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轮作影响土壤磷有效性的研究进展

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摘　要：磷作为植物主要的营养元素之一，关乎农作物的产量及品质。在耕地质量下降及土壤磷缺乏或有效性低等多重影响下，提高土壤磷有效性成为国内外关注的焦点。采用 2 种及 2 种以上的作物进行轮作，对改良土壤、提高农业生产效率及恢复农田生态系统功能等方面具有积极的影响。因此，本研究梳理总结不同作物轮作情况下对土壤理化性质、土壤磷形态转化、土壤微食物网等方面的研究进展。其中，一方面从土壤理化性质与土壤磷形态转化之间相关关系入手，分析轮作对土壤磷有效性的影响；另一方面，从土壤微食物网的结构变化、基因调控等作用下的土壤磷形态转化与磷的生物地球化学循环角度，在分子水平上深入探讨不同作物轮作对土壤磷有效性的影响。通过文献综述发现不同作物轮作可改变土壤理化性质和土壤微食物网结构，从而影响土壤磷的形态转化，以提高土壤磷的有效性，促进作物产量及品质的提升，说明不同作物轮作是改善土壤磷有效性的重要农业管理措施，今后需加强这方面的研究及不同作物轮作组合模式的探索，为保障国家粮食安全、农作物品质等方面提供重要的支撑，因此相关研究具有重要的社会、经济和生态环境意义。

关键词：轮作；土壤理化性质；土壤磷形态；土壤微食物网；磷有效性
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Review on the Effects of Crop Rotation on Soil Phosphorus Availability

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Abstract: Phosphorus is one of the essential nutrients for plant growth, and plays a crucial role in determining crop yield and quality. Due to the combined pressure of decreased arable land quality and soil phosphorus deficiency or low bioavailability, the improvement of soil phosphorus availability has become a global concern. The rotation of two or more crops has positive effects on soil improvement, crop production efficiency and the restoration of agricultural ecosystem function. This study reviews the research progress on the effects of crop rotation on soil physiochemical properties, soil phosphorus transformation, and soil micro-food web. Firstly, the relationship between soil properties and phosphorus transformation is analyzed to assess the impact of crop rotation on phosphorus availability. Secondly, from the perspective of soil micro-food web and gene regulation, the transformation and biogeochemistry cycle of soil phos-

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phorus was analyzed at the molecular level. It is summarized that crop rotation can affect soil phosphorus transformation through altering soil physiochemical properties and micro-food network structure, which can improve soil phosphorus availability, and ultimately promote crop yield and quality. We indicate that crop rotation is an important agricultural management measure for improving soil phosphorus availability. It is suggested to strengthen the related research and explore the combination model of crop rotation in the future. It would provide powerful support for food security and crop quality, and is of great significance in social economy and ecological environment.

Keywords: crop rotation; soil physical and chemical properties; soil phosphorus forms; soil micro-food web; phosphorus availability

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1　引言

众所周知，提高土壤磷有效性一直是国内外关注的热点和难点。磷作为植物必需的营养元素之一，极易和土壤中铝、铁、钙等阳离子生成难溶性物质，从而降低农作物对磷的可利用性[1-3]，威胁粮食安全和土壤生态安全[4-6]。在世界人口压力耦合耕作土壤质量下降等多重问题影响下，迫切需要研发提升土壤磷有效性的高效途径。

人们从长期的农业实践中发现，通过不同时期在同一地块分别轮流种植 2 种及 2 种以上适生农作物即不同作物轮作[7]，在提高土地利用效率的同时可明显改善土壤环境质量[8]。近年来的研究发现，不同作物轮作有利于通过调节土壤理化性质、土壤微食物网等方面提高土壤磷有效性[9-12]。

土壤磷有效性与土壤磷的形态转化密切相关。据报道，土壤中的 H_2O-P（水溶性磷）、NaOH-Pi（氢氧化钠提取态无机磷）、$NaHCO_3$-Pi（碳酸氢钠提取态无机磷）、HCl-P（盐酸提取态磷）等不同磷形态与土壤磷有效性具有明显相关性[13-14]。因此，本研究着眼于不同作物轮作模式，围绕其通过改变土壤理化性质和土壤微食物网等方面影响土壤磷形态转化和土壤磷有效性进行综述。

2　轮作对土壤磷有效性的影响

2.1　土壤理化性质

2.1.1　轮作对土壤理化性质的影响　不同作物轮作可调节土壤 pH、土壤结构、土壤有机质等基本理化性质，改善土壤环境质量和养分供应能力，提高农作物产量及品质[15-19]。吉林农业大学等单位的学者研究发现，相对于单独种植人参，人参与其他作物轮作后，土壤 pH 升高有效缓解了人参连作引发的土壤酸化问题，同时土壤速效磷等养分供应能力明显得到改善[20]。

王克磊等[21]采用水稻－番茄轮作的农艺措施来治理番茄连作障碍及土壤酸化等问题，发现该轮作模式下的土壤 pH 高于单独连作番茄的土壤 pH，使土壤酸化问题得到缓解并提高了作物产量。

轮作可改良土壤结构，具有增加土壤孔隙度和土壤有机质含量，降低土壤容重、改善土壤团聚体稳定性等多方面的作用[22-27]。西北农林科技大学等单位的研究人员通过 10 年轮作试验研究发现，与连续单作相比较，轮作显著降低土壤容重达 3.8%~8.4%，土壤孔隙度和土壤大团聚体含量均得到提高[24]。另有学者采用 Meta 分析研究了轮作对土壤团聚体稳定性等土壤性状方面的影响，发现与连续单作相比，轮作土壤中的大团聚体含量占比、团聚体稳定性、团聚体中有机碳含量等分别提高了 7%~14%、7%~9%、7%~8%[26]。

2.1.2　土壤理化性质对磷有效性的影响　（1）土壤 pH。土壤 pH 可调节磷的溶解、固化等地球化学反应过程，改变土壤磷的形态，进而对土壤磷有效性产生重要的影响[21, 28-29]（图 1）。有研究表明，土壤 pH 低于 4.0 时，肌醇六磷酸和磷酸盐等的积累可增加有机磷含量约 20%[30]。土壤 pH 在 6.0~7.0 之间时，土壤磷迁移性和有效性最强[31]。土壤溶液中 $H_2PO_4^-$、HPO_4^{2-}等不同活性磷组分占比受土壤 pH 调控[32]；土壤 pH 还可通过影响土壤中铝、铁等金属氧化物及其水合氧化物的形态、价态、结晶度及聚合度等性质影响磷的吸附、沉淀、络合等过程来改变磷有效性[33-36]。不同土壤 pH 条件下粘土矿物的表面电荷和吸附性能的改变也会对土壤磷有效性产生重要影响[37-39]。

（2）土壤结构。土壤结构可通过影响土壤肥力因素（水、肥、气、热）的协调作用进而影响磷的迁移转化[40]。轮作可降低土壤容重、增加土壤孔隙度，从而增加磷的可利用性[41-46]（图 1）。据报道，土壤容重影响土壤中磷向植物根系的迁移性，质地黏重的土壤容重高，磷向植物根系迁移的扩散系数低[47]。土壤孔隙度与土壤磷形态密切相关，土壤孔隙度大、比表面积高有利于提高

土壤磷有效性[48]。

土壤团聚体也对土壤磷有效性具有重要影响[49-52]。对栽培甘蔗的土壤研究发现，大部分活性态有机磷分布在低于 0.053 mm 的团聚体中，铝结合态磷（Al-P）、钙结合态磷（Ca-P）、铁结合态磷（Fe-P）等无机磷分布在大于 0.250 mm 的团聚体中[51, 53]。土壤团聚体的粒径大小与土壤磷有效性具有一定的关系[54]。轮作可通过调控土壤团聚体中磷形态转化来影响磷的有效性[55]。已有研究表明，稻菜轮作可改善土壤团聚体结构，从而显著提高耕层土壤各粒级团聚体中磷的有效性[56]。土壤团聚体粒径大小还可影响磷的迁移性，进而影响土壤磷有效性[57]。通过长期的玉米－小麦轮作定位试验研究，发现 Al-P 和 Ca-P 在不同粒径的团聚体中均得到增加并向大团聚体转移，提高了土壤磷有效性[50]。

（3）土壤有机质。土壤有机质可提供植物必需的营养元素[58]，其含量的增加可提高土壤磷的有效性。土壤有机质可占据土壤矿物中部分磷的吸附位点，从而抑制土壤矿物对磷的吸附固定[59-61]。有机质的存在会导致土壤表面产生大量限速吸附位点，磷的瞬时吸附下降，从而加速磷的迁移[62]。与不加入腐殖酸处理相比，土壤中加入腐殖酸等有机质可以显著降低针铁矿对磷的吸附[63]。土壤矿物表面电荷等性能的差异对不同形态磷的吸附固定及磷有效性具有影响[64-69]。冬小麦－夏玉米轮作试验研究表明，Ca^{2+}可与有机质形成二元复合物，减少磷的吸附性、提高磷的有效性[70-72]。土壤有机质可矿化释放有机磷[73-75]。有机质含量可能会对不同形态磷的占比产生影响，提高有机质含量有利于提高磷有效性[61]。不同作物轮作的合理安排可提高土壤有机质的含量[76-78]。

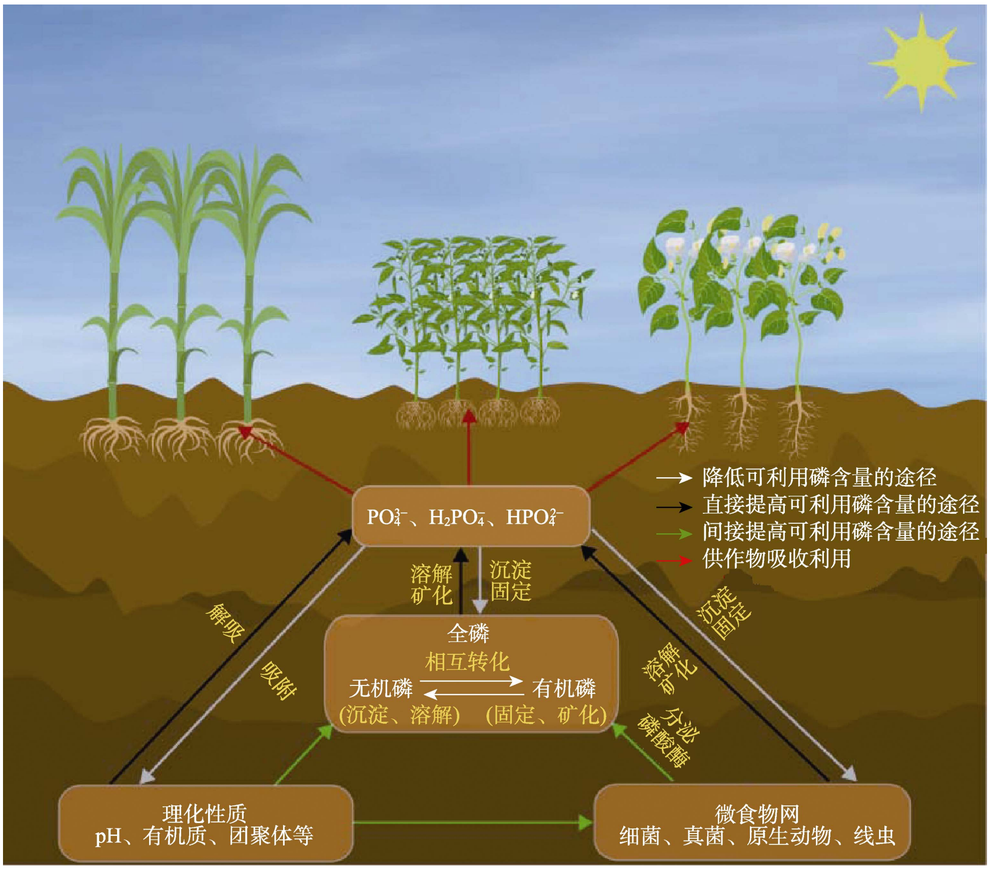

图 1　轮作影响土壤磷有效性的途经

Fig. 1　Pathways influencing soil phosphorus availability through crop rotation

2.2　土壤磷形态转化

土壤中的磷主要包括有机磷和无机磷。土壤无机磷以正磷酸盐为主，其次为无机聚磷酸盐、焦磷酸盐和偏磷酸盐。按溶解性可将无机磷划分为矿物态、水溶态和吸附态等不同无机磷形态[79-81]。按分子结构可将土壤有机磷划分为膦酸盐、磷酸盐、磷酸酯、微生物量磷和多聚磷酸酯等[82-84]。土壤中无机磷和有机磷之间可以相互转化[85]（图 1）。

轮作可促进土壤磷的形态转化[86]。据报道，在小麦－玉米长期轮作模式下，土壤中 Al-P、Fe-P 等无机磷含量显著提高[87]。小麦－水稻长期轮作试验研究发现，铁氧化物及水合氧化物在干湿交替条件下的形态、价态转化影响土壤磷的有效性[88]。无论水－旱轮作还是旱－旱轮作均发现 NaOH-Pi 等有效磷含量显著增加[89-91]。玉米－小麦轮作耦合秸秆还田处理试验研究发现，表层土壤和亚表层土壤中的有效磷含量显著增加[92]。

2.3　土壤微食物网

2.3.1　轮作对土壤微食物网的影响　土壤微食物网由微生物、原生动物及线虫组成[93]，各生物群之间通过资源控制和捕食效应形成营养级联网络[94]。关于轮作模式下土壤微食物网的研究（表 1），发现相对于香蕉单作，香蕉－菠萝、香蕉－水稻免耕轮作可提供具有不同降解程度且数量更多的植物残留物，同时可增加土壤微食物网中食细菌线虫和食真菌线虫等生物类群的数量，提高微生物的磷脂脂肪酸浓度、土壤线虫多样性及其功能代谢足迹，土壤微食物网结构更加稳定[95]。轮作可影响土壤微生物的丰度和组成，改变土壤微生物的群落结构，调节土壤微生态环境[96-97]。据报道，鹰嘴豆－小麦轮作可增强小麦根部 AMF（arbuscular mycorrhizal fungi，丛枝菌根真菌）的定殖，并改变其丰度[98]。在土壤微食物网中，线虫作为重要调节剂对有机残留物分解及养分释放具有明显的影响[99-100]。一方面，线虫从通过自身分泌及排泄等活动可增加土壤有效养分的含量[101]；另一方面，线虫通过捕食等活动促进微生物代谢，提高土壤酶活性和土壤呼吸强度[102-103]。原生动物是土壤微生物及线虫的主要消费者[104-105]。增加原生动物物种的丰度可减少微生物之间的相互竞争，增强亚优势物种生长优势，从而改变微生物群落结构[106]。据报道，相对于玉米连作，玉米－大豆、玉米－燕麦－苜蓿等长期轮作模式可增加作物根际土壤中放线菌门、变形菌门和酸杆菌门的丰度[107]。另有研究表明，相对于玉米单作和大豆单作，大豆－玉米免耕轮作模式可增加 AMF 的丰度、外源菌丝体长度等土壤微生物性状指标[108]。豌豆－玉米轮作则可增加铜弧菌（*Cupriavidus*）和慢生型根瘤菌（*Bradyrhizobium*）等 PSMs（phosphate-solubilizing microorganisms，溶磷微生物）的丰度[109]。

表 1　轮作对土壤微食物网的影响

Tab. 1　Impact of crop rotation on soil micro-food web

编号 No.	轮作类型 Crop rotation type	生物类群 Biological group	文献 Reference
1	香蕉－菠萝 香蕉－水稻	食细菌线虫、食真菌线虫等	[95]
2	鹰嘴豆－小麦	AMF	[98]
3	玉米－大豆 玉米－燕麦－苜蓿	放线菌门、变形菌门和酸杆菌门	[107]
4	大豆－玉米	AMF	[108]
5	豌豆－玉米	PSMs	[109]
6	苜蓿－玉米 苜蓿－马铃薯	线虫	[113]
7	苜蓿－小麦 三叶草－小麦	线虫	[114]
8	黄瓜－菜豆	微生物和原生动物	[117]

2.3.2　土壤微食物网对磷有效性的影响　土壤微食物网是农田生态系统的重要组成部分，可调节土壤磷等养分元素的生物地球化学循环[110-111]。轮作可促进土壤微食物网结构与功能的调节，从而加速磷的矿化过程[112]。霍娜等[113]的研究表明，相对于苜蓿连作，苜蓿－玉米、苜蓿－马铃薯等不同轮作模式下土壤有效磷含量、土壤线虫丰度均显著增加。另有研究表明，相对于小麦单作，4 年连续轮作苜蓿/三叶草－小麦可提高土壤微生物多样性、捕食性和杂食性线虫的数量、土壤磷的矿化速率及有效磷含量[114]。土壤原生动物可通过刺激磷的矿化来影响土壤磷的生物地球化学循环，同时刺激作物对养分的吸收利用[115-116]。黄瓜－菜豆轮作模式下，土壤微生物与原生动物的丰度、有效磷含量均得到显著提高，说明轮作可通过促进土壤微食物网的养分循环来提高土壤磷的有效性[117-118]。轮作可改变土壤磷循环功能基因的丰度[119-122]。已有研究表明，*ppk* 基因可编码聚磷酸盐激酶催化磷单体聚合成聚磷酸盐分子[123]；*ppx* 基因则可编码聚磷酸酶，降解无机聚磷酸盐为磷酸盐[124]。小麦－玉米轮作土壤中有效磷含量与 *ppx* 等功能基因丰度具有一定关系[125]。玉米－甘蓝长期轮作定位试验研究发现，作物吸磷量与 *ppx* 基因丰度呈正相关关系[126]。总体而言，土壤微食物网在土壤磷的生物地球化学循环过程中发挥着重要作用，有助于提高土壤磷有效性[127-129]。

土壤微食物网中与磷的形态转化相关的微生物主要有 AMF 和 PSMs，二者均可提高土壤磷有效性，促进植物生长。AMF 可与植物形成互利共

生体促进磷的吸收利用[130-132]。PSMs 可通过介导生物磷转化增加土壤有效磷含量[133-134]。据报道，PSMs 可将粘土矿物吸附的磷转化为植物可利用的有效磷[135]。AMF 和 PSMs 之间也可互作提高土壤磷的有效性。有研究表明，相对于单独接种 AMF，在咖啡种植中曲霉（*Aspergillus niger* Tiegh, HS165）、短苞青霉（*Penicillium brevicompactum* Dierckx, HS42）与 AMF 共接种，土壤有效磷含量得到显著增加，明显促进了咖啡植株的生长[136]。

土壤有机磷矿化与无机磷溶解对土壤磷的有效性具有重要作用（图 1）。参与催化有机磷矿化的磷酸酶包括：酸性磷酸酶、碱性磷酸酶及磷酸二酯酶，在这些磷酸酶的催化作用下，有机磷可矿化为植物容易吸收利用的磷[137-138]。土壤微生物可通过磷循环功能基因调控磷酸酶的合成[139-141]。AMF 和 PSMs 一方面可促进有机磷的矿化，另一方面可将难溶性矿物态无机磷溶解，促进植物对磷的吸收利用[142-145]。AMF 不仅可以通过定殖在植物根系的菌丝体协助植物获取土壤磷等养分[146]，还可通过分泌磷酸酶矿化有机磷、溶解无机磷以提高土壤磷有效性[137, 147-150]。PSMs 在土壤无机磷溶解过程中占有重要地位，同时可促进有机磷等不同磷形态的转化[151-157]。AMF 与 PSMs 互利共生可增强土壤磷形态转化。有研究发现 AMF 菌丝际富集着大量 PSMs[158-161]。PSMs 可帮助 AMF 溶解土壤中难溶性磷，提高植物通过 AMF 吸收磷的效率[146, 158]；PSMs 则可分泌磷酸酶等分子溶解难溶性无机磷，促进 AMF 对土壤中磷酸盐的吸收和转运，通过 AMF 和 PSMs 的互作强化了磷形态转化，提高土壤磷的有效性[146]。

3 结论与展望

本研究重点围绕不同作物轮作对土壤理化性质、土壤磷形态转化及土壤微食物网等方面的影响，梳理总结了其对提高土壤磷有效性方面的研究进展。主要发现：（1）相对于单作物连作，不同作物轮作可提高土壤 pH、降低土壤容重、增加土壤孔隙度、提高土壤团聚体稳定性；其中，土壤 pH 升高明显缓解了土壤酸化过程，促进了土壤有效磷含量的增加；低容重、高孔隙度等土壤性能有利于磷的迁移转化与吸收利用。（2）不同作物轮作比单一作物连作具有较好的土壤微食物网调节作用。有利于微生物、原生动物及线虫等生物类群彼此之间的协同互作，促进有机磷矿化和无机磷溶解，影响土壤磷的生物地球化学循环过程，提高土壤磷的有效性。

然而，目前的轮作组合模式具有明显的地域特征，并非增加磷有效性的最佳组合模式。展望未来，今后还需加强对不同作物轮作组合模式的探索，以及组合模式下根际微生物群落结构和土壤微食物网结构等方面对磷形态转化过程和相关机制的探究。随着技术发展，高通量测序、磷-核磁共振技术（P-NMR）、基于同步辐射的 X 射线吸收近边结构谱技术（P-XANES）等多技术融合将成为趋势，可为土壤微食物网中磷的代谢路径与磷形态转化微观机制研究提供强有力的技术支撑。

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