Environmental Pollution 359 (2024) 124587

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Prediction of future microplastic accumulation in agricultural soils☆

Tamara Meizoso-Regueira[a], Jose Fuentes[b], Samuel J. Cusworth[c], Matthias C. Rillig[a,d,*]

[a] *Plant Ecology, Institute of Biology, Freie Universität Berlin, Altensteinstr. 6, 14195, Berlin, Germany*
[b] *Galician Research and Development Center in Advanced Telecommunications, Vilar 56-58, 36214, Vigo, Spain*
[c] *Lancaster Environment Centre, Lancaster University, Library Avenue, LA1 4YQ, Lancaster, UK*
[d] *Berlin-Brandenburg Institute of Advanced Biodiversity Research (BBIB), Berlin, Germany*

ARTICLE INFO

Keywords:
Microplastic
Soil
Agriculture
Exponential growth
Global change

ABSTRACT

This study shows the general exponential rise in microplastic accumulation in agricultural soils, with fertilizer application speeding up this increase, and future predictions of microplastic concentrations. Utilizing data from the Broadbalk winter wheat experiment at Rothamsted Research, UK, from 1846 to 2022, Poisson regression models were applied to microplastic counts under different soil treatments, including farmyard manure, inorganic fertilizers, and control conditions. A mass conversion factor was applied to obtain the w/w relationship. Results indicated a significant annual increase in microplastic concentrations across all treatments, with fertilized soils showing a notably higher accumulation rate. Our study forecasts that, in 50 and 100 years from now, soils treated with fertilizers are expected to reach microplastic concentrations of 168.9 mg kg^{-1} (95% CI: 60.32–473.09) and 1159 mg kg^{-1} (95% CI: 200.49–6699.8) respectively, levels converging on those used in many experiments. This highlights the urgent need for strategies to mitigate microplastic pollution in agricultural fields. The results also help to choose predicted concentrations in global change experiments, as well as to motivate further research to explore the mechanisms of microplastic accumulation and the integration of these insights into broader agricultural and ecological models to guide sustainable practices and environmental conservation.

1. Introduction

Plastics are synthetic or semi-synthetic materials made of a wide range of polymers that have broad impacts on human activities (Thompson et al., 2009). Its use has revolutionized several sectors, such as industry, packaging and agriculture (Jehanno et al., 2022). Plastic waste persists in natural ecosystems by breaking down through several pathways, including chemical, physical, and biological processes (Chamas et al., 2020); however, plastics are highly resistant materials, taking decades to hundreds of years to be degraded, leading to the accumulation of plastic residues in the environment (Musa et al., 2024; Zhang et al., 2021). Plastic pieces smaller than 5 mm in size are generally referred to as microplastics and are considered important pollutants in the environment (Rillig & Lehmann, 2020), capable of being transported globally through different media (Kiran et al., 2022). Some sources of microplastics in terrestrial environments include poorly managed landfill sites and the application of treated sewage sludge (biosolids), fertilizers and plastic mulching on cultivated land (Cusworth et al., 2024; Fei et al., 2022; Jahandari, 2023). Although microplastics have been recognized as a significant pollutant in aquatic environments for decades, their impact on terrestrial ecosystems has only relatively recently gained traction in research (Rillig, 2012; Rillig & Lehmann, 2020; Rillig et al., 2024).

These pollutants pose an environmental risk by virtue of having a wide range of adverse impacts on soil health and ecosystem functioning, as well as on soil biota (Rillig & Lehmann, 2020; Sajjad et al., 2022) and biodiversity loss (Hu et al., 2019). Microplastics are known to alter soil properties, including soil structure, bulk density and water holding capacity (de Souza Machado et al., 2019; Yang et al., 2021), which are essential for root penetration and water retention and drainage. Several studies have also shown alteration of biogeochemical cycles, affecting nutrient cycling and its availability for plants (Kumar et al., 2023). They can also affect carbon sequestration processes and act as vectors for other pollutants, such as heavy metals and organic contaminants (Khoshnamvand, 2023; Rillig et al., 2021). From a global change perspective, microplastics have relatively recently been considered as a

---

☆ This paper has been recommended for acceptance by Zeng.

* Corresponding author. Plant Ecology, Institute of Biology, Freie Universität Berlin, Altensteinstr. 6, 14195, Berlin, Germany.
E-mail address: rillig@zedat.fu-berlin.de (M.C. Rillig).

https://doi.org/10.1016/j.envpol.2024.124587
Received 29 April 2024; Received in revised form 9 July 2024; Accepted 19 July 2024

factor of global change *(Bank et al., 2022)*, considering the global scale of impact, the clear anthropogenic origin, and significant ecological impacts and long-term persistence *(Bank et al., 2022; Kvale et al., 2020)*. A fundamental aspect of global change research is predictability. Therefore, estimating plastic production trends and future microplastic concentrations in the environment is not only a matter of great urgency for policy makers, but also a major research question to be addressed *(Cusworth et al., 2024; Henseler et al., 2022; Huang et al., 2023)*.

In the past two decades, half of all plastics ever manufactured were produced - 79% of which have ended up in landfill- and this production is predicted to double by 2050 *Geyer et al. (2017); OECD, 2022* forecasts a 2–3 factor increase in production by 2060 if no mitigation efforts are taken. By then, it is predicted that 12,000 million metric tons of plastic pollution will reside in agricultural and other terrestrial areas *(Geyer et al., 2017; Williams & Rangel-Buitrago, 2022)*. Additionally, 1000 to 4000 microplastic particles per kilogram were found in agricultural biosolids *(Koelmans et al., 2022; Radford et al., 2023)*, suggesting that long-term composting significantly raises soil microplastic levels and demonstrating that fragmentation contributes to microplastic accumulation *Zhang et al. (2022); Adhikari et al. (2024)* also noted biosolids' role in increasing soil microplastic accumulation over time in UK agricultural soils. Most predictive studies focus on plastic production trends or future pollution levels in aquatic ecosystems *(Geyer et al., 2017; Lebreton et al., 2019; Williams & Rangel-Buitrago, 2022; OECD 2022)*, demonstrating that macroplastic accumulation could potentially quadruple by 2050 in the surface ocean. However, such predictions are not yet available for agricultural ecosystems, despite the particular risk this pollutant poses to the agricultural sector *(Hofmann et al., 2023)*. Therefore, improving the accuracy of long-term predictions of microplastic accumulation in agricultural systems is essential in order to take protective measures for soil ecosystems.

We here present a complementary analysis based on the data published in *Cusworth (2024)*. In this study, the authors have counted the amount of microplastics in the Broadbalk winter wheat experiment sample archive at Rothamsted Research, UK, at 18 different time points between 1846 and 2022, and under three treatments: farmyard manure (FYM), inorganic fertilizer (N3(P)KMg) and no soil amendments (Nil). The soil sampling depth was 0–23 cm, using a 1.5 g sample for analysis. The microplastic particles they have counted were of unknown composition and had a size larger than 10 μm. Considering the longevity of the samples, these data present a unique opportunity to conceptualize and model the processes behind the accumulation of microplastics in agricultural soils over time. We also wished to extract the growth rate to make future projections, directly applicable to experiments conducted in a global change ecology context.

2. Methods

2.1. Data acquisition and model selection

We used the dataset published in *Cusworth et al. (2024)*, which includes microplastic counts in agricultural soil of the Broadbalk winter wheat experiment at Rothamsted Research, UK. These microplastic counts amount to 18 time points between 1846 and 2022. In order to model the increase of microplastics in soil we used the variable "year" as an independent variable, and "microplastic counts" as the dependent variable. In addition to these variables, the original dataset differentiated between different treatments, including: no soil amendments (Nil, from now on called "control"), and with two different fertilizers (FYM and N3(P)KMg). As *Cusworth et al. 2024* noted, the microplastic accumulation growth trend was significantly different among the control and both fertilizers, while no significant differences occurred between fertilizers. Thus, we independently analyzed each treatment of the dataset.

The microplastic measure in the dataset corresponded to increasing counts per time unit, necessitating a non-negative integer model, and preliminary descriptive analysis also showed considerable linearity of increase of the log mean rate. Finally, the sampling design used by *Cusworth et al. (2024)* implied independence between data points, as they were extracted from different samples for each time point. Therefore, we used a Poisson regression model to explain the processes underpinning the microplastics accumulation in agricultural soil, as the data met all model assumptions *(Roback & Legler, 2021; Hilbe, 2014)*.

2.2. Statistical analyses

A Poisson regression model is a type of Generalized Linear Models (GLMs) for data where the response variable follows a Poisson distribution. Generalized Linear Models extend linear regression by linking the response variable to linear predictors via a specific function, called the link function, accommodating the requirements of response variables with non-normal distributions. For the case of Poisson variables, where the response is limited to the range $(0, +\infty)$, the natural logarithm serves as the canonical link function, constituting the following linear relation of the independent variables x and parameters β.

$Y \sim Poisson(\lambda);\ g(\lambda(x,\beta)) = ln(\lambda(x,\beta)) = x'\beta$ (Roback & Legler, 2021).

Thus, in our concrete case of a single predictor, and by applying the inverse link function, we obtain the model for a simple Poisson regression:

$\lambda(x,\beta) = e^{\beta_0+\beta_1 x} = e^{\beta_0}\left(e^{\beta_1}\right)^{x}$ (Roback & Legler, 2021),where.

e^{β_0}: $\lambda(0,\beta)$, the expected response value for $x = 0$

e^{β_1}: expected rate of increase of the response by unit of x.

Statistical significance of exponential time effects in models was tested using t-tests, while model fit was assessed through Likelihood Ratio Tests (LRT), deviance pseudo-R^2, and Akaike Information Criterion, with lower AIC values indicating better fit. These are included in the supplementary materials. Poisson models can suffer from overdispersion and zero inflation. While the data exhibited limited overdispersion, the early zeroes could be a concern. For this reason, we fitted negative binomial models and zero inflated models to check for these issues. We used the pseudo R^2 and AIC to compare the model fits, concluding that the overdispersion and effect of zeroes was minimal, and that the Poisson model presented the best fit. The ANOVA in *Cusworth et al. (2024)* found significant differences between control and fertilizer groups but not within different fertilizers. Based on these findings, we treated the control group as a separate dataset to capture its distinct effect. Because of the lack of differences between fertilizers reported by the ANOVA, we merged fertilizer groups to assess if they influenced the relationship with time. Our analysis showed that fertilizers did not significantly affect this relationship, leading us to create a unified model for all fertilizer groups "Fertilizers_mean" by averaging both values. We applied the conversion factors of 8.9 mg of microplastics per kilogram of soil and 2914 microplastic counts per kilogram of soil, extracted from the average quantities on European soils proposed by *Büks & Kaupenjohann (2020)*, in order to present the exponential growth of microplastics accumulation in units of milligram per kilogram of soil. This w/w accounts for variations in soil density and microplastic distribution, which may vary greatly from sample to sample. Thus, this conversion allows for standardization across different samples, making it easier to compare with data from other studies. It is also a common unit in pollution reports, facilitating communication with regulatory institutions and adherence to international guidelines for environmental quality.

All statistical analyses and modeling were performed in R version 4.2. Visualizations were created using *ggplot2 (Wickham, 2016)*, *viridis (Garnier et al., 2024)* and *cowplot (Wilke, 2024)* packages, while model comparison tests were calculated with the *MASS* package *(Venables & Ripley, 2002)* and data processing was done with the *dplyr* package (Wickham et al., 2023i).

3. Results and discussion

We fitted a Poisson model of microplastic accumulation in agricultural soil over time for each of the classes discussed above and found significant effects. We present model estimations and future predictions using microplastic counts (Fig. 1) and after applying the w/w conversion factor (Fig. 2). Extrapolation to the future causes wider confidence intervals as time progresses, implying increased uncertainty and reduced reliability of long-term predictions. The coefficients and significance tests of the models are included in the supplementary materials. The exponentiated coefficients can be directly interpreted as multiplicative effects on the microplastic counts. For each additional year, the expected count is multiplied by the factor given by the exponentiated year coefficient. This corresponds to roughly a yearly increase of 3.54% for the control, 3.34% for FYM, 3.93% for N3(P)KMg and 4.01% for the fertilizers mean. After applying the inverse link function, we obtain the exponentiated coefficients, as in the following model equations:

$$\lambda_{control}(x,\beta) = 1.265759\times10^{-30}\cdot(1.035403)^{x};\quad \lambda_{FYM}(x,\beta) = 1.321777\times10^{-28}\cdot(1.033446)^{x};$$

$$\lambda_{N3PKMg}(x,\beta) = 1.587753\times10^{-33}\cdot(1.039253)^{x};\quad \lambda_{Fertilizers\_mean}(x,\beta) = 3.293227\times10^{-34}\cdot(1.040086)^{x}$$

Thus, the models shown in Fig.s. 1 and 2 indicate an exponential trend in microplastic concentrations in agricultural soil. The control group showed a less pronounced, but nevertheless still exponential growth, with approximately 16 mg kg^{-1} of microplastics by 2040, which is expected as it likely represents soil conditions without additional amendments. The FYM treatment had the sharpest exponential increase in microplastic concentration, suggesting that the type of soil amendment affects microplastic addition into soil. The fertilizers mean model exhibited more than double of the microplastic accumulation compared to the control group, showing that approximately 44.4 mg kg^{-1} of microplastics, with a 95% confidence interval of 25.64–76.86 mg kg^{-1}, can be expected by 2040 in agricultural soils with fertilizer usage. In addition, the 50- and 100-years predictions from now would be, respectively: 168.9, with a 95% confidence interval of 60.32–473.09 mg kg^{-1}, and 1159 mg kg^{-1}, with a 95% confidence interval of 200.49–6699.8 mg kg^{-1}. These estimates are in the range of microplastic levels (e.g., 0.4% w/w) applied in many current experiments (*Lozano et al., 2021*; *de Souza Machado et al., 2019*).

Overall, a clear trend of exponential increase in microplastic concentrations in agricultural soil is evident, irrespective of treatment, raising concerns about the sustainability of using organic manure or other treatments, as they contribute to the long-term accumulation of microplastics in soil, posing drastic ecological consequences. These results support previous studies (*Zhang et al., 2022*; *Radford et al. 2023*; *Adhikari et al., 2024*), where long-term compost and biosolids application contributed substantially to microplastic concentrations in soil. We have forecasted that the yearly growth rate of microplastics in soils with fertilizer usage is expected to increase by an additional 0.47% annually compared to the soil without amendments, resulting in an average increase of approximately 4.01% per year. These results represent an improvement on the current state of the art, as no studies have predicted the general trend of microplastic accumulation in agricultural soils and the contribution of fertilizers to this annual growth rate. The use of

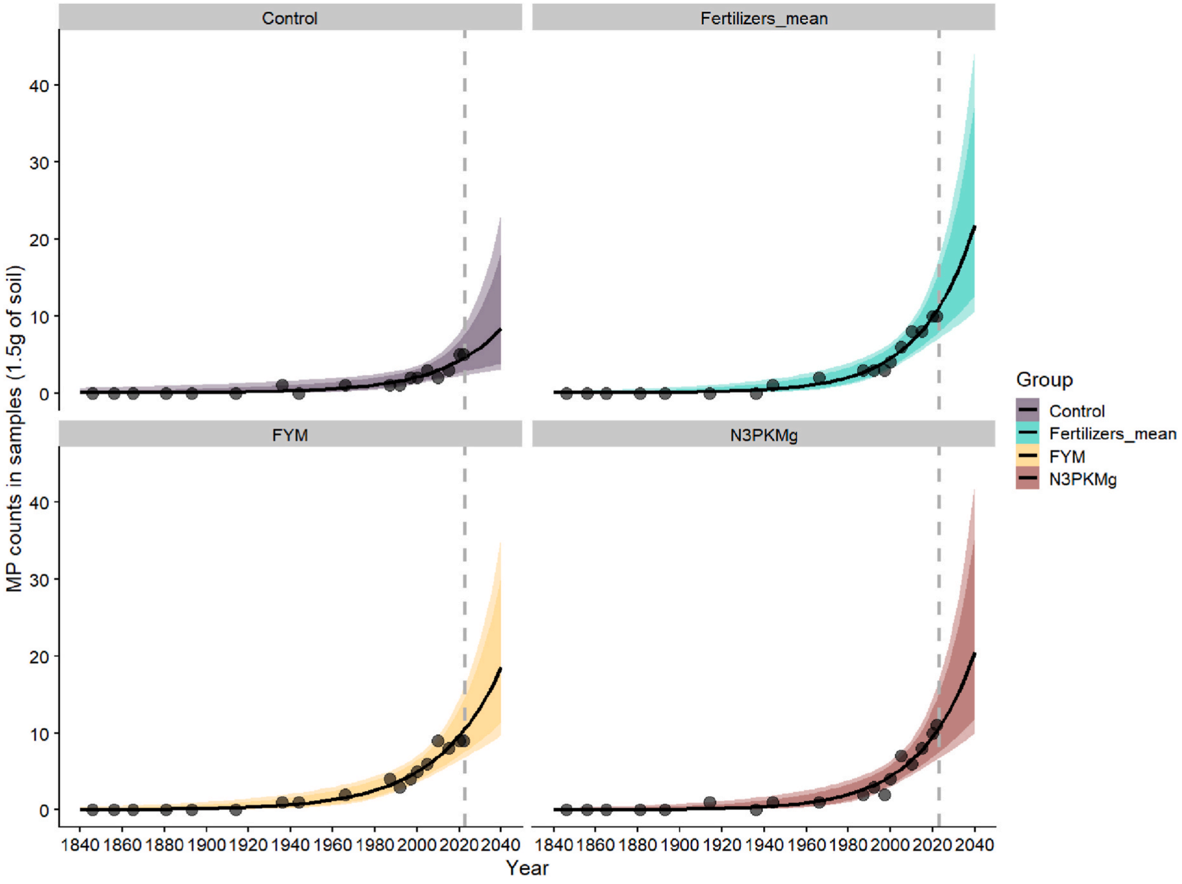

Fig. 1. Exponential growth of microplastic in soil over time expressed as counts per 1.5 g soil. Darker shade corresponds to 95% CI, while lighter shade corresponds to 99% CI. The vertical line represents the point where future predictions are made based on previous data points. The shaded areas around the lines represent confidence intervals or prediction intervals, showing the range of uncertainty around the predictions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

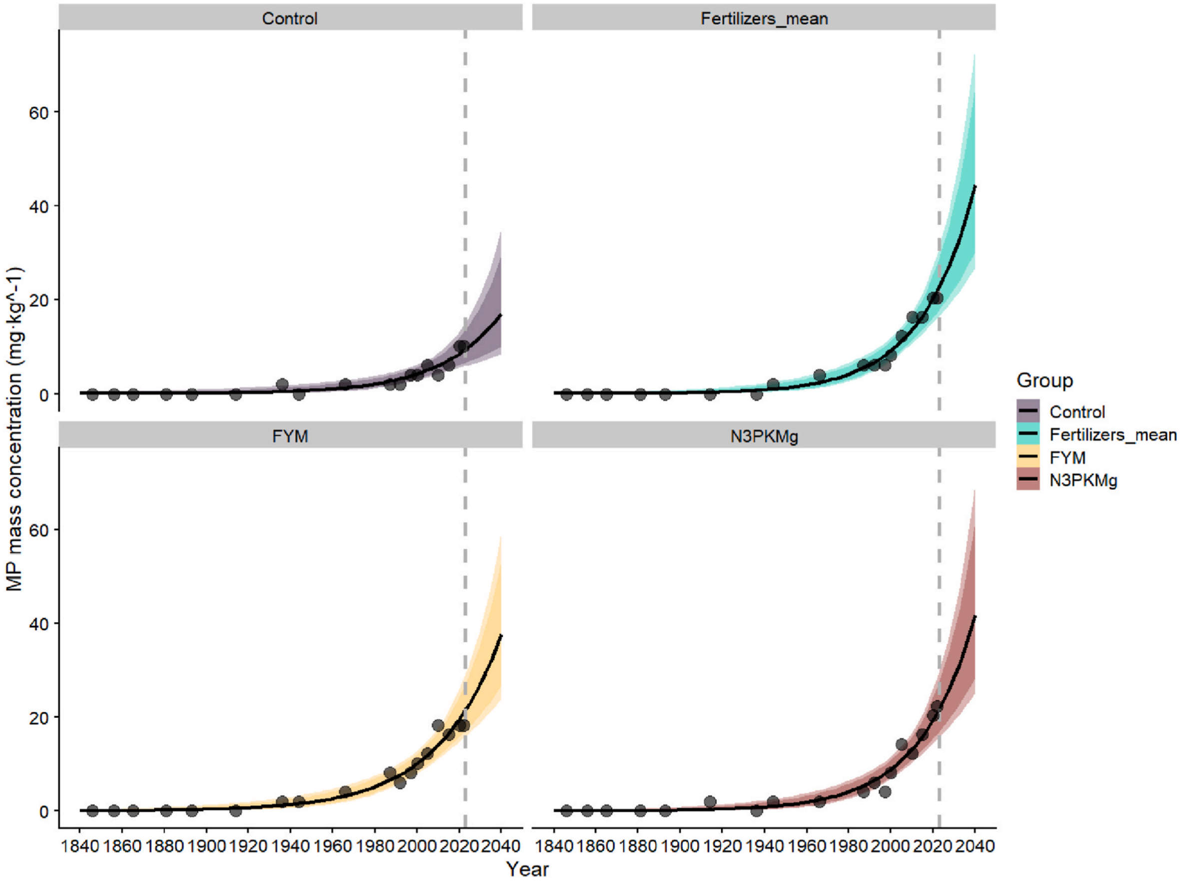

Fig. 2. Exponential growth of microplastic in soil over time expressed as mass. Darker shade corresponds to 95% CI, while lighter shade corresponds to 99% CI. The vertical line represents the point where future predictions are made based on previous data points. The shaded areas around the lines represent confidence intervals or prediction intervals, showing the range of uncertainty around the predictions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fertilizers significantly contributes to the exponential growth of microplastic concentrations in agricultural soils, potentially having negative effects on soil fauna, microbiota, and crop production (Cusworth et al., 2024). This poses a potential threat to agricultural productivity, suggesting the need to consider the impacts of microplastic pollution in fertilizer use regulations.

Regarding the assessment of the models, they provided extremely accurate predictions. This exponential trend likely correlates with the growth in plastic production expected by 2050, as discussed by Henseler et al. (2022); Huang et al. (2023); Geyer et al. (2017). This correlation might act as a proxy for understanding plastic production trends, indicating correlation rather than causation. However, this serves as a foundation for developing future mechanistic models. Plastic production could explain the exponential trend in microplastic accumulation, so including these additional factors or comparing different models in the future could offer deeper insights into underlying mechanistic relationships. Despite these considerations, the models remain highly effective for prediction under a business-as-usual scenario. They also offer the possibility of integrating these results into predictive models for other ecological processes, like soil carbon level forecasts, improving their accuracy by adding more context and providing supplementary information.

Future changes in plastic production and use could lead to different values and growth rates, even deviating from the exponential trend. If plastic use trends increase, we would expect a continued accumulation of microplastics, exacerbating negative ecological impacts. With regulations to reduce plastic use and improve waste management, the rate of microplastic mass accumulation could slow down. Nonetheless, existing plastic and microplastics will continue to fragment into smaller pieces, still increasing the abundance of microplastic particles and becoming more easily incorporated deeper into the soil, remaining in the ecosystem for decades to hundreds of years, and posing a risk of entering groundwater (Zhang et al., 2021; Musa et al., 2024).

Therefore, comparison of the predictions in Figs. 1 and 2 allows us to consider some important differences. The counts prediction in Fig. 1 is likely more accurate and realistic due to continuous fragmentation, leading to an exponential increase in particle numbers regardless of plastic production trends. In contrast, the mass prediction in Fig. 2 may be less reliable; while particle numbers increase, the total mass might remain constant or even decrease. This could result in overprediction, as we used a fixed w/w conversion factor and microplastic fragmentation could produce higher counts without increasing mass, or underprediction due to detection limits missing smaller fragments, as the dataset we used counted only particles larger than 10 μm, meaning smaller fragments were not included in the predictions.

We consider these potential errors an opportunity for refining our predictions including more parameters, and encourage future research to consider these possible improvements. Nevertheless, this study highlights the importance of proactive measures to mitigate future microplastic pollution in agricultural ecosystems. This prediction will also support new experimental parameters to be chosen in scientific research related to global change and agricultural ecosystems, representing future pollution levels in their experiments. In this way, these predictive models are necessary to guide mitigation laws, simulating potential pollution scenarios if such laws are not implemented.

4. Conclusions

In conclusion, this study offers a first forecast of the exponential growth in microplastic levels in agricultural soils, accounting for the contribution of fertilizers to this trend and the annual percentage growth rate, which resulted to be 0.47% higher in the case of soil with fertilizer usage than in soil without agricultural amendments. The models had a high level of accuracy and could help to extrapolate future microplastic concentrations in agricultural soils, providing simulations of future scenarios for microplastic pollution. With business-as-usual, our prediction for 100 years in the future converges on levels of microplastic pollution currently used in experiments, potentially reaching 6699.8 mg of microplastics per kg of soil (0.67% w/w). Our results invite further research to explore additional factors that explain mechanistic relationships in the process of microplastic accumulation in soil, as well as integration into other models that explain future ecological processes in agricultural ecosystems. We suggest further analyses and modeling of soil archive collections globally to determine accurate average estimates.

CRediT authorship contribution statement

Tamara Meizoso-Regueira: Writing – original draft, Methodology, Formal analysis. **Jose Fuentes:** Writing – review & editing, Methodology, Formal analysis. **Samuel J. Cusworth:** Writing – review & editing. **Matthias C. Rillig:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data and code are available in a figshare repository: https://doi.org/10.6084/m9.figshare.26022178.v1.

Acknowledgments

The data was generated from analysis of samples obtained from the Rothamsted Sample Archive. The Rothamsted Long-Term Experiments – National Bioscience Research Infrastructure (RLTE-NBRI) is funded by the UK Research and Innovation – Biotechnology and Biological Sciences Research Council (UKRI-BBSRC) under award BBS/E/RH/23NB0007 (2023-2028). The RLTE-NBRI is also supported by the Lawes Agricultural Trust.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.124587.

References

Adhikari, K., Pearce, C.I., Sanguinet, K.A., Bary, A.I., Chowdhury, I., Eggleston, I., Xing, B., Flury, M., 2024. Accumulation of microplastics in soil after long-term application of biosolids and atmospheric deposition. Sci. Total Environ. 912, 168883 https://doi.org/10.1016/j.scitotenv.2023.168883.

Bank, M.S., Mitrano, D.M., Rillig, M.C., Lin, C.S.K., Ok, Y.S., 2022. Embrace complexity to understand microplastic pollution. Nat. Rev. Earth Environ. 3, 736–737. https://doi.org/10.1038/s43017-022-00365-x.

Büks, F., Kaupenjohann, M., 2020. Global concentrations of microplastics in soils: a review. SOIL 6 (2), 649–662. https://doi.org/10.5194/soil-6-649-2020.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L., Suh, S., 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng. 8 (9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635.

Cusworth, S.J., Davies, W.J., McAinsh, M.R., et al., 2024. Agricultural fertilizers contribute substantially to microplastic concentrations in UK soils. Communications Earth & Environment 5, 7. https://doi.org/10.1038/s43247-023-01172-y.

de Souza Machado, A.A., Lau, C.W., Kloas, W., Bergmann, J., Bachelier, J.B., Faltin, E., Becker, R., Görlich, A.S., Rillig, M.C., 2019. Microplastics can change soil properties and affect plant performance. Environmental Science & Technology 53, 6044–6052. https://doi.org/10.1021/acs.est.9b01339.

Fei, X., Guo, Y., Wang, Y., et al., 2022. The long-term fates of land-disposed plastic waste. Nat. Rev. Earth Environ. 3, 733–735. https://doi.org/10.1038/s43017-022-00354-0.

Garnier, S., Ross, N., Rudis, R., Camargo, P.A., Sciaini, M., Scherer, C., 2024. Viridis(Lite) - Colorblind-friendly color maps for R. https://sjmgarnier.github.io/viridis/ viridis package version 0.6.5.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782 https://doi.org/10.1126/sciadv.1700782.

Henseler, M., Gallagher, M.B., Kreins, P., 2022. Microplastic pollution in agricultural soils and Abatement measures: a model-based assessment for Germany. Environ. Model. Assess. 27, 553–569. https://doi.org/10.1007/s10666-022-09826-5.

Hilbe, J.M., 2014. Poisson regression. In: Modeling Count Data. Cambridge University Press, pp. 35–73.

Hofmann, T., Ghoshal, S., Tufenkji, N., Adamowski, J.F., Bayen, S., Chen, Q., Demokritou, P., Flury, M., Hüffer, T., Ivleva, N.P., Ji, R., Leask, R.L., Maric, M., Mitrano, D.M., Sander, M., Pahl, S., Rillig, M.C., Walker, T.R., White, J.C., Wilkinson, K.J., 2023. Plastics can be used more sustainably in agriculture. Communications Earth & Environment 4, 332. https://doi.org/10.1038/s43247-023-00982-4.

Huang, H., Mohamed, B.A., Li, L.Y., 2023. Accumulation and fate of microplastics in soils after application of biosolids on land: a review. Environ. Chem. Lett. 21 (5), 1745–1759. https://doi.org/10.1007/s10311-023-01577-3.

Hu, D., Shen, M., Zhang, Y., Li, H., Zeng, G., 2019. Microplastics and nanoplastics: would they affect global biodiversity change? Environ. Sci. Pollut. Res. Int. 26 (19), 19997–20002. https://doi.org/10.1007/s11356-019-05414-5.

Jahandari, A., 2023. Microplastics in the urban atmosphere: sources, occurrences, distribution, and potential health implications. Journal of Hazardous Materials Advances 12, 100346. https://doi.org/10.1016/j.hazadv.2023.100346.

Jehanno, C., Alty, J.W., Roosen, M., De Meester, S., Dove, A.P., Chen, E.Y.-X., Leibfarth, F.A., Sardon, H., 2022. Critical advances and future opportunities in upcycling commodity polymers. Nature 603, 803–814. https://doi.org/10.1038/s41586-021-04350-0.

Khoshnamvand, N., 2023. Micro- and nanoplastics as carriers for other soil pollutants. In: Maddela, N.R., Reddy, K.V., Ranjit, P. (Eds.), Micro and Nanoplastics in Soil. Springer, Cham. https://doi.org/10.1007/978-3-031-21195-9_6.

Kiran, B.R., Kopperi, H., Venkata Mohan, S., 2022. Micro/nano-plastics occurrence, identification, risk analysis and mitigation: challenges and perspectives. Rev. Environ. Sci. Biotechnol. 21, 169–203. https://doi.org/10.1007/s11157-021-09609-6.

Koelmans, A.A., Redondo-Hasselerharm, P.E., Nor, N.H.M., de Ruijter, V.N., Mintenig, S.M., Kooi, M., 2022. Risk assessment of microplastic particles. Nat. Rev. Mater. 7, 138–152. https://doi.org/10.1038/s41578-021-00411-y.

Kumar, A., Mishra, S., Pandey, R., Yu, Z.G., Kumar, M., Khoo, K.S., Thakur, T.K., Show, P.L., 2023. Microplastics in terrestrial ecosystems: Unignorable impacts on soil characteristics, nutrient storage, and its cycling. TrAC, Trends Anal. Chem. 158, 116869 https://doi.org/10.1016/j.trac.2022.116869.

Kvale, K., Prowe, A.E.F., Chien, C.-T., Landolfi, A., Oschlies, A., 2020. The global biological microplastic particle sink. Sci. Rep. 10, 16670 https://doi.org/10.1038/s41598-020-72898-4.

Lebreton, L., Egger, M., Slat, B., 2019. A global mass budget for positively buoyant macroplastic debris in the ocean. Sci. Rep. 9, 12922 https://doi.org/10.1038/s41598-019-49413-5.

Lozano, Y.M., Lehnert, T., Linck, L.T., Lehmann, A., Rillig, M.C., 2021. Microplastic Shape, polymer type, and concentration affect soil properties and plant Biomass. Front. Plant Sci. 12, 616645 https://doi.org/10.3389/fpls.2021.616645.

Musa, I.O., Auta, H.S., Ilyasu, U.S., Aransiola, S.A., Makun, H.A., Adabara, N.U., Abioye, O.P., Aziz, A., Jayanthi, B., Maddela, N.R., Prasad, R., 2024. Micro- and nanoplastics in environment: degradation, detection, and ecological impact. Int. J. Environ. Res. 18, 1. https://doi.org/10.1007/s41742-023-00551-9.

OECD, 2022. Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options. OECD Publishing. https://doi.org/10.1787/de747aef-en.

Radford, F., Horton, A., Hudson, M., Shaw, P., Williams, I., 2023. Agricultural soils and microplastics: are biosolids the problem? Frontiers in Soil Science 2. https://doi.org/10.3389/fsoil.2022.941837.

Rillig, M.C., 2012. Microplastic in terrestrial ecosystems and the soil? Environmental Science & Technology 46 (12), 6453–6454. https://doi.org/10.1021/es302011r.

Rillig, M.C., Lehmann, A., 2020. Microplastic in terrestrial ecosystems. Science 368, 1430–1431. https://doi.org/10.1126/science.abb5979.

Rillig, M.C., Leifheit, E., Lehmann, J., 2021. Microplastic effects on carbon cycling processes in soils. PLoS Biol. 19 (3), e3001130 https://doi.org/10.1371/journal.pbio.3001130.

Rillig, M.C., Kim, S.W., Zhu, Y.G., 2024. The soil plastisphere. Nat. Rev. Microbiol. 22, 64–74. https://doi.org/10.1038/s41579-023-00967-2.

Roback, P., Legler, J., 2021. Beyond Multiple Linear Regression: Applied Generalized Linear Models and Multilevel Models in R. CRC Press.

Sajjad, M., Huang, Q., Khan, S., Khan, M.A., Liu, Y., Wang, J., Lian, F., Wang, Q., Guo, G., 2022. Microplastics in the soil environment: a critical review. Environmental Technology & Innovation 27, 102408. https://doi.org/10.1016/j.eti.2022.102408.

Thompson, R.C., Swan, S.H., Moore, C.J., vom Saal, F.S., 2009. Our plastic age. Phil. Trans. Biol. Sci. 364 (1526), 1973–1976. https://doi.org/10.1098/rstb.2009.0054.

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with R, fourth ed. Springer.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag.

Wickham, H., François, R., Henry, L., Müller, K., Vaughan, D., 2023. dplyr: a grammar of data manipulation. R package. Retrieved from, version 1.1.4. https://github.com/tidyverse/dplyr.

Wilke, C., 2024. cowplot: Streamlined plot theme and plot annotations for 'ggplot2'. R package version 1.1.3. Retrieved from. https://wilkelab.org/cowplot/.

Williams, A.T., Rangel-Buitrago, N., 2022. The past, present, and future of plastic pollution. Mar. Pollut. Bull. 176, 113429 https://doi.org/10.1016/j.marpolbul.2022.113429.

Yang, L., Zhang, Y., Kang, S., Wang, Z., Wu, C., 2021. Microplastics in soil: a review on methods, occurrence, sources, and potential risk. Sci. Total Environ. 780, 146546 https://doi.org/10.1016/j.scitotenv.2021.146546.

Zhang, K., Hamidian, A.H., Tubić, A., Zhang, Y., Fang, J.K.H., Wu, C., Lam, P.K.S., 2021. Understanding plastic degradation and microplastic formation in the environment: a review. Environmental Pollution 274, 116554. https://doi.org/10.1016/j.envpol.2021.116554.

Zhang, J., Wang, X., Xue, W., Xu, L., Ding, W., Zhao, M., Liu, S., Zou, G., Chen, Y., 2022. Microplastics pollution in soil increases dramatically with long-term application of organic composts in a wheat–maize rotation. J. Clean. Prod. 356, 131889 https://doi.org/10.1016/j.jclepro.2022.131889.