黑土区宽垄和窄垄耕作的顺坡坡面土壤侵蚀对比

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摘 要：宽垄耕作具有明显的增产效应，但顺坡宽垄耕作的坡面土壤侵蚀研究鲜见报道。该文基于野外大型坡面径流场观测和室内模拟降雨试验，对比分析了中国黑土区顺坡宽垄和窄垄耕作的坡面土壤侵蚀差异。结果表明，野外观测和室内模拟条件下顺坡宽垄坡面侵蚀量较之于顺坡窄垄坡面分别减少64.4%~90.4%和33.2%~57.9%，同时2种垄作方式下坡面侵蚀量与径流量均呈现出良好的线性关系（R^2≥0.81），但顺坡宽垄处理下的坡面侵蚀量随径流量的增加幅度小于顺坡窄垄处理。野外观测结果还表明，2种垄作方式的坡面侵蚀量皆与降雨侵蚀力PI_{30}和径流量呈显著正相关关系，顺坡宽垄较之于顺坡窄垄减少的坡面侵蚀量随着PI_{30}的增大而呈降低趋势，当PI_{30}为430～605时，顺坡宽垄较顺坡窄垄的坡面土壤侵蚀量减少74.8%～90.4%，当PI_{30}为1520～1708时，顺坡宽垄较顺坡窄垄的坡面土壤侵蚀量减少64.4%和66.5%。无论是野外观测还是室内模拟试验均表明，与传统的顺坡窄垄相比，顺坡宽垄具有较好防治坡面土壤侵蚀效果。因此，在东北黑土区推广宽垄耕作对保护黑土资源有重要意义。

关键词：土壤；侵蚀；径流；顺坡宽垄；顺坡窄垄；东北黑土区；野外观测；室内模拟
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0 引 言

垄作是一种非常普遍的耕作方式，具有保土温、提高水分利用效率和作物产量等多方面优势[1-3]。东北黑土区地形多为漫川漫岗地，受农户地块不连续的影响，以横坡垄作为主的保护性耕作措施不能得到很好的应用，进而致使顺坡垄作、斜坡垄作等成为最普遍的耕作方式[4-5]。顺坡垄作通常被认为会加剧坡面水流汇集，而机械犁耕下的垄丘相对较为疏松，土壤抗侵蚀能力较弱，因此在强降雨条件下往往会造成严重的坡面土壤侵蚀[5-6]。

窄垄也称小垄，一般指宽度为30~70 cm的较小规格垄丘，垄上一般仅种植一行作物[7-8]。宽垄也称大垄，是在20世纪90年代引进美国大豆平作密植的基础上，与我国传统垄作模式相结合而形成的[9]。经过多年的发展改进，逐步形成了宽度为90~140 cm的不同规格垄丘，垄上一般种植2~6行作物[8-11]。野外调查发现，在中国东北黑土区，大型农机具耕作的集约化经营农场，宽垄耕作方式已得到大面积推广。王庆杰等[10]认为宽垄耕作方式能够改善土壤结构，增加土壤蓄水保水能力，是东北黑土区一种较理想的保护性耕作技术。汪顺生等[11]研究表明，与常规种植模式相比，宽垄种植模式下小麦水分生产效率最高，产能最优。韩毅强等[8]通过对比宽垄和窄垄2种耕作方式，认为宽垄处理可以有效提高0~20 cm耕层土壤含水量，同时增加光照强度和玉米产量。

近年来，国内外学者对不同垄作方式下坡面土壤侵蚀特征进行了大量研究[5-6, 12-14]，而对宽垄耕作方式的研究大多局限于作物产量、土壤水热变化等[15-18]，针对顺坡宽垄耕作的坡面土壤侵蚀定量研究鲜见报道，而分析宽垄耕作对坡面土壤侵蚀阻控作用将对黑土资源保护和指导农业生产具有重要意义。鉴于此，本文基于野外大型坡面径流场观测数据和室内模拟降雨试验资料，对比分析东北黑土区农耕地顺坡宽垄和窄垄耕作的坡面土壤侵蚀，评价顺坡宽垄耕作的防蚀效应，以期为中国黑土资源保护和减少农耕地水土流失提供科学依据。

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1　材料与方法

1.1　研究区概况

研究区位于黑龙江省克山县城西北粮食沟流域（125°49'48"E，48°3'52″N），属于典型中层黑土区[19]。地形总体趋势为东北高、西南低，从丘陵起伏的山脉向漫川漫岗的平原过渡，平均海拔236.9 m，农田地面坡度大多在1°~7°之间。克山县属寒温带大陆性季风气候，年平均气温2.4 ℃，降雨集中在6—9月份，年平均降水量500 mm，雨热同期。

1.2　试验设计

1.2.1　野外大型自然坡面径流场布设

在克山县粮食沟流域农耕地上建立了长缓坡大型自然坡面径流场2个，其分别为320 m（长）×3 m（宽）顺坡宽垄坡耕地和320 m（长）×2 m（宽）顺坡窄垄坡耕地，二者地形条件完全相似，地面坡度变化于2°~7°。根据当地宽垄和窄垄规格，选取的顺坡宽垄垄高为15 cm，垄间距110 cm，垄丘顶宽70 cm；顺坡窄垄垄高15 cm，垄间距65 cm，垄丘顶宽20 cm（图1）。在每个径流场出口处安装xyz-2型径流泥沙自动收集装置一套，实时监测次降雨下2个大型坡面径流场的径流和侵蚀过程；并安装美国Onset Computer Corporation公司生产的HOBO气象站进行天然降雨过程的观测。

a. 顺坡宽垄　　b. 顺坡窄垄

a. Wide longitudinal ridge tillage　　b. Narrow longitudinal ridge tillage

图1　野外径流场顺坡宽垄和顺坡窄垄坡面照片

Fig.1　Photos of wide and narrow longitudinal ridge tillage runoff plots

1.2.2　室内模拟降雨试验

室内模拟降雨试验在黄土高原土壤侵蚀与旱地农业国家重点实验室人工模拟降雨大厅进行，顺坡宽垄供试土槽规格为8 m（长）×2.2 m（宽）×0.6 m（深），顺坡窄垄供试土槽规格为8 m（长）×1.3 m（宽）×0.6 m（深）。模拟降雨系统选用侧喷式降雨系统，降雨高度18 m，降雨均匀度大于80%。根据东北黑土区侵蚀性降雨特征[20]，造成严重土壤侵蚀的降雨强度变化于23.4~103.2 mm/h，降雨历时介于20~80 min，因此设计模拟降雨强度为50、75和100 mm/h，降雨历时60 min。基于东北黑土区顺坡垄作改为横坡垄作的临界坡度[4]，设计试验坡度为5°。

供试土壤为采集于野外径流场旁边的0~20 cm耕层黑土，其砂粒（> 50 μm）质量分数为10.7%，粉粒（2~50 μm）为48.7%，黏粒（< 2 μm）为40.6%，有机质质量比为37.2 g/kg（重铬酸钾—外加热法）。设计顺坡宽垄和顺坡窄垄（图2）规格与野外坡面径流场一致。模拟降雨试验设计3个降雨强度、2个垄作方式的6个试验处理，每个试验处理设计2个重复，共计试验处理12次。每场次模拟降雨试验结束后，试验土槽重新填土制作顺坡宽垄或顺坡窄垄坡面。

a. 顺坡宽垄　　b. 顺坡窄垄

a. Wide longitudinal ridge tillage　　b. Narrow longitudinal ridge tillage

图2　室内模拟顺坡宽垄和顺坡窄垄坡面照片

Fig.2　Photos of wide and narrow longitudinal ridge tillage of laboratory simulation experiments

1.3　试验步骤和方法

对于野外2个大型自然坡面径流场，坡面径流泥沙自动收集装置为哈尔滨柏亮科技开发有限公司生产的xyz-2型无动力水土流失过程自动监测装置，径流收集为翻斗式。每场次侵蚀性降雨结束后，导出数据采集器中的径流量数据，并收集自动取样瓶中的泥沙，同时重新更换取样瓶，以便下次观测。将采集的径流泥沙样带入室内，量取每个取样瓶中径流泥沙样品质量，然后将采集的径流泥沙样放入105 ℃的烘箱烘干称质量，计算含沙浓度和侵蚀量。

对于室内模拟试验，根据野外测定的犁底层和耕作层的土壤容重分别装填试验土槽。为保持野外采集的耕层土壤的原有结构，对供试土壤采用不过筛、不研磨处理，仅剔除秸秆、根系等杂物，并将大土块按照自然节理分成稍小的土块用于装填土槽[13, 21-23]。土槽底部装填5 cm厚的细沙作为透水层，沙层之上填装15 cm厚，土壤容重为1.3 g/cm^{3}的犁底层和20 cm厚，土壤容重为1.2 g/cm^{3}的耕作层，采用分层填土法，每5 cm为一层，耕作层填土完成后按照垄高15 cm、垄间距为65 cm制作顺坡窄垄，按照垄高15 cm、垄间距110 cm制作顺坡宽垄。试验前一天，用纱网覆盖土槽，用30 mm/h降雨强度进行预降雨至坡面产流为止，之后静置12 h开始正式降雨；径流泥沙观测采用人工定时采集各时段的径流泥沙全样。每场次试验结束后重新装填土槽并修建顺坡宽垄和顺坡窄垄，模拟降雨试验步骤和径流泥沙观测与文献[6]一致。

1.4　数据处理

采用Excel 2013软件进行径流泥沙数据处理和降雨重现期计算，SPSS 23.0软件进行相关性分析，采用Matlab 2013a软件进行三维曲面图制作和方程拟合。

2　结果与分析

2.1　侵蚀性降雨特征

2018年度收集侵蚀性降雨资料5场次，次降雨量均＞20 mm/h，次侵蚀性降雨量变化为22.6~67.8 mm，对应的最大30 min降雨强度（I_{30}）变化于10.8~35.2 mm/h。该

5场次降雨均具有雨量较大，降雨历时较短，I_{30}较大的特征，降雨特征符合东北黑土区侵蚀性降雨标准[24]，具有较强的代表性（表1）。基于克山县1961—2014年日降雨观测资料，采用Pearson-Ⅲ 概率分布推算各次降雨的重现期[25]，得出P1场次降雨为三年一遇的侵蚀性强降雨，P2~P5均为一年一遇降雨。

表1 2018年次侵蚀性降雨特征

Table 1 Erosive rainfall characteristics in 2018

次降雨编号 Rainfall number	降雨量 Rainfall /mm	降雨历时 Rainfall duration /min	平均雨强 Average rainfall intensity /(mm·h^{-1})	I_{30} /(mm·h^{-1})	PI_{30}
P1	67.8	1954	2.1	25.2	1708.6
P2	42.8	975	2.6	10.8	462.2
P3	43.2	635	4.1	35.2	1520.6
P4	22.6	960	1.4	19.2	433.9
P5	24.4	225	6.5	24.8	605.1

Note: I_{30}, maximum 30min rainfall intensity; PI_{30}, rainfall erosivity.

2.2 顺坡宽垄和顺坡窄垄耕作的次降雨坡面径流侵蚀对比

表2表明，5场次侵蚀降雨下顺坡宽垄径流量和侵蚀量分别介于1.1~13.2 mm和3.0~188.3 t/km^2，顺坡窄垄坡面径流量和侵蚀量分别介于3.4~30.6 mm和25.4~562.6 t/km^2。顺坡窄垄坡面径流量和侵蚀量分别是顺坡宽垄坡面径流量和侵蚀量的2.1~3.3倍和2.8~10.4倍。此结果表明，在相同降雨条件下，顺坡宽垄耕作较之顺坡窄垄可减少坡面径流量和侵蚀量分别为51.3%~70.0%和64.4%~90.4%，其减少幅度受降雨特征的影响。当PI_{30}为430~605时和1520~1708时，顺坡宽垄较窄垄的坡面土壤侵蚀量分别减少74.8%~90.4%和64.4%~66.5%。通过对比2个垄作方式的坡面径流系数，发现顺坡窄垄坡面在5场次侵蚀性降雨下的径流系数均大于顺坡宽垄坡面，其原因可能是单位面积顺坡窄垄坡面拥有比顺坡宽垄坡面多的垄沟，每条垄沟都成为一个小型集水区，这些集水区促使了坡面径流的汇集。此外，由于宽垄垄丘平面面积较大且垄丘与垄沟间的横向比降小，因此垄丘向垄沟方向的径流汇集速率小于窄垄，雨水在垄丘上的滞留时间相对较长，从而导致降水入渗率大于窄垄坡面。特别是P1和P3的2场次降雨下，顺坡窄垄坡面的径流系数分别达到45.1%和53.7%；造成径流系数较大的原因主要是该2场次降雨的I_{30}均较大，分别为25.2和35.2 mm/h，短历时高强度降雨降低了入渗作用，尤其是顺坡窄垄坡面多条垄沟的汇水作用也加快了地表径流过程。2个垄作坡面的平均含沙浓度变化特征与径流量、径流系数和侵蚀量变化趋势一致，顺坡宽垄坡面的平均含沙浓度为顺坡窄垄坡面的0.5倍。对于该5场次侵蚀性降雨，顺坡宽垄和顺坡窄垄的坡面累积径流量分别为28.3和65.8 mm，二者相对应的坡面累积侵蚀量分别为364.1和1100.5 t/km^2，说明顺坡宽垄耕作较之顺坡窄垄分别减少56.8%坡面径流量和66.9%坡面侵蚀量。

表2 顺坡宽垄和顺坡窄垄耕作的坡面径流量、径流系数、侵蚀量和含沙浓度对比

Table 2 Comparisons of runoff, runoff coefficient, soil loss and sediment concentration under wide and narrow longitudinal ridge tillage

降雨场次 Rainfall events	径流量 Runoff /mm		径流系数 Runoff coefficient /%		侵蚀量 Soil loss /(t·km^{-2})		含沙浓度 Sediment concentration /(kg·m^{-3})	
	顺坡宽垄 Wide longitudinal ridge tillage	顺坡窄垄 Narrow longitudinal ridge tillage	顺坡宽垄 Wide longitudinal ridge tillage	顺坡窄垄 Narrow longitudinal ridge tillage	顺坡宽垄 Wide longitudinal ridge tillage	顺坡窄垄 Narrow longitudinal ridge tillage	顺坡宽垄 Wide longitudinal ridge tillage	顺坡窄垄 Narrow longitudinal ridge tillage
P1	13.2	30.6	19.4	45.1	188.3	562.6	4.3	18.4
P2	1.5	5.0	3.6	11.8	3.0	31.2	2.0	6.2
P3	11.3	23.2	26.2	53.7	156.7	440.6	13.8	19.0
P4	1.1	3.4	5.0	15.0	6.4	25.4	5.6	7.5
P5	1.2	3.6	5.0	14.6	9.7	40.7	8.0	11.5

2.3 顺坡宽垄和顺坡窄垄坡面侵蚀量与径流量和PI_{30}的关系

降雨侵蚀力因子是影响坡面土壤侵蚀速率的重要指标[26]，有研究表明EI_{30}与PI_{30} (P指次雨量)之间高度线性相关，在降雨能量E不易获得的情况下，PI_{30}可以代替EI_{30}来表征降雨侵蚀力因子[27-28]。为此，这里分析了PI_{30}对2种耕作方式下坡面径流量和侵蚀量的影响，结果表明2种垄作坡面侵蚀量与径流量和PI_{30}均呈显著或极显著正相关（表3）。进一步分析表明，2种垄作坡面侵蚀量与径流量均呈极显著正相关，这与前人在不同地区的研究结果相似[29-30]。

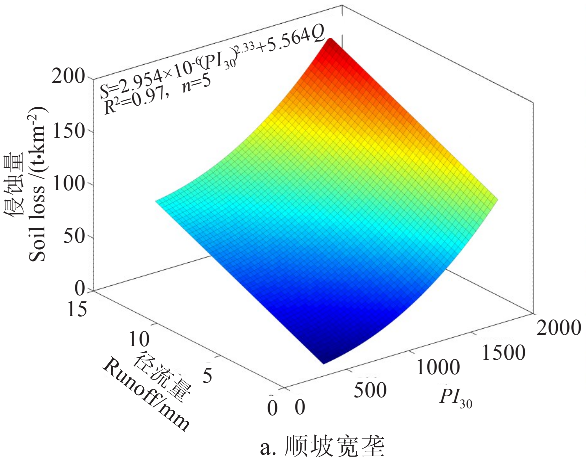
表3 顺坡宽垄和顺坡窄垄耕作的侵蚀量与径流量和PI_{30}的相关关系

Table 3 Correlations among soil loss, runoff and PI_{30} under wide and narrow longitudinal ridge tillage

	顺坡宽垄 Wide longitudinal ridge tillage			顺坡窄垄 Narrow longitudinal ridge tillage		
	径流量 Runoff	侵蚀量 Soil loss	PI_{30}	径流量 Runoff	侵蚀量 Soil loss	PI_{30}
径流量 Runoff	1	0.998**	0.948*	1	0.998**	0.987**
侵蚀量 Soil loss	0.998**	1	0.955*	0.998**	1	0.995**
PI_{30}	0.948*	0.955*	1	0.987**	0.995**	1

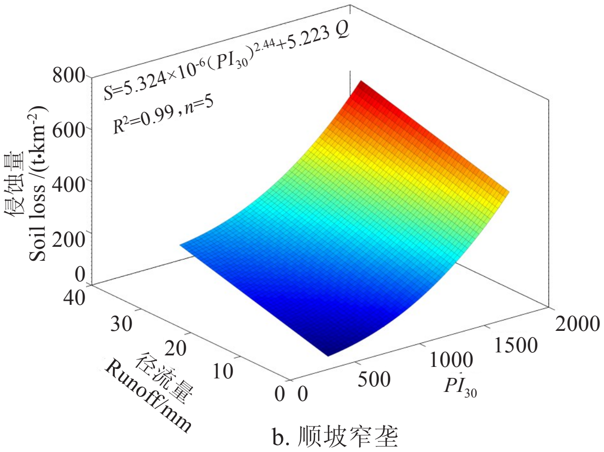
注/Note：* P<0.05，n=5；** P<0.01，n=5。

通过Matlab 2013a软件进一步分析侵蚀量与PI_{30}和径流量的关系，发现2种垄作坡面侵蚀量皆随着径流量和PI_{30}的增加而增大，但增加幅度有所差异，其中顺坡窄垄坡面的侵蚀量随径流量和PI_{30}的增加幅度明显大于顺坡宽垄坡面。顺坡宽垄和顺坡窄垄坡面侵蚀量与PI_{30}呈幂函数关系，而坡面侵蚀量与径流量呈线性关系（图3）。



a. 顺坡宽垄

a. Wide longitudinal ridge tillage



b. 顺坡窄垄

b. Narrow longitudinal ridge tillage

注：方程中S为侵蚀量，t/km^2；Q为径流量，mm。

Note: In fitting equation, S is soil loss, t·km^{-2}; Q is runoff, mm.

图3 顺坡宽垄和顺坡窄垄坡面侵蚀量与径流量和PI_{30}的关系

Fig.3 Relationship between soil loss, runoff and PI_{30} under wide and narrow longitudinal ridge tillage

3 讨 论

顺坡垄作通过改变地表形态和汇流过程进而影响坡面土壤侵蚀，垄沟可以加速坡面水流的汇集，进而加剧坡面土壤侵蚀。东北黑土区较为普遍的顺坡窄垄耕作方式，一方面导致单位面积垄沟条数较多，而每一条垄沟均为一个小型集水区，为径流的汇集提供了更多的路径；另一方面，垄丘与垄沟之间的坡度相对较大（30°~60°），加之垄丘土壤容重较小（1.0~1.2 g/cm^3），垄沟两侧的垄丘边坡为径流提供了丰富的泥沙来源。与顺坡窄垄相比，顺坡宽垄耕作的单位面积垄沟条数减少，垄丘顶部平坦，垄丘与垄沟之间的横向比降小于顺坡窄垄（图1和图2），削弱了侧方汇水能量，使坡面径流量和侵蚀量均有所减小。降雨雨型决定PI_{30}的大小，野外观测条件下大多数降雨类型为长历时、低强度的中小型降雨，造成的坡面土壤侵蚀也相对较小，罕见降雨量和降雨强度均较大的短历时高强度暴雨，而较严重的土壤侵蚀多发生在这种极端降雨条件下[20]。顺坡宽垄和窄垄耕作的坡面侵蚀量与径流量、PI_{30}分别呈现出线性关系和幂函数关系，这是由于在PI_{30}较小时，即降雨量或降雨强度较小，在野外长缓坡农地，坡面径流能量小，所造成的土壤侵蚀较弱；而当PI_{30}较大时，如短历时高强度的暴雨，坡面径流瞬时能量大，所造成的坡面土壤侵蚀急剧增加，这与前人的研究结果类似[31-33]。

室内模拟试验可进一步解释顺坡宽垄和窄垄耕作对坡面径流侵蚀的影响（表4）。在50、75和100 mm/h的3种降雨强度下，2种垄作模式的坡面土壤侵蚀变化与野外观测结果相似，即顺坡宽垄坡面的侵蚀量明显小于顺坡窄垄，前者坡面侵蚀量较后者坡面侵蚀量减少了33.2%~57.9%。而在3个降雨强度下，顺坡宽垄和窄垄坡面径流变化规律与野外观测结果有差异，其中在50 mm/h降雨强度下，顺坡宽垄坡面的径流量较之顺坡窄垄减少了14.8%，在75 mm/h降雨强度下，二者的径流量基本相同，在100 mm/h降雨强度下，顺坡宽垄坡面的径流量较之顺坡窄垄增加了26.8%。其原因是正式模拟降雨试验前进行的前期降雨所造成的，即正式试验前一天，用30 mm/h降雨强度进行预降雨至坡面产流为止，导致土壤水分基本处于饱和状态。而野外坡面由于前期降雨以及汇流面积和地表糙度等因素的影响，导致其与室内模拟降雨试验的结果有所差异。

表4 室内模拟试验的顺坡宽垄和顺坡窄垄坡面径流量与侵蚀量

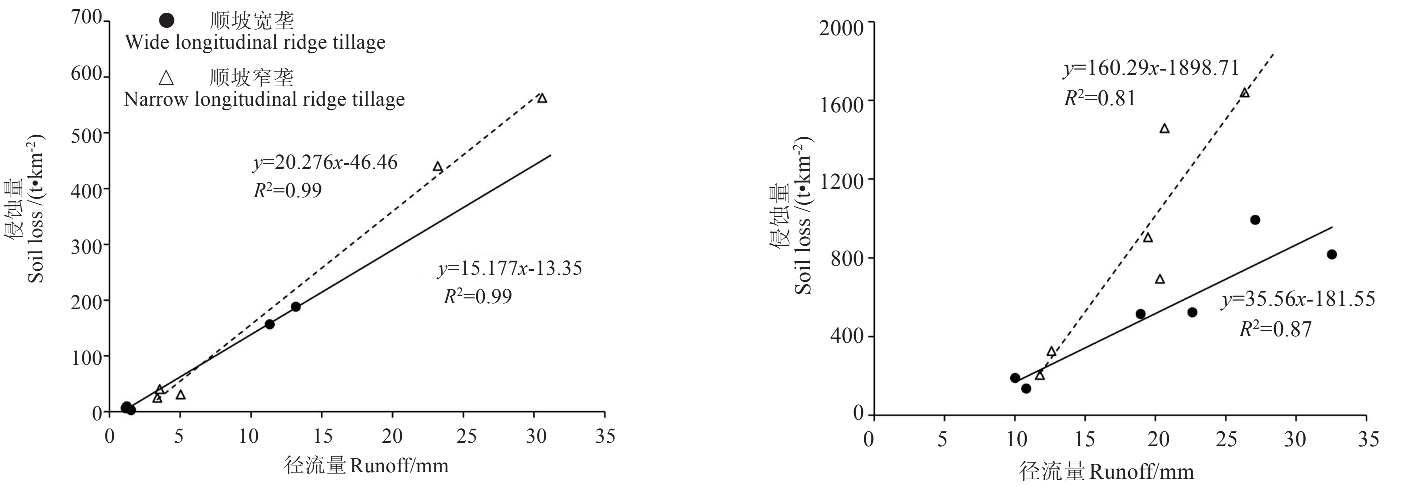
Table 4 Runoff and soil loss of wide and narrow longitudinal ridge tillage in laboratory simulation experiments

降雨强度 Rainfall intensity /(mm·h^{-1})	径流量 Runoff /mm		侵蚀量 Soil loss /(t·km^{-2})	
	顺坡宽垄 Wide longitudinal ridge tillage	顺坡窄垄 Narrow longitudinal ridge tillage	顺坡宽垄 Wide longitudinal ridge tillage	顺坡窄垄 Narrow longitudinal ridge tillage
50	10.4±0.6	12.2±0.6	162.4±37.8	265.7±36.3
75	20.1±1.6	19.9±0.6	534.1±43.0	799.7±49.1
100	29.8±3.9	23.5±4.0	905.8±43.9	2151.6±77.3

注：表中数据为平均值±标准差。Note: Data in the table are mean value ± standard deviation.

图4表明，基于野外坡面径流场观测和室内模拟降雨试验的2种垄作坡面侵蚀量与径流量均呈现出良好的线性关系（R^2＞0.81），通过对该线性方程进行趋势预测，可以看出基于野外观测的顺坡宽垄坡面侵蚀量随径流量的增加幅度小于顺坡窄垄坡面，这与室内模拟试验的结果一致。室内模拟试验和野外径流场观测结果均表明宽垄耕作较之窄垄耕作可减少坡面土壤侵蚀，具有较好的防蚀效应。

大多数研究结果均表明宽垄耕作可以有效提高单位面积作物产量，主要表现为种植密度的增加[7]，东北黑土区的研究也表明大垄（宽垄）双行耕作方式比传统窄垄耕作玉米产量提高了6.70%~9.49%[10]。目前，宽垄耕作方式在大型集约化农场应用比较广泛，而尚未普及到个体农户，原因可能是农户缺少大型机械，现有农机具较小且适用于传统



a. 野外观测
a. Field observation

b. 室内模拟
b. Laboratory simulation

图4 野外观测和室内模拟条件下顺坡宽垄和顺坡窄垄坡面侵蚀量与径流量的关系

Fig.4 Relationship between runoff and soil loss of wide and narrow longitudinal ridge tillage under field observation and laboratory simulation

窄垄耕作方式，窄垄耕作普适性较高。因此，今后在个体农户中普及宽垄耕作方式可望在提高单位面积产量的同时，也有效减少坡面土壤侵蚀，有利于黑土资源的保护。

4 结 论

1）野外大型自然坡面径流场观测条件下，顺坡宽垄相较于顺坡窄垄可以有效减少坡面径流量和侵蚀量。与顺坡窄垄坡面相比，顺坡宽垄坡面径流量和侵蚀量分别减少51.3%~70.0%和64.4%~90.4%。同样，在室内模拟降雨条件下，在50、75和100 mm/h的3种降雨强度下，顺坡宽垄较之顺坡窄垄的坡面侵蚀量减少33.2%~57.9%。

2）野外次降雨条件下顺坡宽垄和窄垄坡面侵蚀量与径流量和降雨侵蚀力PI_{30}皆呈显著正相关关系，2种垄作方式下坡面侵蚀量皆随PI_{30}的增大呈幂函数增加，但顺坡窄垄坡面侵蚀量的增大幅度大于顺坡宽垄坡面，顺坡宽垄较之于顺坡窄垄减少坡面侵蚀量的比例随PI_{30}的增大而呈降低趋势。与顺坡窄垄相比，当PI_{30}为430~605时，顺坡宽垄坡面侵蚀量减少74.8%~90.4%，当PI_{30}为1520~1708时，顺坡宽垄坡面侵蚀量减少64.4%和66.5%。

3）顺坡宽垄耕作可以减少单位面积垄沟的数量和径流汇集路径，进而减少坡面径流量。野外大型自然坡面径流场观测和室内人工模拟降雨试验结果均表明顺坡宽垄相较于传统窄垄耕作具有较好的防蚀效果，是一种值得推广的耕作模式。

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Comparison of soil erosion between wide and narrow longitudinal ridge tillage in black soil region

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Abstract: Wide longitudinal ridge tillage has significant effects for increasing crop yield. Field observation shows that in the black soil region of Northeast China, wide longitudinal ridge tillage has been widely promoted in the intensive farms on which large agricultural machines are used. However, hillslope soil erosion of wide longitudinal ridge tillage is seldom studied. Therefore, in typical black soil region, in this study, two large natural runoff plots with gentle slope gradient were established in Liangshigou watershed in Keshan County, Heilongjiang Province. One was wide longitudinal ridge tillage with 320 m slope length and 3-m slope width and another was narrow longitudinal ridge tillage with 320 m slope length and 2 m slope width. Ridges were established on a field of silty clay loam (USDA classification). The slope gradients ranged from 2°-7°. According to literature review and field measurements of the wide and narrow ridges in black soil region of Northeast China, the used wide ridges were 15-cm high, 110-cm wide; the used narrow ridges were 15-cm high, 65 cm wide. A laboratory simulated rainfall experiment was conducted in the simulated rainfall hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling City, China. The soil used in the laboratory simulated rainfall experiment was collected in the natural runoff plot. According to the standard of erosive rainfall in Northeast black soil region of China, the simulated rainfall intensities were 50, 75 and 100 mm/h. Each rainfall experiment lasted 60 min. The wide and narrow ridges used in the simulated experiments were consistent with the large natural runoff plot in Keshan County. Based on the runoff plot observation and laboratory simulated rainfall experiments, the differences of hillslope soil erosion between wide and narrow longitudinal ridge tillage in black soil region of China were analyzed. The results showed that under both field runoff observation and laboratory simulation, hillslope soil losses from the wide longitudinal ridge tillage hillslope were 64.4% - 90.4% and 33.2% - 57.9% lower than that from the narrow longitudinal ridge tillage. Field observation indicated that there were significant or strong significant positive correlations among the soil loss, runoff and PI_{30}. The increment of soil loss with runoff and PI_{30} in narrow ridge-tillage system was larger (P< 0.05) than that in wide ridge-tillage system. The relationship between soil loss and PI_{30} was power function, while the relationship between soil loss and runoff was linear function (R^2>0.99). Indoor simulated experiments showed that there were linear relationships between soil loss and runoff under two longitudinal ridge tillage systems (R^2≥0.81). The increment of soil loss from the wide longitudinal ridge tillage system was lower (P< 0.05) than that from the narrow longitudinal ridge tillage system. Compared with the narrow longitudinal ridge tillage, the reduction of soil loss by wide longitudinal ridge tillage decreased with the increase of PI_{30}; when PI_{30} was 433.9 - 605.1, the reduction of soil loss by the wide longitudinal ridge tillage was 74.8%-90.4% and when PI_{30} were 1520.6 and 1708.6, the reduction of soil loss by the wide longitudinal ridge tillage was 64.4%-66.5%. Both field observation and simulated experiments displayed that the wide longitudinal ridge tillage had better effects on controlling hillslope soil erosion, compared with the traditional narrow ridge tillage. Therefore, promotion of wide ridge tillage system might have great significance in protecting Mollisol resources in the black soil region of Northeast China.

Keywords: soils; erosion; runoff; wide longitudinal ridge tillage; narrow longitudinal ridge tillage; black soil region; field observation; laboratory simulation