Environmental Management (2010) 46:525–530
DOI 10.1007/s00267-010-9555-6

EDITORIAL

Bioenergy Sustainability in China: Potential and Impacts

Jie Zhuang · Randall W. Gentry · Gui-Rui Yu · Gary S. Sayler · John W. Bickham

Received: 14 January 2010 / Accepted: 19 August 2010 / Published online: 14 September 2010

Abstract The sustainability implications of bioenergy development strategies are large and complex. Unlike conventional agriculture, bioenergy production provides an opportunity to design systems for improving eco-environmental services. Different places have different goals and solutions for bioenergy development, but they all should adhere to the sustainability requirements of the environment, economy, and society. This article serves as a brief overview of China's bioenergy development and as an introduction to this special issue on the impacts of bioenergy development in China. The eleven articles in this special issue present a range of perspectives and scenario analyses on bioenergy production and its impacts as well as potential barriers to its development. Five general themes are covered: status and goals, biomass resources, energy plants, environmental impacts, and economic and social impacts. The potential for bioenergy production in China is huge, particularly in the central north and northwest. China plans to develop a bioenergy capacity of 30GW by 2020. However, realization of this goal will require breakthroughs in bioenergy landscape design, energy plant biotechnology, legislation, incentive policy, and conversion facilities. Our analyses suggest that (1) the linkage between bioenergy, environment, and economy are often circular rather than linear in nature; (2) sustainability is a core concept in bioenergy design and the ultimate goal of bioenergy development; and (3) each bioenergy development scheme must be region-specific and designed to solve local environmental and agricultural problems.

Keywords Bioenergy sustainability · Emissions · Energy plants · Marginal land

J. Zhuang (✉)
Biosystems Engineering and Soil Science, Institute for a Secure and Sustainable Environment, Center for Environmental Technology, The University of Tennessee, Knoxville, TN 37996, USA
e-mail: jzhuang@utk.edu

R. W. Gentry
Department of Civil and Environmental Engineering, Institute for a Secure and Sustainable Environment, The University of Tennessee, Knoxville, TN, USA

G.-R. Yu
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

G. S. Sayler
Center for Environmental Biotechnology, UT-ORNL Joint Institute of Biological Science, The University of Tennessee, Knoxville, TN, USA

J. W. Bickham
Center for the Environment, Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN, USA

Introduction

China has an immense need for new energy resources to feed economic growth and security. Already the largest importer of oil and the second largest consumer of energy in the world, China's annual energy demand is projected to grow by about 4–5% per year through 2015 (NDRC 2007; Yu 2007). China is thus making efforts that are targeted to increasing the share of renewable energy in its total energy mix to 15% by 2020 (NDRC 2007; Shen and others 2010). Bioenergy will play a prominent role in the energy portfolio and has the potential for large-scale development that should benefit the economies of remote rural areas.

However, bioenergy production systems are complicated by many factors, such as those reflected in the principles for sustainability (capacity to endure): natural resource availability, social-economic benefits, technology efficiency, eco-environmental services (including biodiversity), and policy. The challenge is to design a system that can address these factors while being practical, replicable, and appropriate for various scenarios. An important challenge, in addition to energy supply, is to invigorate rural economies while reducing environmental pollution, increasing carbon sequestration, and protecting food security. In this sense, bioenergy sustainability is even more important in China than in many other areas of the world because, while China possesses only 7% of the world's fresh water and cropland, 3% of its forests, and 2% of its oil, it is home to 21% of the world's population. Development of non-grain bioenergy crops and the productive use of marginal lands are therefore crucial for food and feed security in China. Drought-resistant perennial energy plants that can live on nutrient poor soils, such as switchgrass (*Panicum virgatum*), Yang grass (*Leymus chinensis*), poplar (*Populus* spp.), and *Jatropha curcas*, are likely to provide a valuable economic stimulus for agriculturally poor rural areas while at the same time helping to achieve a more sustainable energy plan.

Given the current interest in bioenergy development in China, the guest editor decided to organize this special issue of *Environmental Management* to illustrate the advances in bioenergy production, biomass assessment, energy plants, and environmental impacts in China to a wider renewable energy research and industry audience. The papers here were selected from talks and posters presented at the China-US workshop on *Bioenergy Consequences for Global Environmental Change*. The workshop was organized by the China-US Joint Research Center for Ecosystem and Environmental Change (http://jrceec.utk.edu) and held on 11–15 October 2008, in Beijing, China, with the sponsorship of the U.S. National Science Foundation (NSF) and the Natural Science Foundation of China (NSFC). More than eighty representatives from academia, government, and industry in China and the United States gathered to present and discuss their latest scientific findings and current challenges to bioenergy development.

All of the submitted papers for this special issue were subjected to a rigorous peer review in accordance with the policies of this journal. The articles accepted for publication cover a wide range of topics relating to the potential and impacts of bioenergy production. To facilitate understanding of the complexity of bioenergy development, the guest editor has grouped the papers into five common themes: status and goals, energy potential of biomass resources, energy plants, environmental impacts, and economic and social impacts.

Status and Goals of China's Bioenergy Development Program

Bioenergy development is one of the priorities of China's renewable energy strategy and has been written into the Long-term National Economic and Social Development Strategy (NDRC 2007). According to the Bureau of Energy created under China's National Development and Reform Commission (NDRC), the development goal for renewable energy by 2020 amounts to 15% of the total energy capacity, while the goal for biomass-based energy is 30GW (15% of the renewable energy consumption). This 30GW goal does not include biomass currently used in 1,600 industry boilers (Seligsohn and Bradley 2009). Achievement of these goals will result in annual emission reductions of 33 million metric tons of carbon dioxide and 2.4 million metric tons of sulfur dioxide (Yu 2007). Key areas for bioenergy development include (1) biogas production from biowaste, such as methane generation in rural areas, (2) biomass gasification and solidification from agricultural residues, (3) biomass-to-liquid fuel, such as biodiesel and ethanol, and (4) straw-fired heat and power generation.

In 2000, China granted licenses to five plants owned by four companies to produce starch-based fuel ethanol in the provinces. Annual bioethanol production capacity was about 0.92 million metric tons in 2005, 1.50 million metric tons in 2007, and 1.94 million metric tons in 2008 (Li and Chan-Halbrendt 2009), of which 80% was produced from corn. Rapid progress caused increases in the price of corn and a grain shortage in some regions. To avoid such impacts, the Chinese government decided in 2006 to shut down these ethanol production facilities and encourage only non-grain based ethanol production. This regulation turned the direction of bioenergy development to corn stover-based ethanol production. The annual consumption of gasoline of China in 2008 was 60 million metric tons. This gasoline might be provided by constructing a cellulosic ethanol industry network consisting of 1,000 plants, each with 60,000 metric tons production of ethanol a year, or 600 plants, each producing 100,000 metric tons per year (Bao 2008). The commercialization of a cellulosic ethanol plant with the production capacity of 50,000–100,000 metric tons per year will be the target of the 12th Five-year National Development Plan of China (2011–2015).

The Energy Potential of China's Biomass Resources

Shen and others (2010) analyzed the availability and spatial distribution of biomass resources in China. The total exploitable annual capacity for biomass is one billion tons (500 million tons of coal equivalents [TCE]). Of the estimated 700 million tons of biomass from agricultural residues, half can be used to generate energy, representing a coal savings of 160 million TCE. Livestock and poultry manure, theoretically, could yield enough biogas to generate the equivalent of 57 million TCE. Firewood and wood biomass energy could generate 200 million TCE, and municipal solid waste and wastewater could generate nearly 93 million TCE. China plans to convert 30% of total municipal waste to energy by 2030 (Seligsohn and Bradley 2009). As for crop residues, nearly 40% comes from corn, followed by rice (27%), wheat (15%), oil crops (10%), beans (5%), and others (1%). Their average acquirable rate is 38.9%. However, the distribution of biomass resource reserves varies considerably among the provinces and autonomous regions.

At present, biomass energy resources in China are mainly used in conventional combustion technologies. However, newer technologies, such as gasification, liquefaction, and power generation, are being developed rapidly. The major technologies for liquid biofuels are ethanol fuel technology and bio-oil technology. Mu and others (2010) made a life-cycle assessment of ethanol produced from four different wood feedstocks using two different conversion routes (biochemical and thermochemical) that also included various indirect impacts. Their analysis probed the effects of technological advances and process modifications. The impacts they considered were greenhouse gases (GHG), water consumption, and fossil energy use. The analyses suggest that although these two routes are comparable in technical performance in terms of ethanol yield and energy efficiency at the plant level, their environmental performance varies.

Similarly, Wu and others (2010) applied life-cycle assessment to analyzing a food-processing wastewater treatment plant. They included a thorough investigation of the economic and environmental impacts of the plant that was based on energy and material flows. The assessment model established through the study is useful for evaluating the environmental impacts associated with wastewater produced from a bioenergy system. To analyze the embodied energy of biomass production, Hu and others (2010) presented an integrated approach (VIP model), which combines the ecosystem model with emergy analysis to optimize the amount of irrigation required for sustainable development of cropping systems. The model's application to a wheat–maize rotation cropping system demonstrates that the new approach is more flexible than conventional emergy analysis and has potential to optimize resource allocation, resource-savings, and agricultural sustainability when bioenergy is developed.

Energy Plants

There are more than 4,000 species of plants in China with potential for bioenergy production (Lin and others 2006). They include forest species such as poplar and willow; grassland species such as bamboo and Yang grass (*Leymus chinensis*); farmland species such as corn, sugarcane, sweet potatoes, and transgenetic plants; wetland species such as the common reed and narrow-leaf cattail; and aquatic species such as algae. Among them, 154 species contain oil in seeds greater than 40%, and 30 species of shrubs or arbor plants are rich in organic chemicals that can be used to produce biofuels (Fu and Huang 2006; Ma and others 2007).

In Li and others (2010b), 64 species that are being developed as potential energy plants in China are introduced. It is obvious that energy plant growth depends on their biological and environmental suitability to each region. The species used for lignocellulosic biomass, mostly drought-resistant perennial energy plants, are mainly distributed in northern China, while oilseed crops for biodiesel are dominant in the tropical and subtropical zones of China. By analyzing natural distribution and growth conditions, Li and others found 15 energy plants that have strong environmental adaptability and could be fully utilized and cultivated at a large spatial scale. In the study, energy plant species suitable for cultivation in different regions in China are suggested according to climate conditions.

Further, Li and others (2010b) briefly describe recent advances in biotechnology being used to improve energy plants in China, such as molecular markers, genetic transformation, and gene discovery. Biotechnology remains the key for reducing the cost and time for bioenergy conversion. Important genes related to production and stress tolerance may be discovered. For instance, over-expressing (or suppressing) some key genes to regulate energy conversion, enrichment, and distribution in the energy plants is promising. With China's wide range of complicated climate conditions, breakthroughs in biotechnology are critical for the large-scale development of lignocellulosic bioenergy.

Switchgrass (*Panicum virgatum* L.) is a deep-rooted, stress-tolerant, warm-season perennial grass that can be grown on marginal lands or rotated with other crops. Its fossil fuel energy ratio (i.e., the ratio of energy delivered to fossil energy used during production) is 5.3, in contrast to 1.4 for corn. It is thus a potentially major bioenergy plant for the United States. Plantation experiments of switchgrass on the Loess plateau in the northwestern China were initiated in 2001. Field experiments demonstrated the successful establishment of switchgrass in this semi-arid environment (400–500 mm annual precipitation). This is of major significance when introducing grass species for forage or bioenergy use because switchgrass is the only species successfully established on the Loess plateau after testing of several thousand non-native forage grass species since the 1990s.

Shui and others (2010) investigated allelopathy and its chemical basis in nine switchgrass accessions as compared to perennial ryegrass (*Lolium perenne* L.) and alfalfa (*Medicago sativa* L.). They found that the allelopathic effect was related to switchgrass ecotype, but not related to ploidy level. Their work indicates that switchgrass has the potential to reduce the growth of native forages and disturb the ecological balance in the region through allelopathy. In addition, Xu and others (2010) studied seedling biomass and allocation, transpiration water use efficiency, and species competition between switchgrass (*Panicum virgatum* L.) and milkvetch (*Astragalus adsurgens* Pall.). Water stress significantly reduced seedling biomass production but increased the ratio of root to shoot. Switchgrass is the dominant species and much more aggressive than milkvetch under dry soil conditions, whereas milkvetch is the dominant species under wet conditions. The total biomass data for both species indicated some degree of resource compensation when the two species are planted in the same plot. An increase in water-use efficiency is the main driving mechanism, particularly under dry soil conditions.

As for switchgrass feedstock for ethanol production, Moon and others (2010) pointed out that switchgrass is not agronomically mature and there is a need to domesticate and solve the recalcitrance problem. Regulatory sustainability will necessitate biocontainment of transgenic switchgrass since gene flow is of paramount importance to regulators. To be deregulated, any transgenic switchgrass will likely have an extraordinarily high biosafety factor, which must be considered as an integral part of the research and development plan in a regulated environment. They recommend that mechanisms that ensure biocontainment of transgenes be instituted, especially for perennial grasses.

Environmental Impacts

China's 11th Five Year Plan for Renewable Energy Development (2006–2010) calls for increasing biomass sources (NDRC 2007). This goal is, however, constrained by natural resource conditions. China is a nation with a large area of highlands and uplands with mountainous and hilly areas occupying 43% of the national land total. The per capita food cropland area is less than 0.1 hectare and arable lands are mostly distributed in the east. It is practically impossible to switch cropland to biofuel production. Therefore, the Chinese central government issued a regulation in 2006 to ban any further increases in production of starch-based ethanol, whether from wheat or corn. Future biofuel production should be non-grain based only. This new direction may improve the health and services of eco-environmental systems. Li and others (2010a) assessed the potential for CO_2 emission reduction by developing non-grain based ethanol in China based on the land occupation and types of feedstocks. The results show that non-grain based bio-ethanol production can potentially reduce CO_2 emissions from the 2007 levels by 11 million tons and 49 million tons in 2015 and 2030, respectively (5.5 and 25 times the reduction capacity in 2007). Further, growing bioenergy crops on marginal lands may also affect methane emissions. Fu and Yu (2010) and Zheng and others (2010) estimated the temporal and spatial patterns of methane emissions from croplands and carbon dioxide emissions from forestlands, respectively. The results by Fu and Yu (2010) indicate that methane emissions in China rose at an annual rate of 2% from 1990 to 2006 due to increases in rice cultivation, livestock populations, and field burning of crop residues. Overall, the studies by these two groups suggest that development of bioenergy crops may change China's greenhouse gas emissions due to land use changes and an increase in animal food supply requirements (e.g., grasses for both forage and biofuel).

In addition to improving environmental sustainability and security while reducing concerns for food, economic gains can also be made when bioenergy development is integrated with ecological restoration. For example, many non-food bioenergy plants are perennials with deep root systems. Ecological restoration using these plants can thus lead to an increase in land productivity for food (as compared to the tilled farming system) in terms of improvements in soil and water conservation. Bioenergy-driven restoration of degraded ecosystems can also increase terrestrial carbon sequestration due to large biomass production and root residues as well as slowing decomposition of soil organic materials under no-till conditions. Overall, China has large areas of marginal land for growing bioenergy plants. There are approximately 260 million hectares of marginal lands in China (China Statistical Yearbook 2007; Li and others 2010a). Among them, 35 million hectares are suitable for food crops, 55 million hectares are suitable for growth of trees and/or shrubs, and 35 million hectares are saline-alkali lands that might be used for cultivating salt-resistant bioenergy plants. Assuming that drought-resistant bioenergy crops can be cultivated on part of this land, China plans to grow more herbaceous and woody plants in the northwestern desert areas. By 2020, 13 million hectares (32 million acres) of bioenergy forest will be planted to provide biomass for the production of six million tons of biodiesel oil and 15 million kW of annual power generation (Yu 2007).

As discussed in Shui and others (2010) and Xu and others (2010), Chinese scientists are testing the adaptability and bioenergy potential of switchgrass in northwestern China. Switchgrass provides an excellent nesting habitat for many species of native wildlife. Its root mass can reach deeper than two meters, acting as belowground carbon and nutrient sinks. Switchgrass also requires fewer fertilizer applications than annual crops such as corn, and it allows greater infiltrations and less erosion from surface flow and wind. In addition, unfertilized switchgrass can be used as vegetative filter strips and riparian buffers in agricultural watersheds to protect local water resources. Results from a number of watershed studies of switchgrass find export reductions of sediment, nitrogen, and phosphorus by 50–95%, 25–90%, and 20–85%, respectively (Dale 2008). The percentage of retention is positively related to the width of the buffer along riparian corridors. Therefore, when a perennial grass like switchgrass is planted on eroded lands that were previously used for agriculture (e.g., the Loess plateau of China), there are many more environmental benefits than there are for unmanaged lands.

Economic and Social Impacts

Bioenergy sustainability depends upon farmers making the correct decisions about land use patterns and the adoption of energy plants. In general, China has a bioenergy market of billions of dollars per year. However, given a competitive economic environment, it is unclear whether biomass energy can be economically sustainable. Currently, more than 60% of the cost for bioenergy is in feedstock costs (Liu and Gu 2008). This provides an opportunity for farmers to increase their income. A potential risk of high feedstock cost is that it may cause an increase in land conversion from food to fuel production, eventually causing a food–energy conflict. To avoid this problem, a basic premise is that cultivating bioenergy crops must not infringe on grain supply and marketing. This requires not only breakthroughs in biotechnology for biomass productivity but also effective coordination between farmers and industry through bioenergy certification. Utilization of marginal lands for bioenergy can also increase the economic contribution of bioenergy because the costs for ecological restoration can be reduced. Co-firing of coal and biomass (e.g., 10–20% biomass) in power plants (referred to as biocoal) is another approach to benefiting farmers economically while producing clean energy. This is because the addition of biomass to coal can create an effective mechanism that allows farmers to share the profits of the coal energy industry. This biocoal approach is likely to be particularly important for China because it can lessen the rural socio-economic conflicts between rich owners of coal mines and poor local farmers. As for the societal impacts of bioenergy development, English (2008) maintains that an understanding of bioenergy economics is important but it is not sufficient. Psychological, cognitive, and cultural factors, which shape a farmer's values and beliefs, are just as important as economics. All these economic and social factors must be dealt with at the policy level. Shen and others (2010) reviews three common policy options in China's biomass development, including the feed-in law, renewable portfolio standards, and tendering. They suggest that the Chinese government should take integrated measures—including legislation, strategic planning, and economic incentives—to guarantee the sustainable development of bioenergy in different regions.

Summary and Outlook

Bioenergy represents an opportunity for not only clean energy but also the improvement of environmental conditions and rural economies. However, it requires some scrutiny as to its sustainability. Plantations of drought-resistant perennial energy plants on nutrient poor lands have unparalleled potential for serving as a win–win situation for emission reductions, renewable energy use, revitalized rural economy, and food security. However, China, like the rest of the world, will need to explore options in the choice of energy plants, legislative changes, strategic planning options, and economic incentives to fully realize the potential of biomass as an important source of renewable energy. Eventually a certification scheme to ensure sustainable use of the land will be necessary. Current technical barriers in China include incomplete biomass assessment, inefficient conversion technologies, poor linkages from R&D to commercialization, and a lack of coherent and clear environmental policy incentives, standards, and regulatory systems for converting wastes to biofuel, as well as domestic facility suppliers testing.

In general, the papers presented in this special issue make the following suggestions on China's bioenergy development. First, China's bioenergy approach must be integrative and diverse, but adherence to economic and environmental sustainability is critical. Second, a huge potential for bioenergy exists in the west of China (contingent upon breakthroughs in plant biotechnology), while production in eastern China should be mainly based on agricultural and forest wastes to promote regional food security. Third, priority in bioenergy development should be given to the regions with coal mines or other environmentally degraded areas to promote a comprehensive, clean development scheme. Last, a white paper providing guidance on bioenergy development, including policy options, marketing regulations, and equipment standards, should be issued at the national level and be integrated into the current ecological restoration policy and investment strategy.

Acknowledgments This special issue is the outcome of a China-US joint workshop "Bioenergy Consequences for Global Environmental Change" held on October 15-17, 2008 in Beijing and organized by the China-US Joint Research Center for Ecosystem and Environmental Change (JRCEEC; http://jrceec.utk.edu). The workshop was jointly funded by the U.S. National Science Foundation (Grant Nos. NSF-OISE-0757267), the Natural Science Foundation of China (NSFC), and the Chinese Academy of Sciences.

References

Bao J (2008) An industrial demonstration of corn stover-based ethanol processing in China. The proceeding of China–US workshop on bioenergy consequences for global environmental change, pp 81–82

China Statistical Yearbook (2007) China Statistics Press

Dale VH (2008) Selecting metrics for sustainable bioenergy feedstocks. The proceeding of China–US workshop on bioenergy consequences for global environmental change, pp 49–53

English M (2008) Socioeconomic considerations with biofuels production. The proceeding of China–US workshop on bioenergy consequences for global environmental change, pp 42–44

Fu D-J, Huang H-W (2006) Brief introduction of exploitation and utilization of fuel plants resources. Journal of Wuhan Botanical Research 24:183–190

Fu C, Yu G-R (2010) An estimation and temporal and spatial pattern analysis of methane emissions from agriculture in China. Environmental Management. doi:10.1007/s00267-010-9495-1

Hu S, Mo X-G, Lin Z-H, Qiu J-X (2010) Emergy assessment of a wheat–maize rotation system with different water assignments in the North China Plain. Environmental Management. doi: 10.1007/s00267-010-9543-x

Li S-Z, Chan-Halbrendt C (2009) Ethanol production in China: potential and technologies. Applied Energy 86:5162–5169

Li H-Q, Wang L-M, Shen L (2010a) Potential of CO_2 emission reduction by developing non-grain based bio-ethanol in China. Environmental Management. doi:10.1007/s00267-090-9418-1

Li X-F, Su M, Yang M-F, Shen S-H, Jiang G-M, Qi D-M, Chen S-Y, Liu G-S (2010b) Major energy plants and their potential for bioenergy development in China. Environmental Management. doi: 10.1007/s00267-010-9443-0

Lin C-S, Li Y-Y, Liu J-L, Zhu W-B, Chen X (2006) Diversity of energy plant resources and its prospects for the development and application. Henan Agricultural Sciences 12:17–23

Liu G-S, Gu W-B (2008) Advances in research on germplasm resources and molecular biology of the energy plants sweet sorghum. The proceeding of China–US workshop on bioenergy consequences for global environmental change, pp 47–48

Ma L-X, Shao HB, Wu G, Chu LY (2007) Resource evaluation of main oil plants and functional zone planning in China. In: Proceedings of the third international green energy conference, June 18–20, 2007, Sweden, pp 214–226

Moon HS, Abercrombie JM, Kausch AP, Stewart CN (2010) Sustainable use of biotechnology for bioenergy feedstocks. Environmental Management. doi:10.1007/s00267-010-9503-5

Mu D-Y, Seager T, Rao S-P, Zhao F (2010) Comparative streamlined life cycle assessment of lignocellulosic ethanol production: biochemical vs. thermochemical conversion. Environmental Management. doi:10.1007/s00267-010-9494-2

National Development and Reform Commission (NDRC) (2007) The Middle and Long Term Plan for Renewable Energy Development (in Chinese)

Seligsohn D, Bradley R (2009) Energy and climate policy action in China. World Resources Institute Fact Sheet, June 2009. http://pdf.wri.org/factsheets/factsheet_china_policy.pdf

Shen L, Liu L, Yao Z, Liu G, Lucas M (2010) Development potentials and policy options of biomass in China. Environmental Management. doi:10.1007/s00267-010-9476-4

Shui J-F, An Y, Ma Y-Q, Ichizen N (2010) Allelopathic potential of switchgrass (*Panicum virgatum* L.) on perennial perennial ryegrass (*Lolium perenne* L.) and alfalfa (*Medicago sativa* L.). Environmental Management. doi:10.1007/s00267-010-9454-x

Wu J-G, Meng X-Y, Liu X-M, Li W-W, Liu X-W, Xu D-Q, Sheng G-P, Yu H-Q (2010) Life cycle assessment of a wastewater treatment plant focused on material and energy flows. Environmental Management. doi:10.1007/s00267-010-9497-z

Xu B-C, Deng X-P, Zhang S-Q, Shan L (2010) Seedling biomass partition and water use efficiency of switchgrass and milkvetch under monoculture and mixture in response to various water availabilities. Environmental Management. doi:10.1007/s00267-010-9496-0

Yu G-R (2007) Status of bioenergy development in China: overview. The proceeding of China–US workshop on bioenergy production and sustainability: environmental aspects, pp 20–22

Zheng Z-M, Yu G-R, Sun X-M, Li S-G, Wang Y-S, Wang Y-H, Fu Y-L, Wang Q-F (2010) Spatio-temporal variability of soil respiration of forest ecosystems in China: influencing factors and evaluation model. Environmental Management. doi:10.1007/s00267-010-9509-z