经营措施对森林生态系统碳储量影响的研究进展

王祖华,刘红梅,王晓杰,郝俊鹏,关庆伟
(南京林业大学 森林资源与环境学院,江苏 南京 210037)

[摘 要] 基于国内外相关研究成果,回顾与分析了树种选择、施肥、延长轮伐期、间伐和收获对森林植被碳储量、凋落物碳储量和土壤有机碳含量的影响,认为目前有关经营措施对森林生态系统碳储量的影响机理研究仍然比较模糊,还需要进行长期的跟踪研究。

[关键词] 树种选择;间伐和收获;轮伐期;碳储量;森林生态系统
[中图分类号] S714 [文献标识码] A [文章编号] 1671-9387(2011)01-0083-06

Progress of management on carbon storage of forest ecosystems

WANG Zu-hua, LIU Hong-mei, WANG Xiao-jie,
HAO Jun-peng, GUAN Qing-wei
(*College of Forest Resources and Environment, Nanjing Forestry University, Nanjing, Jiangsu* 210037, *China*)

Abstract: Based on the correlative results of home and abroad, the authors summarized the effects of tree species selection, fertilization, change rotation, thinning and harvesting on carbon stock of forest vegetation, forest litter and SOC. The results of relevant studies suggest that the mechanism of management impacts on carbon storage of forest ecosystem is still vague, and a long track study is needed.

Key words: tree species selection; thinning and harvesting; rotation; carbon storage; forest ecosystem

以 CO_2 为主的温室气体的增加,导致全球气候变暖、降水分布不均、生物多样性丧失等现象的发生,已威胁到人类的生存和发展,因而引起了国际社会的普遍关注[1-2]。全球森林面积约占陆地面积的 26%,但其碳储量占陆地植被碳储量的 80%以上,且森林生态系统每年固定的碳约占整个陆地生态系统的 2/3[3],因此,森林生态系统对减缓气候变化具有重要作用。

然而,森林生态系统的固碳能力受到森林经营措施的影响[4]。在《京都议定书》的框架下,随着碳贸易市场的逐渐成熟,关于经营措施如何影响森林生态系统的固碳能力,现已成为经营者及政府关心的焦点问题[5]。我国人工林面积居世界第 1 位,但其结构不稳定、生产力低[6],而提高人工林的经营管理水平、增强其土壤有机碳储量,是减缓全球气候变化的一种可能机制和最有希望的选择[7]。目前,多数研究表明,经营措施对森林碳储量的影响效果不同[4,8],且因森林资源的空间异质性和时间的动态性,很难用某个点的试验性研究结果来解释某种经营措施的影响机制[9]。

目前,虽然已有关于经营措施对森林土壤有机碳储量影响的综述[4,8,10],但还鲜见关于经营措施影响森林生态系统碳储量的系统研究。为此,笔者在分析国内外相关研究成果的基础上,综合分析了树种选择、施肥、轮伐期调整、间伐和收获对森林植被、凋落物和土壤层碳储量的影响,以期为科学制定营

* [收稿日期] 2010-06-04
[基金项目] 林业公益性行业科研专项"南方低效生态公益林改造与恢复技术研究与示范"(200904015)
[作者简介] 王祖华(1981-),男,安徽安庆人,博士,主要从事森林生态系统碳、氮循环研究。E-mail:zuhua131627@126.com
[通信作者] 关庆伟(1964-),男,满族,辽宁沈阳人,教授,博士生导师,主要从事城市生态学和恢复生态学研究。
E-mail:guanjapan999@yahoo.com.cn

林措施提供参考。

1 树种对森林生态系统碳储量的影响

选择生长速率快、寿命长的树种造林,是提高森林固碳量的最有效途径。如阔叶林的年固碳量分别是杉木林和马尾松林的 4.48 和 4.57 倍[11];毛竹林的年固碳量是杉木人工林、热带山地雨林和马尾松林的 2～4 倍[12]。按树种的耐阴程度、演替次序等属性进行混交配置造林,可使林内的资源利用率提高 30%,从而提高生物量[13]。

不同森林类型因凋落物质量、根系等特征的不同而影响土壤有机碳含量。许多研究均证实,阔叶林土壤有机碳储量大于针叶林[4,14-15]。这是由于森林土壤的有机碳主要来源于凋落物分解和根的周转,而针叶林的凋落物中含有较多难以分解的物质,使其分解速率减小[15],导致土壤碳储量较少;阔叶林则可以分配更多的生物量到根,使土壤碳库中来自根周转的碳量增加[4]。

Xu 等[16]发现,种植竹子可使土壤有机碳(SOC)、易氧化 SOC、可溶性 SOC 含量增加。但也有研究发现,针叶林土壤有机碳含量大于阔叶林[17],这可能与不同树种在不同立地条件下对土壤化学性质、微生物活性和生物量的影响存在差异有关[18]。Chigineva 等[19]发现,不同树种凋落物分解过程中的微生物活性不同,如山杨林凋落物分解过程中的真菌数是云杉林的 1.84 倍 ,其对 SOC 的稳定性有一定影响。纯林土壤的 pH 和动物活性均低于混交林,导致通过土壤动物将土壤表层有机质带到矿质土壤层的量减少[20]。不同树种还通过根系影响 SOC 的垂直分布[14],如浅根系的树种可以增加土壤表层有机碳含量,而深根系树种对深层土壤有机碳含量有一定影响[4]。

2 施肥对森林生态系统碳储量的影响

Footen 等[21]发现,在氮贫乏的林地施加氮肥,不仅可提高花旗松幼苗的生长量,而且还能增加其净生态系统生产力(NEP)[22]。然而,当过度施氮肥或由于大气氮沉降造成氮肥超出林木的吸收能力时,就会出现氮饱和现象而导致林分衰退[23]。

施肥对枯枝落叶层和土壤有机碳含量的影响机理比较复杂。在北方和温带森林里,含氮量高的树叶分解速率高,而在亚热带森林中,磷含量对树叶分解速率起着关键作用[24]。Kaspari 等[25]研究表明,钾肥可以促进纤维素分解,一些微量元素,如铁、镁等可以促进叶分解,而磷对两者的分解均具有促进作用。也有研究表明,施加氮肥可减缓凋落物的分解速率[26]。Canary[27]发现,冷杉林施氮肥 16 年后,其生物量碳增加,而 SOC 无显著变化;类似结果在美国佛罗里达州湿地松人工林的施肥试验中也有发现[28]。施碱石灰可提高土壤微生物活性,但也会造成可溶性有机碳(DOC)流失,导致林地有机碳减少[29-30]。

然而,近年来的研究却发现,施加氮肥会增加土壤有机碳储量[7,31]。如 Tan 等[32]发现,森林退化为耕地后土壤有机碳含量降低,而施入氮肥后,土壤有机碳含量增加。但将氮肥与磷肥、钾肥混合施用时,土壤有机碳储量又会降低[31]。除氮肥外,施加有机肥、农家肥等也能增加土壤有机碳含量[33-34]。另外,在研究施肥对森林生态系统碳储量的影响时,还应考虑肥料生产和使用过程中的碳排放[35]。

3 延长轮伐期对森林生态系统碳储量的影响

森林成熟前,树种或林分的生产力会逐年提高,当其年蓄积量的增加量等于平均每年增加量后,其生长速率开始下降,固碳速率也随之下降[36]。然而为获取木材,大部分地区在森林经营中选择的轮伐期均未到达这个“生长顶点”。因此,应延长轮伐期以增加林分的固碳量。Jiang 等[37]采用模型模拟不同轮伐期对北方森林碳储量的影响时发现,采用 30 年轮伐期时的碳储量仅占 100 年轮伐期的 12%。在林分到达生物量开始下降的阶段之前,延长轮伐期可增加森林碳储量[4];但到达生长量顶点后,森林生态系统碳储量将会减少[38]。因此,应合理选择轮伐期。

然而,延长轮伐期对土壤有机碳的影响效果不同。Schulze 等[39]发现,延长轮伐期意味着减少对林分的干扰,有利于土壤碳储量增加。Diochon 等[40]对北美红云杉林的研究表明,将轮伐期由 60 年延长至 100 年,会增加土壤有机碳储量。而模型研究结果却表明,随着轮伐期增加,土壤有机碳储量却呈减少趋势[41-42]。

4 间伐对森林生态系统碳储量的影响

间伐可从林内移出一定比率的木材蓄积量,因此也就减少了植被的碳储量。有研究指出,间伐使加拿大黄松林的 NEP 减少了 1/3,且直至 16 年后仍未能恢复到间伐前的水平[43]。模型研究发现,间

伐后约 60 年，植被碳储量才能达到原有水平[44]。但间伐可使林地光能利用率提高 60%[43]，且林下更新会弥补移出木带走的碳储量[45]。

间伐后林分密度减小，地面温度升高，因而会加快枯枝落叶的分解，减少凋落物量。Jandl 等[4]发现，凋落物碳储量随间伐强度的增加而减少。Alam 等[46]利用 Sima 模型研究发现，随间伐强度的增加，100 年后芬兰森林生态系统碳储量将会减少。

间伐后土壤温度和湿度升高，使土壤有机质分解加快，导致土壤有机碳储量减少[47]。然而，Vargas 等[48]的研究表明，伐去林内直径小于 2 cm 的林木，5 年后土壤有机碳储量高于未间伐林地。与未间伐林分相比，林冠层间伐的方式减少了土壤有机碳储量，而林下层间伐的方式反而使土壤有机碳储量有所增加[49]。除此之外，还有研究指出，间伐对土壤有机碳储量的影响不显著[50-51]。

5　收获对森林生态系统碳储量的影响

收获是最普遍的森林经营措施，对碳储量的影响因收获方式不同而存在差异。选择收获方式对碳储量的影响效果与间伐相似[52]；而皆伐则可显著影响碳储量。Finer 等[53]发现，皆伐可导致芬兰、挪威云杉碳储量减少 1/3，而全树收获方式可使林分碳储量减少 81%[37]。

收获可改变土壤的水热条件，通过影响凋落物的分解速率和微生物的活性来影响土壤有机碳储量[54-55]。著名的“Covington Curve”表明，森林收获后，20 年内土壤有机碳下降近 50%[56]，且在 20～50 年后才可增加[57-58]。这是因为采伐降低了土壤有机质的来源量，促进了 SOC 的矿化，加速了 DOC 的淋溶，从而导致 SOC 降低[59]。Chatterjee 等[60]对美国怀俄明州黑松和黄松林的研究表明，收获对土壤有机质和微生物的种群结构具有负效应，很可能减少了针叶林土壤的碳储量。

收获还会减少荷兰山毛榉、花旗松和落叶松林的土壤有机碳含量[14]。然而整合分析表明，收获对森林土壤有机碳储量的影响不大，且主要受收获利用方式的影响[61]，如全树利用收获会减少土壤表层的有机碳储量，而部分利用收获则可使林地留有残留物[62]，从而增加土壤有机碳的来源，提高土壤的有机碳储量[63]。

Liu 等[64]采用 Forcast 模型模拟收获对森林碳储量的长期（400 年）影响时发现，由于收获的木材作为木制品仍固定着碳，因此收获后的林分碳储量高于未收获林分。但收获后留下的枝、叶等，均有利于土壤有机碳的保存[65]。

6　问题与展望

6.1　存在问题

1）许多经营措施均会导致森林生态系统碳储量减少，如间伐、收获等，且短时间内森林净碳量很难增加。因此，如何在经营管理过程中使森林生态系统的碳损失量降至最低，是林业经营中应解决的关键问题。

2）目前，有关研究主要分析了经营措施对森林生态系统植被和土壤碳储量的影响，未包括经营措施实施过程中的能源消耗（如机器采伐、运输过程等）释放的碳量，以及将采伐的林木加工成木制品后继续固定的碳量，或用作生物质能源替代能源密集性材料而减少工业生产中的碳排放量，即对碳量尚缺乏系统、全面的研究。

3）现有的研究大多只关注短期效应，而森林结构和功能对经营活动的响应可能需要相当长的时间才会显现，尤其是目前关于经营活动对土壤层有机碳的影响程度及机理仍不明确，急需进行长期的跟踪研究。

6.2　展　望

1）探讨科学的经营技术，提高森林碳储量。以间伐为例，何时间伐、如何选择间伐木（小径级或大径级）、采用何种间伐方式（条状或块状）和间伐强度、间伐木如何处理（留在林内、加工木制品或用作生物质能源）等问题，均需设固定样地进行长期监测。

2）构建经营措施对森林生态系统碳储量影响的预测模型。由于森林经营措施对森林生态系统碳储量的影响具有长期效应。故在生产实践中，需借助模型来预测经营措施对森林生态系统碳储量的影响效果。但目前缺乏综合考虑木制品固碳和生物质能源替代作用的森林生态系统碳储量预测模型，特别是随着碳积分市场的逐渐成熟和碳汇林业的发展，亟待构建此类模型。

3）加强经营活动对森林土壤有机碳影响机理的研究。土壤有机碳主要取决于凋落物和细根的分解量与土壤呼吸量之间的平衡。因此，应对间伐后林内的土壤温度、湿度和光照强度等林内气候因子，以及凋落物的分解速率，细根的结构、寿命及呼吸，微生物活性的变化等进行长期的动态监测，并探讨气候因子与凋落物和细根的分解速率等因素的有机联

系,这些均是揭示经营活动影响土壤有机碳机理的基础研究。

4)综合评价经营措施对森林生态系统服务功能的影响。研究某种经营方式对森林碳储量的影响时,还应考虑其对生物多样性等服务功能的干扰作用。例如,除去林内小径级的间伐方式能增加森林植被碳储量[5],但其能否同时提高物种多样性;是否存在某种既可以增加森林碳储量,又能提高物种多样性的间伐方式或强度,这些问题均需进行深入的研究与探讨。

[参考文献]

[1] IPCC. Fourth assessment report: synthesis report. Summary for policy makers [EB/OL]. (2007-11-17)[2010-05-21]. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf.

[2] Oreskes N. The scientific consensus on climate change [J]. Science, 2004, 306(5702): 1686.

[3] Kramer P J. Carbon dioxide concentration, photosynthesis, and dry matter production [J]. Bio Science, 1981, 31: 29-33.

[4] Jandl R, Lindner M, Vesterdal L, et al. How strongly can forest management influence soil carbon sequestration? [J]. Geoderma, 2007, 137(3/4): 253-268.

[5] Hoover C, Stout S. The carbon consequences of thinning techniques: Stand structure makes a difference [J]. Journal of Forestry, 2007, 105(5): 266-270.

[6] 陆元昌,张守攻,雷相东,等. 人工林近自然化改造的理论基础和实施技术 [J]. 世界林业研究, 2009, 22(1): 20-27.
Lu Y C, Zhang S G, Lei X D, et al. Theoretical basis and implementation techniques on close-to-nature transformation of plantations [J]. World Forestry Research, 2009, 22(1): 20-27. (in Chinese)

[7] Lal R. Forest soils and carbon sequestration [J]. Forest Ecology and Management, 2005, 220(1): 242-258.

[8] 李正才,傅懋毅,杨校生. 经营干扰对森林土壤有机碳的影响研究概述 [J]. 浙江林学院学报, 2005, 22(4): 469-474.
Li Z C, Fu M Y, Yang X S. Review on effects of management disturbance on forest soil organic carbon [J]. Journal of Zhejiang Forestry College, 2005, 22(4): 469-474. (in Chinese)

[9] Nave L E, Vance E D, Swanston C W, et al. Harvest impacts on soil carbon storage in temperate forests [J]. Forest Ecology and Management, 2010, 259(5): 857-866.

[10] Hoover C M. Soil carbon sequestration and forest management: challenges and opportunities [C]// Kimble J M, Heath L S, Birdsey R A, et al. The potential of US forest soils to sequester carbon and mitigate the greenhouse effect. Boca Raton: CRC Press, 2003: 211-238.

[11] Zhao M, Kong Z H, Escobedo F J. Impacts of urban forests on offsetting carbon emissions from industrial energy use in Hangzhou, China [J]. Journal of Environmental Management, 2010, 91(4): 807-813.

[12] 周国模,吴家森,姜培坤. 不同管理模式对毛竹林碳贮量的影响 [J]. 北京林业大学学报, 2006, 28(6): 51-55.
Zhou G M, Wu J S, Jiang P K. Effects of different management models on carbon storage in *Phyllostachys pubescens* forests [J]. Journal of Beijing Forestry University, 2006, 28(6): 51-55. (in Chinese)

[13] Pretzsch H. Diversity and productivity in forests: evidence from long-term experimental plots [C]//Scherer-Lorenzen M, Körner C, schulze E. Forest diversity and function: temperate and boreal systems. Berlin Heidelberg: springer, 2005: 41-46.

[14] Schulp C J E, Nabuurs G J, Verburg P H, et al. Effect of tree species on carbon stocks in forest floor and mineral soil and implications for soil carbon inventories [J]. Forest Ecology and Management, 2008, 256(3): 482-490.

[15] Vallet P, Meredieu C, Seynave I, et al. Species substitution for carbon storage: Sessile oak versus Corsican pine in France as a case study [J]. Forest Ecology and Management, 2009, 257(4): 1314-1323.

[16] Xu Q F, Xu J M. Changes in soil carbon pools induced by substitution of plantation for native forest [J]. Pedosphere, 2003, 133(3): 271-278.

[17] Thomas S C, Malczewski G. Wood carbon content of tree species in Eastern China: Interspecific variability and the importance of the volatile fraction [J]. Journal of Environmental Management, 2007, 85(3): 659-662.

[18] Malchair S, Carnol M. Microbial biomass and C and N transformations in forest floors under European beech, sessile oak, Norway spruce and Douglas-fir at four temperate forest sites [J]. Soil Biology and Biochemistry, 2009, 41(4): 831-839.

[19] Chigineva N I, Aleksandrova A V, Tiunov A V. The addition of labile carbon alters litter fungal communities and decreases litter decomposition rates [J]. Applied Soil Ecology, 2009, 42(3): 264-270.

[20] Thuille A, Schulze E D. Carbon dynamics in successional and afforested spruce stands in Thuringia and the Alps [J]. Global Change Biology, 2006, 12(2): 325-342.

[21] Footen P W, Harrison R B, Strahm B D. Long-term effects of nitrogen fertilization on the productivity of subsequent stands of Douglas-fir in the Pacific Northwest [J]. Forest Ecology and Management, 2009, 258(10): 2194-2198.

[22] Jassal R S, Black T A, Cai T B, et al. Impact of nitrogen fertilization on carbon and water balances in a chronosequence of three Douglas-fir stands in the Pacific Northwest [J]. Agricultural and Forest Meteorology, 2010, 150(2): 208-218.

[23] Bauer G, Bazzaz F, Minocha R, et al. N additions on tissue chemistry, photosynthetic capacity, and carbon sequestration potential of ared pine (*Pinus resinosa* Ait.) stand in the NE United States [J]. Forest Ecology and Management, 2004, 196: 173-186.

[24] Berg B, Laskowski R. Litter decomposition: a guide to carbon

and nutrient turnover [EB/OL]. (2006-03-16) [2010-05-21]. http://www.elsevier.com/wps/find/bookseriesdescription.cws_home/BS_0139/description.

[25] Kaspari M, Garcia M N, Harms K E, et al. Multiple nutrients limit litterfall and decomposition in a tropical forest [J]. Ecology Letters, 2008, 11(1): 35-43.

[26] Hobbie S E. Nitrogen effects on decomposition: A five-year experiment in eight temperate sites [J]. Ecology, 2008, 89(9): 2633-2644.

[27] Canary J D. Additional carbon sequestration following repeated urea fertilization of second-growth Douglas-fir stands in western Washington [J]. Forest Ecology and Management, 2000, 138(1): 225-232.

[28] Harding R B, Jokela E J. Long-term effects of forest fertilization on site organic matter and nutrients [J]. Soil Science Society of America Journal, 1994, 58: 216-221.

[29] Jandl R, Kopeszki H, Bruckner A, et al. Forest soil chemistry and mesofauna 20 years after an amelioration fertilization [J]. Restoration Ecology, 2003, 11(2): 239-246.

[30] Lundström U, Bain D, Taylor A, et al. Effects of acidification and its mitigation with lime and wood ash on forest soil processe: A review [J]. Water Air&Soil Pollution: Focus, 2003, 3(4): 5-28.

[31] Nave L E, Vance E D, Swanston C W, et al. Impacts of elevated N inputs on north temperate forest soil C storage, C/N, and net N mineralization [J]. Geoderma, 2009, 153(2): 231-240.

[32] Tan Z, Liu S, Tieszen L L, et al. Simulated dynamics of carbon stocks driven by changes in land use, management and climate in a tropical moist ecosystem of Ghana, agriculture [J]. Ecosystems&Environment, 2009, 130(3): 171-176.

[33] Moscatelli M C, Lagornarsino A, De Angelis P, et al. Short- and medium-term contrasting effects of nitrogen fertilization on C and N cycling in a poplar plantation soil [J]. Forest Ecology and Management, 2008, 255(3): 447-454.

[34] Smaill S J, Clinton P W, Greenfield L G. Nitrogen fertilizer effects on litter fall, FH layer and mineral soil characteristics in New Zealand *Pinus radiata* plantations [J]. Forest Ecology and Management, 2008, 256(4): 564-569.

[35] Sathre R, Gustavsson L, Bergh J. Primary energy and greenhouse gas implications of increasing biomass production through forest fertilization [J]. Biomass&Bioenergy, 2010, 34(4): 572-581.

[36] Tyrrell M L, Ashton M S, Spalding D, et al. Forests and carbon: a synthesis of science, management, and policy for carbon sequestration in forests [EB/OL]. (2009-07-16) [2010-05-21]. http://www.yale.edu/gisf/publications.

[37] Jiang H, Apps M J, Peng C H, et al. Modeling the influence of harvesting on Chinese boreal forest carbon dynamics [J]. Forest Ecology and Management, 2002, 169(1): 65-82.

[38] Tang J, Bolstad P V, Martin J G. Soil carbon fluxes and stocks in a Great Lakes forest chronosequence [J]. Global Change Biology, 2009, 15: 145-155.

[39] Schulze E D, Lloyd J, Kelliher F M, et al. Productivity of forests in the Eurosibe rian boreal region and their potential to act as a carbon sink: A synthesis [J]. Global Change Biology, 1999, 5: 703-722.

[40] Diochon A, Kellman L, Beltrami H. Looking deeper: An investigation of soil carbon losses following harvesting from a managed northeastern red spruce (*Picea rubens* Sarg.) forest chronosequence [J]. Forest Ecology and Management, 2009, 257(2): 413-420.

[41] Kaipainen T, Liski J, Pussinen A, et al. Managing carbon sinks by changing rotation length in European forests [J]. Environmental Science and Policy, 2004, 7(3): 205-219.

[42] Johnson K, Scatena F N, Pan Y. Short and long-term responses of total soil organic carbon to harvesting in a northern hardwood forest [J]. Forest Ecology and Management, 2009, 259(3): 1262-1267.

[43] Campbell J, Alberti G, Martin J, et al. Carbon dynamics of a ponderosa pine plantation following a thinning treatment in the northern Sierra Nevada [J]. Forest Ecology and Management, 2009, 257(2): 453-463.

[44] Spring D A, Kennedy J O S, Mac Nally R. Optimal management of a forested catchment providing timber and carbon sequestration benefits: Climate change effects [J]. Global Environmental Change Part A, 2005, 15(3): 281-292.

[45] Chiang J M, McEwan R W, Yaussy D A, et al. The effects of prescribed fire and silvicultural thinning on the aboveground carbon stocks and net primary production of overstory trees in an oak-hickory ecosystem in southern Ohio [J]. Forest Ecology and Management, 2008, 255(5): 1584-1594.

[46] Alam A, Kilpeläinen A, Kellomäki S. Impacts of thinning on growth, timber production and carbon stocks in Finland under changing climate Scandinavian [J]. Journal of Forest Research, 2009, 23(6): 501-512.

[47] Piene H, Van Cleve K. Weight loss of litter and cellulose bags in a thinned white spruce forest in interior Alaska [J]. Canadian Journal of Forest Research, 1978, 8: 42-46.

[48] Vargas R, Allen E B, Allen M F. Effects of vegetation thinning on above-and belowground carbon in a seasonally dry tropical forest in Mexico [J]. Biotropica, 2009, 41(3): 302-311.

[49] Ryu S R, Concilio A, Chen J, et al. Prescribed burning and mechanical thinning effects on belowground conditions and soil respiration in a mixed-conifer forest, California [J]. Forest Ecology and Management, 2009, 257(4): 1324-1332.

[50] Boerner R E J, Huang J J, Hart S C. Fire, thinning, and the carbon economy: Effects of fire and fire surrogate treatments on estimated carbon storage and sequestration rate [J]. Forest Ecology and Management, 2008, 255(8): 3081-3097.

[51] Kim C, Son Y, Lee W K, et al. Influences of forest tending works on carbon distribution and cycling in a *Pinus densiflora* S. et Z. stand in Korea [J]. Forest Ecology and Management, 2009, 257(5): 1420-1426.

[52] Laporte M F, Duchesne L C, Morrison I K. Effect of clear cutting, selection cutting, shelter wood cutting and microsites on soil surface CO_2 efflux in a tolerant hard wood ecosystem of northern Ontario [J]. Forest Ecology and Management, 2003, 174(1): 565-575.

[53] Finer L, Mannerkoski H, Piirainen S, et al. Carbon and nitrogen pools in an old-growth, Norway spruce mixed forest in eastern Finland and changesassociated with clearcutting [J]. Forest Ecology and Management, 2003, 174(1): 51-63.

[54] Gray A N, Spies T A, Easter M J. Microclimatic and soil moisture responses to gap formation in coastal Douglas-fir forests [J]. Canadian Journal of Forest Research, 2002, 32(2): 332-343.

[55] Hassett J E, Zak D R. Aspen harvest intensity decreases microbial biomass, extracellular enzyme activity, and soil nitrogen cycling [J]. Soil Science Society of America Journal, 2005, 69(1): 227-235.

[56] Covington W W. Changes in forest floor organic matter and nutrient content following clearcutting in northern hardwoods [J]. Ecology, 1981, 62(1): 41-48.

[57] Black T A, Harden J W. Effect of timber harvest on soil carbon storage at Blodgett experimental forest [J]. California Canadian Journal of Forest Research, 1995, 25(8): 1385-1396.

[58] Cohen W B, Harmon M E, Wallin D O. Two decades of carbon flux from forests of the Pacific Northwest [J]. BioScience, 1996, 46(11): 836-844.

[59] Yanai R D, Currie W S, Goodale C L. Soil carbon dynamics after forest harvest: an ecosystem paradigm reconsidered [J]. Ecosystems, 2003, 6(3): 197-212.

[60] Chatterjee A, Vance G F, Pendall E, et al. Timber harvesting alters soil carbon mineralization and microbial community structure in coniferous forests [J]. Soil Biology and Biochemistry, 2008, 40(7): 1901-1907.

[61] Johnson D W, Curtis P S. Effects of forest management on soil C and N storage: meta analysis [J]. Forest Ecology and Management, 2001, 140(2): 227-238.

[62] Taylor A R, Wang J R, Kurz W A. Effects of harvesting intensity on carbon stocks in eastern Canadian red spruce (*Picea rubens*) forests: An exploratory analysis using the CBM-CFS3 simulation model [J]. Forest Ecology and Management, 2008, 255(10): 3632-3641.

[63] Busse M D, Sanchez F G, Ratcliff A W, et al. Soil carbon sequestration and changes in fungal and bacterial biomass following incorporation of forest residues [J]. Soil Biology and Biochemistry, 2009, 41(2): 220-227.

[64] Liu G L, Han S. Long-term forest management and timely transfer of carbon into wood products help reduce atmospheric carbon [J]. Ecological Modelling, 2009, 220(13): 1719-1723.

[65] Jones H S, Garrett L G, Beets P N, et al. Impacts of harvest residue management on soil carbon stocks in a plantation forest [J]. Soil Science Society of America Journal, 2008, 72(6): 1621-1627.

(上接第 82 页)

[12] 巩 杰, 陈利顶, 傅伯杰, 等. 黄土丘陵区小流域土地利用和植被恢复对土壤质量的影响 [J]. 应用生态学报, 2004, 15(12): 2292-2296.
Gong J, Chen L D, Fu B J, et al. Effects of land use and vegetation restoration on soil quality in a small catchment of the Loess Plateau [J]. Chinese Journal of Applied Ecology, 2004, 15(12): 2292-2296. (in Chinese)

[13] 周正朝, 上官周平. 人为干扰下子午岭次生林土壤生态因子的动态变化 [J]. 应用生态学报, 2005, 16(9): 1586-1590.
Zhou Z C, Shangguan Z P. Dynamic changes of soil ecological factors in Ziwuling secondary forest area under human disturbance [J]. Chinese Journal of Applied Ecology, 2005, 16(9): 1586-1590. (in Chinese)

[14] 鲍士旦. 土壤农化分析 [M]. 3 版. 北京: 中国农业出版社, 2005: 29-57.
Bao S D. Physical and chemical analysis of soil [M]. 3 edition. China Agriculture Press, 2005: 29-57. (in Chinese)

[15] Wandde M, Yang X. Influence of tillage on the dynamics of loose and occluded particulate and humified organic matter fractions [J]. Soil Biol Biochem, 2000, 32: 1151-1160.

[16] 郝仕龙, 李志萍. 半干旱黄土丘陵区生态建设与经济发展模式探讨: 以固原上黄试区为例 [J]. 中国水土保持科学, 2007, 10(5): 11-15.
Hao S L, Li Z P. Model of ecological construction and economical development in semiarid hilly area of Loess Plateau: A case study in Shanghuang test area in Guyuan [J]. Science of Soil and Water Conservation, 2007, 10(5): 11-15. (in Chinese)

[17] 黄占斌, 徐炳成, 苏 敏, 等. 延安飞马河试验示范区农业生产的调查研究 [J]. 水土保持通报, 2002, 22(3): 73-75.
Huang Z B, Xu B C, Su M, et al. Investigation on agricultural status and development of Feima River experimental and demonstrational area in Yanan city [J]. Bulletin of Soil and Water Conservation, 2002, 22(3): 73-75. (in Chinese)

[18] 张小文, 张世强, 蔡迪花, 等. 黄土高原西部不同土地利用与土壤侵蚀的相互作用 [J]. 兰州大学学报: 自然科学版, 2008, 44(2): 9-14.
Zhang X W, Zhang S Q, Cai D H, et al. Interaction between land use and soil erosion in West Loess Plateau [J]. Journal of Lanzhou University: Natural Science Edition, 2008, 44(2): 9-14. (in Chinese)

[19] 郭兆元. 陕西土壤 [M]. 北京: 科学出版社, 1992: 363-369.
Guo Z Y. Shaanxi soil [M]. Beijing: Science Press, 1992: 363-369. (in Chinese)