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摘要：绿肥在用地养地、保障粮食安全和改善生态环境等方面具有重要的作用。为了探究绿肥对主作物系统的影响，本文查阅了 2015 年以来主作物耦合绿肥的相关文献，归纳了绿肥对主作物农艺性状、病虫草害的防控以及对土壤理化性质等的影响。总体上，绿肥可有效改善土壤理化性质，促进养分转化，提高主作物对养分、水分的利用效率；影响主作物生理生化，促进主作物生长，提高主作物产量和品质，有效降低主作物病虫害的发生和危害，是实现绿色循环农业的重要途径。本文根据研究现状，对未来的研究方向进行了展望，提出加强对绿肥种植经济效益的评估和绿肥 – 主作物一体化病虫害防控方面的研究，进一步强化绿肥产品的推出与销售。

关键词：绿肥；作物生长；作物病害；作物虫害；作物草害；土壤理化性质；耦合

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Research progress on the effects of green manure on the growth, disease, pests, weeds, and soil of main crops

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Abstract: Green manure plays an important role in cultivating land, ensuring food security, and improving ecological environments. To explore the influence of green manure on main crop systems, this paper reviewed the relevant literature concerning the coupling of green manure with main crops since 2015 and summarized the influence of green manure on the agronomic traits of these main crops. In general, green manure can effectively improve soil physical and chemical properties, promote nutrient transformation, and improve the nutrient and water use efficiency of main crops. Using green manure important way to realize green circular agriculture by affecting the physiology and biochemistry, promoting the growth, improving the yield and quality, and effectively reducing the occurrence and harm of diseases and pests on main crops. Furthermore, according to the current research situation, we provided future research directions, evaluated the economic benefits of green manure cultivation, proposed research for the integrated prevention and control of green manure and main crops, and strengthened the case for introducing and selling green manure products.

Keywords: green manure; crop growth; crop diseases; crop pests; crop weeds; physical and chemical properties of soil; coupling

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据第 3 次全国国土调查显示，截止 2019 年 12 月 31 日，我国耕地面积 19.18 亿亩 (约 1.32 亿 hm^2)，约占世界耕地面积的 8.6%。但我国人口众多，粮食需求量高。在实际生产中为保证足够的产量，往往存在过度利用耕地的现象，加之连续翻耕加重表层营养物质流失，造成土壤"重用轻养"，长此以往将造成土地养分减少、耕层变薄，进而导致粮食产量减少[1-3]，因此，土壤的保护性耕作很有必要。

绿肥是指具有提供养分、合理用地养地、部分替代化肥、提供饲草来源、保障粮食安全等方面作用的栽培农作物[4]，是我国传统农业的精华，具有减排固碳、改善生态环境、减少土壤侵蚀、提高土壤肥力和质量、减轻病虫草害发生和维持生物多样性等功能[5]。常见的绿肥作物有豆科的箭筈豌豆 (*Vicia sativa*)、毛叶苕子 (*V. villosa*)、紫云英 (*Astragalus sinicus*)、白三叶 (*Trifolium repens*) 等，禾本科的多年生黑麦草 (*Lolium perenne*)、鼠尾草 (*Salvia japonica*)，十字花科的肥田萝卜 (*Raphanus sativus*)、油菜 (*Brassica napus*)、二月兰 (*Orychophragmus violaceus*) 等。绿肥的起源最早可追溯到 3 000 年前我国的周朝[6]，种植绿肥是土壤养分输入的重要来源，合理利用绿肥能够同时兼顾提高作物产量和保持土壤养分[7]，阻隔原菌的传播和侵染，减少病害的发生[8]。同时，间作绿肥可有效改善小气候，减轻过强光照造成的植物叶部温度过高、植物萎蔫甚至死亡[9]，为植物提供合适的生长环境。如在香蕉 (*Musa nana*) 行间套种花生 (*Arachis hypogaea*) 能有效调节蕉园温湿度，促进香蕉生长，提高产量和品质[10]。

基于 Web of Science 和 CNKI 数据库，在英文数据库以论文题目中分别以 green manure + agronomic trait、green manure + diseases、green manure + pests、green manure + weeds、green manure + soil，在 CNKI 数据库以绿肥 + 农艺性状、绿肥 + 病害、绿肥 + 虫害、绿肥 + 草害、绿肥 + 土壤检索自 2015－2022 年论文共 1 488 篇，分别有 110、202、110、190 和 876 篇，内容涉及主作物生长、病害、虫害、杂草、土壤结构和土壤微生物等方面内容 (图 1)。本文重点关注绿肥作物对于主作物农艺性状及病虫草害的影响，间或对于土壤的一些影响，归纳总结了相关文献。

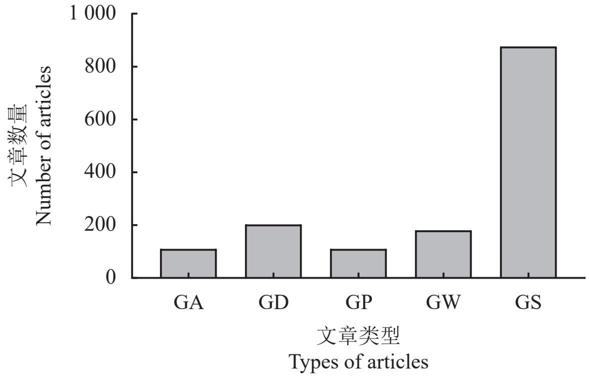

图 1　不同绿肥研究方向的文章数量

Figure 1　Numbers of articles on different green manure research directions

GA：绿肥 + 农艺性状；GD：绿肥 + 病害；GP：绿肥 + 虫害；GW：绿肥 + 杂草；GS：绿肥 + 土壤。

GA: green manure + agronomic trait; GD: green manure + diseases; GP: green manure + pests; GW: green manure + weeds; GS: green manure + soil.

1　绿肥对主作物农艺性状的影响

绿肥－主作物系统中，主作物的产量、株高、茎粗、籽粒产量等指标是评价其种植模式是否有效最直观的数据和最有效的办法。绿肥可影响主作物养分吸收及循环、生理生化物质代谢，进而影响主作物株高、产量、籽粒产量等农艺性状[11-13] (图 2、图 3)。Grunwald 等[14] 的研究发现，间作糙伏毛燕麦 (*Avena strigosa*)、黑麦 (*Secale cereale*)、肥田萝卜、箭筈豌豆等绿肥，可增加甜菜 (*Beta vulgaris*) 生物量在 32% 以上。

绿肥对主作物的促进作用受多种因素影响，作物生长过程中降水、光照以及管理措施，均会影响绿肥培肥促生效应。如受降雨及积温影响，刚果臂形草 (*Urochloa ruziziensis*) [15]、冬豌豆 (*Pisum sativum*)、黑麦、亚麻荠 (*Camelina sativa*)、芥菜 (*B. juncea*) [16] 未显著提高玉米 (*Zea mays*) 籽粒甜菜的块根产量。绿肥间作玉米的研究发现，亚麻荠、遏蓝菜 (*Thlaspi arvense*)、冬黑麦降低玉米产量 8.7%、9.5% 和 9.8% [17]，黑麦、燕麦 (*A. sativa*)、红三叶 (*T. pretense*)、埃及三叶草 (*T. alexandrinum*) 降低玉米产量 5.8%～8.6% [18]。Negrini 等[19] 也发现，间作豇豆 (*Vigna unguiculata*)

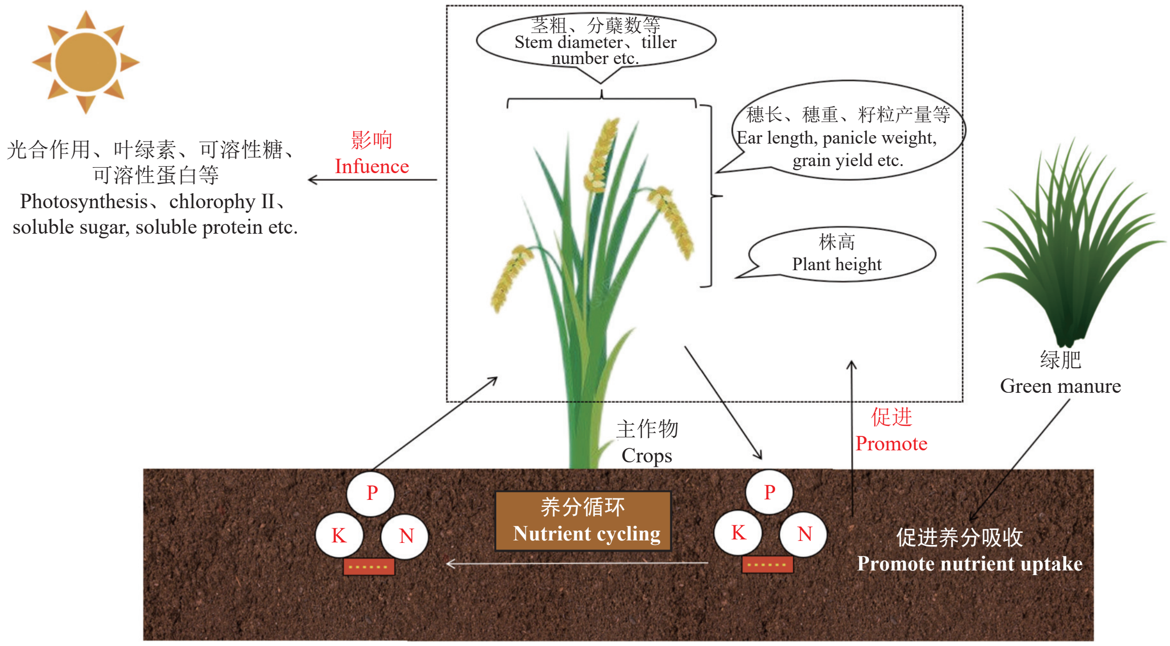

图 2　绿肥对于主作物农艺性状的影响

Figure 2　Effects of green manure on the agronomic characteristics of main crops

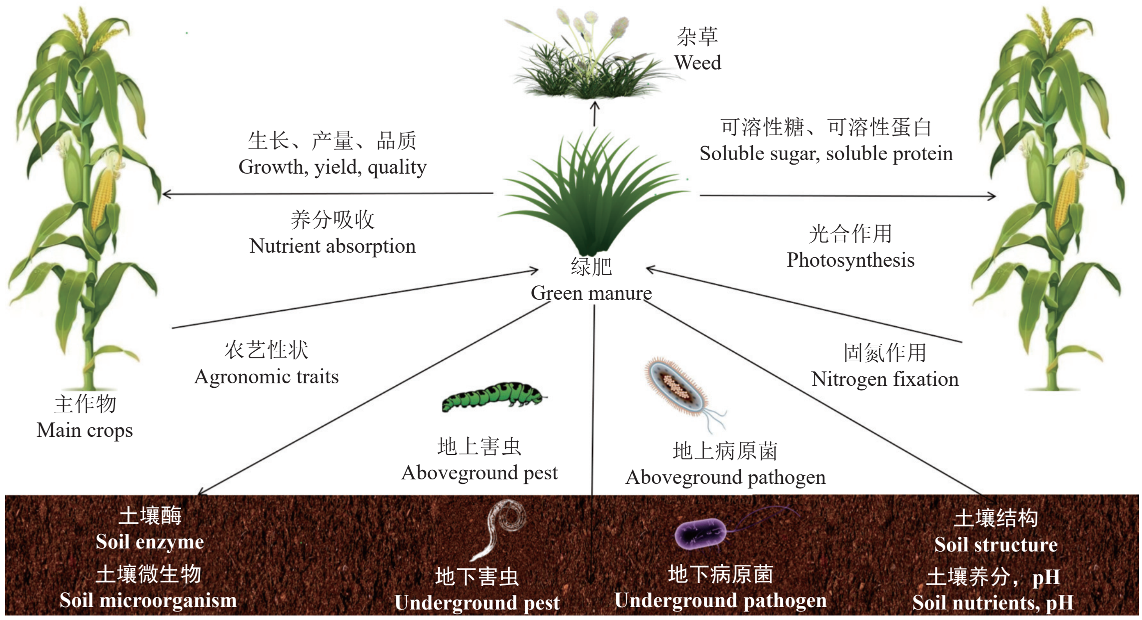

图 3　绿肥－主作物耦合系统

Figure 3　Green manure－main crop coupling system

和白羽扇豆 (*Lupinus albus*) 时，莴苣 (*Lactuca sativa*) 产量为单作时的 62% 和 77%。但这种消极作用会因绿肥作物的播种时间而改变，在莴苣播种 40 d 后播种豇豆和白羽扇豆，莴苣的直径分别为单作的 86% 和 89% [19]。在绿肥－主作物系统中，虽然一些案例中绿肥未促进主作物的一些农艺性状，但考虑到其对系统土壤改良、其自身的生物量等，不啻为发展绿色循环和可持续农业行之有效的模式。

绿肥影响主作物生长及产量与其培肥地力、改善植物养分密切相关，尤其是对主作物氮的吸收和利用。Da Silva 等[20] 研究发现，种植菽麻 (*Crotalaria juncea*)、木豆 (*Cajanus cajan*)、天鹅绒豆 (*Mucuna prurens*) 和珍珠粟 (*Pennisetum glaucum*) 增加水稻 (*Oryza sativa*) 中 N、Mg、S、Cu 等各种元素含量。白

羽扇豆、藜豆 (*M. aterrima*)、绿豆 (*Phaseolus radiatus*)、田皂角 (*Aeschynomene afraspera*) 等可固定空气中游离氮，是主作物－绿肥系统中主要累积营养元素是氮元素的主要原因，也是绿肥促进主作物生长的重要原因[21-23]。绿肥亦可通过降低 C/N 来实现营养物质的循环，从而提高主作物的产量[24]。需要注意的是，当绿肥－主作物系统养分不足的时候，绿肥会和主作物产生竞争。因此，应合理搭配绿肥种类、改变耕作时间，避免和减少绿肥与主作物竞争资源，提高绿肥作物在主作物生长过程中的养分供应效率 (图 3)。

此外，绿肥也可改变主作物生理生化物质的含量，提高主作物品质。如紫云英和箭筈豌豆增加小青菜 (*B. chinensis*) 的可溶性蛋白含量在 27.3%～33.6%，增加菜苔中的可溶性糖含量在 62.6%～72.6% [25]。谢克孝等[26] 的试验中，白三叶、金盏菊 (*Calendula officinalis*)、南苜蓿 (*Medicago polymorpha*) 降低茶叶中的茶多酚含量和酚氨比 21.44% 和 23.46%，从而达到提高茶叶口感和品质的作用。种植绿肥亦可促进主作物光合作用，例如种植绿肥增加大豆 (*Glycine max*) 总叶绿素含量 7.95% [27]。

2　绿肥对主作物抗病虫草害的影响

2.1　绿肥对主作物病害的影响

主作物间作绿肥的种植模式不仅可有效降低主作物气传、雨水、灌溉传播等病害的发生，亦可对土传、种传及苗木传播病害的发生与传播起到很好的防治作用 (图 3)。涉及到的绿肥作物有大麦 (*Hordeum vulgare*)、黑麦、大豆、红三叶、芥菜、芜菁 (*B. rapa*) 等。涉及到的主作物以马铃薯 (*Solanum tuberosum*)、水稻、小麦 (*Triticum aestivum*) 为主 (表 1)。绿肥对主作物病害的消减作用与耕作管理措施密切相关，如 Kadziene 等[28] 发现白芥 (*Sinapis alba*) 和白三叶降低深耕和直接播种处理下小麦赤霉病 (*Fusarium graminearum*) 的发病率 29% 和 21%，降低浅耕处理下小麦赤霉病发病率 91%。Handiseni 等[29] 发现芥菜降低水稻纹枯病 (*Rhizoctonia solani*) 严重度 10%～39%。土传病害病原可在土壤中存活多年，连续侵染和危害作物，防治困难。大量研究表明，绿肥对主作物土传病害防控效果优于气传等病害 (表 1)。如香蕉行间种植田菁 (*Sesbania cannabina*) 和白三叶，香蕉枯萎病发病率降低 33.09%～79.92% [30]。芥菜、芜菁、肥田萝卜、暗紫野豌豆 (*V. benghalensis*) 可降低向日葵 (*Helianthus annuus*) 黄萎病 (*Verticillium dahliae*) 病情指数达 35.8% [31]。Parajuli 等[32] 也发现，红三叶连续两年降低红枫 (*Acer palmatum* ‘Atropurpureum’) 根部病害严重度 55.07% 和 61.46%。

种子和苗木是病害传播的重要途径，致病的病原菌潜伏在植物种子、块茎或幼苗上，随播种开始发病，亦可能作为田间侵染源，导致健康植株发病。Larkin 等[33] 的研究表明，间作白芥、芥菜、高粱 (*Sorghum bicolor*)、欧洲油菜 (*B. napus*)、大豆、大麦、红三叶，可以降低马铃薯块茎上黑痣病 (*Rhizoctonia solani*) 的病斑面积 0.5%～1.0%，降低发病率 15%～41%；同时对马铃薯疮痂病 (*Streptomyces scabies*) 也有很好的防效，块茎上病斑面积降低 8%～14%，发病率降低 11%～13% [33]。此外，某些芸薹属绿肥也可抑制病原菌数量，降低主作物发病率。Wen 等[34] 研究发现芥菜和欧洲油菜可以降低大豆根系的立枯丝核菌和镰刀菌 (*Fusarium virguliforme*) 的数量，增加大豆产量。Hossain 等[35]也发现芥菜和白芥产生组成多样化的代谢产物，如异硫氰酸盐，降低豌豆根腐病发病率。

绿肥对于主作物病害的防控作用，原因之一可能是由于绿肥为主作物提供物理屏障，阻碍了病菌的传播，如间作花生使得玉米之间形成屏蔽，降低玉米茎腐病发病率 42.5% [36]。病原与植物协同进化，形成不同专化型，绿肥多与主作物遗传背景差异大，主作物病原多不能侵染和危害绿肥，如种植白芥的第 1 年和第 2 年，降低辣椒疫霉 (*Phytophthora capsici*) 引起的辣椒 (*Capsicum annuum*) 疫病的致死率 83% 和 75% [37]。绿肥轮作能够给后茬的主作物提供更多的有机质输入、改善土壤肥力和结构、增加微生物生物量和活性，从而抑制种带病原菌或者块茎里病原菌的传播，如毛叶苕子和绛三叶草 (*T. incarnatum*) 作为豆科作物，通过固氮作用为主作物供给养分，促进主作物生长以抵御病害的侵染[38]。芸薹类作物亦能产生硫代葡萄糖苷等物质，通过化感作用，抑制主作物病害发生[35]。

2.2　绿肥对主作物虫害的影响

我国农作物病虫害有 1 600 多种，其中可造成

表 1 绿肥对主作物病害的影响

Table 1 Effects of green manure on main crop diseases

绿肥 Green manure crop	主作物 Main crop	病原 Pathogen	影响 Influence	参考文献 Reference
白芥 *Sinapis alba* 白三叶 *Trifolium repens*	小麦 *Triticum aestivum*	禾谷镰刀菌 *Fusarium graminearum*	降低深耕和直接播种处理下小麦赤霉病的发病率29%和21%，降低浅耕处理下小麦赤霉病发病率91% Reduced the incidence of wheat *Gibberella* by 29% and 21% under deep tillage and direct sowing treatment, and reduced the incidence of wheat *Gibberella* under shallow tillage treatment by 91%	[28]
芥菜 *Brassica juncea*	水稻 *Oryza sativa*	立枯丝核菌 *Rhizoctonia solani*	降低水稻纹枯病严重度10%～39% Reduced the severity of rice sheath blight by 10%～39%	[29]
田菁 *Sesbania cannabina* 白三叶 *Trifolium repens*	香蕉 *Musa nana*	尖孢镰刀菌 *Fusarium oxysporum*	香蕉枯萎病发病率降低33.09%～79.92% The incidence of banana wilt disease decreased by 33.09%～79.92%	[30]
芥菜 *Brassica juncea* 芜菁 *Brassica rapa* 肥田萝卜 *Raphanus sativus* 暗紫野豌豆 *Vicia benghalensis*	向日葵 *Helianthus annuus*	大丽轮枝菌 *Verticillium dahliae*	降低向日葵黄萎病35.8%的病情指数 Reduced the disease index of sunflower *Verticillium* wilt by 35.8%	[31]
红三叶 *Trifolium pratense*	红枫 *Acer palmatum* ‘Atropurpureum’	立枯丝核菌 *Rhizoctonia solani* 钟器疫霉菌 *Phytopythium vexans* 烟草疫霉菌 *Phytophthora nicotianae*	红三叶连续两年降低红枫根部病害55.07%和61.46%的严重度 Red clover reduced the severity of root diseases of red maple by 55.07% and 61.46% for two consecutive years	[32]
白芥 *Sinapis alba* 芥菜 *Brassica juncea* 高粱 *Sorghum bicolor* 欧洲油菜 *Brassica napus* 大豆 *Glycine max* 大麦 *Hordeum Vulgare* 红三叶 *Trifolium pratense*	马铃薯 *Solanum tuberosum*	立枯丝核菌 *Rhizoctonia solani* 链霉菌疥疮链霉菌 *Streptomyces scabies*	降低马铃薯块茎上黑痣病的病斑面积0.5%～1.0%，降低发病率15%～41%;降低马铃薯疮痂病病斑面积8%～14%，降低发病率11%～13% Reduced the spot area of potato black scurf by 0.5～1.0%, and reduced the incidence rate by 15%～41%；Reduced potato scab disease area by 8%～14%, and reduced incidence by 11%～13%	[33]
芥菜 *Brassica juncea* 欧洲油菜 *Brassica napus*	大豆 *Glycine max*	立枯丝核菌 *Rhizoctonia solani* 镰刀菌 *Fusarium virguliforme*	降低大豆根系的立枯丝核菌和镰刀菌的数量，增加大豆产量 Reduced the number of *Rhizoctonia solani* and *Fusarium virguliforme* in soybean roots and increased soybean yield	[34]
芥菜 *Brassica juncea* 白芥 *Sinapis alba*	豌豆 *Pisum sativum*	根腐丝囊霉 *Aphanomyces euteiches*	芥菜和白芥产生组成多样化的代谢产物，如异硫氰酸盐，可降低豌豆根腐病发病率 Mustard greens and white mustard produce metabolites of diverse composition, such as isothiocyanate, which reduce the incidence of pea root rot	[35]
花生 *Arachis hypogaea*	玉米 *Zea mays*	不明确 Unspecified	间作花生使得玉米之间形成屏蔽，降低玉米茎腐病发病率42.5% Intercropping peanuts formed shields between maize, reducing the incidence of maize stem rot by 42.5%	[36]
白芥 *Sinapis alba*	辣椒 *Capsicum annuum*	辣椒疫霉 *Phytophthora capsici*	种植白芥的第1年和第2年，降低辣椒疫霉引起的辣椒疫病83%和75%的致死率 In the first and second years of planting white mustard, the fatality rate of pepper blight caused by *P. capsici* was reduced by 83% and 75%	[37]

严重危害的在 100 种以上，重大流行性、迁飞性病虫害有 20 多种，包括稻飞虱 (*Delphacidae*)、白背飞虱 (*Sogatella furcifera*)、褐飞虱 (*Nilaparvata lugens*)、蚜虫 (*Aphidoidea*) 和棉铃虫 (*Helicoverpa armigera*) 等[39-41]，呈现出种类多、影响大和局部爆发成灾等。绿肥可降低主作物虫害的发生如油菜、卷心菜 (*Brassica oleracea*)、水芹 (*Oenanthe javanica*)、芥菜、播娘蒿 (*Descurainia sophia*) 能抑制番茄 (*Solanum lycopersicum*) 上根结线虫 (*Meloidogyne*) 的活性[42]。芥菜、肥田萝卜、芝麻菜 (*Eruca sativa*) 可有效降低马铃薯囊肿线虫 (*Globodera*) 的种群数量[43] (表 2)。

对其他作物的研究也表明，芜菁、芥菜、油菜能够有效防治烟草的根结线虫病，分别使根结线虫病发病率下降 38.5%、27.5%、50.5%，增加烤烟产量 8.7%、15.5%、24.7% [44]。同时，Do Nascimento 等[45] 也发现大托叶猪屎豆 (*C. spectabilis*) 和御谷 (*P. americarum*) 单播时降低秋葵 (*Abelmoschus esculentus*) 上的根结线虫种群数量 61%，混播时降低根结线虫种群数量 85%。Djian-Caporalino 等[46] 也发现种植苏丹草 (*S. sudanense*) 可以降低田间根结线虫种群密度 77%～94%。

除线虫之外，紫云英、毛叶苕子和箭筈豌豆等绿肥对玉米黏虫 (*Mythimna separata*) 等迁飞性害虫的生长、种群增长也有抑制作用，如降低黏虫 5 龄

表 2　绿肥对主作物虫害的影响

Table 2　Effects of green manure on main crop pests

绿肥 Green manure crop	主作物 Main crop	病虫 Pests	影响 Influence	参考文献 Reference
芥菜 *Brassica juncea* 肥田萝卜 *Raphanus sativus* 芝麻菜 *Eruca sativa*	马铃薯 *Solanum tuberosum*	囊肿线虫 *Globodera*	可有效降低马铃薯囊肿线虫的种群数量 Reduced the population of *Globodera*	[43]
芜菁 *Brassica rapa* 芥菜 *Brassica juncea* 油菜 *Brassica napus*	烟草 *Nicotiana tabacum*	根结线虫 *Meloidogyne*	降低根结线虫病发病率38.5%、27.5%、50.5%，增加烤烟产量8.7%、15.5%、24.7% The incidence of root-knot nematode disease was reduced by 38.5%, 27.5% and 50.5%, and the flue-cured tobacco production was increased by 8.7%, 15.5% and 24.7%	[44]
大托叶猪屎豆 *Crotalaria spectabilis* 御谷 *Pennisetum glaucum*	秋葵 *Abelmoschus esculentus*	根结线虫 *Meloidogyne*	绿肥单播时降低秋葵上的根结线虫种群数量达61%，混播时降低根结线虫种群数量85% The population of root-knot nematodes on okra was reduced by 61% during single sowing of green manure and by 85% during mixed sowing	[45]
苏丹草 Sorghum sudanense	多种蔬菜 Vegetables	根结线虫 *Meloidogyne*	降低田间77%～94%根结线虫种群密度 Reduced the population density of root-knot nematodes by 77%～94% in the field	[46]
紫云英 *Astragalus sinicus* 毛叶苕子 *Vicia villosa* 箭筈豌豆 *Vicia sativa*	玉米 *Zea mays*	黏虫 *Mythimna separata*	降低黏虫5龄幼虫相对生长率、相对取食率、食物利用率和食物转化率，缩短害虫生长发育历期，减轻危害 Reduced the relative growth rate, relative feeding rate, food utilization rate and food conversion rate of armyworm fifth instar larvae, shortened the growth and development period of pests, and decreased damage	[47]
菽麻 *Crotalaria juncea* 荞麦 *Fagopyrum esculentum*	咖啡 *Coffea arabica*	咖啡潜叶蛾 *Leucoptera coffeella*	招募咖啡潜叶蛾的天敌胡蜂的物种数和多样性指数间接促进对于病虫的防控 Increased the species number and diversity index of wasps, the natural enemy of *L. coffeella*; indirectly promotes the control of pests and diseases	[48]
菜豆 *Phaseolus vulgaris* 䅟 *Eleusine coracana*	玉米 *Zea mays*	叶蝉 *Cicadellidea*	通过干扰叶蝉的求偶行为来阻止玉米病毒病的传播，阻止了害虫本身的大面积爆发 By interfering with the leafhopper's courtship behavior, the spread of maize virus disease was stopped, preventing a large outbreak of the pest itself	[49]

幼虫相对生长率、相对取食率、食物利用率和食物转化率，缩短害虫生长发育历期，减轻危害[47]。同时，一些绿肥如菽麻、荞麦 (*Fagopyrum esculentum*)，可招募咖啡潜叶蛾 (*Leucoptera coffeella*) 天敌胡蜂 (*Vespidae*)，间接促进对于病虫的防控[48]。昆虫在病害的传播中也占据重要位置，绿肥可有效阻断昆虫对病害的传播。Page 等[49] 的试验证实菜豆 (*P. vulgaris*) 和移 (*Eleusine coracana*) 可以通过干扰叶蝉 (*Cicadellidea*) 的求偶行为来阻止玉米病毒病的传播，也阻止了害虫本身的大面积爆发。

综上，绿肥对主作物虫害的防控作用可归纳为：形成物理屏障，消减了病虫的种群密度[45]；提高土壤养分、促进主作物生长，提高主作物对害虫的整体抗性[44]；增加害虫天敌的种群密度，减少害虫数量[48]；产生具有抑制害虫的化合物，降低病虫为害[42]；影响害虫本身的取食、生长和发育等过程减轻其危害程度[47]，以避免其种群数量增长过快，爆发危害[49] (图 3)。

2.3 绿肥对主作物草害的影响

我国每年受杂草危害的耕地面积达 9 333 万 hm^2 以上，造成粮食损失 300 多万 t，“十三五”期间，我国农田杂草发生面积增加 0.4%，防治面积增加 4.5%，挽回粮食损失 2.79×10^7 t，占全国总产量的 4.3%。但杂草防治中防治难、成本大等问题仍突出。现代化杂草防治措施仍以农业措施为基础、化学措施为重要手段。在贯彻实施“两减”项目中，绿肥等生态防治方法对防治杂草危害尤为重要[50] (表 3)。

绿肥生育期短、生物量高，可快速形成覆盖，对杂草的生长和抑制具有很好的作用。Gfeller 等[51] 发现，种植地三叶草 (*T. subterraneum*) 抑制反枝苋 (*Amaranthus retroflflexus*) 田间杂草生长，降低总杂草干重 69.4%。种植糙伏毛燕麦 (*A. strigosa*)、多花黑麦草 (*L. multiflorum*)、箭筈豌豆、肥田萝卜降低了玉米田间杂草干重 57.24% [52]。Sodré等[53] 也发现，种植高粱、尾稃草属植物 (*U. brizantha*)、刚果臂形草降低大豆田中杂草的竞争力、阻止杂草蔓延和扩

表 3 绿肥对主作物杂草的影响

Table 3 Effects of green manure on main crop weeds

绿肥 Green manure crop	主作物 Main crop	影响 Influence	参考文献 Reference
地三叶草 *Trifolium subterraneum*	反枝苋 *Amaranthus retroflflexus*	抑制反枝苋田间杂草生长，降低总杂草干重69.4% It inhibited the growth of weeds and reduced their total dry weight by 69.4%	[51]
糙伏毛燕麦 *Avena strigosa* 多花黑麦草 *Lolium multiflorum* 箭筈豌豆 *Vicia sativa* 肥田萝卜 *Raphanus sativus*	玉米 *Zea mays*	降低了玉米田间杂草干重57.24% The dry weight of weeds in a maize field was reduced by 57.24%	[52]
高粱 *Sorghum bicolor* 尾稃草属植物 *Urochloa brizantha* 刚果臂形草 *Urochloa ruziziensis*	大豆 *Glycine max*	降低大豆田中杂草的竞争力、阻止杂草蔓延和扩展，降低杂草多样性 Reduced the competitiveness of weeds in soybean fields, prevented the spread and expansion of weeds, and reduce their diversitys	[53]
芸薹类植物 *Brassica*	大豆 *Glycine max*	大豆田中，芸薹类植物对杂草的抑制作用优于禾本科和其他绿肥作物 In soybean fields, *Brassica* species exhibited better weed inhibition than grasses and other green manure crops	[54]
多种绿肥 Many species of green manure	不明确 Unspecified	绿肥增加杂草的主要采食者脊角步甲属昆虫(*Poecilus chalcites*、*P. lucumblandus*)和斑步甲属昆虫(*Anisodactylus rusticus*)的数量，从而间接防控主作物草害 Green manure crops increase the populations of the main weed feeders *Poecilus chalcites*, *P. lucumblandus*, and *Anisodactylus rusticus*, thereby indirectly controlling damage to the main crops	[55]

展，降低杂草多样性。芸薹类植物的化感作用在杂草防治上同样有效，且优于禾本科和其他绿肥[54]。Menalled 等[55] 发现，种植绿肥增加杂草的主要采食者脊角步甲属昆虫 (*Poecilus chalcites*、*P. lucumblandus*) 和斑步甲属昆虫 (*Anisodactylus rusticus*) 的数量，从而间接防控主作物草害。以上都证明了绿肥防治草害具有广阔的应用前景，可进行大面积应用。

绿肥能够防控杂草的主要机制可归纳为：1) 绿肥促进了主作物本身的生长发育，使其能够优先占据空间和养分等生长资源、抵抗杂草侵染，菽麻、墨西哥丁香 (*Gliricidia sepium*)、高粱、田菁在有效抑制杂草生长的同时，增加棉花 (*Gossypium hirsutum*) 产量，提高棉花干鲜物质量[56]。2) 绿肥会通过增加与杂草之间的竞争，包括水分、氧气、光照、生存空间等，来抑制杂草的生长发育[52-53]。如 Cutti 等[52] 发现，绿肥在玉米生长早期，即竞争的关键期，覆盖土壤、充分利用水分和阳光，使杂草生长受限，促进主作物生长。3) 绿肥通过分泌一些物质，产生化感作用，由此抑制周围杂草的生长，达到草害防治的目的[54]。4) 绿肥为各类昆虫和动物提供了更好的栖息空间，增加了它们对于杂草和杂草种子的采食，由此抑制杂草蔓延[55] (图 3)。

3　绿肥对土壤的影响

土壤是绿肥和主作物生长的基质，绿肥的种植对于改善土壤的养分、水分、pH 以及土壤结构和土壤微生物群落组成等都有其意义。程滨等[57] 归纳了果园绿肥对于土壤含水量、温度、容重、养分、pH、有机质、土壤酶、土壤微生物等各方面的影响，在此基础上，我们探究了主作物间作绿肥对于土壤的影响 (图 3)。

3.1　对土壤结构的影响

土壤结构决定土壤透气性、蓄水能力等，传统农业常通过耕地、犁地等农业措施来改善土壤结构，为植物根系提供更好的生存环境。绿肥为改善土壤结构提供了一种新的方式，豌豆、肥田萝卜、糙伏毛燕麦增加土壤大孔隙率 15.84%，显著降低土壤密度 15.54%，提高大豆产量和千粒重 10.90% 和 21.34% [58]。对绿肥－果园系统的研究表明，富士苹果 (*Malus pumila*) 行间间作油菜增加了土壤的大孔隙数量、大孔隙面积、大孔隙周长和大孔隙度，显著改善了土壤结构[59]。

3.2　对土壤化学性质的影响

3.2.1　对土壤 pH 的影响

适宜的土壤 pH 是确保植物健康生长的重要条件，绿肥可有效改良土壤 pH。Khan 等[60] 的研究表明，芥菜可增加土壤 pH 达 7.62%。行间种植小须芒草 (*Schizachyrium scoparium*) 2 年后，苹果园土壤 pH 较无绿肥处理降低 6.83%～7.19% [61](表 4)。此外，圆叶决明 (*Chamaecrista rotundifolia*)、油菜、宿根羽扇豆 (*L. perennis*) 提高茶园土壤 pH 达 11.94% [62]。

3.2.2　对土壤养分的影响

绿肥对主作物土壤养分的影响多有报道。朱亚琼等[63] 的研究发现，种植花生、鹰嘴豆 (*Cicer arietinum*)、白花草木樨 (*Melilotus albus*) 分别提高土壤有机质、全氮、全磷、全钾、碱解氮、有效磷达 40.43%、50.00%、10.00%、27.93%、76.75%、45.13%，增加玉米和油菜地上生物量 23.19% 和 16.68%。同样的，木豆、刀豆 (*Canavalia brasiliensis*)、高粱、刚果臂形草也增加玉米田中土壤总氮、微粒氮、矿物氮等各种形式氮的含量[64]。绿肥不仅改变土壤养分，也可促进植物对土壤水分的吸收和利用，如 Blanco-Canqui 等[66] 发现，多种绿肥混播减少因地表径流、泥沙流失造成的养分流失，还可以减少硝酸盐等营养物质的淋失，降幅高达 95%。同样，在 Çerçioğlu [67] 的研究中，多种绿肥作物混播使土壤饱和导水率逐年增加，最高可增加 64.6%。但也有研究发现，黑麦草 (*L. perenne*) 则降低苹果园 0－5 cm 土层含水量 1.80%～5.77% [68]。这表明，绿肥对于土壤水分的促进效果受到地理环境及降水等因素的影响，要综合所在区域的天气及蓄水条件，选择合适的绿肥作物，采取适当的管理措施。

3.3　对土壤酶活性的影响

土壤中各类酶活性直接反映了土壤微生物的活性，土壤酶能促进土壤中物质分解和循环，从而提高土壤中的养分含量。黑麦和绛三叶草增加了土壤中的微生物和可分解利用的基质含量，从而显著增加大豆田中与有机质分解相关磷酸酶和二乙酸荧光素水解酶活性[69]。同时，白三叶也增加了富士苹果园中各种土壤酶活性，如 CBH (纤维素酶)、NAG (N-乙酰-β-D-葡萄糖苷酶) 和 PHOS (磷酸酶)[70] 等。

表 4 绿肥对土壤的影响

Table 4 Effects of green manure on soil

绿肥 Green manure crop	主作物 Main crop	影响 Influence	参考文献 Reference
小须芒草 *Schizachyrium scoparium*	苹果 *Malus pumila*	2年后，苹果园土壤pH较无绿肥处理降低6.83%～7.19% After two years, the soil pH of the apple orchard decreased by 6.83%～7.19% compared with that of non-green manure treatment	[61]
圆叶决明 *Chamaecrista rotundifolia* 油菜 *Brassica napus* 宿根羽扇豆 *Lupinus perennis*	茶树 *Camellia sinensis*	提高茶园土壤pH达11.94% Increased the soil pH of tea trees by 11.94%	[62]
花生 *Arachis hypogaea* 鹰嘴豆 *Cicer arietinum* 白花草木樨 *Melilotus albus*	玉米 *Zea mays* 油菜 *Brassica napus*	提高土壤有机质、全氮、全磷、全钾、碱解氮、有效磷达40.43%、50.00%、10.00%、27.93%、76.75%、45.13%，增加玉米和油菜地上生物量23.19%和16.68% The soil organic matter, total nitrogen, total phosphorus, total potassium, alkaline hydrolyzable nitrogen, and available phosphorus reached 40.43%, 50.00%, 10.00%, 27.93%, 76.75%, and 45.13%, respectively; increased the aboveground biomass of maize and rapeseed by 23.19% and 16.68%, respectively	[63]
木豆 *Cajanus cajan* 刀豆 *Canavalia brasiliensis* 高粱 *Sorghum bicolor* 刚果臂形草 *Urochloa ruziziensis*	玉米 *Zea mays*	增加玉米田中土壤总氮、微粒氮、矿物氮等各种形式氮的含量 Increased the content of total soil nitrogen, particulate nitrogen, mineral nitrogen, and other forms of nitrogen in maize fields	[64]
木豆 *Cajanus cajan* 洋刀豆 *Canavalia ensiformis* 花生 *Arachis hypogaea*	玫瑰 *Rosa rugosa*	增加玫瑰田中K、Mg、B含量达46.15%、16.67%、31.58%外，减少土壤Zn、Fe、S含量达34.80%、50.23%、18.00% The contents of K, Mg and B in rose fields increased by 46.15%, 16.67%, and 31.58%, respectively, and the contents of soil Zn, Fe and S decreased by 34.80%, 50.23%, and 18.00%, respectively	[65]
多种绿肥 Many species of green	玉米 *Zea mays* 大豆 *Glycine max*	减少因地表径流、泥沙流失造成的养分流失，还可以减少硝酸盐等营养物质的淋失，降幅高达95% Reduced nutrient loss due to surface runoff and sediment loss; can also reduce the leaching of nutrients such as nitrates by up to 95%	[66]
多种绿肥 Many species of green manure	大豆 *Glycine max* 玉米 *Zea mays*	多种绿肥作物混播使土壤饱和导水率逐年增加，最高可增加64.6% The mixed planting of a variety of green manure crops increased the water conductivity of soil saturation year by year, up to 64.6%	[67]
黑麦草 *Lolium perenne*	苹果	黑麦草降低苹果园0－5 cm土层1.80%～5.77% 的含水量 Ryegrass reduces the water content of the 0－5 cm soil layer in an apple field by 1.80%～5.77%	[68]
黑麦 *Secale cereale* 绛三叶草 *Trifolium incarnatum*	大豆 *Glycine max*	增加土壤中的微生物和可分解利用的基质含量，从而显著增加大豆田中与有机质分解相关的磷酸酶和二乙酸荧光素水解酶活性 The phosphatase and fluorescein diacetate hydrolase activities related to the decomposition of organic matter in soybean fields were significantly increased by increasing the content of microorganisms and degradable substrates in soil	[69]
白三叶 *Trifolium repens*	富士苹果 *Malus pumila*	增加了富士苹果园中各种土壤酶活性，如CBH (纤维素酶)、NAG (N-乙酰-β-D-葡萄糖苷酶)和PHOS (磷酸酶)等 The activity levels of various soil enzymes, such as CBH, NAG, and PHOS, were increased	[70]
平托花生 *Arachis pintoi* 毛蔓豆 *Calopogonium mucunoides* 洋刀豆 *Canavalia ensiformis* 距瓣豆 *Centrosema pubescens*	可可 *Theobroma cacao*	提高革兰氏阴性菌与革兰氏阳性菌的比例，降低了真菌生物量 Increased the ratio of gram-negative to gram-positive bacteria; reduced fungal biomass	[71]
多种绿肥混播 Mixed sowing of various green manures		增加了真菌和革兰氏阳性菌的比例，使土壤微生物群落组成发生了显著变化 Increased the ratio of fungi to gram-positive bacteria, the soil microbial community composition was affected	[72]
毛叶苕子 *Vicia villosa*	桑 *Morus alba*	提高桑园中土壤细菌、真菌和放线菌数量86.8%、151.7%和168.4% The number of bacteria, fungi, and actinomycetes in the mulberry fields increased by 86.8%, 151.7%, and 168.4%, respectively	[73]

3.4　对土壤微生物的影响

土壤微生物数量与土壤结构、养分含量及通气状况等因素密切相关，果园绿肥覆盖能提高微生物量和微生物活性，影响微生物数量及群落组成。如平托花生 (*A. pintoi*)、毛蔓豆 (*Calopogonium mucunoides*)、洋刀豆 (*Canavalia ensiformis*)、距瓣豆 (*Centrosema pubescens*) 可提高革兰氏阴性菌与革兰氏阳性菌的比例，而降低了真菌生物量[71]。荞麦、埃及三叶草、向日葵、野萝卜 (*R. raphanistrum*) 则增加了真菌和革兰氏阳性菌的比例，使土壤微生物群落组成发生了显著变化[72]。毛叶苕子可提高桑园中土壤细菌、真菌和放线菌数量 86.8%、151.7%、168.4%，随种植时间延长，促进作用更为明显[73]。

4　展望

绿肥是我国传统农业的重要组成部分，是保障我国食物安全、提升农产品竞争力的重要途径。国家对绿肥的重视程度日益提升，绿肥种植面积不断扩大。基于绿肥产业需求和研究现状，建议今后进一步加强以下方面的研究：1) 绿肥经济效益的评价。目前的研究大多从作物本身的产量上去评估绿肥的有效性，较少考虑到实际生产中所需投入的经济需求，无法衡量这种农业措施最后的经济效益如何。2) 绿肥防治主作物病害。目前主要集中在玉米、马铃薯、小麦、大豆、水稻上，涉及到的主作物品种较少、深度较浅，无法对更多地区、更多主作物品种的生产提供指导意义。3) 绿肥－主作物一体化的认识。应强化绿肥在系统中的生态、经济效益的研究。4) 努力创新绿肥品种、适配装备、发展产品、积极示范推广绿肥产业。5) 积极探讨绿肥的利用方式，拓展“绿肥 +”产品和市场，提升农产品竞争力。

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