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森林伐后碳减排核算方法演进与展望

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摘要: 森林生态系统的碳汇功能对我国完成“双碳目标”具有独特意义, 其中森林伐后碳减排, 包括木质林产品全生命周期内的碳储和替代减排, 是增强林业中长期碳减排能力的重要路径。当前我国森林伐后碳减排研究尚落后于欧美等发达国家, 不利于我国林业国家碳库模型的构建以及更好地指导固碳增汇的森林管理策略。系统回顾了近 30 余年国内外学术界关于森林伐后碳减排方法学的演进动态, 总结了碳循环和碳减排模型的核心参数, 为推进我国森林伐后碳减排研究提供理论基础。学术界近 30 余年涉及方法模型的主要成果如下: ①建立并完善了立足于木材采伐国的生产法和简单分解法, 以及立足于终端木质林产品消费国的储量变化法和大气流动法两类方法框架; ②形成了体系化的碳储计算模型, 并在包括发达国家和主要发展中国家取得了大量实测数据和参数积累; ③初步完成了替代减排分析模型和基于情景设定的分析框架, 并在以欧美国家为主体的部分地区进行了应用。在梳理历史文献的基础上, 本研究认为当前存在的方法缺陷包括: 第一, 既有依靠实测调研获取数据的成本过高, 限制了研究国家的深度和广度, 尤其导致广大发展中国家研究较为薄弱; 第二, 当前方法框架在追踪木质林产品贸易流方面较为欠缺, 难以形成生命周期链条的上下游国家的有机整合; 第三, 替代减排基本假设对社会经济规律下的替代考虑较为薄弱, 影响其评估结果的客观性。研究认为, 首先应加强在既有实测数据的基础上总结一般规律、形成经验模型, 降低发展中国家的数据获取成本; 其次应建立一种立足于中间木质林产品生产国的方法框架, 并结合多区域投入产出模型力图整合生命周期上下游国家; 最后, 引入包括经济学经典的替代弹性和产业关联分析可能是增强替代减排客观性的路径。

关键词: 森林; 林产品; 碳循环; 温室气体减排; 生命周期

Methodological evolution and frontiers of post-harvest greenhouse gas mitigation assessment

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Abstract: Carbon sequestration of forest ecosystem has unique and significant contributions to the “carbon peak and neutrality” strategy in China. The greenhouse gas mitigation function of forestry includes not only pre-harvested stages, i.e., carbon sinks in forests, but also post-harvest stages. The post-harvest greenhouse gas mitigation, including life-cycle carbon stocks and substitution benefits of harvested wood products, plays a critical role in middle- and long-term carbon sink of forestry. Currently, the post-harvest greenhouse gas mitigation researches of China are far more cutting-edge compared to those of Europe and America. As a result, existing China's post-harvest greenhouse gas mitigation researches are insufficient

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for constructing a comprehensive national forestry carbon budget model and designing effective policies of forest management for increasing carbon sink. We systematically reviewed the post-harvest greenhouse gas mitigation researches in the recent 30 years to outline methodological revolution in post-harvest greenhouse gas mitigation in this period and to summarize the key parameters of the models used in previous studies. The major achievements in post-harvest greenhouse gas mitigation assessment methodology in the recent 30 years include: 1) the establishment of Production Approach and Simple Decay Approach, which is timber-harvesting country-based assessment frameworks, and Stock-Change Approach and Atmospheric Flow Approach, which is end-use country-based assessment frameworks; 2) the establishment of systematic carbon stock calculation method which had been applied in developed countries and major developing countries; 3) primary establishment of substitution model and scenario-based analytical framework which were mainly applied in substitution benefit assessment of harvested wood products in European and American countries. Our literature review reveals three major methodological shortcomings of existing studies. First, the expensive data collection cost of existing field survey restricted the wide application of high-tired method, resulting in large research gap in developing countries. Second, international trade flows are hard to track under existing methodological frameworks, restricting comprehensive assessment of the countries involved in harvested wood product supply-and-use chain. Lastly, the substitution benefit assessment ignored the real substitution under socio-economical rules, undermines the accuracy of the results. We suggest that future studies should: 1) summarize general rules and empirical models based on existing parameters to reduce the data collection cost in developing countries; 2) establish an analytical framework based on semi-finished harvested wood product manufacturing country and use multiregional input-output table to link the countries involved in the supply-and-use chain; 3) introduce the classical economic substitution elasticity and industrial linkage analysis as a potential approach to improve the substitution benefit assessment.

Key Words: forest; harvested wood product; carbon cycle; greenhouse gas mitigation; life cycle

无论在全球层面应对气候变化还是单一国家实现“碳达峰”和“碳中和”,林业独有的固碳储碳功能是当前最主要的低成本直接降低大气中二氧化碳浓度的手段。我国近 20 多年的大规模持续植树造林和森林恢复显著地增加了我国森林生态系统的碳汇水平^[1-2],使我国成为全球主要的森林碳汇贡献国之一^[3]。然而,我国近三次森林资源清查表明,由于宜林地面积不断减少、造林成本不断增加,我国新增森林面积出现萎缩^[4-6];同时由于我国大量人工林以速生丰产树种为主^[7-8],碳汇能力在未来二三十年随着森林成熟趋于下降乃至停滞^[9-10]。我国当前依赖造林的增汇效果将在未来趋于递减^[11],需要开拓更广阔的碳减排路径提升我国林业长期气候减排潜力。

以森林采伐作为分界线,相对主要依靠造林、抚育、再造林等方式促进森林吸纳二氧化碳的能力的伐前碳减排^[2,10,12],伐后碳减排则主要通过木质林产品全生命周期内使用和废弃物管理保存产品所含的碳,同时减少高碳强度的产品使用获得减排效应^[13-14]。相关研究表明,综合考虑伐前和伐后碳减排能够更加准确全面地评估一国林业气候减排潜力^[15-17],对指导旨在提升气候减排潜力的森林管理行为^[18-20]、乃至国际间气候责任分配具有重要的理论价值和现实意义^[21-22]。我国作为全球最大的木质林产品生产国、贸易国和消费国,自 2010 年起占全球木质原材料进口的 40%、木质林产品产量的 27% 以及消费量的 22%^[23-25],具有大量的森林伐后碳减排潜力以及国际间涉林气候利益诉求。当前我国学者在森林伐后碳减排领域已进行了大量前期研究^[26-31],但在方法层级以及完整生命周期构建等方面仍落后于国外同行,与我国林业与林产品大国的地位极不相称。我国部分学者在森林伐后碳减排研究方面已进行了总体评述^[14,32-33],进一步开展系统深入的方法学论述,对构建我国森林伐后碳循环国家模型具有重要意义。

本研究系统回顾了近 30 余年 IPCC(Intergovernmental Panel on Climate Change,政府间气候变化委员会)和国内外学术界关于森林伐后碳减排核算方法的演进动态,总结国内外碳减排模型核心参数,并针对当前模

型方法的不足进行讨论和展望, 以期为我国森林伐后碳减排研究以及未来我国森林伐后碳循环国家模型构建做理论准备。

1 核算方法框架更替

森林伐后碳减排研究起源于 20 世纪 90 年代前后^[34-36], 并在进入 21 世纪后获得了蓬勃发展^[13-14, 37]。方法框架是森林伐后碳减排核算的基石, 主要解决碳储和碳排放“算哪些”(即哪些进出口贸易流需要纳入计算)、“归属谁”(即产生的碳储和碳排放归属于哪个国家)、“用什么指标”(即核算碳储变动还是碳通量变动)的问题。在 30 多年研究历史中, 关于方法框架的演替形成了如表 1 所示的阶段特征。

表 1 森林伐后碳减排方法框架及阶段特征

Table 1 Methodological framework and periodic change of post-harvest greenhouse gas mitigation assessment

时间 Time	标志性报告与 代表性研究 Milestone reports and representative studies	学术界重大方法改进 Major methodological improvement in research community	IPCC 方法调整 Methodological changes of Intergovernmental Panel on Climate Change
1990—2003 年	[38—42]	基本确立了 4 种方法框架的核算逻辑	并未考虑森林伐后碳循环和碳减排
2004—2006 年	[43—45]	通过一阶衰减法的建模解决了森林伐后碳循环各碳池中碳储变动核算难题	引入一阶衰减法模块并将 4 种方法列为备选方法由缔约国自由选择
2007—2010 年	[46—48]	对于 4 种方法进行对比应用, 主流森林伐后碳循环模型与软件开始出现	无
2011—2018 年	[15, 30, 49—52]	注重森林管理的价值, 生产法成为该阶段主流	生产法被 IPCC 确定为统一方法并舍弃出口木质林产品碳储的核算
2019—2022 年	[23, 25, 53]	对方法框架无进一步改进	再次将 4 种方法列为备选方法由缔约国自由选择

1.1 1990—2003 年: 早期萌芽

在 90 年代, 学术界对森林伐后碳循环研究尚处于萌芽时期, IPCC 于 1996 年修订的国家温室气体清单指南并未将其纳入考量^[38]。学术界经过 10 余年的初步探索后, Winjum 等^[39]和 Lim 等^[40]提出了生产法 (Production Approach)、储量变化法 (Stock-change Approach) 和大气流动法 (Atmospheric Flow Approach) 的框架概念 (图 1), 并于 2003 年被 IPCC 采纳为备选方法^[41]。Ford-Robertson 在 2003 年提出了另一种名为简单分解法 (Simple Decay Approach)^[42]的方法。以上 4 种方法的整体框架被沿用至今, 但由于生产法和储量变化法关注于木质林产品碳储量评估, 简单分解法和大气流动法则关注于更难实时追踪的碳通量, 因此生产法和储量变化法的应用更为广泛^[13-14, 37]。

1.2 2004—2006 年: 方法框架的成熟

尽管学术界已经在 2000 年前后确定了主流方法框架, 但在具体计算碳储量方面应遵循何种规则仍然存在不足。Skog 等^[43]以及 Pingoud 和 Wargner^[44]完成了基于指数分布的在用和废弃木质林产品碳储计算方法建模解决了这一问题, 并于 2006 年正式列入 IPCC 国家温室气体清单指南^[45], 标志着森林伐后碳减排的方法框架走向成熟。2009 年 UNFCCC (United Nations Framework Convention on Climate Change) 亦要求《京都议定书》的附件 I 国家必须将森林伐后碳循环纳入气候减排的一部分^[47]。

1.3 2007—2010 年: 方法框架的应用与争论

以图 1 中的 A、B 两国为例 (A 国为森林伐后碳减排报告国), 生产法和简单分解法以木材采伐国 (A 国) 为基准进行森林伐后碳循环评估, 无论该木材是否用作国内加工、消费、废弃, 其碳储量/碳排放量都归属于木材采伐国; 储量变化法和大气流动法则相反, 只要是被 A 国最终消费的木质林产品, 无论其来源如何, 其产生的碳储量/碳排放量都归属于该消费国。因此, 木质林产品贸易将影响各个方法核算结果的准确性、适用性, 以及各国森林伐后气候权益的归属^[21-22, 24]。

2006 年起,学术界在国家层面上对上述方法进行对比应用,试图回答何种方法应当作为统一方法^[46,54—56]。但此类研究往往仅从一国获得碳储量多寡、或依托本国数据得出评估结果的精度角度出发,选择对本国最有利的方法,因而无法形成学术界的共识^[37]。与此同时,由于生产法着眼于木材采伐国,在衔接伐前碳循环和森林管理具备先天的优势,能够尽可能保证木质林产品来源于可持续的森林经营活动,因此整合伐前与伐后碳循环和碳减排的研究往往采用生产法,并逐渐形成了国家林业碳循环模型^[18,48—49,57]。

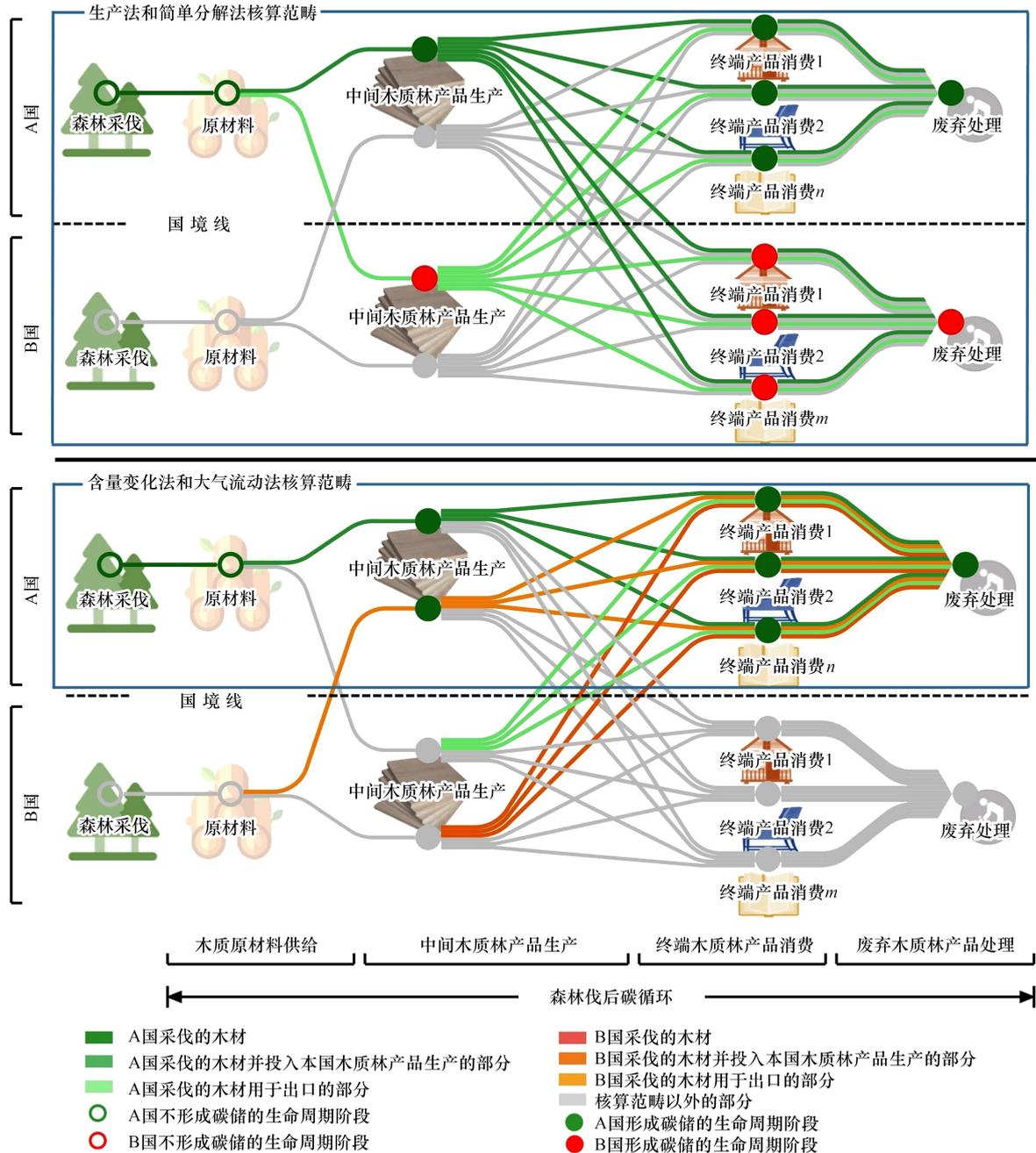


图 1 四种森林伐后碳减排方法框架的物质流核算范畴

Fig.1 Accounting scope of material flows under the four post-harvest greenhouse gas mitigation assessment approaches

1.4 2011—2018 年:生产法成为统一方法

在基于生产法的林业碳循环模型取得了较好的成果的基础上,结合应对毁林和森林退化带来的大量碳排放^[58]的需要,UNFCCC 在 2011 年的德班会议上明确要求《京都议定书》的附件 I 国家必须采用生产法报告本

国森林伐后碳循环^[50]。IPCC 在 2013 年对国家温室气体清单指南的修订上进一步将生产法作为统一方法,并要求各国必须区分森林管理等级(Forest Management Reference Level)^[51]。得益于 IPCC 对于生产法的推动,基于此方法的森林伐后碳循环研究自 2011 年起成为学术界主流^[15-16,49,52,59-63]。

1.5 2019 年至今:重新回到 4 种方法并立

然而,由于基于生产法的研究均无法追溯出口至国外的木质林产品的碳储和碳排放动态^[24,37],学术界仍然存在关于生产法和储量变化法的争论^[27,52,64-67]。有鉴于此,IPCC 于 2019 年对国家温室气体清单指南的修订中,放弃对生产法作为统一方法,而是将 4 种方法由各国自由选择^[53]。同时,该指南中界定的生产法仍然沿用 2013 年修订版本,即为了简化需要,对出口至国外的木质林产品不予考虑^[51,53]。

2 碳储计算方法发展动态与核心参数汇总

在确定具体核算框架的基础上,碳储计算方法主要用于计算木质林产品生命周期内的碳储量,主要包括在用木质林产品和废弃物(加工环节的废弃木料和退出使用环节的废弃木质林产品)所积累的碳储量。IPCC 推荐一阶衰减法计算两类碳储量,学术界主要的争论在于其对于在用木质林产品碳储计算是否合理。

2.1 在用木质林产品碳储

2.1.1 在用木质林产品碳储核算的理论逻辑

在用木质林产品碳储量计算可以视为经典的“注水—放水”的蓄水池问题,即由累计流入量(累计消费的木质林产品)扣除累计流出量(累计废弃的木质林产品)。其中,流入量可以通过统计或调查数据获取,废弃量则需要建模。学术界认为,对于每一单位的初始木质林产品消费量(以所含碳量计量),在其后每年废弃的比率服从一定的概率分布(以概率密度函数表示),由此,其在后续每一年的废弃量则为两者的乘积^[44,68-72]。则对于一个时间序列的木质林产品消费量来说,累计废弃量为:

$$C_{\text{decay}}(t) = \int_0^t EU(t - \tau) \times f(\tau) d\tau \quad (1)$$

式中, $C_{\text{decay}}(t)$ 为到 t 年累计废弃的木质林产品, EU 为终端消费的木质林产品数量, τ 为木质林产品自消费后所经历的时间(以年数计), f 为废弃比率随时间的概率密度函数。

在完成废弃量的计算后,在用木质林产品碳储($C_W(t)$)和碳汇量(即年碳储增量)可以通过公式(2)—(3)计算:

$$C_W(t) = \sum_0^t EU(t) - C_{\text{decay}}(t) \quad (2)$$

$$\Delta C_W(t - 1) = C_W(t) - C_W(t - 1) \quad (3)$$

2.1.2 IPCC 一阶衰减法的数理原理

学术界早期研究假定木质林产品的废弃速率服从指数分布^[43-44,68],即每年的废弃量与上一年的存量之比是一个固定值,因此对于每一单位的初始消费的木质林产品,最大废弃量出现在消费后第一年并在其后年份逐渐降低。这一假设在 2006 年被 IPCC 采纳^[45],并进一步假设当年新生产的木质林产品会有半年的废弃时间,形成如公式(4)所示的一阶衰减法(First-order Decay Method)并且沿用至今^[51,53]。

$$C_W(t) = e^{-k'} \times C_W(t - 1) + \frac{1 - e^{-k'}}{k'} EU(t - 1) \quad (4)$$

式中, $k' = \ln(2) / HL$,表示由半衰期(HL)决定的每年废弃速率。

2.1.3 学术界对于在用木质林产品衰减模型的修正

然而指数分布关于废弃速率的假设与现实存在较大的冲突:实际生活中,木质林产品往往存在一个“期望寿命”,并且在“期望寿命”时出现最大的废弃量,在“期望寿命”左右集中废弃、其余时间则较少废弃。此类分布以正态分布^[70-71]、卡方分布^[71-72]和伽马分布较为常见^[69,72]。由于正态分布和卡方分布以及前述的指

数分布都是伽马分布的特殊情况,Marland 等^[69]认为可以统一采用伽马分布刻画在用木质林产品的废弃速率。然而,作为一种双参数的分布函数,伽马分布需要更多的基础数据才能求解各种产品废弃速率的函数曲线。相较而言,IPCC 默认的一阶衰减法仅需要半衰期一个数据即可确定废弃速率的函数曲线,因此尽管伽马分布更加科学^[70,72],但主流学术界均使用一阶衰减法作为核算在用木质林产品碳储量的方法。Bates 等^[72]通过对伽马分布函数的水平和垂直参数进行重复赋值发现,在设定其水平参数为 2,即将伽马分布转化为卡方分布后,能够在保持伽马分布客观性方面的优势的同时,利用既有半衰期参数确定各类产品的废弃速率函数曲线(公式(5))。

$$C_{\text{decay}}(t) = \int_0^t EU(t - \tau) \times \frac{\tau^{(k''-1)}}{\Gamma(k'') 2^{k''}} e^{-\frac{\tau}{2}} d\tau \quad (5)$$

式中, k'' 为垂直参数,通过代入半衰期时间点和累计废弃量 50%确定。

2.1.4 核心参数汇总

本研究在回顾国内外文献的基础上,对半衰期这一在用木质林产品碳储核算的核心参数汇总如表 2 所示。

表 2 主要木质林产品使用半衰期/a

Table 2 Half-life of the major categories of harvested wood products

国家/地区 Countries/ regions	IPCC 第三层级方法 IPCC Tier-3 Method			IPCC 第二层级方法 IPCC Tier-2 Method			
	建筑用材 Construction lumber	木家具 Wooden furniture	参考文献 References	锯材 Sawnwood	人造板 Wood-based panels	纸和纸板 Paper and paperboard	参考文献 References
北美洲 North America				35	25	2	[45,51,53]
加拿大 Canada	66	29	[15,48,73-75]				
美国 United States	65	30	[46,76-77]				
欧洲 Europe							
德国 Germany	35	17	[18]				
爱尔兰 Ireland	67	30	[61,78]				
芬兰 Finland	21	—	[79-80]				
法国 France	17	11	[19]				
捷克 Czech Republic	45	—	[81]				
葡萄牙 Portugal	21	14	[56,82-83]				
瑞士 Switzerland	55	35	[84]				
西班牙 Spain	17	12	[65]				
欧盟整体 Europe Union, aggregate	43	27	[55,85]				
欧洲整体 Europe, aggregate	35	25	[85]				
亚洲 Asia							
日本 Japan	33	20	[52,62,86]				
其他 Other	40	23	[25]				

第三层级方法下的各国半衰期数据以相应文献的平均值计算,“其他国家”的半衰期为表中所列国家的平均值;第二层级方法下,最新的 IPCC 报告^[51,53]假定硬木类木质林产品半衰期为 30a,即锯材和人造板的平均值

2.2 废弃物碳储

2.2.1 核算方法数理原理

废弃物可能会采用焚烧、露天堆放、填埋、回收利用等方式处理(其中加工废弃木料往往假设不被回收利用),由于焚烧和回收利用的废弃物不会产生碳储量,废弃物碳储量的计算主要针对露天堆放或者填埋处理的废弃物^[13]。学术界普遍采用 IPCC 推荐的基于指数分布的一阶衰减法评估其碳储量,如公式(6)所示:

$$C_{\text{waste}}(t+1) = \sum_{\delta} e^{-\delta k''} \times \text{Inflow}(t-\delta) \quad (6)$$

式中, $C_{\text{waste}}(t+1)$ 为 $t+1$ 年废弃物形成的累积碳储量; $\text{Inflow}(t)$ 为在 t 年新流入露天堆料场或填埋场中分解部分的废弃物; δ 为废弃物自废弃年开始所经历的时间; k'' 为由各类废弃物分解半衰期所确定的分解速率, 其计算方法与公式(4)中的 k' 相似。IPCC 推荐的半衰期数据为: 无氧分解下硬木类木质林产品半衰期为 29a, 纸类产品为 15a; 有氧分解下则分别为 16.5a 和 8.25a^[53,87]。

由于填埋处理的废弃物会产生甲烷, 其 28 倍于二氧化碳的温室效应需要在碳储计算中进行扣除。填埋场甲烷排放量计算方法如公式(7)所示。

$$E_{\text{methane}}(t) = 0.5 \times E_{\text{an_landfill}}(t) \times \frac{16}{12} \times 28 \times (1 - MC) \times (1 - OX) \quad (7)$$

式中, E_{methane} 为甲烷排放量; $E_{\text{an_landfill}}$ 为填埋场产生的碳排放(以碳量计), 可以由累计流入填埋场无氧分解部分的总碳量扣除当年的碳储量计算得出; MC 为产生的甲烷中人为收集利用或者焚烧的比例; OX 为甲烷自然氧化比例, 一般设定为 10%。

据此, 填埋场扣除甲烷温室效应的净碳储量为:

$$NC_{\text{an_landfill}} = C_{\text{an_landfill}} - \left[E_{\text{methane}} - 0.5 \times E_{\text{landfill}} \times \frac{44}{12} \times (1 - MC) \times (1 - OX) \right] \quad (8)$$

式中, $NC_{\text{an_landfill}}$ 为净碳储量; $C_{\text{an_landfill}}$ 为无氧分解部分的碳储量, 可以通过公式(6)所示的方法计算得出。

2.2.2 核心参数汇总

既有文献表明, 废弃物被各类处理方式进行处理的比例是计算其碳储量的核心参数。由于加工环节的废弃木料多采用焚烧处理(能源化利用)^[15,46,52,85]或者缺乏数据^[30], 木质林产品碳储研究往往更关注废弃木质林产品的处理^[13,37]。本研究回顾了历史文献, 对美国、加拿大、中国、日本、欧盟、澳大利亚等主要木质林产品生产国家和地区的废弃木质林产品经各种处理方式的比例总结如表 3。

表 3 主要国家和地区废弃木质林产品各处理方式占比

Table 3 Fractions of retired harvested wood products that were disposed of in major countries and regions

国家/地区 Countries/regions	硬木类木质林产品 Solid harvested wood products				纸类产品 Paper products				参考文献 References
	焚烧 Combustion	露天堆放 Open dump	填埋 Landfill	回收 Recycle	焚烧 Combustion	露天堆放 Open dump	填埋 Landfill	回收 Recycle	
	北美洲 North America								
加拿大 Canada	0.25 (0.09—0.31)	0.50 (0.02—0.71)	0.23 (0—0.74)	0.01 (0—0.09)	0.25 (0.09—0.31)	0.47 (0.01—0.71)	0.16 (0—0.54)	0.12 (0—0.66)	[15]
美国 United States	0.25 (0.09—0.31)	0.52 (0.02—0.71)	0.22 (0—0.74)	0.01 (0—0.09)	0.25 (0.09—0.31)	0.49 (0.01—0.71)	0.16 (0—0.54)	0.11 (0—0.49)	[46]
欧洲 Europe									
法国 France	0.9	0	0.1	0	0.9	0	0.1	0	[19]
其他欧洲国家 Other Europe countries	0.69	0	0	0.31	0.29	0	0	0.71	[85]
亚洲 Asia									
中国 China	0.02 (0—0.35)	0.82 (0—1)	0.16 (0—0.9)	0	0.01 (0—0.16)	0.6 (0—0.97)	0.10 (0—0.53)	0.29 (0.03—0.53)	[30]
日本 Japan	0.53	0	0.31	0.16	0.53	0	0.31	0.16	[52]
韩国 South Korea	0.18	0	0.12	0.7	0.29	0	0.61	0.1	[88]
大洋洲 Oceania									
澳大利亚 Australia	0	0	1	0	—	—	—	—	[89]

部分国家的废弃处理方式占比随时间发生变动, 本研究仅报告其均值和数值范围(括号内数值); 美国和加拿大在废弃物处理方面整体相似度较高, 仅部分年份有区别

3 替代减排评估方法进展与核心参数汇总

3.1 核算方法数理原理

木质林产品替代减排的评估方法较为统一,但在生命周期涵盖范围方面的差异往往决定了计算公式中变量的取值,进而影响替代减排效应的评估结果。当前替代减排计算主要首先评估出替代系数(Displacement Factor)^[14,90-91],即每一单位木质林产品(以碳量计)所能替代的其他产品减少的碳排放量(公式(9)),而后再在此基础上乘以木质林产品总消费量即可得出木质林产品总替代减排量。

$$DF = \frac{GHG_{\text{nonwood}} - GHG_{\text{wood}}}{WU_{\text{wood}} - WU_{\text{nonwood}}} \quad (9)$$

式中, DF 为替代系数, GHG_{wood} 和 GHG_{nonwood} 分别为木质林产品和非木质的替代品消费带来的碳排放量; WU_{wood} 和 WU_{nonwood} 分别为木质林产品和替代品所含有的木材量(以碳量计),其中,在材料替代时(如木材替代钢材), WU_{nonwood} 取值为 0,在产品替代时(如木结构房屋替代钢结构房屋), WU_{nonwood} 取值可以为正。

理论上说, GHG_{wood} 和 GHG_{nonwood} 的取值应该为木质林产品和替代品全生命周期内的碳排放量,即碳足迹。但实际研究中,由于研究目的或者研究数据的限制,往往仅能考虑产品生产和运输过程中的碳排放^[91]。

3.2 核心参数汇总

木质林产品主要替代类型包括产品替代和材料替代两类,其中产品替代主要涵盖能源(木质能源替代化石能源)、建筑(木结构建筑或者建筑部件替代非木结构建筑或者建筑部件)、家具(木家具替代非木家具)和其他产品替代,材料替代则以木质林产品替代非木材料且不区分具体产品类型和使用场景(如用木质林产品替代钢材、塑料等)。针对上述替代类型,本研究对主要国家木质林产品替代系数汇总如表 4 所示。可以看出,用于替代能源的木质林产品产生的碳减排效应低于替代其余产品;整体上替代建筑类产品的碳减排效应是主要产品替代类型中最佳的一种;材料替代由于并未考虑具体应用类型,其碳减排效应可能存在高估。

表 4 主要国家和地区木质林产品替代系数

Table 4 Displacement factor of harvested wood products in major countries and regions

国家/地区 Countries/regions	产品替代 Product substitution				材料替代 Material substitution	参考文献 References
	能源 Energy	建筑 Construction	家具 Furniture	其他 Others		
北美洲 North America						
加拿大 Canada	0.65 (-0.08—2)	2.06 (0.99—2.61)			0.54 (0.38—0.77)	[20,92—95]
美国 United States		2.03				[96]
墨西哥 Mexico					1.23 (0.45—2)	[97]
欧洲 Europe						
法国 France	0.11 (0.08—0.14)	0.07 (0.03—0.18)	0.05 (0.05—0.08)	0.04 (0.01—0.07)	1.28	[19,98]
德国 Germany	1.04 (0.67—2.5)	1.36 (0.16—2.4)	1.55 (1.42—1.62)	1.44 (1.35—1.62)	1.43 (1.3—1.5)	[99—106]
丹麦 Denmark					2.1	[107]
芬兰 Finland	0.76 (0.47—1.4)	1.1	0.9	3.55 (1.4—7.38)	1.82 (1.3—2.4)	[108—110]
瑞典 Sweden	0.91 (0.55—1.27)				2.31	[112]

续表

国家/地区 Countries/regions	产品替代 Product substitution				材料替代 Material substitution	参考文献 References
	能源 Energy	建筑 Construction	家具 Furniture	其他 Others		
瑞士 Switzerland	0.36 (0.13—0.6)				0.79 (-0.34—4.1)	[112]
欧洲整体 Europe, aggregate		0.37 (-0.11—1.51)	0.18 (0.16—0.2)	0.54 (0.10—1.24)		[113]
亚洲 Asia						
中国 China	0.77 (0.56—0.96)	2.43 (0.68—3.48)	1.42 (1.38—1.46)			[114—115]
日本 Japan	0.44	0.39 (0.19—1.21)	0.17			[62, 116]
韩国 South Korea	0.11 (0.08—0.14)				0.04	[88]
大洋洲 Oceania						
澳大利亚 Australia					2.1	[117—118]
新西兰 New Zealand		4.17 (1.05—15)				[119]

替代系数为各文献平均值,括号中的数值为历史文献的取值区间,对于3位以上小数的数据,本文保留2位小数点

4 森林伐后碳减排方法亟待改进之处

森林伐后碳减排研究本质上是为了解决两方面的内容,即更准确评估其对于整个森林生态系统的碳减排能力,以及在此基础上推动缓解气候变化的政策。这需要在强化研究国家的广度和深度、加强生命周期上下游国家的整合、提升替代减排的客观度方面进一步深入研究。当前森林伐后碳减排方法在上述三方面尚存在数据要求难以放宽、跨国家的方法框架欠缺、替代减排假设缺乏社会经济的考量等方面的不足。

4.1 传统调研方法数据获取成本过高

传统调研方法数据获取成本过高是制约森林伐后碳减排研究国家的广度和深度的主要原因。一个完整的森林伐后碳减排研究需要庞杂的数据支持各生命周期环节内的物质流分析、碳储计算以及替代减排分析。自2006年起,IPCC温室气体清单指南推荐缔约国采用第三层级方法编制森林伐后碳减排清单,其核心要求是各国需要量化终端木质林产品消费量及其半衰期^[45],进一步推高了森林伐后碳减排清单编制的技术要求。由于终端木质林产品消费量及其半衰期往往不在统计数据范畴之内,这成为我国和巴西等主要发展中国家从IPCC第二层级方法向第三层级方法跃进的主要瓶颈^[30,67]。造成数据成本过高的一大根源在于,既有研究收集数据(尤其是第二节所述的参数数据)往往采用传统实测调研的方式^[13—14]。由于森林伐后碳减排清单编制往往在区域和时间尺度上较为宏观,通过实测调研获取数据意味着高昂的成本以及难以在广大发展中国家推广。

4.2 跨国家的方法框架欠缺

造成生命周期上下游国家难以整合的关键在于,当前森林伐后碳循环在方法学上欠缺一个有效的跨国家方法框架。从图1可以看出,当前学术界采用的4种IPCC方法分别从生命周期的上游(原材料供给端)或下游(最终消费端)沿着生命周期链条往下游或上游追踪木纤维流动及其碳储碳排放。其在追踪过程中不可避免会面临大量的木质林产品生产国作为媒介,使整个追踪过程极为复杂。在全球大约有200个国家的背景下,以生产法为例,一个木材采伐国的木材可能会出口至200个中间木质林产品生产国进行加工,其生产的中间木质林产品理论上可能出口至200个终端木质林产品消费国用作最终使用,在此过程中产生 $1 \times 200 \times 200 = 40000$ 个贸易流。实际生活中,中间木质林产品到终端木质林产品的加工过程往往涉及多道工序、且每道工序

序所生产的产品都存在贸易的可能,其引发的贸易流将呈指数级增长。因此,需要在方法框架上进行创新,用以在森林伐后碳减排评估时有效整合生命周期上下游国家。

4.3 替代减排假设缺乏社会经济的考量

影响替代减排评估客观性的深层因素在于,当前替代减排评估方法的基本假设缺乏社会经济的考量。一方面,既有研究均暗含木质林产品和非木质林产品是完全可替代的、功能一致的^[14,52,90-91]。以建筑为例,对于独栋或者低层建筑以及建筑构件(如木地板),这一假定或许是存在的;但对于高层建筑,往往难以出现替代的可能,这对于我国这类城市用地较为紧缺无法大规模建造独栋或低层建筑的国家尤为现实。另一方面,更大的缺陷是,既有研究往往忽视了产业间的联系对木质林产品和替代品实际消费量的干扰^[120]。这种产业间的联系形成的经济规律往往决定了在现实生活中一种产品消费量的增减对另一种产品消费量的实际影响,更符合“替代效应”本身的社会现实。相对既有研究主观假定未来木质林产品和非木质林产品的消费数量,考虑产业间联系的替代可能对替代减排数量产生较大的修正甚至产生完全相反的结论。

5 研究展望

针对上述三方面的方法缺陷,本研究认为以下途径可能是未来的改进方向:

第一,应通过学术界在调研手段取得的既有数据成果基础上加强合作,总结发现参数数据的一般规律、形成经验模型,从而降低其他缺乏基础数据的国家的森林伐后碳减排清单编制门槛。同时,欧美国家的研究经验表明,借鉴经济水平相似的国家的基础数据是弥补本国数据缺乏的有效方式^[20,78],可以作为重要的补充手段。

第二,应建立以中间木质林产品生产国为立足点的方法框架,从方法学层面降低贸易流追踪的难度,形成生命周期上下游国家的整合。在此基础上,借鉴以多区域投入产出模型为代表的经济模型量化出口木质林产品的终端消费也可以作为一个重要的突破方向^[25,121-122]。

最后,应在区分木质林产品功能替代关系的基础上,引入经济模型量化微观产品层面的替代弹性和宏观的产品所在行业层面之间的溢出或挤占效应,客观地量化社会经济实际中因增加木质林产品消费对其替代品消费量的实际变动,从而更科学地评估木质林产品相对其替代品的替代减排能力。

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