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基于微塑料生态风险值的畜禽粪便农田承载力估算

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摘要 为防控农田土壤微塑料污染,以新疆生产建设兵团的种养业生产系统为研究对象,构建土壤微塑料毒性数据库,采用物种敏感度分布法确定土壤微塑料的预测无效应浓度;运用风险商法和土壤环境影响预测法,定量评估农田土壤微塑料环境容量;结合物质流分析法,估算畜禽粪便农田承载力。结果表明:1)新疆生产建设兵团每hm²农田可承载的生猪、奶牛、肉牛、肉鸡和蛋鸡数量分别为79.7头、0.7头、1.9头、476.2羽和69.9羽。由于畜禽粪便中微塑料质量分数相对较高,微塑料已经成为了粪肥施用的限制因素。2)当来自粪肥和农膜的微塑料输入量分别降低30.0%,畜禽粪便农田承载力可提高42.8%和8.5%。面向农田土壤生态风险防控,微塑料已制约了畜禽粪肥安全施用与农田承载力,建议加强畜禽饲料与饮用水的微塑料监测,防控饲养环节微塑料污染,保障粪肥安全还田与土壤健康。

关键词 畜禽粪便农田承载力;微塑料;生态风险评估;土壤环境;新疆生产建设兵团

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Estimation on farmland bearing capacity of animal manure based on microplastic ecological risk value

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Abstract To prevent microplastic pollution in farmland soil, the agriculture and animal husbandry production system of Xinjiang Production and Construction Corps (XPCC) was taken as the research object. A soil microplastics toxicity database was established, and the species sensitivity distribution method was employed to determine the predicted no-effect concentration of soil microplastics (PNEC_{soil}).

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The risk quotient method and soil environmental impact prediction method were used to assess the environmental capacity of microplastics in farmland soil quantitatively. Additionally, the material flow analysis method was utilized to estimate farmland bearing capacity of animal manure. The results showed that: 1) The farmland bearing capacity of animal manure of swine, dairy cattle, beef cattle, broiler and layer in XPCC was 79.7 heads, 0.7 heads, 1.9 heads, 476.2 birds and 69.9 birds per hectare, respectively. Due to the relatively high mass fraction of microplastics in animal manure, microplastics became the factor limiting the application of manure. 2) When the amount of microplastics in manure and agricultural film was reduced by 30.0%, the farmland bearing capacity of animal manure could be increased by 42.8% and 8.5%. In terms of farmland soil ecological risk prevention and control, microplastics was emerged as one of the limiting factors for the safe application of animal manure and the bearing capacity of farmland. It is recommended to enhance the monitoring of microplastics animal feed and drinking water, to prevent and control microplastic pollution in the breeding process and ensure the safe return of manure to the fields and healthy soil.

Keywords farmland bearing capacity of animal manure; microplastics; ecological risk assessment soil environment; Xinjiang Production and Construction Corps

塑料制品充斥人们日常生活,但在物理、化学和生物等作用下,这些被抛弃在环境中的塑料能够破碎形成尺寸 <5 mm的塑料碎片或颗粒,这些被统称为微塑料^[1]。其中,直径为1~5 mm的,通常采用目视法筛分;直径 <1 mm的,肉眼难以分辨。微塑料作为一种新污染物,被广泛发现存在于海洋、陆地、大气、动植物和人体中,对生态系统安全与人体健康带来巨大威胁^[2-4]。

作为新污染物的农田土壤微塑料,其污染问题引发了广泛关注。已有研究采集上海^[5]、杭州湾^[6]、辽宁^[7]和北京^[8]的农田土壤检测发现,这4个地方的微塑料平均丰度分别为78、571、3 605和1 405个/kg。从土地利用类型来说,果园土壤微塑料丰度最高(2 677个/kg),菜地次之(1 752个/kg),粮食作物(970个/kg)和经济作物(946个/kg)相对最低;从尺寸上看,以200~500 μm 和500~1 000 μm 为主,占比分别为34.5%和22.3%;形状多为碎片和薄膜状;颜色主要是米色和灰色;材质以聚丙烯(PP)和低密度聚乙烯(LDPE)为主^[9]。农膜作为农田最直接的微塑料来源,主要成分就是LDPE^[10]。由于机械磨损和紫外线辐射等,导致农膜的破损和老化,使其表面形态和尺寸形状发生变化,进而形成微塑料进入到农田土壤中,造成严重的农田土壤生态环境污染风险。与此同时,粪肥也是农田土壤微塑料来源之一。在鹰潭国家农业生态系统观测站的22年定位试验发现,长期施用猪粪的土壤中的微塑料丰度为43.8个/kg,显著高于对照组的16.4个/kg^[11]。在山东德州农科院基地花生

地^[12]和江苏南京六合试验基地辣椒大棚^[13]也得到了类似结论,施用粪肥都显著增加了土壤微塑料的丰度。由此可见,科学调控粪肥施用量,对于农田土壤微塑料污染风险防控极其重要。

本研究拟以新疆生产建设兵团的种养业生产系统为研究对象,构建土壤微塑料毒性数据库,采用物种敏感度分布法确定土壤微塑料的预测无效应浓度;运用风险商法和土壤环境影响预测法,定量评估农田土壤微塑料环境容量;结合物质流分析法,估算每 hm^2 农田可施用粪肥量,评估畜禽养殖潜力,以期为区域种养结合与土壤微塑料污染防控提供参考资料。

1 材料与方法

1.1 研究对象

新疆生产建设兵团位于新疆维吾尔自治区境内,种植业与畜禽养殖业发达,2021年肉类、禽蛋、牛奶年产量分别为59.1万、14.7万和78.0万t;粮食、棉花和蔬菜的种植面积分别为30.0万、87.0万和6.7万 hm^2 ,其产量分别为280.9万、208.3万和476.4万t^[14]。当地的干旱气候致使农作物种植过程中需要使用大量农用塑料膜,新疆生产建设兵团单位面积农膜用量从2011年的46.2 kg/hm^2 增长到2021年56.2 kg/hm^2 ^[14](图1),农膜残留问题已成为当地农业面源污染治理的重要问题之一^[15]。因此,开展新疆生产建设兵团农田土壤的微塑料输入量估算、风险评估和规划设计研究极其重要。

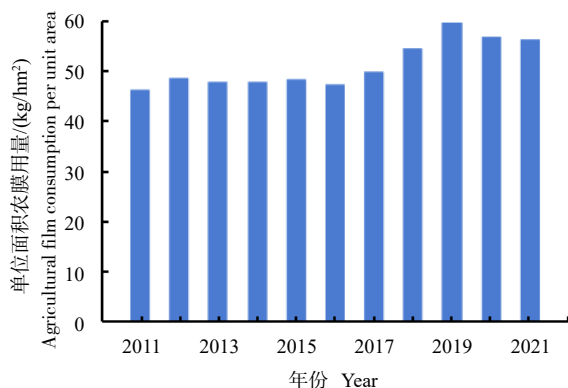


图1 2011—2021年新疆生产建设兵团农膜用量

Fig.1 Agricultural film consumption of XPCC from 2011 to 2021

1.2 研究内容

为兼顾理论研究、实际生产现状与数据可获得性,本研究假定新疆生产建设兵团农田土壤的微塑

料输入途径包括农膜的使用和畜禽粪便的还田。其中,农膜输入主要是当地大量使用地膜,残留的地膜破碎或分解后形成微塑料。畜禽粪肥输入主要是养殖过程中的饲料和饮用水中存在大量微塑料,其被动物摄入后随粪便一起排泄^[16]。

基于对研究内容的分析,本研究首先采用文献检索与数据整理构建土壤微塑料毒性数据库,采用物种敏感度分布法^[17]确定土壤微塑料的预测无效应浓度。其次,运用风险商法^[18]和土壤环境影响预测方法^[19],定量评估新疆生产建设兵团农田土壤微塑料环境容量。然后,结合物质流分析法,确定微塑料各输入途径(包含畜禽粪肥和农膜)的输入量。最后,根据畜禽粪便中微塑料质量分数和畜禽粪便排泄系数等参数,估算出每 hm^2 农田可施用粪肥量与可承载畜禽养殖量,即畜禽粪便农田承载力。畜禽粪便农田承载力计算流程见图2。

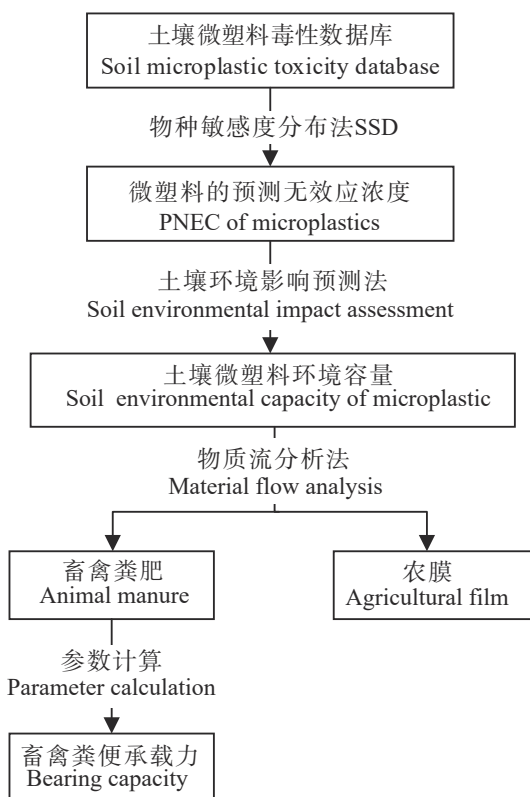


图2 畜禽粪便农田承载力计算流程

Fig. 2 Calculation process of farmland bearing capacity of animal manure

1.3 计算数据与方法

1.3.1 农田土壤微塑料环境容量

根据环境基准制定技术指南^[17],土壤微塑料的预测无效应浓度($\text{PNEC}_{\text{soil}}$)可采用物种敏感度分布

法计算获得。因此,本研究在中国知网和 Web of Science 数据库进行文献检索,获得在土壤环境中无脊椎动物(包含蚯蚓、蜗牛等)和陆生植物(包含水稻、玉米、小麦等)的82条微塑料毒性数据,构建土

壤微塑料毒性数据库(表1)。运用物种敏感度分布法中的 Logistic 分布模型进行拟合,获得概率密度分布函数,推导出 5% 危险浓度(HC₅)为 0.002 g/kg。进而,依据环境基准制定技术指南^[17],采用式(1)计算获得农田土壤微塑料环境容量:

$$\begin{cases} \text{PNEC}_{\text{soil}} = \frac{\text{HC}_5}{\text{AF}} \\ \text{RQ} = \frac{\text{PEC}}{\text{PNEC}_{\text{soil}}} \\ Q = \frac{(\text{PEC} - c_b)DS\rho_b}{t} \end{cases} \quad (1)$$

式中:AF为评估因子,本研究中取1^[18];RQ为风险商值,本研究中取1;PEC为农田土壤微塑料的最大质量分数,mg/kg;Q为农田土壤微塑料的环境容量,mg/hm²;c_b为农田土壤微塑料的现状观测值,根据文献^[20-29],本研究中取0.000 19 g/kg;D为农田耕层厚度^[30],m;S为农田面积,本研究中取1 hm²;ρ_b为土壤容重^[31],kg/m³;t为达到环境容量所需时间,在本研究中将短期、中期和长期分别取20、50和100 a。

表1 土壤微塑料毒性数据库
Table 1 Soil microplastic toxicity database

敏感物种 Sensitive species	微塑料种类 Types of microplastics	毒性/(g/kg) Toxicity	敏感物种 Sensitive species	微塑料种类 Types of microplastics	毒性/(g/kg) Toxicity
蚯蚓 Earthworm	LDPE	70.00 ^[32]	紫花苜蓿 Lucerne	LDPE	100.00 ^[64]
	PS	2.50 ^[32]		PLA	100.00 ^[64]
	PE	39.60 ^[33]	大豆 Soybean	PE	0.10 ^[65]
	PE	1.50 ^[34]		PE	10.00 ^[66]
	PE	1.00 ^[35]		PLA	1.00 ^[67]
	PS	0.01 ^[36]		PS	0.20 ^[68]
	PS	<0.01 ^[37]	菠菜 Spinach	PS	0.20 ^[69]
	PS	<0.01 ^[38]		PS	0.80 ^[70]
	PP	1.00 ^[39]	花生 Peanut	PE	0.20 ^[71]
秀丽隐杆线虫 Caenorhabditis elegans	LDPE	1.50 ^[40]		PS	0.02 ^[48]
	PS	0.01 ^[41]	莴苣 Lettuce	LDPE	30.00 ^[72]
	PS	0.01 ^[42]		PVC	50.00 ^[73]
	PA	<0.01 ^[43]		PE	1.00 ^[74]
	PE	<0.01 ^[43]	樱桃萝卜 Cherry radish	PP	5.00 ^[75]
	PP	<0.01 ^[43]		PE	1.00 ^[75]
弹尾虫 Springtails	PVC	<0.01 ^[43]	黄瓜 Cucumber	PE	1.00 ^[76]
	PS	1.00 ^[44]		PS	0.05 ^[77]
小麦 Wheat	PE	45.50 ^[45]		PA	1.00 ^[78]
	PS	0.20 ^[46]	葱 Scallions	PES	2.00 ^[79]
	PE	0.04 ^[47]		PS	20.00 ^[79]
	PS	0.02 ^[48]	生菜 Lettuce	PS	10.00 ^[80]
	PP	0.10 ^[49]		LDPE	10.00 ^[81]
	HDPE	0.10 ^[49]		LDPE	10.00 ^[82]
	PLA	0.50 ^[49]	小白菜 Pakchoi	PS	0.01 ^[83]
	PE	80.00 ^[50]		PE	36.00 ^[84]
	PP	0.50 ^[51]	紫花地丁 Viola yedoensis	PE	0.50 ^[85]
	PE	5.00 ^[51]	绿豆种子 Mung bean seeds	PE	1.00 ^[86]

表 1（续）

敏感物种 Sensitive species	微塑料种类 Types of microplastics	毒性/(g/kg) Toxicity	敏感物种 Sensitive species	微塑料种类 Types of microplastics	毒性/(g/kg) Toxicity
蜗牛 Snail	PET	0.14 ^[52]	上海青 Greengrocery	PP	22.00 ^[84]
	PET	10.00 ^[53]	辣椒 Chili pepper	PE	0.05 ^[88]
玉米 Maize	PS	0.02 ^[48]	向日葵种子 Sunflower seeds	PS	0.02 ^[48]
	PVC	5.40 ^[54]	菜心种子 Choy sum seeds	PS	0.50 ^[89]
	PLA	100.00 ^[55]	棉花 Cotton	HDPE	10.00 ^[90]
	PS	1.00 ^[56]	菜豆 Kidney bean	PLA	5.00 ^[91]
	PE	1.00 ^[57]	胡萝卜 Carrot	PP	3.00 ^[92]
水稻 Rice	PS	0.25 ^[58]	番茄 Tomato	MP	4.00 ^[93]
	PLA	<0.01 ^[59]	洋葱种子 Onion seeds	PS	0.10 ^[94]
	PS	0.20 ^[38]	大白菜 Chinese cabbage	HDPE	2.50 ^[95]
	PVC	50.00 ^[60]	多年生黑麦草 Perennial ryegrass	PLA	1.00 ^[96]
	PP	50.00 ^[61]	拟南芥 Arabidopsis	PS	0.30 ^[97]
	PE	10.00 ^[62]	家独行菜 Lepidium oleraceum	PC	20.00 ^[98]
	PS	1.00 ^[63]	少花龙葵 Solanum frutescens	PE	1.00 ^[99]

注：LDPE, 低密度聚乙烯；PS, 聚苯乙烯塑料；PE, 聚乙烯；PP, 聚丙烯；PA, 聚酰胺；PVC, 聚氯乙烯；HDPE, 高密度聚乙烯；PLA, 聚乳酸；PET, 聚对苯二甲酸乙二醇酯；PES, 聚醚砜；MP, 未说明具体种类的微塑料。

Note: LDPE, low-density polyethylene; PS, polystyrene plastic; PE, polyethylene; PP, polypropylene; PA, polyamide; PVC, polyvinyl chloride; HDPE, high-density polyethylene; PLA, polylactic acid; PET, polyethylene terephthalate; PES, polyethersulfone; MP, unspecified type of microplastics.

1.3.2 农田土壤微塑料的输入

根据物质流分析法,新疆生产建设兵团农田土壤的微塑料输入途径主要包括农膜和畜禽粪肥。因此农田土壤微塑料环境容量为农膜和畜禽粪肥的微塑料输入量之和。依据物质流分析法,采用式(2)计算得到畜禽粪肥的微塑料最大输入量:

$$\begin{cases} Q=Q_p+Q_m \\ Q_p=m_p\cdot E_p \\ E_p=0.2535ET+4.3668\times \\ \qquad 10^{-13}UV-0.9857 \end{cases} \quad (2)$$

式中:Q_p为农膜残留的微塑料输入量,mg/hm²;Q_m为畜禽粪肥的微塑料最大输入量,mg/hm²;m_p为农膜用量,本研究中取 56.21 kg/hm²^[14];E_p为农膜的

微塑料排放系数,%,由经验公式^[100]推导计算得出;ET 为农膜曝光时间,本研究中取 180 d;UV 为紫外线强度,本研究中取 5 498.8 MJ/m²^[100]。

1.3.3 畜禽粪便农田承载力

根据畜禽粪便中微塑料质量分数、畜禽粪便排泄系数、收集率与损失率等参数,推导计算出每 hm²农田可承载畜禽养殖量,计算公式为:

$$\begin{cases} N_m=Q_m/w_m \\ n=N_m/H \end{cases} \quad (3)$$

式中:w_m为畜禽粪便中微塑料质量分数^[11,16,101-106](表 2);N_m为单位面积农田可施用粪肥量,kg;n 为单位面积畜禽养殖量,头或羽;H 为畜禽整个饲养周期的粪便排泄量(以干物质计)^[107-108],kg/头或 kg/羽。

表2 畜禽粪便中微塑料质量分数

Table 2 Microplastics content in animal manure

种类 Type	样本量/个 Sample size	质量分数/(mg/kg) Mass fraction
鸡粪 Chicken manure	40	256.6
牛粪 Cattle manure	18	303.7
猪粪 Swine manure	42	177.8

1.4 情景分析

为探究农膜和畜禽粪肥微塑料输入对畜禽粪便农田承载力的影响程度,本研究采用情景分析法,以蛋鸡为例,仿真分析农膜和畜禽粪肥微塑料输入量降低5.0%~30.0%时,每降低5.0%,畜禽粪便农田承载力的变化趋势。

2 结果与分析

2.1 新疆生产建设兵团畜禽粪便农田承载力估算

根据畜禽粪便农田承载力计算流程(图2),将

风险商值 $RQ=1$ 代入式(1)~(3),计算获得新疆生产建设兵团畜禽粪便农田承载力。当达到环境容量所需时间为短期时,新疆生产建设兵团每 hm^2 农田可承载生猪、奶牛、肉牛、肉鸡和蛋鸡的养殖量分别为651.9头、5.8头、15.9头、3 895.9羽和571.8羽;中期时,分别可承载222.7头、2.0头、5.4头、1 331.1羽和195.4羽;长期时,分别可承载79.7头、0.7头、1.9头、476.2羽和69.9羽(图3)。其中,蛋鸡的承载力较生猪更低,这主要是因为鸡粪中的微塑料质量分数远高于猪粪(表2)。

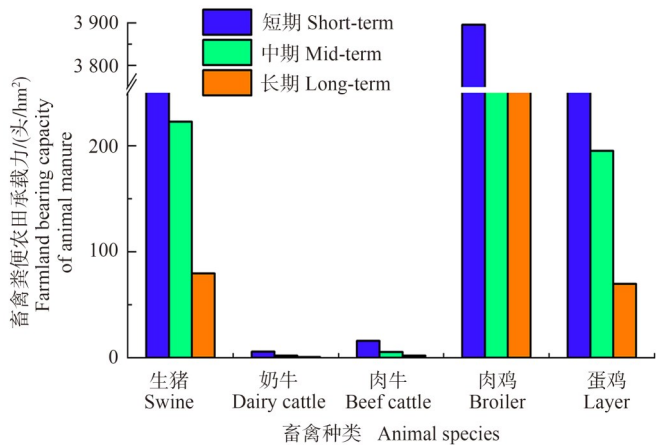


图3 新疆生产建设兵团畜禽粪便农田承载力估算结果

Fig. 3 Estimation result of farmland bearing capacity of animal manure in XPCC

考虑到研究成果的推广与应用,本研究将新疆生产建设兵团的畜禽粪便农田承载力依照粪便排泄量与粪便微塑料质量分数等因素转化为猪当量,即100头猪相当于0.9头奶牛或2.4头肉牛或597.6羽肉鸡或87.7羽蛋鸡。

2.2 情景分析

本研究对新疆生产建设兵团畜禽粪便农田承载力进行情景分析,结果见图4。以蛋鸡为例,随着农膜或粪肥微塑料输入量降低,畜禽粪便农田承载

力呈现增加趋势。其中,当粪肥微塑料输入量降低30.0%时,畜禽粪便农田承载力提高了42.8%,为279.1羽/ hm^2 ;而农膜输入量降低30.0%时,承载力仅提升了8.5%,为212.0羽/ hm^2 。由此可见,在相同变化幅度情况下,粪肥微塑料输入对畜禽粪便农田承载力的影响程度高于农膜残留。因此,降低畜禽粪便中微塑料质量分数,从而降低畜禽粪肥微塑料输入量,是提升畜禽粪便农田承载力的重要途径。

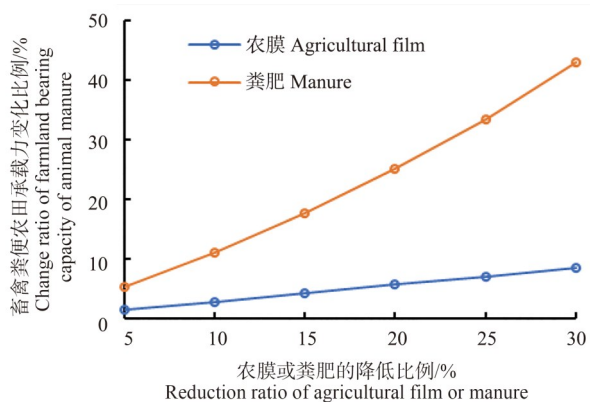


图4 农膜或粪肥的降低对畜禽粪便农田承载力的影响

Fig. 4 Effects of reducing agricultural film or manure on the farmland bearing capacity of animal manure

3 讨论

3.1 与现有行业标准计算结果的对比分析

依据NY/T 3877—2021《畜禽粪便土地承载力测算方法》^[109],计算得到新疆生产建设兵团生猪、奶牛、肉牛、肉鸡和蛋鸡的畜禽粪便承载力平均值分别为43.1头/hm²、4.8头/hm²、15.9头/hm²、789.7羽/hm²和6280.3羽/hm²。而本研究估算得到的畜禽粪便承载力分别为79.7头/hm²、0.7头/hm²、1.9头/hm²、476.2羽/hm²和69.9羽/hm²(图3)。对比可知,除了生猪,本研究估算得到的承载力均低于行业标准结果,其主要原因是猪粪微塑料质量分数相对较低,而鸡粪和牛粪都相对较高(表2)。这也从侧面证明,微塑料已经成为畜禽粪肥安全施用的限制因素之一。从方法学层面分析,行业标准主要考察的是作物养分需求与供给关系,而本研究意在土壤微塑料积累与风险防控,两者探讨问题不完全一致,但目标都是促进畜禽粪肥科学安全施用与区域种养平衡。

3.2 防控微塑料污染,保障粪肥安全还田

根据畜禽饲养环节生产现状,畜禽粪肥微塑料主要来源于饲料和饮用水2大途径。在饲料途径,Xu等^[110]采用分子光谱法定性判定了饲料原料鱼粉中含有PE、PP和PS。Wu等^[16]也在华南地区养殖场饲料样品中检测到PE、PP、PEC和PET。饲料中的微塑料考虑来自于饲料的外包装袋、饲料厂的生产、运输管道与设备等。在饮水途径,水库、河流和湖泊等环境水样均检测出微塑料^[111],导致养殖场饮水中也含有微塑料,并且养殖场的塑料管道、饮

水器等老化分解等问题都会增加畜禽饮用水中的微塑料量^[16,112]。因此,建议未来严格控制饲料来源,加强饲料质量监测;优化饲料生产过程管理,减少原料与塑料设施设备的摩擦或接触;加强水体微塑料检查,采用过滤等多种措施去除饮用水中的微塑料;新建畜禽养殖场可考虑使用不含塑料的环境友好材料代替塑料制品。

农膜同样作为土壤微塑料的输入途径^[113-115],也需要给予足够的重视。实地调研发现,新疆生产建设兵团已经大力开展了残膜回收利用工作,当季农田废旧地膜回收率达到90%以上^[116]。并且《新疆生产建设兵团“十四五”生态环境保护规划》^[117]中也明确提出“严格执行《农用薄膜管理办法》,大力推广地膜回收机具,采取有偿回收方式,逐步建立农用薄膜回收网点,继续推进兵团废弃农膜污染综合治理考核工作。”随着新疆生产建设兵团农膜回收管理工作的持续深入推进,未来能有效减缓农田土壤微塑料的输入。

3.3 研究局限及展望

微塑料作为新污染物,其主要流动路径为:农膜残留→农田土壤。本研究构建了畜禽粪便农田承载力定量模型并进行分析,发现畜禽粪肥对农田土壤微塑料生态污染风险和承载力影响较大(图4)。这说明,畜禽养殖阶段,即饲料、设施设备→畜禽→粪肥→农田土壤的污染物流动路径不能忽视。由此可见,微塑料污染物风险防控,不能仅仅关注农膜残留,还需要防控畜禽养殖所带来的微塑料,更需要种植业与畜禽养殖业协同防控工作,减少农田土壤微塑料输入量,保障农田土壤健康与区域种养结合。

在常规农田土壤物质平衡研究中,农资投入、灌溉水和大气干湿沉降是主要输入途径。由于缺乏相关的研究支撑,本研究暂未考虑灌溉水和大气干湿沉降等途径的微塑料输入。随着未来基础试验研究与数据完善后,本研究团队将进一步完善计算方法。

4 结论

本研究构建了基于微塑料生态风险值的畜禽粪便农田承载力模型,运用风险商法和土壤环境影响预测法,估算得到新疆生产建设兵团的畜禽粪便农田承载力,初步得到以下结论:

1)新疆生产建设兵团每 hm^2 农田可承载的生猪、奶牛、肉牛、蛋鸡和肉鸡数量分别为 79.7 头、0.7 头、1.9 头、476.2 羽和 69.9 羽。除了生猪,本研究估算得到的承载力均低于行业标准结果,其主要原因是畜禽粪便中微塑料质量分数相对较高。微塑料已经成为限制畜禽粪肥施用的因素之一。

2)当粪肥和农膜微塑料输入量分别降低 30.0%,畜禽粪便农田承载力可提高 42.8% 和 8.5%。

3)面向农田土壤生态风险防控,微塑料已制约了畜禽粪肥安全施用与农田承载力。建议加强畜禽饲料与饮用水的微塑料监测,防控饲养环节微塑料污染,保障粪肥安全还田。

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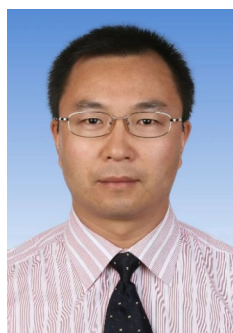
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