upward trend (CR = 0.9 > CR = 0.7 > CR = 0.3).

3.3. Effect of Macroplastics Amount of Plastic Film on Soil Nutrients

Mantel analysis was conducted to examine the relationship between soil nutrients and the characteristics of plastic film use. The results of the Mantel analysis showed that the CR and the presence of macroplastics were the factors most strongly correlated with SOC. However, the characteristics and quantity of plastic film macroplastics had no effect on AP or AK (Figure 3). Consequently, we employed correlation analysis to further investigate the impact of macroplastics on soil nutrients.

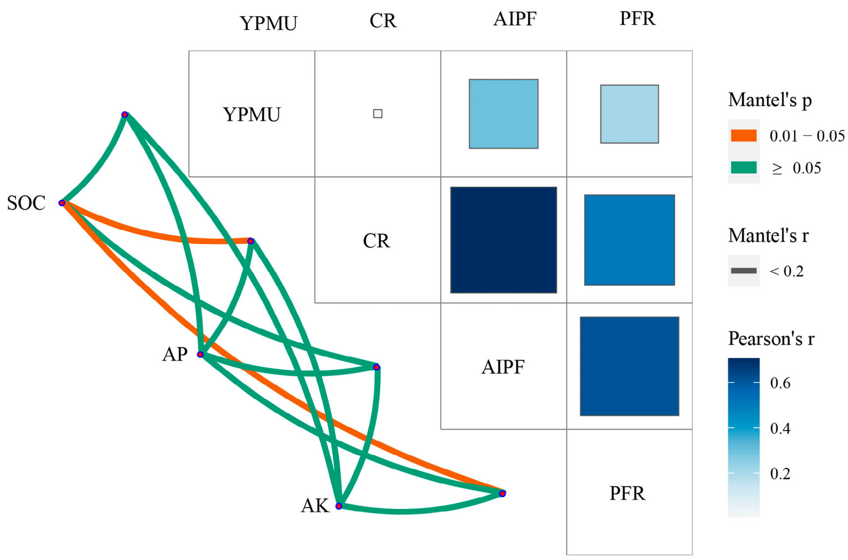

Figure 3. Soil nutrients in paired comparison with the characteristics of plastic film use. SOC, soil organic carbon; AP, soil available phosphorus; AK, soil available potassium; YPFU, years of plastic film use; CR, plastic film covering ratio; IPF, usage intensity of plastic film; PFDM, plastic film-derived macroplastics.

The relationship was analyzed through a fitting analysis between the amount of macroplastics in plastic film and SOC under different soil types and annual plastic film inputs (Figure 4a). A positive correlation was observed between macroplastics and SOC (R^2 = 0.437). For clay soil (R^2 = 0.468) and loam soil (R^2 = 0.389), the change in organic carbon due to soil macroplastics was less pronounced than that in sandy soil (R^2 = 0.912). Furthermore, the annual plastic film input had no significant effect on the relationship between the amount of macroplastics in plastic film and SOC.

As depicted in Figure 4b, a negative correlation was observed between the amount of macroplastics in plastic film and AP (R^2 = 0.387). For clay soil (R^2 = 0.454) and loam soil (R^2 = 0.395), the impact of macroplastics on soil available phosphorus was less significant compared with sandy soil (R^2 = 0.768). Additionally, the annual plastic film input did not influence the relationship between the amount of macroplastics in plastic film and AP.

The correlation analysis between the amount of macroplastics in plastic film and AK revealed an overall positive correlation (R^2 = 0.300). However, the contribution of macroplastics to soil exchangeable potassium was lower compared with sandy soil (R^2 = 0.596) in both clay (R^2 = 0.422) and loamy soil (R^2 = 0.238). Moreover, the annual amount of plastic film input did not affect the relationship between the amount of macroplastics in plastic film and AK (Figure 4c).

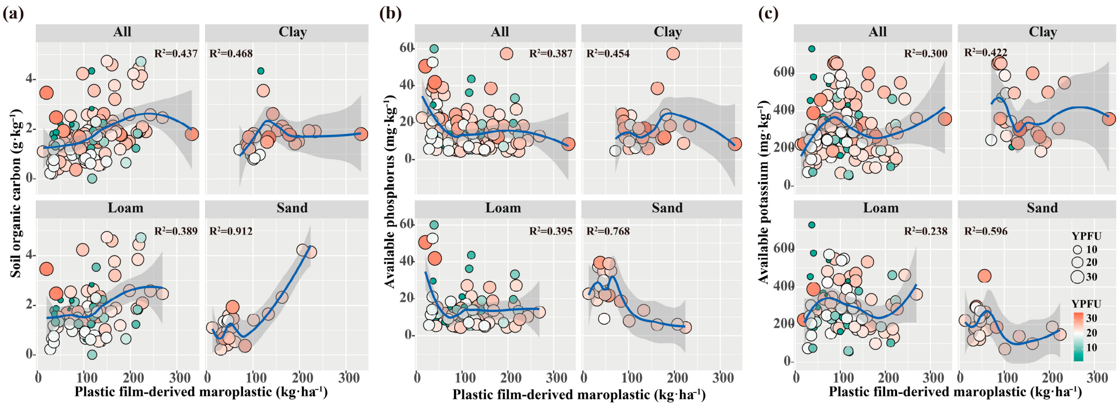

Figure 4. Relationships between soil nutrients ((**a**): soil organic carbon; (**b**): soil available phosphorus; (**c**): soil available potassium) and plastic film-derived macroplastics. YPFU, years of plastic film use.

4. Discussion

The usage intensity of plastic film and covering ratio can reflect the dependence of agriculture on PFM, as well as the characteristics of PFM applications in the region [5]. Different characteristics of plastic film in different regions of northern Xinjiang were detected, whereby areas with low usage intensity of plastic film and film covering ratio had a higher mean annual crop growth rate than areas with higher usage intensity of plastic film and covering ratio. This result shows that PFM technology is still in the rapid-growth stage in areas where the amount of plastic film is lower. Therefore, on the basis of ensuring farmland productivity and food security, the rational use of mulching technology is the primary problem faced in areas where plastic film applications are in a rapid-growth stage. Further research should address these problems, such as strengthening the thickness of plastic film for mechanical recycling and developing specific environmentally friendly biodegradable mulching films for different crops.

Based on previous results, it is shown that the lower limit of the macroplastics amount of plastic film in farmland mainly depends on the amount of plastic film input and that the upper limit of macroplastics mainly depends on the plastic film recovery measures [11,12,27]. Moreover, the characteristics of macroplastics were also affected by the annual input, age, thickness, and covering ratio of plastic film, and the crop and soil types [28]. Therefore, it is necessary to use data from multiple sampling points to study the factors influencing the macroplastics characteristics of farmland plastic film. Our results show that the macroplastics were mainly influenced by the annual amount, service life, thickness, and proportion of plastic film, as well as the crop and soil type in typical PFM farmland in northern Xinjiang.

Our results show that the annual amount, service life, thickness, and proportion of plastic film, as well as the crop and soil type, all have a considerable influence on the macroplastics in typical mulching farmland in northern Xinjiang. Among them, the annual input, service life, thickness, and the increase in the covering ratio of plastic film all increased the macroplastics amount of plastic film in soil. This result is consistent with previous research on the macroplastics characteristics of plastic film. In terms of the total amount of macroplastics, the cotton field had the highest amount, and the watermelon field had the lowest amount. A meta-analysis of plastic film pollution also showed that the amount of macroplastics in the cotton field was the highest; however, the reasons for this were not analyzed. Our survey of typical film-covered farmland in northern Xinjiang showed that cotton was mostly planted in clay and loam soils, whereas watermelon was mostly planted in sandy soil. Therefore, we further infer that there is likely a relationship between the macroplastics amount of plastic film and the soil type, and further research is needed to distinguish the reasons for the increase in the amount of macroplastics. However, two problems need to be paid attention to regarding the method used to determine the macroplastics amount of plastic film. The first is that our sampling method only involved collecting the macroplastics that were visible to the naked eye; therefore, the amount of small microplastics was ignored. Second, smaller microplastics may move along the soil profile to deeper soil layers. All of these factors may have led to the underestimation of plastic film-derived macroplastics in this study. Therefore, further research is needed to distinguish and quantify microplastic accumulation of different sources and sizes in the soil.

Plastic film-derived microplastics are mostly composed of carbon; therefore, their integration into the soil can represent the main source of non-plant carbon [29,30]. Plastic film-derived macroplastics are gradually fixed in the soil and mix with soil minerals or organic compounds through biological and non-biological processes [31]. Then, these carbon compounds may be locked in soil aggregates, be physically protected from decomposition by microorganisms, and subsequently increase the storage of SOM [23]. Our results also show a positive correlation between macroplastics and SOC and that the macroplastics in clay provided the strongest explanation for SOC content (Figure 3). This result may have been caused by two reasons. One is that plastic film-derived microplastics have a large surface area that can adsorb the organic matter secreted by the roots, thus promoting the formation of soil aggregates and increasing SOC [32]. In addition, some studies support the inference that macroplastics can increase SOC [33]. Zhang et al. [34] found that a large amount of accumulated low-density polyethylene macroplastics (up to 0.35%) may improve soil fertility. Liu et al. [35] found that the addition of microplastics can lead to the accumulation of dissolved organic carbon by stimulating enzyme activity. However, some studies were carried out from the perspective of exogenous carbon assimilation microorganisms, and the results showed that macroplastics increased the metabolism of microorganisms and accelerated SOC decomposition, thus reducing soil nutrients [36]. Our study only interpreted the contribution of macroplastics to soil SOC by constructing the correlation between macroplastics and SOC and may have overestimated the contribution of macroplastics to SOC. Therefore, further research should be carried out from the aspects of carbon allocation and adsorption of the plant rhizosphere by plastic film-derived microplastics, rhizosphere key functional microbial species (such as nitrifying bacteria), and soil functions (such as SOM decomposition, nutrient cycling, and greenhouse gas emissions). Further, it is necessary to develop methods to quantify the carbon derived from plastic film to determine its contribution to soil carbon. This will have important implications for understanding the concept of true soil carbon storage, especially in the context of the wide use of agricultural film.

No correlation was detected between the macroplastics amount of plastic film and soil available potassium, and a significant negative correlation was found between soil available phosphorus. The results of our study were consistent with the results of a previous field investigation and pot experiment, whereby the increase in macroplastics reduced soil available phosphorus [28,37]. This is mainly because the increase in the macroplastics amount of plastic film inhibits the microbial biomass and enzyme activity and reduces the compatibilization of inorganic phosphorus and the mineralization of organic phosphorus mediated by related microorganisms [38,39]. At the same time, the negative impact of macroplastics on root growth and root exudates will further feed back into the phosphorus release process [20,40]. Our results show that the macroplastics amount of plastic film in clay provided the strongest explanation for the available phosphorus in the soil. This is mainly because the plastic film fragments cannot directly affect the effective nutrients of the soil, but they indirectly affect the effective nutrients of the soil by affecting the soil and microorganisms [26]. The results of this study revealed the role of the soil type in the availability of soil nutrients from macroplastics. Further research should be carried out to study the interference degree and amount of soil microbial and organic substrate contact, so as to reveal the influencing mechanism of macroplastics on soil available nutrient release.

5. Conclusions

This paper studied the characteristics of PFM and plastic film-derived macroplastics, and their effects on soil nutrients in typical mulching farmland in northern Xinjiang, China.

The results showed that the area with a small amount of plastic film, low usage intensity of plastic film, and low proportion of plastic film had greater application potential. The amount of plastic film input (including the annual investment, service life, thickness, and the covering ratio of plastic film) was identified as the promoting factor for the increase in the macroplastics amount of plastic film. The macroplastics increased SOC content and reduced soil available phosphorus content but had no effect on soil available potassium content. This paper provides evidence regarding the relationship between macroplastics and soil nutrients in farmland systems.

Author Contributions: Writing—Original Draft Preparation, T.J. and X.L.; Writing—Review and Editing, J.C.; Conceptualization and Data Curation, J.P.; Conceptualization and Project Administration, Q.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by National Key Research and Development Program of China (No. 2023YFD1701902). We gratefully acknowledge the anonymous reviewers for their valuable comments on the manuscript.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data can be obtained from the corresponding authors upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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