Bioenergy production and environmental impacts

Compared with the conventional fossil fuel, bioenergy has obvious advantages due to its renewability and large quantity, and thus plays a crucial role in helping defend the energy security. However, the bioenergy development may potentially cause serious environmental alterations, which remain unclear.. Our analysis shows that more and more attention is being paid to the environmental protection as the development of bioenergy, and among the influencing terms of bioenergy production, water issues (i.e., water quantity and quality) gain the greatest concern, whereas the least attention has been given to soil erosion. Although we recognize that the bioenergy production can indeed exert negative effects on the environment in terms of water quantity and quality, greenhouse gas emissions, biodiversity and soil organic carbon, and soil erosion, the adverse impacts varied greatly depending on biomass types, land locations, and management practices. Identifying the reasonable cultivation locations, appropriate bioenergy crop types, and optimal management practices can be beneficial to environment and sustainable development of bioenergy. In this field, Chinese bioenergy production has lagged behind and does not match its rising energy consumption, but it has a great potential of and demand for biomass-based energy especially under its urbanization, in spite of the negative environmental impacts.

Energy is the basic requirement of the development in almost every aspect of a society in the world, and it is also needed by the existence of ecosystems, life itself, and human civilizations . However , the utilization of conventional energy sources can yield a series of problems. First, the conventional energy (i.e., fossil fuel) is not renewable, and its excessive use will lead to serious energy crisis, which is now a big concern of the world. Second, the utilization of the traditional fossil fuels can also be polluting sources that accelerate global warming, such as the increase of carbon dioxide and other greenhouse gases. Third, the emitted nitrogen oxides due to fossil fuel combustion compromise air quality and do harms in human health .

Feedstocks of biofuel production include the grains (e.g., corn kernel and soybean), cellulosic materials such as crop residue (e.g., corn stover).

In addition, sustainable bioenergy production can efficiently reduce the risk of energy poverty and contribute to the economic development, especially in developing countries Governments around the world are thus trying to promote the bioenergy production as well as seeking appropriate policies or laws to regulate its development. For instance, the US implemented the Energy Independence and Security Act (EISA) in 2007, aiming to increase availability of renewable energy through biofuel production (US Congress 2007). The Malaysia government has introduced the Fifth Fuel Policy in the Eighth Malaysia Plan 2001–2005 to encourage the bioenergy production (Tock et al. 2010). The European Commission has set mandatory targets for an overall share of 20% renewable energy in EU's transport consumption in 2020 (Van Dam and Junginger 2011). China, as the largest developing country and the second largest economic entity in the world, has a great inherent demand for the bioenergy production in meeting the fast-growing economy, preventing the energy crisis, and meeting the target of greenhouse gas emission reduction. In fact, China has a great potential of bioenergy crop cultivation due to its high profit and environmental benefits in replacing the slope cropland by perennial grass (switchgrass), especially considering the occurring urbanization and accompanied mass migration in China.

Environmental issues

Water quantity and quality

The effects of bioenergy production on water quantity are mainly through the potential water consumption of bioenergy crops and conversion of land use. For example, the wide expansion in corn ethanol production (first-generation biofuel) in US, encouraged by EISA in 2007, was projected to generate potential water stress at regional and local scales because the corn requires more water compared to other crops (e.g., wheat and soybean) due to the additional water consume in almost every growing stage, especially the joining stage. Particularly, it is estimated that a typical corn-ethanol plant (with a production capacity of 100 million gal/year) uses as much water as a community of 5000 people (Service RF 2009), demonstrating the relatively larger potential water consumption of corn cultivation. In addition, the corn stover removal can also cause increased ET and reductions of water yield at the watershed scale though the magnitude of which varied with watershed and harvest rate. The land use conversion, mainly from the native agricultural land or grassland to perennial grasses (e.g., switchgrass and Miscanthus) can also significantly and directly influence the hydrological processes such as ET, surface runoff, water yield, and soil water storage at regional scale. A significant water quality concern with respect to increasing cultivation of bioenergy crops is nutrient pollution resulting from surface runoff and infiltration to groundwater. The most important polluting source of nutrient pollution is nitrate. As reported by EPA (2011), corn has the highest fertilizer use and low nutrient use efficiency compared to other bioenergy crops. Therefore, increasing the frequency of corn plantation in the corn and soybean rotation system or replacing it with continuous corn would significantly lead to more nitrate to waterways and decrease soil nitrogen content .Nevertheless, there are substantial benefits in land use transition from arable to perennials. Growing perennial grasses reduces 30–40% of the total nitrogen loss compared with conventional cotton cropping system at the watershed scale simulated that growing bioenergy crops in marginal or erodible areas can not only reduce the streamflow but also the nutrient losses using the scenario analysis with Soil and Water Assessment Tool (SWAT). Additionally, growing perennial grasses needs almost no pesticide, which is helpful for the water quality improvement

GHG emissions

Reduction of GHG emissions is one of the most important terms considered in the bioenergy production. Among the GHGs, CO_2 and N_2O are two primary components because of their large quantity and multi-approaches of production (Dunn et al. 2013; Qin et al. 2016). Theoretically, net CO_2 emissions resulting from the direct use of biofuels are far less than the utilization of fossil fuel, which has been proven by many studies (Dunn et al. 2013; Fu et al. 2014; Wang et al. 2012). By replacing fossil fuel, Liu et al. (2017) quantified that the maximum potential switchgrass production on marginal land would reduce emissions by 29 million tons $CO_{2\text{-eq}}$/year. The model results also suggest that for transportation use in the US, 40–85% of GHG emissions can be reduced using ethanol relative to gasoline on a per megajoule (MJ) energy basis, though the magnitude of GHGs reduction varied greatly among different feedstocks. Nevertheless, the indirect effects of bioenergy production on CO_2 emissions are also important concerns (Dunn et al. 2013; Searchinger et al. 2008), such as the disturbance of CO_2 emissions due to the land use transitions (Hill et al. 2006; Sang and Zhu 2011). In a recent review of potential biofuel impacts, Harris et al. (2015) stated that the land transitions from arable to the second generation bioenergy crops can result in slight reduction of CO_2 emissions, and the land conversion from native grassland to first generation bioenergy crops and short rotation coppice (SRC) showed a pronounced increase in CO_2 emissions. Therefore, it is necessary and significant to consider the appropriate bioenergy crop types and management practices when considering the mitigation of CO_2 emissions.

Compared with CO_2, the N_2O is another important greenhouse gas due to its large potential in global warming (298 times that of CO_2), and agriculture is the largest producer of this gas (Williams et al. 2010). Similar to CO_2 emission, the land transitions are the major factors influencing N_2O emissions. For example, Harris et al. (2015) summarized that the effect of conversion from arable to SRC and perennial grasses was a very small reduction of – 0.2 t/ha y for N_2O, but the land conversion from grassland to SRC can cause slight increase in N_2O emissions. In addition, by replacing fossil fuel, Liu et al. (2011) asserted that the use of biomass produced on marginal land for energy could result in a positive environmental impact on national GHG emissions. However, the corn expansion, driven by the demand for ethanol, may also stimulate the N_2O emission. The corn cultivation need much more fertilizer compared with other crops, especially the nitrogen fertilizer, which is the substrate for soil denitrification process, aggravating N_2O emission directly. Therefore, the reasonable choice of bioenergy plant type and planting locations is also very important in controlling the N_2O emissions.

Bioenergy has obvious advantages compared to the traditional fossil fuel, because of their large quantity and renewability, and thus plays a crucial role in defending the energy security of the globe. However, it is significant to take the resource and environmental cost into account when implementing the bioenergy production. The study summarizes the environmental impacts of bioenergy development based on published results, and our analysis indicated that bioenergy-oriented environmental studies were not given as much attention as bioenergy itself in spite of their increasing trend. Among the influencing terms of bioenergy production, water issues (i.e., water quantity and quality) gain the greatest concern, whereas the least attention has been paid to the soil erosion. Although the bioenergy production can indeed exert negative effects on the surrounding environments, consisting of water quantity and quality, GHG emissions, biodiversity and SOC, and soil erosion, the adverse impacts on environment varied greatly among plant types, land sources, and management practices. Identifying the appropriate cultivation areas, suitable bioenergy crop types, and optimal management practices can be beneficial to both bioenergy production and environment. China has a large potential of bioenergy production, but Chinese bioenergy production has lagged behind and does not match its rising energy consumption. The future research should learn from the leading countries in this field, gain more knowledge, and derive optimal decision support for guiding the development of bioenergy in China and other developing countries. Overall, this study could give a big picture on and be informative in planning the bioenergy development as well as environmental protection.