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我国保护性耕作对农田温室气体排放影响研究进展

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摘　要:农业生产过程是大气温室气体(Greenhouse gas,GHG)一个重要的排放源。20世纪30年代以来,为了防止土壤侵蚀和沙尘暴,许多国家和地区发展并推广了保护性耕作(简称保耕)。近年来,越来越多的研究开始关注保耕对土壤GHG排放和固碳的影响。本文综述了我国近期发表的文章,重点分析了我国保耕措施对农田GHG(CO_2、CH_4、N_2O)排放、固碳以及综合全球增温潜势的影响。结果表明:保耕措施中秸秆还田能促进土壤呼吸,如果将秸秆制成生物炭则对CO_2排放影响很小,免耕能减少土壤呼吸;水稻田秸秆还田促进了CH_4的排放,提高程度从10%~400%,并随着还田量和年限增加而增加,大部分研究也表明水稻田采用免耕降低了CH_4排放;秸秆还田和免耕对土壤N_2O排放具有复杂影响,与还田的秸秆量及其碳氮比、还田方式、气候条件和土壤环境等有关;秸秆还田提高了土壤有机碳含量,而免耕更多是改变了有机碳分布,使更多有机碳聚集于土壤表层;分析评价全球增温潜势时,如果考虑固碳作用,保耕措施将能减少GHG排放甚至使农田转变成碳汇。因此,保耕对全球增温潜势的影响评估应该考虑土壤固碳作用,推广保耕整套技术体系应因地制宜,同时与其他推荐措施相结合,从而实现生态效益和经济效益的双赢。

关键词:二氧化碳;土壤固碳;甲烷;秸秆还田;免耕;全球增温潜势;氧化亚氮

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Impacts of conservation tillage on greenhouse gas emissions from cropland in China: A review

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Abstract: Crop production is one important source of greenhouse gas (GHG) in the world. Conservation tillage (CT), as effective practices to prevent soil erosion and dust storm, recently has been paid attention because of its contribution to soil GHG emission and carbon sequestration (SCS). We reviewed some newly published paper reporting the impacts of CT on emissions of CO_2, CH_4, N_2O, SCS and their global warming potential (GWP) in China. The results showed: straw retention increased CO_2 emission but the application of biochar made from straw did not. No-till generally decreased soil respiration. CH_4 emission was increased by 10%~400% when straw returned in rice paddies, and become more when both the amount of straw returned increased and the period of straw retention lasted. Straw retention and no-till had complex effects on N_2O emission depending on the amounts and C/N ratio of straw returned, retention types, climate and soil properties. Straw retention increased SCS, while no-till altered the vertical distribution of soil organic carbon and concentrated more carbon in the upper layer of soil. CT decreased net GHG emission and even converted some arable fields from carbon pool to sink if SCS was taken into account in GWP calculation. So the extension of CT is important for mitigation GHG emission from cropland.

Keywords: carbon dioxide emission; soil carbon sequestration; methane emission; straw retention; no-till; global warming potential; nitrous oxide emission

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大气中温室气体(Greenhouse gas,GHG)含量的增加是引起全球变暖的重要原因。从1750—2010年大气中二氧化碳(CO_2)、甲烷(CH_4)和氧化亚氮(N_2O)含量分别增加了40%、150%和20%[1],特别是CO_2浓度从277 μL·L^{-1}增长到407 μL·L^{-1}[2]。2010年全球农业贡献了14%的GHG净排放[1]。农作物生产措施会直接或间接影响GHG排放:翻耕、秸秆焚烧、氮肥使用、水稻生产等直接促进土壤GHG排放,机械化措施和化肥、农药的生产都依赖于化石能源使用从而间接排放GHG[3]。因此,采取适宜的农业固碳减排措施,对温室气体减排具有重要意义。

保护性耕作(简称保耕)是世界农业生产中一项重要的推荐措施。为了防止发生像"黑风暴"和水土流失等严重的环境危害,20世纪30年代保耕技术在美国发展起来,并逐渐得到世界许多国家和地区的认同和推广[4]。20世纪90年代我国开始发展机械化免耕技术,2002年原农业部正式将保耕定义为"对农田实行免耕、少耕、并用作物秸秆覆盖地表,以减少风蚀,提高土壤肥力和抗旱能力的先进农业耕作技术",并从国家层面上进行推广[5]。2015年原农业部等部委发布了《全国农业可持续发展规划(2015—2030年)》,继续将保耕作为增加土壤有机质和提升肥力的重要措施。2017年我国保耕面积达到758.4万hm^2,机械化秸秆还田面积、免耕面积和深松面积分别为5 003.3万、1 411.6万hm^{2}和1 112.1万hm^2[6]。这些措施逐渐发展成系统性的保耕,发挥着防止水土流失、培肥地力、固碳减排和减少生产成本的功能。

我国保耕技术因各地不同气候及种植模式表现出差异。我国农作物生产具有熟制多样性、耕地规模小和南方机械化程度低以及秸秆竞争利用等特点,这决定了保耕模式的多样化和类型复杂化[5]。但保耕也具有一些共性的关键技术:(1)少免耕;(2)秸秆还田;(3)杂草及病虫害防治;(4)机械深松[7]。秸秆还田和少免耕是保耕的基本原则,因此我国研究格外关注它们对生态效益的影响[8-9]。我国与保耕相关的研究从2002年开始逐渐增多,内容从传统研究保耕对作物产量、土壤肥力、经济效益等的影响,发展到目前研究保耕对土壤有机碳(Soil organic carbon,SOC)和GHG等的影响[10]。虽然有些综述[11-13]或Meta分析[14-15]讨论了保耕对GHG排放或者土壤固碳(Soil carbon sequestration,SCS)的影响,但当前缺乏对这些影响进行综合分析的综述文章。因此本文选取近期文章,分析了我国保耕对农田GHG(CO_2、CH_4、N_2O)排放和固碳作用的影响,并获取或计算了土壤全球增温潜势(Global warming potential,GWP):$GWP_{soil}=GWP_{N_2O}+GWP_{CH_4}-SCS$。据此本文阐明了:(1)保耕措施对不同土壤GHG排放和SCS的影响;(2)不同地区和作物的保耕措施对土壤GWP影响的差异,以期为国家推广适宜不同作物和环境条件的保耕措施提供建议,从而提升土壤有机质和肥力,推进秸秆全量化利用和固碳减排,同时为科学全面地评价保耕技术和未来的保耕研究提供参考。

1 保护性耕作对GHG排放的影响

保耕主要包括秸秆还田和少免耕等措施,这些措施改变了土壤物理、化学和SOC等性质,这些性质特别是SOC进一步影响了微生物的分解、厌氧发酵、硝化和反硝化等有关GHG排放和固碳过程(图1)[16]。

1.1 CO_2排放

秸秆还田腐解后能有效增加土壤孔隙度,并且能提高SOC含量,因此促进了土壤呼吸和CO_2排放[17]。一些研究发现,对于东北地区单季玉米[18]、华北冬小麦-夏玉米[19]、华南地区水稻-小麦轮作[20]等,秸秆还田提高了7%~45%的CO_2排放量(表1)。随着还田量的增加,CO_2排放量也逐渐增加[21-23]。一些研究发现西北干旱地区和内蒙古秸秆还田降低了6%~20%的CO_2排放量[24-27],原因可能是:(1)秸秆覆盖降低了土壤温度;(2)秸秆覆盖阻碍了CO_2从土壤向大气排放;(3)秸秆覆盖与土壤接触面小导致分解速率低[28]。通常秸秆还田能促进土壤CO_2排放,但是夏文斌等[29]研究发现秸秆制成的生物炭对土壤呼吸影响很小。

河北[40]、陕西[65]和湖北[23]的研究发现免耕约减少40%的CO_2排放(表1)。免耕减少土壤呼吸,是因为免耕使作物残渣覆盖在地表,减少与土壤接触和分解,同时避免耕作破坏团聚体结构[66-67]。保耕过程中免耕减排和秸秆还田促进作用部分抵消,使保耕整体减少了CO_2排放[25,37],同时免耕使秸秆分解速率低于翻入土壤的秸秆分解速率[66]。

1.2 CH_4排放

土壤CH_4排放涉及厌氧环境下的产甲烷菌和甲烷氧化菌参与的一系列反应[68]。土壤CH_4排放主要来源于水稻田。旱田特别是西北干旱地区土壤能够吸收CH_4,表现出弱汇的作用(表1)[24-25]。南方水旱轮作情况下,处于旱作的农田呈现弱源或弱汇的态势[20,46,69-70]。由于水分是微生物分解SOC的限制因素,保耕对这两种条件下CH_4吸收影响比较小[25,32,42]。

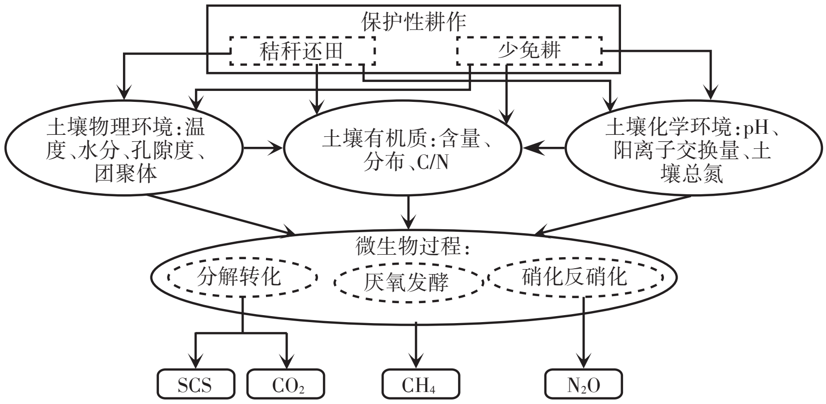

图1 保护性耕作对土壤温室气体排放和固碳的影响

Figure 1 Impacts of conservation tillage on soil greenhouse gas emission and carbon sequestration(SCS)

表1 我国保护性耕作对土壤温室气体排放的影响

Table 1 Impacts of conservation tillage(CT) on soil greenhouse gas emission

种植制度 Cropping systems	地区 Location	保耕措施 CT practices	CO_2/kg $CO_2\cdot hm^{-2}\cdot a^{-1}$	CH_4/kg $CH_4\cdot hm^{-2}\cdot a^{-1}$	N_2O/kg $N_2O\cdot hm^{-2}\cdot a^{-1}$	参考文献 References
水稻	东北地区	秸秆还田-CK		156~170	0.055~0.083	[30]
		秸秆还田-SR		308~374	0.104~0.122	
玉米	东北地区	秸秆还田-CK	9876~13 754	−1.360~0.264	1.419~5.750	[18,31−32]
		秸秆还田-SR	11 051~14 719	−0.810~0.172	2.503~5.510	
小麦-玉米	华北、西北地区	秸秆还田-CK	1137~33 419	−1.525~0.330	1.069~6.000	[19,21,29,33−43]
		秸秆还田-SR	1069~36 201	−0.895~−0.013	0.100~5.200	
		免耕-CK	1137~11 230	−1.10~0.33	0.32~6.00	
		免耕-NT	615~6900	−0.9~−0.2	0.05~6.00	
		保耕-CK	27 250	−2.04~−1.10	3.6~6.0	
		保耕-CT	26 978	−3.36~−0.60	3.24~8.90	
水稻-小麦	华南地区	秸秆还田-CK	5487~12 869	55~662	2.01~3.94	[9,43−53]
		秸秆还田-SR	6147~16 070	149~1200	1.41~7.18	
		免耕-CK		215~415	3.74~6.19	
		免耕-NT		215~394	3.00~8.82	
		保耕-CK		109~415	3.74~6.19	
		保耕-CT		314~522	3.25~5.40	
水稻-油菜	华南地区	秸秆还田-CK	9658	432		[23,54−56]
		秸秆还田-SR	14 063	314		
		免耕-CK	7857~14 049	312~627	0.85~457.00	
		免耕-NT	8239~8600	278~564	0.94~463.00	
早稻-晚稻	华南地区	秸秆还田-CK		202~401	0.568~2.800	[8,57−63]
		秸秆还田-SR		247~461	0.523~2.350	
		免耕-CK		188.71~755.00	−0.03~1.14	
		免耕-NT		170~693	0.181~1.600	
		保耕-CK		201~401	1.14~2.80	
		保耕-CT		368~407	1.84~2.75	
早稻-晚稻-紫云英	华南地区	免耕-CK		234	6.29	[64]
		免耕-NT		404	7.57	

注:有些数值只有一项研究且没有给出标准差,因此不是范围值。下同。

Note:Some values without a range due to only one study and no standard deviation. The same below.

保耕技术对CH_4的影响研究主要集中于厌氧环境的稻田。秸秆还田可以促进CH_4的排放,提高程度从10%~400%[45,71](表1)。随着还田量增加[51]或还田年限[47]延长,CH_4的排放量也会增加。CH_4排放增加是因为秸秆为产甲烷菌提供了丰富底物,同时分解过程消耗氧气又增强了厌氧环境,抑制了甲烷氧化菌的活性[72]。有的研究发现秸秆还田降低了CH_4排放[57,73],这可能是因为还田秸秆富集于土壤表层而进

行有氧分解产生CO_2[72]。与秸秆还田相比,使用秸秆来源的生物炭对CH_4排放影响较小,可能是由于来源于秸秆的生物炭不易被产甲烷菌分解利用。大部分研究表明少免耕降低了CH_4排放[56-57],是因为免耕阻止了土壤CH_4扩散,增强甲烷氧化菌活性,导致CH_4排放减少[74]。Zhao等[15]进行Meta分析表明,与翻耕相比,免耕条件下的稻田CH_4排放减少了30%。也有研究表明免耕促进了CH_4产生[63-64,75],原因可能是免耕可以更好地维持缺氧环境而产生更多的CH_4[64]。

1.3 N_2O排放

土壤N_2O排放主要来源于微生物参与的土壤硝化和反硝化过程[76]。国内学者针对秸秆还田对农田N_2O排放的影响及机理仍然缺乏一致结论。在旱地中,辽宁沈阳玉米种植实验[32]、河北栾城的冬小麦-夏玉米种植实验[37]都表明多年秸秆还田一般促进了N_2O的排放,原因是C/N低的秸秆还田促进微生物的硝化、反硝化作用[74]。也有一些研究发现秸秆还田抑制了N_2O排放,可以减少1%~49%[20,61](表1),原因是秸秆C/N较高而宜于微生物分解利用,减少了硝化与反硝化作用的基质,减少了N_2O排放[77]。Shan等[78]利用Meta分析了秸秆还田对N_2O排放的影响,得出了秸秆还田不会显著影响N_2O排放的结论。不同的秸秆还田量和还田方式、秸秆C/N等都会对N_2O排放产生不同的影响[72]。

免耕对于N_2O排放的影响同样表现出促进[41,57,79]或抑制作用[9,25,50](表1),这与气候类型和土壤性质的差异有关。在干燥的气候条件下,免耕增加通气条件差的土壤N_2O排放,对通气好的土壤影响不大,湿润条件下土壤结论也不一致[74]。Zhao等[15]通过对我国39个研究进行Meta分析,表明稻田中还田结合免耕显著增加了82%的N_2O排放。由于秸秆还田和免耕对N_2O排放影响的复杂性,故不同研究发现保耕对N_2O排放具有促进作用[9,79]和抑制作用[37,49],因此仍需要进一步研究。

2 保护性耕作对SCS的影响

IPCC认为89%的农业GHG减排潜力在于提高SCS水平[80]。Jiang等[32]在辽宁单季玉米种植过程中,对照SOC以0.02 t C·hm^{-2}·a^{-1}速率减少,而以4000、8000 kg干秸秆·hm^{-2}还田处理的SOC含量分别以0.48、1.03 t C·hm^{-2}·a^{-1}速率增加(表2)。近期研究表明,秸秆还田的SCS提高了50%~2240%[51,62]。Xu等[81]分析了自第二次国土普查数据到2010年文献数据,发现近30年来我国农田表土SOC增加了0.07±0.31 Pg C(固碳速率为0.013±0.003 Pg C·a^{-1}),主要原因是秸秆还田等措施。Zhao等[14]利用Meta分析了2013年前的76篇文献,发现秸秆还田相比不还田能增加12%的SOC含量,如果全国进一步推广,SOC将每年增加0.052 Pg C。秸秆还田增加SOC含量是因为投入的新鲜有机质被微生物分解转化,形成了难分解的SOC贮存,同时促进了团聚体对SOC的保护作用[82]。

一些免耕研究表明其能增加SOC含量[55,64](表2),但是不同研究对于免耕的固碳作用存在争议。Baker等[83]通过研究农田深度30 cm土壤发现免耕不会增加SOC,只使更多SOC聚集于土壤表层。Luo等[84]采用Meta方法分析了69对取样深于40 cm的免耕/翻耕实验,结果表明两者SOC变化没有显著差异,从翻耕改成免耕除了双季制能增加SOC含量外,其他种植制度只是改变了SOC分布。虽然单纯免耕不能增加SOC含量,但能避免对团聚体的破坏而保护SOC,同时减少了燃料消耗而产生的GHG排放[3]。因此,综合考虑,免耕在结合调整种植制度等措施的情况下能够发挥固碳减排作用。

3 保护性耕作对土壤GWP的影响

在不考虑SCS的情况下,秸秆还田条件下土壤GWP一般比对照高9%~45%(表2),原因是促进了CH_4的排放[18,47]。一些研究将SCS纳入GWP的计算,发现土壤呈现碳汇状况(表2),如Jiang等[32]研究表明一年一季玉米不还田土壤GWP为492 kg CO_2-eq·hm^{-2}·a^{-1},而秸秆还田GWP为-3040 kg CO_2-eq·hm^{-2}·a^{-1}。李栢锦等[35]发现不还田对照和还田处理的土壤GWP都为负值,分别为-526、-1294 kg CO_2-eq·hm^{-2}。有的研究进一步考虑了作物固碳作用[19,38],但Piao等[86]认为每季作物都会收获并通过食物网重新释放CO_2到大气,因此生物量增长并不会对碳储存做出实际贡献。

4 讨论

我国保耕对土壤GHG排放和SCS影响的研究存在不一致甚至相互矛盾的结果,原因是保耕同时改变了土壤物理、化学和生物等性质[16],这些改变结合我国差异较大的气候和土壤性质导致了不同的研究结果。

保耕对稻田CH_4和N_2O的排放有着复杂的影响。有Meta分析表明我国稻田采用免耕显著降低了30%的CH_4排放,然而却增加了N_2O的排放;与翻耕不还田相比,免耕结合秸秆还田显著增加了82%的N_2O排

表2 我国保护性耕作对土壤固碳和增温潜势的影响

Table 2 Impacts of conservation tillage(CT) on soil carbon sequestration(SCS) and global warming potential(GWP) in China

种植制度 Cropping systems	保耕措施 CT practices	土壤固碳 SCS/t C·hm^{-2}·a^{-1}	全球增温潜势 GWP/kg CO_2-eq·hm^{-2}·a^{-1}	参考文献 References
水稻	秸秆还田-CK		3927~4273	[30]
	秸秆还田-SR		7733~9399	
玉米	秸秆还田-CK	-0.08~0.12	492~1679	[18,31-32]
	秸秆还田-SR	0.93~0.13	-3040~1712	
	保耕-CK	-0.174		[85]
	保耕-CT	1.493~1.955		
小麦-玉米	秸秆还田-CK	-216.54~247.90	-526~2292	[19,21,29,33-43]
	秸秆还田-SR	96.05~454.97	-1294~3211	
	免耕-CK		107~2292	
	免耕-NT		12~2780	
	保耕-CK		1146~2292	
	保耕-CT		881~2631	
水稻-小麦	秸秆还田-CK	0.011~0.224	710~16 335	[9,43-53]
	秸秆还田-SR	0.195~1.368	862~25 359	
	免耕-CK		7222~11 490	
	免耕-NT		7990~10 741	
	保耕-CK		4191~11 490	
	保耕-CT		9471~13 919	
水稻-油菜	免耕-CK	1.122	8044~17 035	[54-57,73]
	免耕-NT	2.331	7225~15 476	
早稻-晚稻	秸秆还田-CK		5884~10 365	[8,57-63]
	秸秆还田-SR		6875~12 797	
	免耕-CK		4770~18 866	
	免耕-NT		4727~17 408	
	保耕-CK	2.37	5884~10 365	
	保耕-CT	2.17	9861~10 723	
早稻-晚稻-紫云英	免耕-CK	0.53	5095	[64]
	免耕-NT	1.31	6735	

放[15]。也有Meta分析表明我国秸秆还田增加了24%的CO_2、12%的N_2O和27%的CH_4排放[87]。史然等[11]综述一些研究认为稻田秸秆还田会显著增加CH_4排放，但对N_2O的影响不一致，即水旱轮作下能减少N_2O排放，但双季稻田则表现出N_2O排放增加。Liu等[87]认为秸秆还田减少N_2O排放的原因是由于下面两个因素抑制了反硝化作用：(1)秸秆腐烂导致了厌氧环境；(2)单独利用高C/N(>30)秸秆会促进土壤氮元素固定。因此，保耕对GHG排放的影响受到各种环境因素的限制。

农田SCS是土壤将大气CO_2以SOC形式进行贮存[88]。只有少部分研究在计算保耕对GHG净排放时考虑了SCS[32,73]，是因为一个作物季内SOC变化难以测定甚至被认为可以忽略不计[89]。Peters[90]和Zhang等[3]认为作物生产中GHG排放应该考虑SCS因素，若不考虑就会忽略农田是碳汇的情况[32,35]。Meta分析表明，与不还田相比，我国秸秆还田下0~20 cm SOC以0.35 t C·hm^{-2}·a^{-1}增加，并且SCS可持续28~62年[91]。在综合计算土壤GWP时，应该考虑固碳作用，只有这样才能认识到保耕措施有可能使农田从碳源转变成碳汇。对于生物量，作物成熟后收获进入食物网再将CO_2释放，因此生物量变化一般不会对SCS产生影响[86]。由于秸秆等有机物质分解转化成SOC是一个长期过程，因此应考虑如何将不同时间尺度上的SCS与GHG排放结合以准确计算土壤GWP。

保耕下的SCS属于土壤碳循环的一部分。计算SCS是通过比较措施实施前后SOC的变化，结果反映了土壤碳输入和碳输出的差值。土壤呼吸实质是一种碳输出，因此计算土壤GWP，避免将土壤呼吸和SCS简单加减，这样可能会产生CO_2排放的重复计

算[38]。保耕对SCS影响的长期性需要建立长期定位监测站和全国监测网络,从而全面、系统地理解保耕对土壤SCS和GHG排放的影响机理。

保耕技术和其他推荐措施结合才能更有效地发挥固碳减排作用[92]。2011年我国主粮生产所用氮肥若按国家推荐量,会减少10%的N_2O排放量[93]。Meta分析表明与连续淹水相比,稻田间歇灌溉减少了52%的CH_4排放却增加了242%的N_2O排放,土壤GWP则降低了47%[94]。保耕推广若结合施用生物炭、测土精准施肥、有机无机肥料优化使用等推荐措施,可以提高固碳0.025 Pg C·a^{-1}[95]。另外,施用CH_4抑制剂、脲酶抑制剂及硝化抑制剂、缓释/控释肥和种植低排放的水稻品种可以降低稻田GHG排放。由此可见,结合适宜的农田管理措施,可以充分发挥保耕在固碳减排方面的潜力。

5　研究展望

尽管我国保耕得到很大推广,但是2017年保耕面积仍然只占农作物总播种面积的4.5%[6]。很多研究证明保耕可以提高土壤养分、有机质和作物产量[96]。结合国家层面进一步推广保耕,需要深入系统了解全国不同区域保耕对土壤GWP的影响,为科学全面地评价保耕技术的生态效益提供参考。

(1)综合评估整套保耕体系的GHG减排效果。目前我国的保耕技术侧重于秸秆还田和免耕而忽视深松技术,缺少农户采用整套保耕体系。国外保耕优势是通过多种措施构成的完整体系实现的,因此我国需要研究适宜于不同区域的完整保耕体系。保耕体系因各地气候及种植模式差异发展出不同模式:如东北地区采取高垄种植避免还田导致的低温;而干旱少雨的西北地区采用整秸覆盖或翻压还田以减少水分的蒸发。在秸秆作为饲料和燃料的地区,需要开拓其他饲料和燃料来源以保证足够的秸秆还田。因此,应该综合评估整套保耕体系进行过程的GHG排放和SCS。

(2)减少评估参数的不确定性。保耕体系中关键技术对土壤GHG排放和SCS产生的影响复杂。不同区域的保耕措施对土壤GWP影响具有明显的区域特征,需要在全国不同农业试验站点进行联网研究,建立相应的保耕措施对GHG影响评估的参数和方法。由于试验田研究结果与农户实际大田种植的结果可能存在差异,因此应该考虑保耕在大田推广时的实际影响。

(3)评估保耕对土壤GWP的影响需要科学考虑SCS。土壤呼吸和固碳作用都是土壤碳循环的表现,评估时需要界定边界以避免少算或重复计算。在短期评估时(如1~2 a内),要同时考虑CO_2的排放和吸收。在长期评估时(如>5 a),要重点考虑SCS作用。

(4)开展全过程评估:保耕对GHG的影响只是整个农业生产对大气GHG影响的重要一环。在农业生产中,各种机械使用消耗能源也会排放GHG,因此,研究保耕对GHG的影响应考虑与农业生产(包括保耕)相关的各种GHG排放源。作物碳足迹是计算作物整个生命周期的GHG动态变化[3],因此可以将作物碳足迹评估引进到保耕体系对GHG排放影响的评估过程。

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