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不同耕作措施土壤结构特征及其影响因素的研究进展

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摘 要：综述不同耕作措施下土壤团聚体稳定性和孔隙结构特征的研究进展，归纳总结影响土壤结构稳定性的主要因素。结果表明，与传统翻耕相比，免耕、深松及其秸秆覆盖还田增加表层土壤大团聚体含量及稳定性，提高大孔隙数量和孔隙度。轮耕系统对土壤结构的影响在不同气候区域和土壤类型间差异较大。土壤结构稳定性与铁铝氧化物形态变化、有机质含量、蚯蚓数量、微生物和线虫丰度及多样性、根系构型及其分泌物、干湿交替及冻融交替次数等因素相关。针对目前研究现状，提出建立长期保护性耕作和轮耕体系监测系统，从铁铝氧化物形态变化、土壤微食物网结构和功能、根系驱动等研究方向进一步解析旱地耕作对土壤结构的影响机制。

关键词：玉米；耕作措施；土壤团聚体；土壤孔隙结构；土壤微生态环境；根系

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Research Progress on the Effects of Tillage on Soil Structure in Dry Farming Regions

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Abstract: The research progress on the effects of different tillage on soil aggregates stability and pore structure characteristics was reviewed in this article, and the main factors affected the soil structure were summarized. The results showed that, compared to conventional plough tillage, no-tillage and subsoiling tillage with straw mulch enhanced the large soil aggregates and aggregate stability, increased soil macropores and total porosity in surface soil. The effects of rotational tillage system on soil structure changed in different climatic regions and soil types. Soil structural stability was related to iron and aluminum oxides in morphological change, organic matter contents, earthworm quantity, abundance and diversity of microorganisms and nematodes, root morphology and exudates, alternation of dry-wet cycle or freeze-thaw cycle times. Based on the current research status, this article looks forward to the future research focus on building a long-term conservation tillage and rotational tillage system monitoring systems. The influence mechanism of tillage on soil structure need be further analyzed from the research directions of iron and aluminum oxides morphological change, microbial food web structure and function, root drive.

Key words: Maize; Conservation tillage; Soil aggregate; Soil pore structure; Soil microenvironment; Root

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土壤结构是指土壤中黏粒、粉粒、砂粒和有机颗粒的排列状况。土壤颗粒在多种力的作用下团聚在一起，形成不同尺度的结构单元，称为结构体或团聚体[1]。土壤大团聚体是由大量小团聚体形成的聚合物[2]。同时，土壤大小团聚体之间及其内部的孔隙也是土壤结构重要组成部分，不仅影响植物生长所需要的水分和养分的供应，而且左右着土壤中的物质交换、能量平衡、微生物活动和作物根系延伸等过程，对提高土壤肥力、增加作物产量和调节土壤环境具有重要作用[3]。耕作是农业生产中不可缺少的重

要田间管理方式，不同耕作措施对土壤扰动范围和强度不同，使其土壤结构特性有较大差异。常见的耕作措施包括旋耕、免耕、翻耕和深松等多种方式及其在不同轮作系统和年际间的组配。近年来随着社会发展和人口增加，农业可持续发展备受关注，保护性耕作成为研究热点。因此，阐明不同耕作措施土壤结构特征及其影响因素，有利于探究其对土壤生产能力和培肥效果的影响，为合理耕作方式的选择提供理论依据。

1 耕作措施对土壤结构的影响

建立提质增效可持续耕作模式是农业发展的迫切需求，土壤结构稳定性是评价土壤质量优劣的重要指标之一，在发挥土壤功能中具有重要作用。不同耕作措施既能通过农机具的破碎与压实作用直接改变农田耕层土壤结构特性，也可通过改变耕层环境间接影响土壤结构稳定性。

1.1 对土壤团聚体的影响

土壤团聚体稳定性是指团聚体抵御外力或外部环境变化而保持原形态的能力[4]。科学研究中通常采用筛分法，将测定的直径>0.25 mm的大团聚体含量、计算获得的平均质量直径(MWD)和几何平均直径(GMD)作为评价土壤团聚体稳定性的重要指标[5]。东北平原黑土区短期研究发现，免耕0～5 cm土层>1 mm的大团聚体含量较初始值提高3.0倍，但6～30 cm土层该粒级团聚体含量降低71.9%。秋翻耕后各土层>1 mm的大团聚体含量均表现出不同程度的下降，旋耕处理介于两者之间[6]。免耕较其他两种耕作还能增加0～20 cm土层>5 mm粒级土壤团聚体含量和稳定性[7]。但长期免耕对土壤团聚体促进作用仅表现在土壤表层，而深松则达到30 cm土层[8]。秸秆还田能提高大团聚体含量、MWD和GMD值，而且旋耕/深翻的轮耕还田模式能促进耕层大团聚体形成和稳定性提高[9]。东北南部棕壤区短期秸秆条带还田发现，旋耕较翻耕更能促进0～10 cm土层大团聚体含量及MWD值的提高[10]。华北平原和黄土高原保护性耕作研究同样表明，免耕增加0～10 cm土层土壤大团聚体含量及稳定性，同旋耕和翻耕在10～30 cm土层差异不显著[11～13]。李慧等[14]在晋南旱地进行的短期夏闲期轮耕研究发现，深松/深翻轮耕比连续免耕、翻耕或深松耕更能提高0～50 cm土层大团聚体含量及其稳定性。红壤坡耕地占南方红壤面积的70%，短期免耕能增加2～8 mm粒级团聚体含量，免耕和翻耕20 cm处理均比翻耕30 cm更有利于大团聚体的形成和稳定[15]。西南紫色土丘陵区短期保护性耕作发现，旋耕和翻耕秸秆覆盖均比传统翻耕增加0～5 cm土层大团聚体含量[16]，同时横坡耕作比顺坡耕作团聚体稳定性强、抗蚀性强[17]。总体来看，免耕及其秸秆覆盖处理均促进耕层土壤团聚体稳定性的提高，免耕后会降低因频繁耕作而导致的土壤团聚体破碎，但长期应用后促进效果仅表现在表层。短期轮耕系统对土壤团聚体稳定性的影响在区域研究中差异较大，有待建立长期定位试验继续开展相关研究。

1.2 对土壤孔隙结构的影响

土壤孔隙特征能更好反应土壤结构对土壤养分供应、水分保持和渗透、气体交换等过程的调控作用[18]。不同耕作措施形成的耕层土壤孔隙结构会随耕作实施年限产生变化。翻耕能打破犁底层，形成全松的耕层构造，3年的应用能提高耕层土壤孔隙度，打破土壤孔隙之间的孤立性，增加连通性[19]。但实施16年后，0～20 cm土层土壤大团聚体含量降低，大孔隙数量和长度随之减少，中小孔隙成为主导[12]。免耕形成全紧耕层构造，8年的应用能增加0～40 cm土层80～1 000 μm的孔隙数量，提高孔隙成圆率[20]。但免耕25年以后，土壤大孔隙密度和连通性与翻耕差异不再显著，并在播种深度以下形成硬土层，该层孔隙度和孔隙联通性均小于底土层[21]。间隔深松形成苗带紧行间松的耕层结构，实施16年后同免耕具有相同优势，均改善了0～10 cm土层总孔隙度，但两者同翻耕在10～20 cm土层孔隙大小分布上差异不显著[12]。宁南旱区3年轮耕试验发现，免耕/深松/深松轮耕处理较连年免耕和翻耕显著降低了0～20 cm土层土壤孔隙度，较深松/免耕/免耕轮耕处理提高了20～40 cm土层土壤孔隙度[22]。耕作措施对土壤孔隙结构的影响在不同的实施年限及轮耕系统间存在不一致性，一方面由于减少耕作可以增强土壤团聚体稳定性和提高土壤孔隙度；另一方面长期少免耕又导致土壤板结降低孔隙度，而适时深松或翻耕能降低土壤紧实度，增加孔隙度和通透性。因此，基于长期定位试验和因地制宜建立多种轮耕措施、轮耕周期和适宜秸秆还田量所构成的保护性耕作体系监测对于揭示耕作措施差异对土壤孔隙结构的影响规律至关重要。

2 影响因素

不同耕作措施土壤结构稳定性受内部因素、生物因素和外部因素的协同作用。内部因素包括土壤特性和胶结物质，土壤特性分为土壤类型、质地、阳离子交换量、土壤酸碱度等，胶结物质包括黏土矿

物、有机质等。生物因素包括微生物及其分泌物、土壤动物、植物根系等。外部因素主要是气候和地形引起的土壤干湿交替和冻融交替过程。

2.1 铁铝氧化物

土壤中铁铝氧化物、层状硅铝酸盐矿物等是黏土矿物主要成分,是土壤矿物中最活跃组分,其颗粒细小,比表面积大,在黏粒絮凝过程中起最重要的作用,影响土壤结构的稳定性[23]。土壤团聚体中游离态和络合态铁铝氧化物含量均与团聚体稳定性显著正相关,均为0.053~0.250 mm粒级团聚体的主要胶结剂[24,25]。东北草甸黑土0~20 cm土层游离结晶态铁铝氧化物含量高于无定形态铁铝氧化物含量,均与大团聚体含量呈显著正相关。应用3年翻耕后,对比旋耕提高0~20 cm土层无定型态铁氧化物含量和团聚体破坏度[26]。实施免耕12年后较翻耕和旋耕增加0~50 cm土层无定型态铁氧化物含量[27]。游离态铁氧化物还与超微孔隙(<0.1 μm)含量显著正相关,其同黏土矿物的胶结是形成直径为0.001~0.1 μm孔隙的主要原因[28]。基于长期定位试验研究土壤黏土矿物演化对不同耕作措施的影响机制,对于解析土壤结构稳定性具有重要意义。

2.2 土壤有机质

土壤有机质是形成0.25~2.0 mm粒级团聚体的主要胶结剂,并通过多种复合机制与矿质土粒形成有机——矿质复合体,其含量与土壤结构性、吸附性、渗透性等密切相关[29]。有机质含量高的土壤其团聚体稳定性大于有机质含量低的土壤[30],其对雨滴等机械打击和消散作用的敏感程度减弱,土壤抗腐蚀能力增强[31]。土壤有机质具有一定的弹性和膨胀性,在受外力作用时有机质颗粒会使土壤表现出可压缩性和具有缓冲性,从而阻止压力从土壤表层向下传递[32]。免耕后由于有机质含量上升使土壤结构变化较小,土壤压缩性提高,团聚体稳定性增强,从而削弱外力压实对大团聚体的破坏作用[33]。农机具机械破碎和压实通常会降低土壤总孔隙度,尤其是大孔隙度,而有机质含量较高的土壤能降低容重增加幅度,提高大孔隙占比,改善土壤孔隙连通性[34]。

2.3 土壤微生物

土壤微生物在土壤生物化学循环过程中发挥重要作用,是土壤生态系统重要组成部分。土壤微生物既能通过菌丝和分泌物的黏结作用直接影响土壤结构,也可以通过微生物群落结构及其次级代谢产物和土壤理化性质共同作用影响土壤碳固定,从而间接影响土壤结构稳定性。X射线断层扫描发现,细菌的细胞壁带电荷以及细胞外存在黏性化合物能使黏粒进一步絮凝[35]。在细菌分解植物残体时也产生一些多糖和有机胶体,能促进团聚体团聚,并保持土壤表层团聚体的稳定性。真菌菌丝也能分泌多糖和有机复合物形成黏性网络将独立的土壤颗粒和微团聚体黏结在一起形成大团聚体[36]。对不同耕作措施下的农田生态系统研究表明,真菌能通过促进团聚体稳定性的提高而降低有机质分解速率,进而增加有机碳固存。同时,真菌占优势的微生物群落其固碳能力大于细菌占优势的群落[37]。微生物在土体中的分布和活动还与土壤孔隙大小、连接度和通气性相互作用。一方面大小不同的孔隙为微生物提供独特生存空间和底物供应,另一方面活性微生物可以改变土壤孔隙的几何形状和连通性[38,39]。如与作物根系伴生的丛枝菌根真菌能够生产球囊霉素以增强土壤团聚性,来促进土壤中大孔隙的形成以利于菌丝发育[40]。虽然在不同耕作措施对土壤结构稳定性方面已有了大量的研究,但至今对土壤结构稳定性的生物学机制仍知之甚少。

2.4 土壤食微线虫

土壤食微线虫可以通过取食细菌和真菌影响微生物群落结构,还可以通过其自身周转和与作物根系、微生物互作来参与土壤有机质分解而间接影响土壤结构稳定性[41]。免耕比常规耕作更能提高土壤线虫多度、群落成熟度指数和结构指数[42]。因为长期免耕保持土壤结构相对稳定,减少因土壤侵蚀导致的线虫损失[43]。同时免耕有利于提高植物寄生类线虫丰度,而常规耕作则增加食微生物线虫活性[44]。在秸秆还田后,会先降低植食线虫和食真菌线虫的相对丰度,提高食细菌线虫和杂/捕食线虫相对丰度[45]。因为在秸秆腐解初期,食细菌线虫发挥重要作用,但是随着分解进程,食真菌线虫重要性逐渐增加,这与有机物料还田后细菌和真菌群落变化趋势相一致[46]。土壤微生物和食微动物间的互作显著影响土壤碳循环过程,体现了土壤微生物网的生态功能,今后的研究中可以结合高通量测序和稳定同位素示踪技术来深入揭示不同耕作措施下土壤微食物网对土壤结构的作用机制。

2.5 蚯蚓

蚯蚓能通过取食、分泌黏液、挖掘洞穴、排泄等活动在改变土壤结构上发挥重要作用,生物学家称它们为“土壤工程师”[47]。蚯蚓能消耗和排泄植物的残体,并将其纳入土壤团聚体中,促进大团聚体的形成和稳定。一方面,蚯蚓能分泌大量黏液促进黏砂粒黏结为团聚体,促进微团聚体的形成[48];另一方

面，能影响土壤微生物活性间接作用于团聚体的稳定[49]。常规耕作由于机具切割直接降低土壤中蚯蚓数量，而保护性耕作能降低土壤扰动，有利于增加蚯蚓丰富度[50]。使用医用CT扫描和内窥镜技术观察蚯蚓活动对土壤结构的影响，发现蚯蚓孵化后，大块土壤的生物孔隙度从30%增加到80%，主要是提高直径<0.5 cm的生物孔隙数量[51]。

2.6 作物根系

作物根系通过直接和间接两种方式影响土壤结构，主要表现为根系能提高土壤水稳性团粒、非毛管孔隙的直接作用和增加土壤有机质含量的间接作用[52]。根系通过机械缠绕的直接作用改善土壤结构，根系密度越大，根系稳定土壤结构的作用越强[53]。0.1～0.4 mm直径的根毛对于团聚体的形成除了缠绕和串联作用外，根系网络及根土界面的黏结作用是根系固结土壤的作用机制[54]。作物根系还能稳定表层土壤结构，创造抗冲性强的土体构型来抵御土壤侵蚀[55]。同时，低分子量的根系分泌物在短期内就能提高土壤微生物活性，促进大团聚体形成，增强土壤团聚体稳定性。其中的葡萄糖有利于土壤细菌的生长和驱动微团聚体的形成，而苹果酸和谷氨酸则促进真菌的繁殖和促进微团聚体进一步的胶结[56]。随着作物根系的衰老死亡，其残茬为土壤微生物和动物提供有机底物，经过土壤微食物网循环，促进土壤有机质含量的增加[57]。根系分布及其分泌物对根际土壤微生态环境的作用是影响土壤大团聚体形成的重要因素，解析保护性耕作下根系驱动土壤剖面结构稳定性的机制，为构建合理耕层提供新的理论依据。

2.7 干湿交替和冻融交替

旱地土壤含水量受降雨量和作物根系吸水的调控作用在季节中变化显著，相比于含水量稳定的土壤，频繁的干湿交替过程将加快土壤大团聚体的破碎，使其向小团聚体转变[58]。同时，大团聚体的破碎促进土壤微生物接触被大团聚体包裹的有机质，加速其分解和矿化，降低团聚体稳定性[59]。室内模拟实验发现，干湿交替降低免耕表层土壤微生物多样性，且交替频率越高，干旱强度越大，多样性降低越显著，但对旋耕垄作土壤微生物多样性影响不显著[60]。在冻融交替的过程中，土壤水分在液态和固态之间的转变，对土壤团聚体产生的影响类似干湿交替过程，土体会因为膨胀和收缩作用产生裂缝和挤压，使大团聚体崩碎[61]。冻融交替会增加小团聚体含量，但是随着冻融循环次数增加，团聚体含量变化系数将趋于稳定[62]。CT扫描发现，冻融循环不改变0～40 cm土层大孔隙结构，但能使其粗糙度增加，孔壁断裂，破坏土壤微孔隙结构[63]。

3 结论与展望

国内外研究人员对不同耕作措施如何影响土壤结构稳定性进行大量研究，免耕及其秸秆覆盖还田等保护性耕作措施通过减少土壤扰动，降低土壤大团聚体破坏率，同时增加水稳性大团聚体数量及其稳定性、大孔隙数量和孔隙度，进而提高土壤结构稳定性，但长期应用后土壤结构优势仅表现在表层。在对不同气候区域、土壤类型进行的轮耕研究发现，土壤结构稳定性存在不一致性。土壤铁铝氧化物形态变化、有机质含量、蚯蚓数量、微食物网功能、根系生长、干湿交替、冻融交替等因素均与土壤结构稳定性密切相关，可作为解析不同耕作措施影响土壤结构稳定性机制的重要指标。

(1)各区域因地制宜分别以抗旱增收、控制沙尘暴和农田沙漠化、节水节本、抵御春旱和控制风蚀为主要目标建立保护性耕作技术体系。开展新型保护性耕作技术模式定位监测试验研究，建立长期监测数据库。强化多学科融合，整合有关科研人员，形成农机、栽培、土壤、植保、信息、管理等多学科交叉融合的保护性耕作技术研究团队。加强与企业、地方的合作，加快科研成果转化与应用。

(2)在土壤结构定量化研究中引入新技术新方法。示踪技术广泛应用于解析追踪物质在不同土壤团粒结构中的迁移路径，除环境同位素这一常用示踪剂外，稀土元素示踪方法在阐明土壤团聚体周转过程中也得到发展。此外，计算机断层扫描技术能快速无损的获得土壤孔隙三维结构，可以从团聚体到土体尺度对土壤孔隙结构定量化分析。这些新技术新方法为揭示不同耕作措施对土壤结构的影响及其对作物根系生长、动物活动及冻融交替等环境变化的响应研究提供了契机。

(3)作物根际是土壤生物交互作用的热区，根际效应显著提高土壤团聚体稳定性，促进土壤团聚体固碳。通过解析还田秸秆和根系分泌物中的碳源如何通过微生物能量通道进入土壤微生物网，并被送到较高营养级供给食微动物利用过程，对揭示土壤结构稳定性的生物学机制有重要意义。

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