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基于模型的农田土壤固碳潜力估算

覃章才, 黄耀*

中国科学院大气物理研究所, 大气边界层物理和大气化学国家重点实验室, 北京 100029
* 联系人, E-mail: huangy@mail.iap.ac.cn

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摘要 农田生态系统在陆地碳循环中具有重要地位. 增加农田土壤有机碳的固定不仅有助于减缓大气 CO_2 浓度增加速率, 而且对保障国家粮食安全具有重要意义. 基于农田土壤碳饱和理论, 分析了全球 95 个覆盖温带、热带、亚热带等不同气候区农田长期定位试验数据, 并构建了由气温、降水、土壤黏粒含量和 pH 驱动的农田土壤固碳潜力模型(R^2=0.58, n=76). 中国的长期定位试验较好地验证了这一模型(R^2=0.74, n=19). 模型敏感性分析表明, 低温湿润地区、高黏粒含量和低 pH 的土壤具有相对较高的固碳潜力; 高温低湿地区、低黏粒含量和高 pH 的土壤则较低. 利用所建模型和气候、土壤等基础数据, 对中国河南省农田土壤固碳潜力进行了估算. 结果表明, 该省农田表土(0~20 cm)碳饱和密度平均约为 32 t/ha, 南部地区相对较高. 按该省第 2 次土壤普查的有机碳密度估算, 未来可望增加土壤固碳约为 100 Tg.

关键词
农田
模型
土壤有机碳
饱和
潜力

土壤有机碳(soil organic carbon, SOC)库, 作为全球碳循环过程中的重要碳库[1], 具有缓解气候变化、保障粮食安全等多重意义[2]. 土壤有机碳水平主要取决于土壤有机碳输入和输出的平衡. 土壤通过植物光合作用和有机质分解作用获取碳, 而由于土壤呼吸作用和有机质的淋溶、破碎化损失碳[3]. 全球土壤中, 农田土壤拥有相当可观的固碳能力, 在全球碳循环中具有难以取代的地位[2]. 然而, 农田生态系统受到人为活动的影响, 土壤有机碳的时空变异较大. 不合理的农田管理措施, 如土壤有机碳投入的减少(如秸秆移除、有机肥低投入)、土地频繁翻耕等会导致农田土壤净损失碳而成为碳源[4,5]. 相反, 合理的管理措施, 如免耕、增施有机肥等则可以有效地将大气二氧化碳(CO_2)固定在土壤中, 提高农田土壤有机碳含量[2,6,7]. 可见, 农田土壤是潜在的土壤碳汇. 然而, 鉴于土壤的空间异质性及气候变化的区域性, 农田土壤固碳潜力的定量估算仍存在相当大的不确定性.

农田土壤固碳潜力(soil organic carbon sequestration potential, SOC_P)是农田土壤在当地环境条件下所能具有的最大稳定碳库存能力. 目前, 主要有两种方法相对普遍地应用于估算地区或全球的土壤固碳潜力. 一种是基于长期定位试验的外推估算法, 一种是基于情景假设的模型模拟法[8].

由于合理的农田耕作管理措施, 如增施有机粪肥[9]、降低耕作强度[10]、增加轮作密度[10], 同时施用氮肥和作物残茬[11]可以有效固定大气 CO_2, 增加土壤碳蓄积量. 那么通过获取农田生态系统长期定位试验中一种或多种优化管理措施下的农田潜在固碳速率, 并外推到区域甚至全球尺度, 便可以结合农田

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面积估算出当地的农田土壤固碳潜力. Lal[12]和 Lu 等人[13]都通过这种试验外推的方法对中国的农田土壤固碳潜力进行了估算. 然而, 将点尺度(试验点)优化农田管理措施下的土壤潜在固碳速率, 无条件外推到其他地区, 可能与当地实际可操作耕作管理情况相违背. 单独考虑管理措施因素, 也忽视了气候、土壤等环境因素的空间变异对土壤有机碳的影响. 实际上, 气候和土壤因素会影响土壤呼吸作用和有机质分解作用, 从而影响土壤有机碳动态和固碳潜力. 忽略环境因素对土壤固碳潜力的影响势必导致潜力估算的不确定性.

而模型模拟方法则是利用 SOC 动态模拟模型, 如 CEVSA[14~16], CENTURY[17], DNDC[18,19], Roth[19]和 EPIC 等[20], 通过模拟特定优化农田管理措施下的土壤固碳速率或碳贮量来估算土壤固碳潜力. 尽管模拟模型具有一定的理论基础, 可以较好地估算区域潜力, 但该方法仍存在较大的局限性. 大多数模型输入参数多, 变量数据难以获取, 使得模型模拟法估算土壤固碳潜力的实际可操作性较差; 还有些模型在局部地区的 SOC 模拟效果较好, 却无法适用到其他地区[14], 模拟的区域局限性大, 无法进行大尺度外推[21].

本研究通过分析全球不同气候区的农田长期定位试验数据, 建立了一个旱作农田土壤固碳潜力的统计模型, 并用于估算中国河南省农田土壤固碳潜力, 主要目的是为定量估计农田土壤固碳潜力提供一个切实可行、易于操作的方法.

1　材料与方法

1.1　基本原理

图 1 是根据 Stewart 等人[22]、West 和 Six[23]的相关研究所作的 SOC 动态变化图. 从时间角度看(图 1(A)), 在一定的有机碳投入水平下, SOC 含量将随时间呈渐近线趋势变化: 在有机碳投入初期, 低碳土壤的 SOC 含量急剧增加, 并经历一段时间的碳积累阶段; 而后 SOC 增速减缓, 并逐步趋于相对稳定状态[24,25]. 如果外源有机碳投入水平再次增加, SOC 水平较低的土壤仍有可能继续这一过程, SOC 含量再次上升并累积达到新的相对稳定状态. 但是, 针对特定的土壤, 这种继续累积的过程并非必然, 也不是无上限的. 事实上, 当 SOC 含量上升到某一水平后, SOC 将不再随有机碳投入增加而累积, 而是稳定在此状态, 这一稳定状态即为 SOC 饱和状态[23].

从外源有机碳投入水平的角度看(图 1(B)), 稳定状态下的 SOC 含量随着有机碳投入水平的增加也呈渐近线趋势上升: 在外源有机碳低水平投入时期, 低碳土壤经历一段时间 SOC 累积后稳定在某一较低的 SOC 含量水平; 而后随着有机碳投入的继续增加, 土壤 SOC 累积量也增加, 稳定状态下的 SOC 水平也继续上升, 但上升速度趋缓; 当 SOC 水平达到饱和状态后, 稳定状态下的 SOC 含量不再随着有机碳投入的增加而上升[22].

然而, 土壤有机碳的这种“饱和”增长模式是以前的许多研究所忽略或未曾认识到的[22]. 以往关

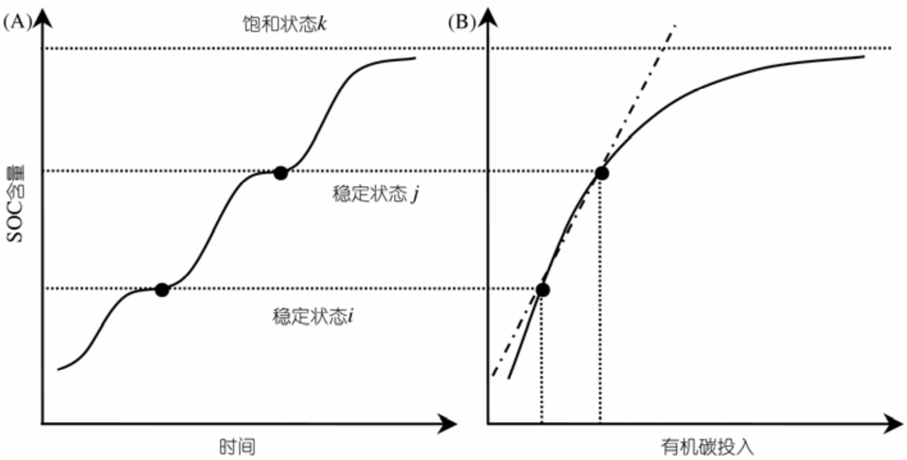

图 1　SOC 随时间和有机碳投入的动态变化[22,23]

(A) 不同有机碳投入水平下 SOC 随时间的变化; (B) 稳定状态下 SOC 随有机碳投入水平的变化

于土壤碳贮量和土壤固碳潜力的研究基于的假设是, SOC 含量与土壤有机碳投入量之间呈正比例; 或者说只要有足够有机碳投入, SOC 含量就可以无限制地增长(图 1(B)点画线所示). 对此, Stewart[22]认为, 以前的许多试验研究表明, SOC 与外源有机碳之间存在线性关系, 是因为大量定位试验的外源有机碳投入范围太小, 无法达到土壤固碳饱和时所需的有机碳投入水平, 从而将阶段性变化误读为线性趋势; 但只要外源有机碳的投入水平足够大, SOC 与有机碳投入之间的关系就表现为“饱和”趋势.

基于对土壤碳饱和的认识, 将饱和水平的 SOC 视为土壤固碳潜力(SOC_P). 点尺度的 SOC_P 可以通过具有高有机质投入的长期定位试验结果进行估计, 而 SOC_P 的空间变异则主要取决于气候和土壤等环境因素[2,8,14,26].

1.2 数据来源

(1) 长期定位试验数据. 为建立土壤固碳潜力模型, 从全球范围获取 95 处旱作农田长期定位试验数据, 形成长期定位试验数据库(附表 1). 这些试验点分布于全球温带、亚热带和热带气候区(http://www.sage.wisc.edu/iamdata/)(图 2), 且具有较高的外源有机碳(厩肥或秸秆)投入(年均 10~40 t/ha). 在这 95 个长期定位试验中, 22 个持续了 10~14 年, 73 个超过 15 年(附表 1). 根据 SOC 的变化, 将最后几年达到饱和的 SOC 测定值假定为该点的 SOC_P 值.

数据库中每个长期定位试验对应的数据包括: 地理数据(经度、纬度)、当地的气候数据(温度、降水)、土壤属性数据(黏粒含量、pH、全氮含量、容重)、试验和管理信息(试验年限、有机碳投入、轮作制度、灌溉情况、取样深度)及 SOC 数据.

正式发表的论文是建模数据库中土壤固碳潜力数据的唯一来源. 其他数据来自多种数据源, 包括正式发表文献、网站(地理、气候信息等)、FAO 全球土壤数据库软件[30](核对、完善土壤数据)、中国科学院南京土壤研究所在线中国土壤数据库(http://www.soil.csdb.cn/)等. 还就缺失和未发表的数据咨询了文章作者和相关研究人员. 对于基础数据库, 有针对性地查询了 SOMNET 全球数据库(http://www.rothamsted.bbsrc.ac.uk/aen/somnet/intro.html). SOMNET 是研究全球长期定位试验有关土壤有机质动态变化的数据库, 在多个国际性研究中起核心作用.

(2) 河南省空间数据库. 为利用模型定量估算河南省的 SOC_P, 建立了该省的空间数据库. 河南省(31°23′~36°22′N, 110°21′~116°39′E)位于中国中部地区, 其东部和中部地区属于华北平原(图 3). 该省处于暖温带-亚热带、湿润-半湿润季风气候区, 冬季寒冷干燥, 夏季炎热湿润. 全省年平均气温 12~16℃, 其中 1 月−3~3℃, 7 月 24~29℃; 年平均降水量 500~900 mm, 全年降水的 50%集中在夏季. 河南省面积约有 16.5×10^6 ha, 农田主要分布在华北平原地区, 以一年两熟(玉米和小麦)轮作为主.

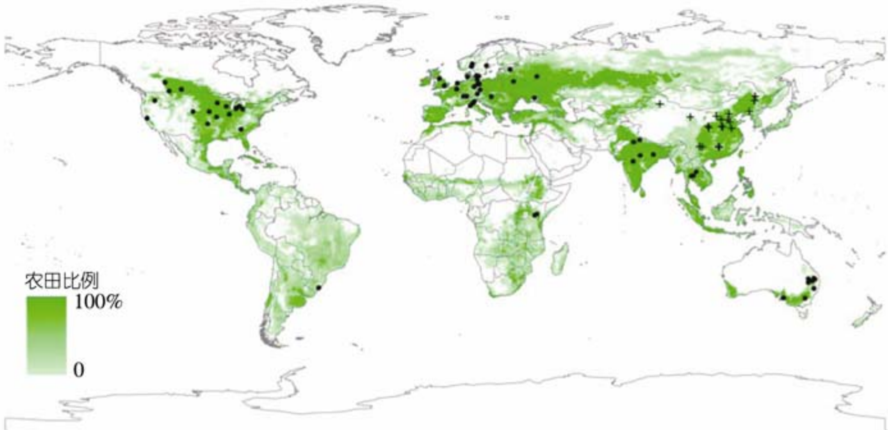

图 2 全球长期定位试验点分布

阴影背景示全球农田分布(农田比例为农田占所在栅格比例, 下文相同; 数据来源: [27~29]). 实心圆点示用于建模的国外试验点(n=76); 十字符号示用于模型验证的国内试验点(n=19)

河南省空间数据库包括气候、土壤和土地利用类型数据. 气候数据主要为年平均气温和年降水总量, 通过来自全国751个气象站点1990~1999年期间的温度和降水资料分析获得. 土壤数据包括SOC、黏粒含量和pH, 主要来自于中国科学院南京土壤研究所的1∶1000000中国土壤数据库. 该数据库基于全国第二次土壤普查信息, 具备完善的土壤空间数据, 土壤属性数据和土壤参考体系等信息[31~33]. 数据库的气候和土壤数据通过ArcGIS[34]空间分析方法, 转化为10 km×10 km栅格数据. 土地利用类型数据主要用于分析农田的空间分布. 根据中国科学院资源环境科学数据中心的土地利用类型遥感监测数据和Liu等人[35]对中国农田面积的估算, 将旱地所占比例大于42.8%的栅格视为河南省农田栅格, 而低于该值的作为非农田栅格.

1.3　点尺度SOC_P估算

根据全球95处长期定位试验, 点尺度的SOC_P通过下式[36]进行计算:

$$SOC_p = SOC \times H \times BD \times (1-F) \times 10^{-1}, \qquad ①$$

式中, SOC_P为单位面积的土壤固碳潜力(t/ha), SOC为相应的土壤有机碳含量(g/kg). H和F分别示土层厚度和土壤中>2 mm砾石的比例, BD表示土壤容重(g/cm^3). 对于缺少容重数据的土壤, 根据土壤有机质含量(SOM(%))进行估算[26,37]:

$$BD = \frac{100}{\frac{SOM}{0.244} + \frac{100 - SOM}{1.64}}. \qquad ②$$

不同厚度土层的土壤有机碳密度, 根据农田土壤有机碳的垂直分布换算为0~20 cm土层的密度[38,39]: $SOC_{0\sim10} : SOC_{10\sim20} : SOC_{20\sim30} : SOC_{30\sim40} = 23:18:13:10$.

1.4　统计方法及模型估算

单相关分析方法可以分析逐对变量之间的相关性; 偏相关分析方法则通过控制其他变量, 进一步确认单相关分析无法分辨的变量间关系. 为定量分析土壤固碳潜力与气候、土壤因子之间的关系, 对长期定位试验的相应变量进行了以上两种统计相关分析.

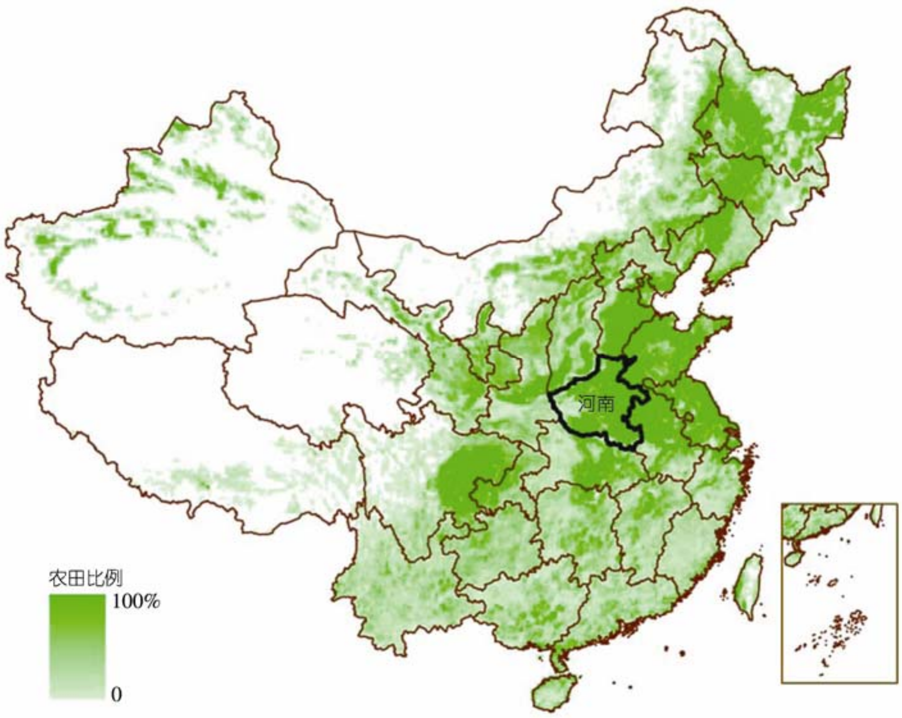

图 3　中国农田空间分布及河南省地理位置示意图

绿色背景示农田分布(数据来源: http://www.resdc.cn/); 粗线框为河南省所处位置

基于相关分析结果, 采用 levenberg-marquardt(LM)和 universal global optimization(UGO)算法(收敛判断指标设定为 1.00×10^{-10})[40,41]建立土壤固碳潜力模型. 在 95 个长期定位试验中, 76 个国外的定位试验用于相关性分析和模型参数确定, 19个国内长期定位试验用于模型验证. 采用敏感性分析方法[42]探讨模型对各驱动变量的响应. 基于河南省气候和土壤空间数据库, 利用模型对该省的 SOC_P 进行定量估算; 采用 ArcGIS[39]空间分析和统计方法, 分析其空间分布特征.

2 结果

2.1 SOC_P与土壤和气候因子的关系

表 1 的 r_{MT}, r_{MP}, r_{CL} 和 r_{pH} 分别表示土壤固碳潜力与年均气温、年降水量和灌溉量、土壤黏粒含量和 pH 之间的单相关系数和偏相关系数. 单相关和偏相关的分析结果均表明, SOC_P 与年均气温和土壤 pH 之间存在负相关关系. 虽然单相关分析无法确认土壤固碳潜力与降水灌溉量和土壤黏粒含量之间的相关关系, 但在控制变量后, 偏相关分析表明它们之间都表现出正相关. 这与以往有关土壤有机碳与气候和土壤因子之间关系的研究[3,43~46]相一致.

表 1 土壤固碳潜力与年均气温(MT)、年均供水量(MP)、土壤黏粒含量(CL)和 pH 之间的相关系数 a)

分析方法	r_{MT}	r_{MP}	r_{CL}	R_{pH}
单相关分析	-0.62^{***}	NS	NS	-0.22^{*}
偏相关分析	-0.65^{***}	0.26^{**}	0.31^{***}	-0.20^{*}

a) *: 显著性 $P<0.1$; **: 显著性 $P<0.05$; ***: 显著性 $P<0.01$; NS: 不显著

2.2 模型建立和验证

基于相关分析(表 1), 建立了用于估算 SOC_P的统计模型. 该模型结合了 SOC_P 对气候和土壤因子的线性及非线性响应(方程③).

$$SOC_P = 140.5\times e^{-0.021\times MT} - 98.8\times e^{-0.42\times MP} - 39.6\times e^{-0.10\times CL} - 4.1\times pH - 27.7 \quad (R^2=0.58,\ n=76), \qquad ③$$

式中, MT 表示年平均气温(℃), MP 表示年平均供水量(100 mm, 年平均降水量与年平均灌溉量之和), CL 表示土壤黏粒含量(%), pH 表示土壤 pH. 模型系数由 76 个国外长期定位试验数据确定.

用中国 19 个站点的长期定位试验(图 1 和附表 1)对 SOC_P 模型(方程③)进行了验证, 并用均方根误差(RMSE)[47]、平均绝对误差(MAE)[47]、模拟效率 EF[21]、拟合指数 IA[48]和线性回归[49]检验模型模拟的准确性和精确性. 验证结果表明, SOC_P模型可以通过当地的气候和土壤因素较好地模拟旱作农田土壤的固碳潜力. RMSE, MAE, EF 和 IA 分别为 7.0, 5.7, 0.71 和 0.92 t/ha, SOC_P 模拟值与观测值之间的回归斜率和截距分别为 0.82 和 5.2 t/ha, 决定系数为 0.74(图 4).

2.3 模型敏感性

为探讨模型中各变量对土壤固碳潜力模拟结果的影响, 采用以下方法对模型进行敏感性分析. 以国外 76 个长期定位试验的气候和土壤数据(表 2)为基础, 改变其中 1 个变量, 而设定其他 3 个变量为常数(分别取 76 个数据的均值), 利用 SOC_P 模型分别模拟土壤固碳潜力随年均气温、年均供水量、土壤黏粒含量和 pH 的变化趋势. 在方程③中设定年均供水量(MP)为 7.5、土壤黏粒含量(CL)为 23.2, pH 6.6, 在年均气温 2.1~28.3℃范围内模拟 SOC_P 的变化, 据此说明固碳潜力对温度的敏感性(图 5(A)).

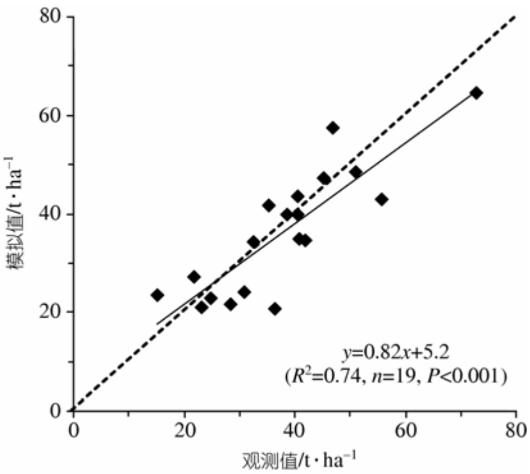

图 4 SOC_P模拟值与观测值的比较

虚线为 1∶1 线

表 2 气候和土壤因子的统计特征

统计值	MT/℃	MP/100 mm	CL(%)	pH
最小值	2.1	3.6	0.6	4.9
平均值	12.4	7.5	23.2	6.6
最大值	28.3	16.0	72.0	8.4

灵敏度分析表明, 随着年均气温的升高, 固碳潜力呈指数下降, 但下降速率相对稳定(图 5(A)). 当年均供水量小于 1000 mm 时, 固碳潜力随供水量的增加呈指数增加, 但增加速率逐渐变小; 当年均供水量大于 1000 mm 时, 增加速率逐渐趋于零(图 5(B)). 表明低温湿润地区农田具有相对较高的土壤固碳潜力, 而高温干旱地区则相反; 在年均供水量大于 1000 mm 的地区, 水分条件不是土壤固碳潜力的限制因子. 与对水分的响应相似, 当土壤黏粒含量较低时, 固碳潜力随黏粒含量升高呈指数增加, 但增加速率逐渐变小; 当黏粒含量大于约 30%时, 增加速率逐渐趋于零(图 5(C)). 与此相反, 固碳潜力随土壤pH升高呈线性下降趋势(图 5(D)). 表明高黏粒含量、低 pH 土壤比低黏粒含量、高 pH 土壤具有更高的固碳潜力; 黏粒含量大于 30%的地区, 土壤固碳潜力受土壤黏粒的影响较小.

2.4 河南省农田SOC_P估算

利用方程③和区域气候、土壤空间数据对河南省农田表土(0~20 cm)固碳潜力(SOC_P)进行估算, 并采用类似于方程①的方法估算 20 世纪 90 年代(全国第 2 次土壤普查)各栅格农田 SOC 密度(SOC_B), 两者之差($\Delta SOC=SOC_P-SOC_B$)即为未来最大固碳能力. 结果表明, 该省SOC_B和SOC_P空间分异明显, 整体表现为南高北低(图 6(A)和(B)), 中、东部地区具有相对较大的固碳空间(图 6(C)).

20 世纪 90 年代, 河南省农田表土有机碳密度均值为 20.0 t/ha, 90%的栅格在 4~28 t/ha 之间(图 7(A)); 达到饱和状态的有机碳密度均值估计为 31.8 t/ha, 90%的栅格在 20~44 t/ha 之间(图 7(B)). 平均而言, 该省潜在的农田土壤碳汇密度为 11.8 t C/ha. 按图 6(C)结果统计, 当该省农田土壤有机碳达到饱和时, 表层土壤(0~20 cm)可以增加固碳 103.4 Tg.

3 讨论

3.1 不确定性及局限性

模型模拟的不确定性主要源自伴随模型建立过程的 3 部分误差: 模型误差、参数误差和输入误差[50]. 理论上, 土壤固碳潜力是指处于碳饱和水平(图 1(A)饱和状态 *k*)时的 SOC 水平, 它不随时间和有机碳投入的变化而改变, 也不因管理措施的不同而有差异. 然而在实际的农田生态系统中, 限于地区的环境条件和农田管理措施, 有机碳投入并非无限的, SOC 含量往往并不能或者无法确认达到土壤固碳潜力的理论值, 而极有可能仅仅达到土壤固碳的中间稳定水平(如图 1(A)中状态 *i* 或 *j* 的 SOC 水平), 这就可能导致土壤固碳潜力的低估. 在这种情况下, 模型所模拟

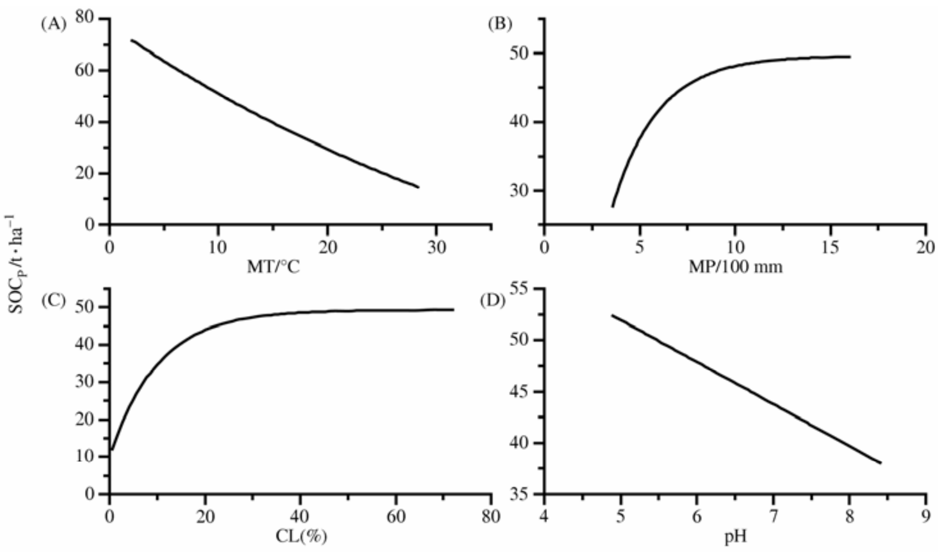

图 5 模型敏感性

(A)~(D) 分别示土壤固碳潜力对年均气温(MT)、年均供水量(MP)、土壤黏粒含量(CL)和 pH 敏感性

的农田土壤固碳潜力是当地环境条件下可达到的最大土壤固碳水平, 而不是碳饱和状态时的土壤固碳水平.

长期定位试验覆盖全球大部分农业区(图 2, 附表 1), 所测定的土壤固碳潜力具有一定代表性. 然而, 由于研究者的经验偏好不同、试验条件限制、研究方法差异等原因, 来自文献报道的同类数据间可能存在较大的系统差异, 使得数据质量存在着较大的不一致性[51]. 尽管很难完全消除这种不一致性, 但筛选数据时采取了一系列标准和措施对数据质量进行控制: (1) 田间试验持续时间长于 10 年; (2) 对部分存疑数据进行不同来源资料的校对、检验, 如文献中土壤数据多经过 FAO 土壤数据库或中国土壤数据库再次核对; (3) 不同标准的数据尽量一致化处理, 如将不同土层 SOC 换算为 0~20 cm SOC. 这些措施可以从一定程度上改善数据质量, 从而增强模型的可靠性.

河南省固碳潜力估算的不确定性主要源自 3 个方面: (1) 所需土壤和气候空间数据皆通过站点数据经空间插值得到, 这难以完全模拟实际变量的空间变异性[52,53], 因而造成潜力估算的空间不确定性; (2) 由于缺乏河南省年均灌溉量的空间数据, 采用年均降水量, 而非年均供水量(方程③中 MT)来计算土壤固碳潜力, 这可能造成对 SOC_P 的低估. 局部栅格水平的 SOC_P 要低于 20 世纪 90 年代的 SOC 值(图 6(C)), 这有悖于土壤固碳潜力的定义. 若考虑固碳潜力对年均供水量的敏感性(图 5(B)), 引入灌溉量数据后估算的 SOC_P 值将高于目前的估计值; (3) 由于土地利用类型的空间分辨率较低, 有可能将 SOC 含量高的林

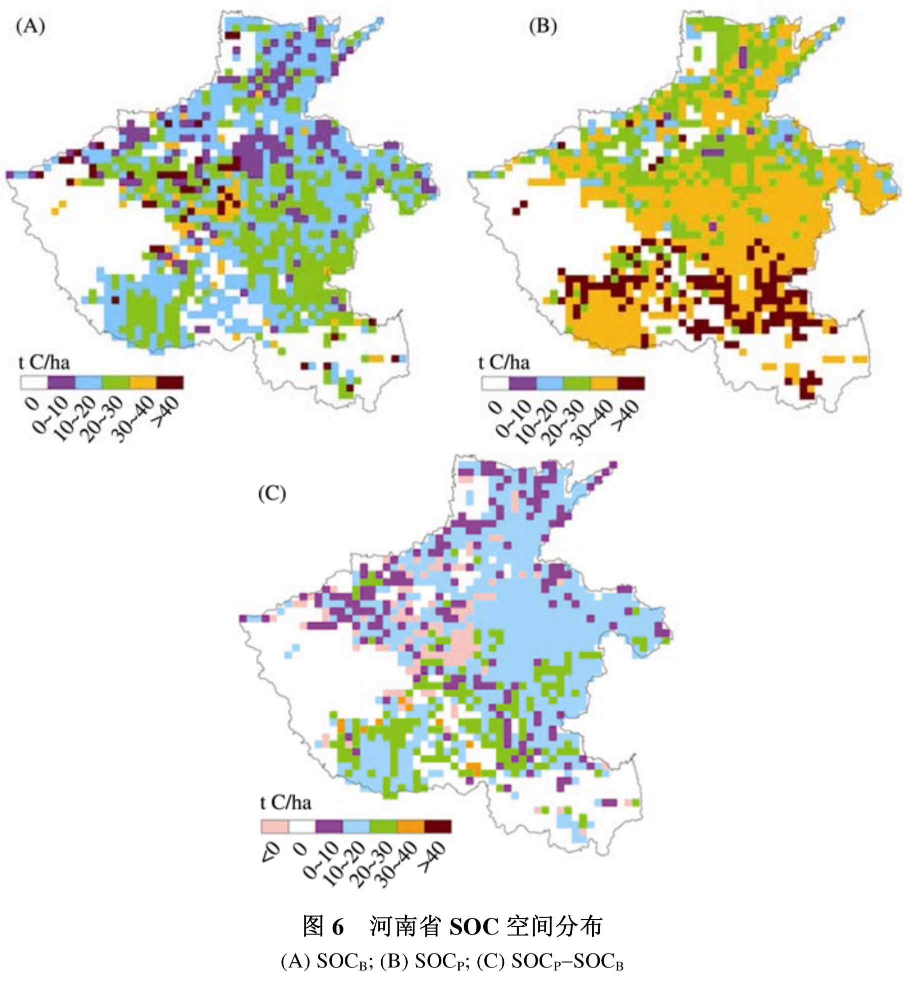

图 6　河南省 SOC 空间分布

(A) SOC_B; (B) SOC_P; (C) SOC_P–SOC_B

地和草地误读为农田. 在固碳空间为负值的栅格中(图 6(C)), 农田面积所占比例平均为 66%, 这必然会导致 SOC_P 估算的偏差.

由于可用于 SOC_P 估算的水田长期定位试验相对较少, 本研究的 SOC_P 模型(方程③)仅针对旱地土壤, 直接采用该模型预测水田 SOC_P 可能会造成偏差. 只有通过水田试验数据进行校正后, 该模型方可用于水田 SOC_P 的估算.

3.2　土壤固碳时间分析

合理的管理措施可以促进农田土壤固碳, 从而增加SOC储量[2,7,12,13]. 一般认为, 在采用优化农田管理措施时, 土壤达到的固碳速率即可视为潜在固碳速率, 在该速率下的土壤固碳量即为固碳潜力[12~14]. 根据 Lal[12], Lu 等人[13]和 Yan 等人[14]估计, 农田土壤潜在固碳速率为 120~610 kg C·ha^{-1}·a^{-1}. 按此潜在固碳速率和估计的固碳潜力(图 6(B)), 河南省农田土壤大约需要 19~98 年达到其固碳潜力(表 3). 这一持续时间与 Yan 等人[14]、West 和 Six[23]的结果大体一致. 但按照土壤固碳速率随 SOC 储量增加渐减的规律[22], 该省农田土壤达到固碳潜力的时间可能会更长些.

4　结论

基于对土壤碳饱和原理的理解和全球长期定位试验数据的分析, 构建了用于定量估算旱地土壤固

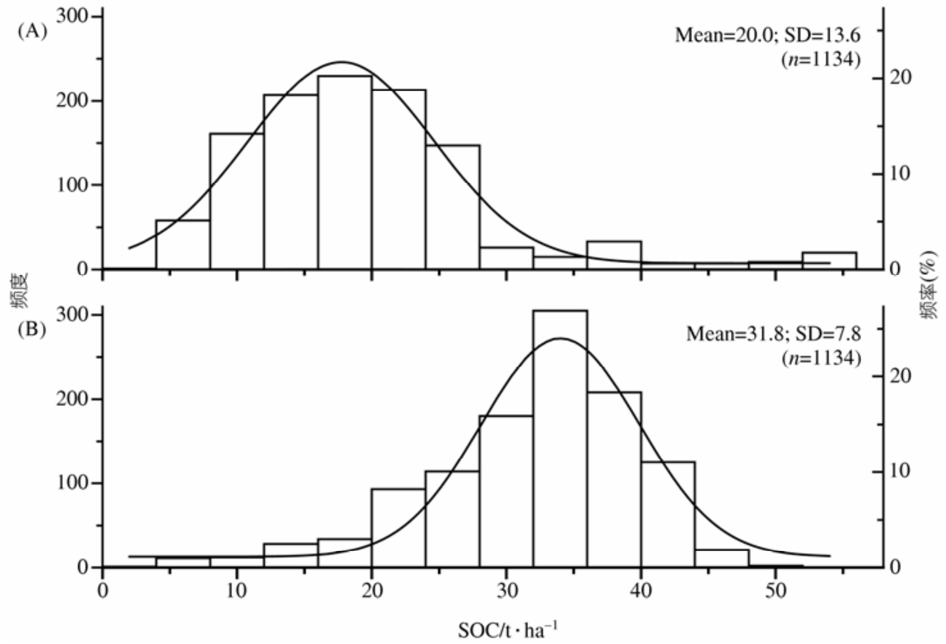

图 7　河南省 SOC 和 SOC_P 的频率分布

(A) SOC 频率分布; (B) SOC_P 频率分布. Mean: 平均值; SD: 标准差; *n* 为栅格数

表 3　河南省农田土壤达到固碳潜力所需的时间 a)

农田管理措施	外推方法	固碳速率/kg C·ha^{-1}·a^{-1}	相关研究	估计的固碳时间/年
推荐农田管理措施	试验外推到全国	200~300	[12]	59~39
秸秆还田	试验外推到河南省	610	[13]	19
施氮肥		209		56
50%CR	模型模拟估算全国	130	[14]	91
100%CR		319		37
50%NT		120		98
100%NT		240		49
50% NT+ 50% CR		182		65
100% NT + 100% CR		401		29

a) 100%NT: 对 100%农田实施免耕; 100%CR: 秸秆 100%还田. 固碳时间为计算所得

碳潜力的统计模型. 模型验证表明, 土壤固碳潜力可以通过气温、降水和灌溉、土壤黏粒含量和 pH 进行较好的模拟. 对河南省农田土壤固碳潜力的估算结果表明, 该省固碳潜力总体呈现南高北低的趋势, 平均碳饱和水平约为 32 t C/ha(0~20 cm 土层). 通过改进农田管理措施, 可望在 19~98 年达到此碳饱和水平. 以 20 世纪 90 年代的 SOC 水平为参照, 该省农田土壤碳增汇潜力约为 100 Tg C. 由于在建模所用的长期定位试验数据中, 有些试验点的碳投入可能未达到理论最大值, 因而用该模型估算的土壤碳饱和水平可能偏低.

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附表 1　长期定位试验数据库基本信息

位置	纬度	经度	年均气温/℃	年均供水量/100 mm	土壤黏粒含量/%	土壤 pH	年限	作物	碳投入类型	参考资料
澳大利亚	31°06′S	150°56′E	17.5	6.76	50.0	8.4	29	谷物	秸秆	[1~3]
澳大利亚	34°58′S	138°38′E	16.8	6.04	18.0	6.2	70	小麦, 燕麦	有机碳	[1~3]
澳大利亚	27°07′S	148°40′E	20.3	5.60	18.0	6.5	20	高粱, 向日葵, 小麦, 大麦, 燕麦	残茬	[4~6]
澳大利亚	28°38′S	148°40′E	20.5	4.77	59.0	7.2	23	高粱, 向日葵, 小麦, 大麦, 燕麦	残茬	[4~6]
澳大利亚	28°24′S	150°17′E	19.9	5.80	34.0	7.4	25	高粱, 向日葵, 小麦, 大麦, 燕麦	残茬	[4~6]
澳大利亚	27°15′S	151°24′E	18.5	5.97	40.0	7.4	35	高粱, 向日葵, 小麦, 大麦, 燕麦	残茬	[4~6]
澳大利亚	26°52′S	150°55′E	19.4	6.15	49.0	7.4	45	高粱, 向日葵, 小麦, 大麦, 燕麦	残茬	[4~6]
澳大利亚	27°12′S	151°12′E	19.0	6.12	72.0	8.1	70	高粱, 向日葵, 小麦, 大麦, 燕麦	残茬	[4~6]
澳大利亚	35°05′S	147°20′E	16.0	5.50	29.0	4.9	21	小麦	秸秆(残茬)	[7,8]
澳大利亚	31′06′S	150°56′E	17.5	6.76	44.3	6.9	34	小麦	秸秆	[9~13]
白俄罗斯	53°31′N	28°07′E	5.5	6.96	5.0	5.4	14	马铃薯, 燕麦	有机肥	[14,15]
比利时	50°24′N	4°43′E	9.1	7.67	13.5	6.6	32	甜菜, 谷物	有机肥	[3,16,17]
巴西	30°51′S	51°38′W	19.4	14.40	22.0	5.3	18	燕麦, 玉米, 豇豆	秸秆	[18~20]
加拿大	53°07′N	114°28′W	2.1	5.47	12.0	5.9	69	小麦, 燕麦, 大麦	粪肥	[21,22]
加拿大	50°17′N	107°48′W	3.5	3.58	42.0	7.0	12	小麦	秸秆	[23~25]
加拿大	50°18′N	107°49′W	3.5	3.58	10.0	5.8	12	小麦	秸秆	[24]
加拿大	49°42′N	112°47′W	5.0	4.02	30.0	7.0	37	小麦	有机肥	[14,26,27]
加拿大	42°13′N	82°44′W	8.9	8.76	37.0	5.7	45	玉米, 大豆	秸秆	[28,29]
中国	40°13′N	116°14′E	11.0	6.00	20.0	8.8	13	小麦, 玉米	有机肥	[30~34]
中国	38°56′N	100°27′E	7.0	5.37	15.0	8.4	22	小麦, 玉米	有机肥	[35~37]
中国	37°46′N	115°44′E	12.6	5.18	10.0	8.1	24	小麦, 玉米	绿肥	[38~41]
中国	47°27′N	126°56′E	1.5	5.30	20.0	6.8	18	小麦, 玉米, 大豆	有机肥	[42,43]
中国	45°40′N	126°35′E	3.5	5.33	9.3	7.2	22	小麦, 玉米, 大豆	有机肥	[44,45]
中国	35°04′N	113°10′E	14.5	10.05	9.0	8.7	14	小麦, 玉米	有机复混肥	[46,47]
中国	34°48′N	113°40′E	14.0	6.34	10.0	8.3	14	小麦, 玉米	有机肥	[48,49]
中国	26°31′N	112°22′E	18.0	13.37	20.5	5.7	13	小麦, 玉米	有机肥	[50,51]
中国	26°45′N	111°53′E	18.0	12.55	35.7	5.7	14	小麦, 玉米	有机肥	[52~54]
中国	34°16′N	117°11′E	14.0	12.67	6.0	8.3	20	小麦, 玉米	有机肥	[55~57]
中国	41°19′N	124°30′E	4.5	5.50	31.0	7.6	22	玉米, 大豆	有机肥	[58~61]
中国	35°12′N	107°40′E	9.2	5.86	24.0	8.4	18	不详	有机肥	[62]
中国	34°18′N	108°01′E	13.0	9.98	16.8	8.6	12	小麦, 玉米	有机肥	[63]
中国	36°54′N	116°36′E	13.1	5.91	10.0	7.8	14	小麦, 玉米	有机肥	[64]
中国	37°54′N	113°06′E	7.3	5.20	10.0	7.9	12	玉米	有机肥, 干草	[65,66]
中国	44°17′N	87°56′E	6.6	3.60	10.0	8.5	13	小麦	秸秆	[67,68]
中国	39°18′N	111°06′E	8.8	4.60	10.0	8.1	12	马铃薯	有机肥	[69]
中国	26°42′N	105°18′E	13.6	12.67	25.0	7.6	11	小麦, 玉米	有机肥	[70]
中国	26°48′N	104°12′E	11.2	9.51	32.5	7.7	11	马铃薯, 玉米	有机肥	[70]
捷克	50°05′N	14°20′E	8.1	4.50	31.3	6.9	51	甜菜, 大麦	有机肥	[2,3,71~73]
捷克	50°05′N	14°20′E	8.8	5.49	22.3	6.6	46	不详	有机肥	[2,74,75]
丹麦	55°28′N	09°07′E	7.7	8.62	12.0	6.5	73	谷物	有机肥	[76,77]
丹麦	55°28′N	09°07′E	7.7	8.69	4.0	6.5	102	谷物	有机肥	[3,77]
爱沙尼亚	58°23′N	26°40′E	4.8	5.82	10.0	6.3	10	马铃薯, 小麦, 大麦	有机肥	[78,79]
法国	54°28′N	2°18′W	11.0	6.40	25.3	8.2	121	小麦, 玉米	有机肥	[3,80~82]
德国	51°24′N	11°53′E	8.7	4.84	21.0	6.6	93	甜菜, 大麦, 马铃薯, 小麦	有机肥	[2,3,72,83,84]
德国	51°31′N	12°00′E	9.2	4.94	12.0	6.0	12	马铃薯, 小麦, 玉米, 大麦, 甜菜	有机肥	[85,86]
德国	51°31′N	12°00′E	9.2	4.94	8.0	6.3	120	黑麦	有机肥	[85~87]
德国	48°22′N	13°12′E	8.7	8.86	16.4	6.9	41	小麦, 玉米	秸秆	[88]
德国	52°28′N	13°18′E	8.7	4.96	2.7	5.0	62	小麦, 马铃薯	有机肥	[3,89]
德国	52°30′N	14°8′E	8.4	5.11	5.0	5.6	38	甜菜, 小麦, 大麦, 黑麦	有机肥	[90~95]
匈牙利	47°19′N	19°00′E	10.3	9.31	31.0	5.8	44	不详	有机肥	[96,97]
印度	20°42′N	77°02′E	25.5	9.75	52.4	8.1	14	高粱, 小麦	有机肥	[98,99]
印度	23°30′N	85°15′E	23.1	16.00	25.3	5.3	30	大豆, 小麦	有机肥	[98~100]
印度	23°12′N	79°57′E	25.0	14.03	58.9	7.6	28	大豆, 小麦, 玉米	有机肥	[101,102]
印度	29°36′N	79°40′E	16.0	10.19	5.8	6.2	33	大豆, 小麦	有机肥	[103~109]
印度	28°38′N	77°09′E	25.5	10.10	14.0	8.3	34	豇豆, 玉米, 小麦	有机肥	[110~115]

续附表 1

位置	纬度	经度	年均气温 /℃	年均供水量 /100 mm	土壤黏粒含量 /%	土壤 pH	年限	作物	碳投入类型	参考资料
意大利	45°21′N	11°58′E	12.8	8.50	52.0	7.9	37	玉米, 小麦, 西红柿, 甜菜	有机肥	[116,117]
意大利	45°21′N	11°58′E	12.8	8.50	0.6	8.1	37	玉米, 小麦, 西红柿, 甜菜	有机肥	[116,117]
意大利	45°21′N	11°58′E	12.8	8.50	15.0	7.8	39	玉米, 小麦	有机肥	[116,117]
意大利	45°21′N	11°58′E	12.4	8.50	29.2	7.8	27	玉米, 甜菜, 大豆	秸秆	[116,118]
意大利	44°33′N	11°21′E	13.0	7.00	28.0	6.9	34	小麦, 玉米, 甜菜	有机肥	[119]
意大利	43°40′N	10°19′E	20.0	9.07	13.9	7.7	26	向日葵, 小麦, 玉米	秸秆	[120,121]
肯尼亚	01°15′S	36°46′E	19.5	9.81	40.0	5.9	25	玉米	有机肥, 秸秆	[14,122,123]
肯尼亚	0°47′S	37°40′E	24.3	7.30	30.8	6.6	13	高粱, 豇豆, 玉米, 木豆	有机肥	[122,124]
荷兰	52°51′N	5°18′E	9.0	8.00	20.0	7.0	65	大麦	有机肥/ 城市固废	[125~128]
挪威	59°40′N	10°46′E	5.3	9.40	25.0	5.5	48	谷物	有机肥	[129,130]
挪威	60°47′N	11°11′E	4.5	6.00	14.0	6.1	74	燕麦, 马铃薯, 小麦, 大麦	有机肥	[37,131,132]
俄罗斯	55°30′N	37°36′E	4.9	5.38	19.0	6.2	28	马铃薯, 小麦, 大麦	有机肥	[15,133]
瑞典	55°42′N	13°43′E	7.3	7.64	13.5	5.6	18	大麦, 小麦, 马铃薯	有机肥	[134,135]
瑞典	54°24′N	13°14′E	8.1	5.90	15.0	5.8	37	不详	有机肥	[14,136]
瑞典	60°′N	17°′E	6.7	5.55	37.0	6.6	37	谷物, 饲用甜菜	有机肥	[3,96,137]
瑞典	54°24′N	13°14′E	8.1	5.90	17.0	7.5	34	小麦, 燕麦, 甜菜	有机肥	[138,139]
瑞典	55°49′N	13°30′E	7.1	7.77	13.0	6.2	34	小麦, 燕麦, 甜菜	有机肥	[138]
瑞典	55°38′N	13°25′E	7.2	6.57	8.0	6.6	34	小麦, 燕麦, 甜菜	有机肥	[138]
瑞典	55°53′N	12°52′E	8.0	5.69	15.0	7.2	38	小麦, 燕麦, 甜菜	有机肥	[138,140]
瑞士	47°30′N	7°33′E	9.5	7.85	20.0	6.4	21	马铃薯, 小麦, 大麦	有机肥	[14,141]
瑞士	47°29′N	8°54′E	8.4	11.83	16.0	6.0	19	小麦, 玉米	秸秆	[16,142,143]
泰国	16°29′N	102°50′E	27.6	11.84	6.9	5.4	27	木薯	木薯秸秆	[14,144]
泰国	14°48′N	100°48′E	28.3	12.60	11.4	5.1	27	玉米	水稻秸秆	[14,144]
泰国	14°52′N	101°39′E	27.0	10.80	11.4	7.0	28	木薯	木薯秸秆	[14,144]
英国	51°49′N	0°21W′	9.2	7.04	23.0	8.0	141	大麦	有机肥, 秸秆	[3,145]
英国	51°49′N	0°21W′	9.1	7.28	18.0	7.5	150	小麦	有机肥, 秸秆	[3,145~147]
乌克兰	46°49′N	36°40′E	6.7	3.89	39.0	7.6	33	玉米, 小麦, 甜菜, 大麦	有机肥	[14,15]
美国	38°32′N	121°47′W	16.0	4.50	21.0	7.0	12	西红柿, 红花, 玉米, 燕麦, 豌豆, 豆类	有机肥, 秸秆	[148]
美国	45°43′N	118°38′W	11.0	4.22	18.0	6.0	70	小麦	有机肥	[149~152]
美国	40°06′N	88°12′W	11.1	9.39	27.0	5.8	122	玉米, 燕麦	有机肥	[153,154]
美国	38°57′N	93°20′W	12.4	9.16	18.0	5.6	110	玉米, 燕麦	有机肥	[153,155]
美国	36°07′N	97°04′W	15.6	8.65	20.0	6.2	110	小麦	有机肥	[156~159]
美国	44°43′N	93°04′W	7.0	8.20	25.0	6.4	14	玉米	秸秆	[160]
美国	33°56′N	83°22′W	16.3	12.45	22.0	7.0	16	高粱, 大豆, 玉米	秸秆	[161,162]
美国	43°18′N	89°21′W	7.6	7.91	29.0	6.8	32	玉米	秸秆	[163~167]
美国	43°20′N	84°07′W	8.7	7.88	26.5	6.8	20	玉米, 甜菜	有机肥, 秸秆	[168,169]
美国	42°40′N	85°28′W	8.6	7.82	7.5	6.5	30	谷物	有机肥	[169,170]
美国	41°12′N	96°24′W	10.2	8.16	30.0	7.1	26	玉米	有机肥	[153,171]
美国	42°24′N	85°24′W	9.2	9.20	14.0	6.2	12	玉米, 大豆, 小麦	有机肥	[172~176]
美国	41°14′N	103°00′W	9.0	4.40	15.0	6.3	31	小麦	秸秆	[177~180]

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