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我国土壤连作障碍成因及其消减机理研究进展

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摘要 为系统了解我国土壤连作障碍的成因与消减机理研究的最新进展,基于2014—2024年中国知网(CNKI)数据库,以“连作障碍”为关键词进行检索,对获得的全国各地该研究领域相关文献进行总结和梳理。结果表明:连作障碍已成为制约我国农业绿色发展的瓶颈,是土壤理化性质恶化、植物化感自毒作用和土壤生态环境恶化3种机制综合作用的结果。其中,生物因素是连作障碍发生的最主要成因,尤其是土传病害,其造成的危害占比超过70%。因此,未来的连作障碍消减策略应更关注生物指标的建立及生物资源的利用。在实践上,应通过科学精准的水肥管理、优化种植结构、保护性耕作和土壤生物调控等综合措施,构建健康的土壤微食物网,促进农业的可持续发展和保障粮食安全。

关键词 连作障碍;土传病害;土壤微食物网;根际调控

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Research progress on the causes and reduction mechanisms of soil continuous cropping obstacles in China

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Abstract To systemically understand the latest research progress on the causes and mitigation mechanisms of continuous cropping obstacles in China, relevant literature indexed in the China National Knowledge Infrastructure (CNKI) database from 2014 to 2024 were searched using “continuous cropping obstacles” as the keyword. The obtained publications on various regions across China were summarized and sorted. The main conclusions are as follows: Continuous cropping obstacles have become a bottleneck restricting the green development of agriculture in China. Their causes involve the combined effects of three mechanisms: deterioration of soil physical and chemical properties, plant allelopathic autotoxicity, and deterioration of the soil ecological environment. Biological factors are the primary cause of continuous cropping obstacles, particularly soilborne diseases, which account for over 70% of the damage. Therefore, future strategies to reduce continuous cropping obstacles should focus on the establishment of biological indicators and the utilization of biological resources. In practice, a comprehensive approach, including scientific and precise water and fertilizer management, optimized planting structures, conservation tillage, and soil biological regulation, should be adopted to build a healthy soil micro-food web to promote sustainable agricultural development and ensure food security.

Keywords continuous cropping obstacle; soil-borne diseases; soil micro-food web; rhizosphere regulation

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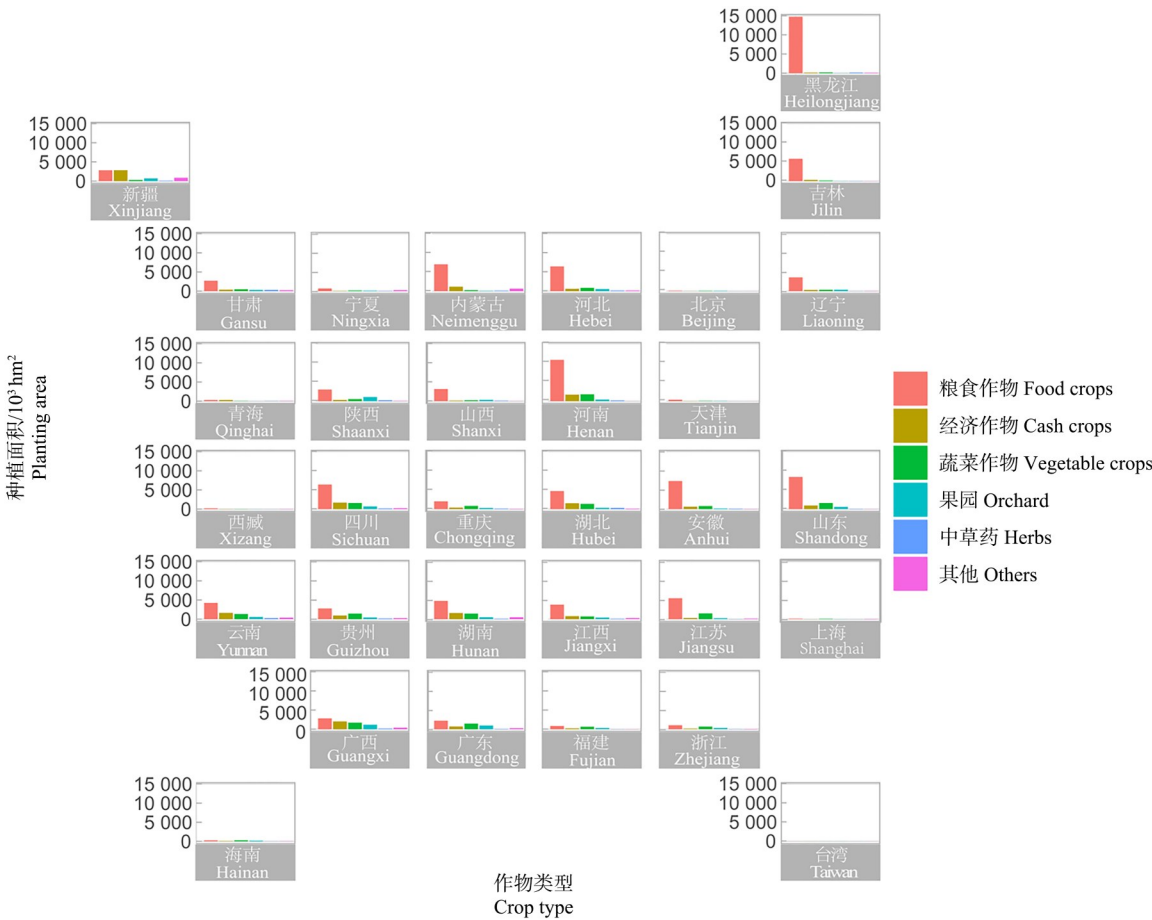
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1 我国连作作物分布特征与土壤连作障碍概况

连作障碍是指在正常的栽培管理措施下,同一块土地连续种植2茬及以上同种同属作物而出现的病虫害、养分失衡情况,进而大幅减产甚至绝产的现象^[1]。我国耕地总面积19.18亿亩,是世界第三大耕地拥有国,同时,我国也是世界第一人口大国,利用占全球9%的耕地资源,满足占全球20%人口的粮食需求^[2],正是这种地少人多的国情,使我国耕地常年连作,不可避免地诱发各种连作障碍问题。连作与非连作相比,平均减产约20%以上^[3-4],值得注意的是中国危害程度高的连作耕地面积>10%,其中规模化种植区发生面积超过20%,当季作物产量损失达20%~80%,严重的连作障碍发生区域几

乎绝产,每年造成的经济损失达数百亿元^[5]。因此,连作障碍已成为制约我国农业产能提升、可持续和绿色发展的最大限制因子之一。

我国连作作物主要分为四大类,包括粮食作物(如水稻、大豆等)、经济作物(如棉花、烟草等)、瓜果蔬菜和中草药等。连作作物分布存在明显的区域特性,如:粮食作物主要分布在东北、华北、四川盆地以及长江中下游地区;新疆是我国棉花主产区,广西是我国糖料作物主要种植区,这2个省也是我国经济作物种植面积最大的省份;随着集约化农业的快速发展,设施园艺作物种植面积逐年扩大,河南、山东、广西设施蔬菜种植面积居全国前三位;我国药材主要种植区域是云贵高原、甘肃和湖北等地(图1)(统计数据未包含港、澳地区。下同)。



依据中华人民共和国国家统计局的《中国统计年鉴》^[2]整理。柱形图的布局依据各省份在中国的相对位置。统计数据未包含港、澳地区的数据。下同。

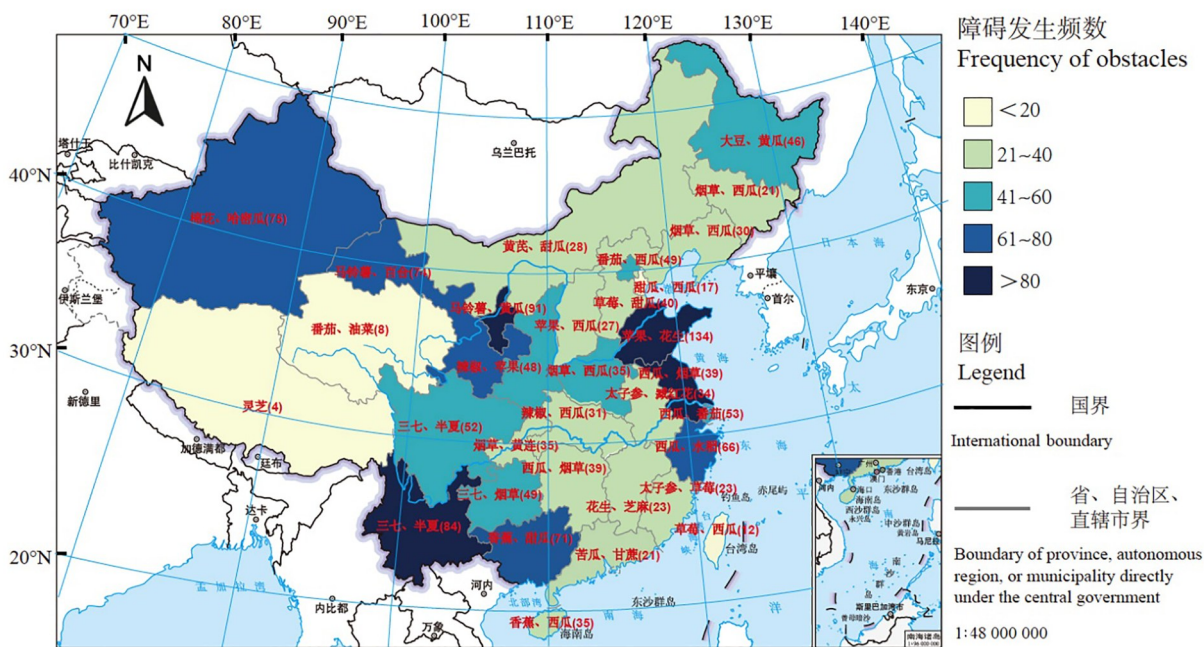
Data are compiled from the *China Statistical Yearbook*^[2] of the National Bureau of Statistics of the People's Republic of China. The layout of the bar chart is based on the relative position of each province in China. The statistics do not include data from Hong Kong and Macao. The same applies below.

图1 我国32个省(自治区、直辖市)连作作物种植面积分布

Fig. 1 Distribution of continuous cropping areas in China's 32 provinces (autonomous regions and municipalities)

为探究连作障碍在不同省份的发生频数分布特征以明确各不同地区的主要连作作物及土传病害危害,本研究以“连作障碍”为关键词,分别结合全国32个省(自治区、直辖市)名称作为检索词,基于中国知网(CNKI)数据库,对2014—2024年收录的中文文献的篇名、摘要及关键词进行精确检索,剔除会议通知、征稿启事等非研究性文献后,统计各省份与连作障碍发生相关的文献,记录数量,结果见图2。可见:易于发生连作障碍的作物主要有:粮食作物主要包括大豆、马铃薯等;经济作物主要为棉花、烟草等;园艺作物如苹果、香蕉等;设施蔬菜作物如番茄、黄瓜等;中草药主要为三七、太子参等。全国32个省(自治区、直辖市)均有连作障碍发生的报道,其中山东、江苏、云南、宁夏四省报道的连作障碍文献数都>80篇,是我国连作障碍报道最多的省份,且这四省都种植了易于发生连作障碍的标志性作物,如云南的三七、山东的苹果、宁夏的马铃薯、江苏的烟草等。黑龙江省是我国大豆主产区,大豆产量占全国40%左右,且大豆连作问题突出,该地区大豆连作3年减产10%~30%^[6-7]。另

外,连作障碍中土传病害的发生与当地土壤和气候条件高度相关,如:我国华南与长江中下游地区地处亚热带及热带季风气候区,夏季漫长、高温、多雨,土壤类型以酸性至强酸性的红壤、黄壤和砖红壤为主,这种高温、高湿、酸性的土壤-气候组合,为青枯病、枯萎病等多种毁灭性土传病害的滋生创造了条件^[8-9];黄淮海与北方设施农业区属于暖温带半湿润季风气候,冬季寒冷,本不完全适宜某些喜温病害的全年发生。然而,近几十年来,以日光温室和塑料大棚为代表的设施农业的迅猛发展,彻底改变了这一格局,设施农业创造了“人造微气候”,其内部常年保持高温、高湿、密闭环境,这恰恰为根结线虫等喜温病害提供了理想的生存和繁殖条件^[10];东北黑土区是我国最重要的商品粮基地,以其肥沃的黑钙土、黑土闻名。气候为中温带季风气候,一年一熟制,这里的土传病害问题主要是长期不合理的农业管理形成,例如,长期连作大豆显著加重了大豆根腐病和孢囊线虫病的发生^[11]。因此,未来防控连作障碍要针对不同地区的不同代表性作物结合当地气候和土壤条件进行针对性地靶向防控。



基于自然资源部标准地图服务网站审图号GS(2016)1601号。图中数字代表连作障碍发生频数。

Based on the map published on the Ministry of Natural Resources Standard Map Service website. The map review number is GS(2016)1601.

The numbers in the figure represent the frequency of continuous cropping obstacles.

图2 我国32个省(自治区、直辖市)连作障碍出现频数分布示意图

Fig. 2 Schematic diagram of the frequency distribution of continuous cropping obstacles in 32 provinces (autonomous regions and municipalities) in China

2 土壤连作障碍成因

连作障碍是植物-土壤-微生物及其环境等诸多因素综合作用的外在表现。其成因错综复杂,目前普遍认为主要包括三大相互关联的机制:土壤理化性质恶化、植物化感自毒作用和土壤生态环境恶化。这三种机制通常相互影响、相互叠加,共同限制作物产能,详见表1。

2.1 土壤理化性质恶化

土壤理化性质恶化常出现在大田作物和设施蔬菜作物,主要包括土壤板结、次生盐渍化、土壤酸化和养分失衡等。我国大田作物长期连作,生理酸性肥料投入过剩容易造成土壤酸化,过量的肥料投入使我国土壤pH平均下降0.13~0.80^[12]。土壤酸化不仅能通过影响土壤金属离子含量造成作物铁毒、铝毒和镉污染等而直接影响作物生长^[13-18],同时还会抑制作物对钙、镁、磷等养分的吸收^[19],甚至可以通过促进某些喜酸性环境土传病原物(如孢囊线虫、枯萎病菌)增殖而间接限制作物产能提升^[20-21]。土壤理化性质恶化的另一表现是土壤养分失衡。不同植物在生长过程中对土壤养分需求不同,植物生长过程中依据自身的生理需求对土壤养分(特别是微量元素)进行选择吸收,因此,长期连作往往也会造成土壤养分失衡和作物体内各种养分比例失调,从而使作物产生各种生理和功能性障碍,进而导致产量低和品质差。如:玉米连作13年后,土壤容重减小,土壤速效钾和有机质含量下降^[22];烟草、黄瓜连作,土壤氮磷钾比例失调^[23-24];葡萄重茬3次以上,土壤微量元素比例失调,葡萄减产^[25]。另外,土壤长期连作,机械耕作压实造成土壤孔隙度降低、通透性变差,植物根系生长和呼吸作用受阻,进而影响植物对水肥的吸收,在设施蔬菜种植过程中大水大肥投入使土壤养分富集,且土壤温度偏高、水分蒸发量大,下层土壤中的养分易随深层土壤水分蒸发而向上扩散,易导致土壤发生次生盐渍化^[26]。因此,连作导致的土壤理化性质恶化是连作障碍的主要特征之一。

2.2 土壤生态环境恶化

土壤生态环境恶化包括根际土传病原微生物丰度增加、土壤线虫群落结构失衡、植食性线虫丰度增加等。夏梅梅等^[27]通过文献计量学分析发现,连作障碍土壤中土壤生物环境恶化、土壤理化性质

改变和植物化感自毒作用占比分别为44%、34%和22%,生物因素是连作障碍发生最主要的成因。值得注意的是由土壤生态环境恶化引起的土传病害是连作障碍最直接、最主要的表现形式,约超过70%的连作障碍危害都是由土传病害引起^[28]。就世界范围而言,研究模型预测结果表明到2050年,世界绝大部分地区土传病害风险将加剧,此时若继续过度依赖化石燃料燃烧、化肥过量投入等传统的资源消耗型资源利用模式将使全球土传病原菌平均丰度在3%以上,这将严重威胁世界粮食安全^[29]。土传病害使世界小麦减产约21.5%、水稻减产约30%,使我国小麦减产约28.1%、水稻减产约32.2%^[30]。而常见的土传病害主要包括各类线虫病害、枯萎病、青枯病、黄萎病和立枯病等。根结线虫被列为世界十大植物寄生线虫之首,其地理分布广,寄主多样,对作物危害极其严重。近年来,随着我国设施蔬菜产业发展,温室蔬菜作物连作,根结线虫病害肆虐;其他植物寄生线虫病害也在我国频发。例如:大豆胞囊线虫多样性的全国调查结果显示,我国除个别省份外,多数大豆种植区均发现有大豆胞囊线虫,大豆胞囊线虫对全国大豆造成约5.5%的产量损失,病害严重地区产量损失甚至高达50%,全国约有10%的大豆种植区遭受胞囊线虫病的严重威胁^[31];黄萎病主要分布在我国棉花种植区,是棉花的第一大病害,被称为棉花的“癌症”^[32]。黄萎病在我国每年发病面积约为250万hm²每年造成经济损失约为2.5亿~3.1亿美元,可使棉花减产10%~30%,病害严重地区甚至造成80%以上减产^[33];青枯病也是我国主要土传病害之一,分布在除黑龙江、内蒙古、西藏外的所有省份,能侵染450多种植物,青枯病可造成烟草减产25%~100%、番茄减产16%~41%、土豆减产64%~65%、茄子减产60%~90%^[34-36]。

2.3 植物化感自毒作用

植物化感自毒作用是指植物根系分泌物、茎、叶淋溶物及植物残体分解所产生的有毒代谢产物在土壤中积累,从而产生抑制根系生长、降低根系活性和改变土壤微生物区系的作用,尤其是这种作用直接毒害作物的同时有助于病原菌的繁殖,最终导致作物生长不良、发病和死亡^[37]。植物化感自毒作用是导致土壤连作障碍发生的主要因子之一。已有研究表明,花生根系分泌物中对羟基苯甲酸、

香草酸和香豆酸等酚酸类物质在土壤中随连作年限的延长而积累,并对花生生长表现出抑制作用^[38]。然而,也有研究得出不同结论,认为花生根系分泌物中的酚酸类物质对花生生长没有直接的抑制作用,主要是通过破坏土壤微生物群落结构,刺激土壤中病原菌的扩繁,引发连作障碍,抑制花生生长^[39]。除花生外,各类药材和设施蔬菜作物也极易发生化感自毒作用,药用植物的化感自毒作用是其连作障碍产生的主要诱因。太子参连作1~3年土壤中酒石酸、丁二酸等有机酸逐年积累^[40],三七连作1~3年土壤中酚酸类物质逐年积累^[41],这些自毒物质严重破坏土壤微生物群落,使药材作物大幅减产甚至绝产。另外,设施蔬菜作物:茄子连作3年后根系分泌的肉桂酸和香草醛可抑制茄子幼苗生长,并促进黄萎病原菌增殖^[42];番茄连作7年根际土壤中脂肪酸逐年积累并抑制番茄幼苗生长^[43];豇豆连作8年根际积累的苯乙酸等有机酸可抑制豇豆幼苗生长等^[44]。因此,植物化感自毒作用诱发的连作障碍不容忽视。

总之,连作障碍的加剧,并非土壤理化性质恶化、生态环境失衡或植物化感自毒中任何单一因素,而是3个因素协同存在、相互催化的恶性循环,详见表1。具体而言,连作导致的土壤板结与酸碱失衡等理化性质恶化,首先为根系分泌的化感自毒物质的积累创造了条件,阻碍其分解;而高浓度的自毒物质继而抑制有益微生物,促进病原菌繁殖,导致土壤生态环境失衡。这个失衡的微生态系统不仅丧失了降解毒素的能力,使自毒作用被无限放大,更无法维持土壤的健康结构与养分循环。最终,这种生态功能的衰退又反作用于土壤本身,进一步加剧了理化性质的恶化。正是这个环环相扣、层层加码的协同破坏效应,加剧连作障碍发生。

3 连作土壤土传病害发病规律与健康评价

3.1 连作土壤土传病害发病规律

土壤中病原微生物、有益微生物与植物共同存在、相互作用,维持着土壤微生态系统稳定,土传病害暴发会打破此平衡,而植物可以通过一般性免疫和特异性免疫2种免疫途径共同调节土壤微生物群落,抑制土传病害暴发^[65]。植物可向根际分泌20%~40%的光合作用固定的碳源用以招募具有高度多样性的根际微生物群落,这些根际微生物可

形成一般性免疫屏障保护植物免受病原物侵染^[66]。连作初期,以根际有益微生物为主导的一般性免疫途径作用于所有病原生物,在保护植物免受病原物侵染过程中发挥主要作用^[67],随着连作年限延长,根际土壤酸化、土壤中酚酸类等自毒物质积累,减弱根际有益微生物抗病能力、促进土壤病原生物增殖并使土壤有益微生物丰度减少,病原物克服基础免疫侵染植物,致使土传病害暴发。Li等^[68]研究发现酸化的土壤pH可通过抑制有益微生物抗真菌物质分泌和含硫化合物合成降低根际土壤对枯萎病的免疫力,这一研究为进一步解释连作条件下病原物如何克服基础免疫提供了依据;病原物侵染过程中植物特异性免疫系统会识别病原微生物从而招募能拮抗病原微生物的特异性功能微生物^[69-71]。植物一般性免疫过程和特异性免疫过程的共同调节使连作后期土壤针对土传病害会形成2种“感病状态”,即持续感病和形成抑病土,详见图3。

由图3(a)可见持续感病状态在整个连作过程中土壤植食性线虫和致病菌丰度持续升高,土壤环境持续恶化。目前有关土传病害的研究主要集中在此类土壤,如有研究表明,西瓜连作21年,减产约25%,黄瓜连作20年减产约50%^[55,72];由图3(b)可见形成抑病土状态,表现为连作前中期土壤病原微生物丰度升高连作后期丰度降低,土壤有益微生物丰度持续升高,最终土壤生物环境趋于稳定。在大豆胞囊线虫的研究中发现,大豆连作前5年病害严重,连作5年后病害缓解,而土壤假单胞菌等有益微生物富集^[73],在小麦全蚀病、纹枯病和立枯病上也有类似发病规律的相关研究报道^[74];由图3(c)可见连作后期抑病土是否形成的关键是由土壤环境、初始微生物状态和植物特异性免疫对功能微生物招募能力的强弱所决定^[75]。因此,基于这一规律,通过调控土壤-植物-微生物协调互作构建健康的土壤微生物网络平衡而实现健康的根际环境是重要的突破方向。

鉴于上述连作土壤土传病害发病规律的复杂性,深入理解和预测土传病害发生和土壤健康状况,对于保障农业土地的持续生产力及维持生态系统服务功能至关重要^[76]。传统的土壤健康评价方法,如:土壤质量综合指数法^[77]、多层次模糊综合评价法^[78-80]等已得到很好的应用。但连作障碍最主要诱因是土壤生物环境的恶化,土壤健康强调的核心

表 1 不同作物连作障碍成因、严重年限及表现

Table 1 Factors, severe years and phenotypes of continuous cropping obstacles of different crops

因素 Parameter	因素分类 Factor classification	作物 种类 Crop type	连作障碍严重年限及表现 Severe years and phenotypes of continuous cropping obstacles	文献 Reference
土壤理化性质恶化 Deterioration of soil physical and chemical properties	土壤酸化 养分失衡 次生盐渍化	玉米	13年,土壤容重减小,土壤速效钾、有机质含量下降	[22]
		烟草	20年,土壤全氮、缓效钾、速效钾含量降低	[23]
		辣椒	6年,土壤酸化、次生盐渍化	[45]
		茄子	5年,土壤酶活降低	[46]
		荞麦	6年,土壤脲酶等各种酶活降低	[47]
		黄瓜	3年,氮磷钾养分失衡、土壤次生盐渍化	[24]
土壤生态环境恶化 Deterioration of soil ecological environment	生态群落失衡 生物种类降低 有益生物减少 有害生物增多	烟草	25年,土壤细菌网络失衡	[48]
		甘薯	2年,土壤有益微生物减少、有害微生物增多,作物产量降低	[47-48]
		大豆	3年,线虫总丰度降低,连作前期植食性线虫丰度增加	[49]
		苎麻	10年,微生物群落失衡,有益微生物减少,有害微生物增多	[50]
		高粱	3年,土壤微生物群落失衡	[51]
		黄瓜	7年,土壤微生物群落失衡,土壤脲酶活性降低,土壤微生物功能多样性降低	[52]
		花生	5年,根系分泌酚酸类物质,破坏土壤微生物群落	[39]
		棉花	25年,土壤黄萎病病原菌积累	[53-54]
		西瓜	21年,土壤微生物群落失衡	[55]
		马铃薯	4年,土壤酶活降低,土壤微生物群落失衡	[56]
			7年,枯萎病发病率达80%	[57]
植物化感自毒作用 Plant allelopathic autotoxicity	自毒物质积累	小麦	4年,小麦立枯病、纹枯病、全蚀病	[58-60]
		大豆	5年,土壤对羟基苯甲酸、香草酸含量升高,抑制大豆幼苗生长	[61]
		茄子	3年,土壤肉桂酸积累,抑制茄子生长,促进黄萎病增殖	[42]
		豇豆	8年,土壤肉桂酸、苯乙酸等有机酸积累,抑制豇豆生长	[62]
		番茄	7年,根系分泌物脂肪酸积累,抑制番茄生长	[43]
		花生	4年,不同组织部位残体水浸液,根系分泌物中豆蔻酸、软脂酸、硬脂酸、对羟基苯甲酸、香草酸、香豆酸等均抑制花生植株生长	[38,59-60]
交互作用 Interaction	土壤环境和生物因素交互作用加剧连作障碍发生	辣椒	高浓度辣椒水浸提物抑制生菜和白菜种子萌发和幼苗生长	[61]
		草莓	6年,土壤酸化、速效磷和有机质含量降低	[62]
			8年,土壤枯萎病等病原微生物和病原线虫丰度升高	
			12年,土壤自毒作用,土壤对羟基苯甲酸等酚酸类物质积累	
		番茄	10年,土壤酸化、富营养化、盐渍化,土壤有益线虫减少、植食性线虫增多	[63]
		太子参	3年,土壤酒石酸、丁二酸等有机酸积累,土壤微生物群落失衡	[40]
		三七	3年,土壤酚酸类物质积累,微生物群落失衡	[41]
		生姜	15年,铝毒,青枯病	[64]
		葡萄	30年,土壤养分失衡,生物群落恶化	[25]

也是土壤的生物功能,土壤健康调控的各项措施也会直接或间接反应在土壤微食物网调控上。合理的土壤健康评价方法能预测土传病害发病规律以便于对土传病害进行针对性防控。然而,土壤生物在过去

由于难以被测量或评估,其重要性常被忽视,但随着生物基因组测序技术和相关成果的快速发展,越来越多的生物指标被用于土壤健康综合评价,为未来推动生物指标评价健康土壤提供了理论和技术依据。

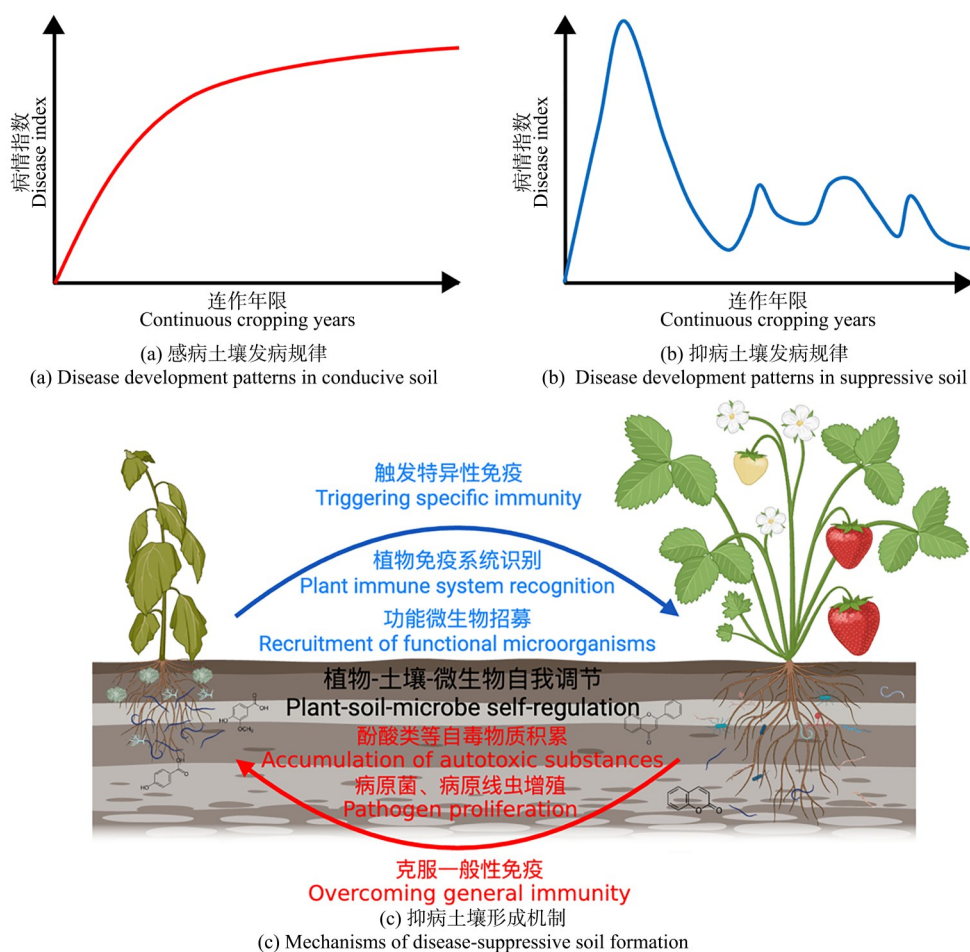


图3 连作土壤土传病害不同的发病模式

Fig. 3 Patterns of soil-borne diseases in continuous cropping soils

3.2 基于线虫特征评价土壤健康

线虫作为土壤中数量最丰富的后生动物,其适应性强、分布范围广,几乎分布在所有类型的土壤,可分为植食性线虫、食细菌线虫、食真菌线虫和捕食/杂食性线虫,占据着土壤食物网的中心位置,具有较高的物种多样性、食性多样性、生活史策略多样性和功能多样性特征^[81]。线虫这些优势奠定了其作为土壤食物网结构和土壤健康指示生物的生态学基础,并发展出一系列基于秀丽线虫、线虫个体分类、生活史策略、功能团、代谢足迹评价土壤微食物网和土壤健康的相关指数和分析方法^[82]。首先,秀丽线虫(*Caenorhabditis elegans*)是一种从土壤中分离出来

的食细菌线虫,身体透明、具有完整的遗传信息、生长周期短且易于室内培养以及具有大量突变体和转基因株系,其对环境变化反应灵敏,能够迅速响应变化的环境条件^[83],因此广泛用于土壤中微塑料^[84-85]、农药毒理学^[86-88]、重金属污染^[89-91]以及化肥污染^[92]等研究,被认为是环境评估有用的模式物种^[93-94]。除秀丽线虫外,许多研究基于线虫群落评估土壤健康,线虫群落分析早期主要基于线虫个体分类,个体分类主要描述线虫群落科、属、种类群数目及丰度,对其多样性的描述一般采用诸如丰富度指数、优势度指数、均匀度指数等各种通用指数^[95],这一阶段的分析可依据土壤植食性线虫占比和土壤线虫群落多样性高低大致

判断土壤健康状况,健康土壤拥有较高的线虫多样性和较低的植食性线虫丰度。20世纪80年代,生物学家 Bongers^[96]将线虫作为指示生物应用到污染土壤检测及恢复中,并依据线虫生活史策略对每科线虫赋予一定的 Cp(Colonizer-persister)值,从而创造性地提出成熟度指数,成熟度指数(Maturity Index, MI)能较好地指示土壤生态系统演替和恢复过程,随后,该指数发展形成如 PPI、MI25、 Σ MI、PPI/MI、 Σ MI25 等不同成熟度指数系列,此类指数目前已成功应用于土壤化学药剂施用和重金属污染评价等领域^[97-98]。21世纪初,Ferris^[99]将上述线虫个体分类学中的线虫食性信息和生活史策略中的 Cp 值相结合,提出线虫功能团,并提出一系列指数如结构指数(Structure Index, SI)、基础指数(Basal Index, BI)、富集指数(Enrichment Index, EI)和通道指数(Channel Index, CI)等,用以描述土壤养分富集状况、土壤食物网结构和功能等,该类指数已应用于评价土壤化肥、有机肥投入以及有机肥品质等^[100-102]。

3.3 微生物群落结合机器学习评价土壤健康

土壤微生物是土壤中最活跃的部分,土壤微生物组在土壤有机质、氮素和磷素等元素循环中起着至关重要的作用,调控多种生态过程,如甲烷、氧化亚氮等温室气体的产生与排放等,并与土壤健康和作物生产密切相关^[103]。以往受限于技术水平,微生物群落分析精度低、准确度差。随着科学技术的发展,高通量测序技术愈发成熟,测序成本不断下降,测序深度不断提高,微生物组学数据激增,传统统计方法已不再适用于高维、稀疏的微生物组数据。依赖于电脑高性能运算和大数据分析的机器学习方法,使微生物群落结合机器学习进行土壤健康评价成为可能。已有研究为微生物群落结合机器学习进行土壤健康评价提供了很好的范例,如:在研究枯萎病时发现细菌数据集对枯萎病发病土壤预测的准确率高达 91.75%,真菌数据集预测的准确率高达 95.25%^[104];在土壤理化性质和土壤质量研究中发现土壤细菌对土地使用情况预测的准确率达 85%,对土壤理化性质分组预测的准确率达 83%,并且能以 50%~95% 的准确率分配正确的土壤质量分数^[105];采用微生物组数据结合随机森林、支持向量机等多种机器学习算法对康奈尔土壤健康评价体系的结果进行了精准预测^[106]。因此,随着测序数据的不断增多,训练集数据库不断扩大,

微生物数据将能以更高的准确度和精度服务于土壤健康评价。

4 土壤连作障碍消减的原理及其技术调控

土壤健康调控可采用物理、化学或生物等措施实现对根际生态系统进行综合调控,即通过对土壤生态过程、作物生长过程及土壤生物间的关系进行调节,为维持土壤健康提供有效保障^[107]。而土壤生物间的关系是土壤健康调控最灵敏的反应指标,土壤所有生物关系的集合构成土壤食物网,包括土壤动物和土壤微生物等在内的所有土壤生物并不是孤立存在,而是通过物种间的共生、竞争和捕食等作用构成复杂的交互作用网络,共同参与土壤生态调控过程^[108]。已有研究明显忽视土壤生物调控、忽视土壤微食物网在土壤物质循环和能量流动过程的调节作用,过分关注土壤肥力指标、过分依赖大水大肥和化学药剂施用为主的连作土壤管理模式,以牺牲土壤环境和土壤可持续性为代价,并且会严重影响我国农产品的安全和品质,这严重制约了农业的绿色发展和资源高效利用,因此,基于我国连作障碍消减的多因素诱发和叠加效应及其机理,未来科学合理的连作障碍消减原理及其调控技术应该在以下 4 个方面进行突破(图 4)。

4.1 设计优化种植结构

连作产生的最根本原因是单一作物连续种植,因此,优化种植结构、通过作物多样化种植打破单一作物连作规律是克服连作障碍最直接的方式。生物多样性促进生态系统功能之间的正向相关性早已建立和认可,越来越多的证据表明,植物群落多样性会影响土壤微生物多样性,进而促进可持续农业所需的功能^[109]。轮作和间作是土壤种植结构优化最常用的方式。合理的轮作措施能有效调控连作失衡的土壤微生物区系,恢复土壤生态服务功能,从而有效缓解连作生物障碍。据报道,香蕉菠萝轮作能有效降低香蕉土传枯萎病发病率,且菠萝残体能诱导真菌烟曲霉和茄病镰刀菌丰度的增加以拮抗枯萎病菌,并促进形成抑病土^[110];蚕豆等豆科作物与其他作物轮作能改善土壤理化性质、提高土壤酶活、提高作物产量^[111]。间作可以通过增强植物根系功能、增强土壤养分有效性和养分吸收空间利用效率而促进土壤微生物生物功能。在玉米花生间作系统,不仅通过花生根瘤菌生物固氮增加土

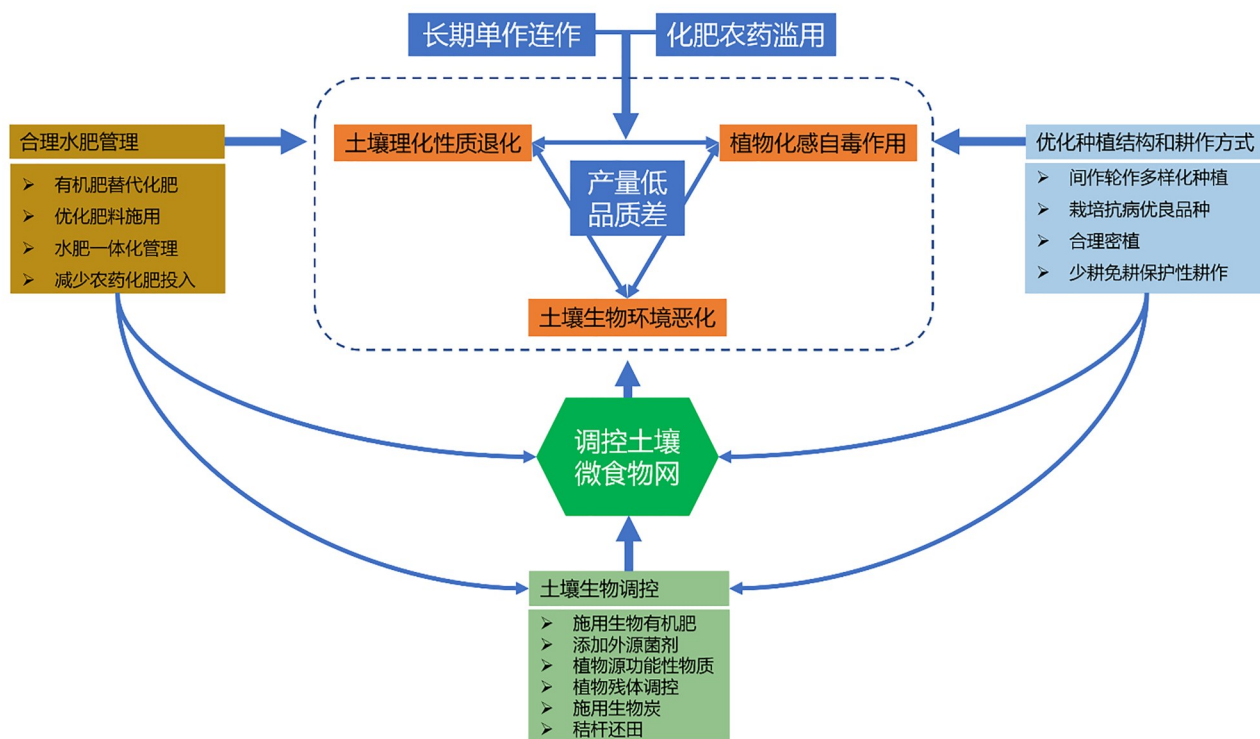


图4 连作障碍消减及其根际健康调控模式图

Fig. 4 Regulation mode of soil health in continuous cropping soil

壤氮素供应进而改善玉米氮营养,而且玉米根系麦根酸分泌增加土壤有效铁含量从而对改善花生铁营养发挥重要的作用^[112-113];木薯和豆科作物间作可增加土壤养分利用率和土壤微生物多样性,显著降低木薯根腐病发病率^[114];在有关花生-木薯间作研究发现,木薯产生的氰化物可诱导间作花生根系乙烯信号释放,该信号可重塑花生根际微生物群落,重塑的微生物群落可加速根际有机氮磷矿化从而提高花生地下部氮磷养分利用率和产量提高^[115]。此外,合理密植也是优化种植结构的有效措施,Liu等^[116]研究发现,三七连作过程中种植密度过高会加速土壤中植物化感物质草酸、抗坏血酸等的积累,加重连作障碍,而种植密度过低又难以保证作物产量,合理密植可在权衡产量与土壤自毒间矛盾时获得最大经济效益。因此,优化种植体系是较为持续有效地解决连作障碍的重要途径之一。

4.2 科学精准的水肥管理

在作物连作过程中,农民为提高作物产量,将化肥作为提高土壤肥力的主要方法,过量施用化肥,忽视有机肥投入,这不仅增加了生产成本,还会造成如土壤板结、土壤酸化、土壤盐渍化、地下水污

染、蔬菜硝酸盐含量超标等一系列问题^[117]。有机肥与化肥相比营养元素较为齐全,能增强土壤保水和保肥能力,长期有机肥施用能够促进土壤团聚体形成,明显改善土壤理化性质,能缓解因化肥过量施用而引发的土壤板结、酸化、盐渍化等问题并能提高土壤抑病能力^[118]。同时,有机肥能调节土壤微食物网结构,随着有机肥施用量增加,有机物细菌降解路径的比率增大,有机肥施用量主要影响处在食物网低营养级线虫的活性和功能,从土壤线虫群落结构和功能的角度来说,适量增加有机肥的施用量可以促进土壤食物网中的物质循环和能量流动^[119]。因而,化肥减量施用、有机肥部分替代化肥是连作障碍调控的重要措施之一。另外,不同作物在不同生育时期对养分的需求不同,要根据土壤性质、肥料性质和作物特性,对肥料进行科学配施,同时对施肥量和施用时间进行精确控制,以此来综合提高土壤养分利用效率、缓解连作过程中因水肥管理不当而带来的各种问题。

4.3 保护性耕作

保护性耕作指在保持农业资源、水资源及土壤资源可持续利用的情况下,减少破坏性农业机械操

作,如少耕、免耕等都属于保护性耕作。作物连作过程中,传统耕作方式频繁翻耕扰动土壤,造成土壤板结、养分和水分流失、土壤团聚体结构被破坏、土壤有机质含量降低等。保护性耕作通过减少大型机械田间作业次数来减少土壤扰动,从而减少土壤结构破坏和土壤表层水分蒸发,有利于提高土壤团聚体和有机质含量,进而降低生产成本和提高作物产量。保护性耕作也可以通过影响土壤微食物网结构来调控土壤健康,保护性耕作可提高耕层微生物生物量和多样性,尤其对土壤真菌生物量提高显著;同时,保护性耕作可提高土壤线虫丰度,提高土壤各粒级团聚体中线虫群落的结构指数和成熟度指数^[120]。李金融^[121]研究发现,保护性耕作可有效缓解花生连作障碍,花生连作3年后产量下降10%~40%,绿肥压青、地膜覆盖等保护性耕作措施可通过增大土壤团聚体碳氮含量、提高土壤有益细菌数量、降低土壤真菌病害等恢复花生产量;Hu等^[122]研究发现,免耕处理可通过提高土壤养分有效性、微生物群落稳定性、阻断病原菌传播路径等途径消减连作障碍。

4.4 土壤生物调控

造成连作生物障碍减产的主要原因是土壤食物网失衡引起的土传病害,尤其是土壤食物网的稳定性决定着连作土壤的感病状态与抑病状态的形成和转化。因此,从调控土壤食物网稳定性角度提升连作土壤健康水平将有利于培育健康土壤并实现作物绿色增产。事实上,自然界存在大量抑病土资源,而抑病土中存在大量有益微生物,这些有益微生物是构成连作土壤基础免疫和特异性免疫的核心资源。对于连作土壤生物调控,针对性地筛选包括抑病土在内的各类复杂环境中的有益微生物,室内富集培养后以生物菌剂或生物有机肥等形式回接到感病土,这有利于重塑健康稳定的土壤微食物网结构^[123]。近年来研究发现抑病土壤微生物菌剂其含有的微生物可分泌水杨酸、赤霉素、生长素等植物激素^[124-126],不仅能有效促进土壤中有机磷矿化、提高土壤养分的生物有效性,而且还能通过诱导植物抗性、拮抗病原菌、与病原菌竞争生态位等抑制病原菌^[127-128]。目前已得到很好应用的外源菌剂包括:芽孢杆菌属、假单胞菌属、青霉菌属、链霉菌属、木霉菌属、丛枝菌根真菌和淡紫拟青霉等。其中,芽孢杆菌针对枯萎病、青枯病、根结线虫病害

等多种土传病害防控中得到较好的应用,如解淀粉芽孢杆菌可协同假单胞菌共同抑制香蕉枯萎病^[129-133];丛枝菌根真菌能活化土壤磷,提高土壤磷的有效性^[134],且可以诱导植物抗性,间接帮助植物抑制病害^[135];另外,淡紫拟青霉目前主要用于根结线虫防控^[136]。

土壤生物调控的另一种方式是挖掘自然界中的植物源或微生物源功能性物质。自然界中针对不同土传病害都存在其病害寄主植物与非寄主植物,即使同一寄主植物又存在其抗病品种与感病品种。因此,通过各种试验手段挖掘非寄主植物与抗病品种根系分泌物中的功能性物质将有利于绿色高效地防控土传病害。根结线虫病害是我国设施菜地连作土壤常见的土传病害之一,Dong等^[137-139]通过比较根结线虫寄主植物番茄与根结线虫非寄主植物茼蒿和蓖麻根系分泌物差异,筛选到了茼蒿的特异性根系分泌物月桂酸以及蓖麻的特异性根系分泌物棕榈酸与亚油酸,这三种物质在抑制南方根结线虫卵孵化、致死南方根结线虫二龄幼虫的同时通过调控 *Mi-flp-18* 基因表达干扰南方根结线虫的趋向性迁移。Lu等^[140]从鸡粪发酵液和木薯酒精废液中鉴定并筛选出防控南方根结线虫的功能性物质棕榈酸甲酯与硬脂酸甲酯,这两种物质均可致死根结线虫二龄幼虫、抑制线虫卵孵化、趋避根结线虫二龄幼虫,并且这2种功能性物质对土壤中有益线虫秀丽线虫的繁殖没有影响^[140],这些研究为研发环境生态友好的线虫防控物质和功能性绿色智能肥料提供了重要的理论和技术依据。

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基于根际生命共同体理论,养分高效是一个从土壤到土壤生物再到植物多界面系统协同互作的系统过程^[141]。因此,解决连作障碍问题必须从系统层面通过调控根际生命共同体各界面作用的级联放大效应而实现连作障碍消减。未来研究突破应是一个从精准诊断到靶向治理,再到系统整合的整体策略(图4):

1)首先,靶向明确,精准防控。我国95%的耕地面积遭受常年连作,连作障碍问题突出,几乎所有省份都有连作障碍发生的报道,连作障碍分布不均,且不同地区都有易于发生连作障碍的标志性作物和标志性土传病害,因此,未来要对不同地区的

不同作物及不同土传病害进行有针对性的靶向精准防控;

2)其次,在明确防控目标后,有针对性地研发和应用生物源产品。土传病害是连作障碍的主要表现形式,然而不同作物的不同土传病害发病规律差异较大,主要有持续感病和后期形成抑病土两大类,促使我们要了解土传病害发病规律,在发病高峰期前进行提前防控并挖掘抑病土微生物资源,探索其抑病机理并研发相应的功能性产品和技术;

3)最终,要实现长效治理,必须进行多因素综合评价与系统性调控。过去人们过分关注土壤肥力指标,过分依赖于大水大肥和化学药剂施用为主的集约化种植模式,这是以牺牲土壤环境和土壤可持续为代价,并且会严重影响我国农产品的安全和品质。连作障碍是植物-土壤-微生物及其环境等诸多因素交互作用的综合表现,其中除了土壤性状,土壤微生物同样在连作障碍发展过程中起着至关重要的作用,而且他们是根际免疫和抑病土形成的生物源基础。因此,未来应更关注生物指标在连作障碍评价中的作用,通过合理的水肥管理、优化种植结构、保护性耕作、土壤生物调控等措施调控土壤微生物网结构,从而实现连作障碍的消减、作物高产稳产和产能提升和可持续绿色发展。

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