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Unintended consequences of bioethanol feedstock choice in China

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HIGHLIGHTS

- Corn grain and wheat grain had bad performances.
- Sugarcane was the possible hitting-point of sugar-based feedstocks.
- Cellulose-based feedstocks had good performances.
- Environmental problem-shifting in ethanol production should be considered.
- Key processes were identified for solving potential environmental problems.

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ABSTRACT

Economic, energy, and environmental impacts of 11 types of bioethanol feedstock in China were evaluated using a mixed-unit input–output life cycle assessment model. Corn grain and wheat grain had higher negative economic, energy, and environmental impacts. Sweet sorghum, cassava, sugar beet, and sugarcane showed better economic performance but increasing negative energy and environmental impacts. Cellulose-based feedstocks in general showed positive economic, energy, and environmental performance; but may lead to increasing negative impacts on freshwater use, global warming, toxicity, and aquatic ecotoxicity. Sugarcane-based bioethanol had the potential to provide positive economic, energy, and environmental impacts in China. Scrap paper-derived ethanol could also become promising under significant government support.

1. Introduction

The first generation biofuels are widely produced including corn-based ethanol in the United States and sugarcane-derived ethanol in Brazil (Sims et al., 2010). Mass production of the first generation biofuels has led to unintended environmental consequences such as increase of life cycle greenhouse gas (GHG) emissions (Sims et al., 2010). Subsequently, the second generation biofuels using cellulosic biomass as feedstock have received increasing attention from the government, industry, academia, and the general public.

China is currently the world's top energy consumer (BP, 2012) and CO_2 producer (Gregg et al., 2008). Developing renewable energy has become a critical strategy for China to maintain its rapid economic growth and improve its environmental sustainability. Bioethanol plays an important role in China's renewable energy development plan (NDRC, 2007). On the other hand, crop residues generated in China each year account for approximately 17.3% of the global total (Lu and Zhang, 2010). Nearly one third of China's crop residues are not properly utilized and cause a variety of issues such as increasing environmental impacts and traffic accidents (Lu and Zhang, 2010). Thus producing ethanol from crop residues can not only utilize otherwise wasted biomass resources but also contribute to China's renewable energy development.

There are currently three types of feedstock available for ethanol production: starch-based feedstock, sugar-based feedstock, and cellulosic feedstock. Crop residues belong to cellulosic feedstock. Given that the development of the first generation biofuels has caused significant unintended consequences, various feedstocks need to be compared from a systems perspective to ensure appropriate feedstock choice for particular regions. Such comparison needs not only to consider environmental impacts but also to take into account impacts on economic growth and energy production.

Numerous studies have been conducted to evaluate life cycle environmental impacts of biofuels derived from a variety of feedstocks (Halleux et al., 2008; Hill et al., 2006; Mishra and Yeh,

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2011; Ou et al., 2009; Rosa et al., 2009; Sassner et al., 2008; Spatari et al., 2005; Yu and Tao, 2009). However, little attention has been paid on potential impacts – not only limited environmental impacts but also impacts on economic growth, energy production, and other environmental aspects – of feedstock selection in China. This study contributes to this field by applying a mixed-unit input–output life cycle assessment model to compare 11 bioethanol feedstocks in China according to 13 categories of life cycle impacts. These feedstocks include four starch-based feedstocks (corn grain using both dry and wet processes, wheat grain, sweet sorghum, and cassava), two sugar-based feedstocks (sugar beet and sugarcane), and five cellulosic feedstocks (switchgrass, cornstalk, wheat straw, wood chips, and scrap paper).

2. Methodology and data

Conventional process-based life cycle assessment (LCA) model has cutoff errors due to the delineation of product system by a finite boundary and the omission of contributions outside the boundary (Suh et al., 2004). On the other hand, economic input–output LCA (EIO-LCA) model – or environmentally-extended economic input–output (EEIO) model – includes the complete chain of economic activities needed to provide particular goods or services within the economy (Matthews and Small, 2000). This study used the mixed-unit input–output life cycle assessment (MUIO-LCA) model which integrates process-based LCA and EIO-LCA addressing the issue of cutoff errors in process-based LCA (Hawkins et al., 2006). Three production processes were considered including feedstock planting, ethanol production, and ethanol combustion. Parameters characterizing these processes were collected from the literature. An MUIO-LCA model was then constructed to incorporate the production processes. In this model, there were n economic sectors and k production processes ($k = 3$ in this study). The resulted MUIO-LCA model is able to quantify life cycle environmental, energy, and economic impacts of producing particular products or services. Detailed descriptions of MUIO-LCA model can be found in Hawkins et al. (2006). Each sector's life cycle biomass demands and environmental impacts could be calculated by Eqs. (1) and (2).

$$\text{Life cycle biomass demands} = [(\mathbf{I} - \mathbf{A})^{-1} - \mathbf{I}]\hat{\mathbf{x}} \tag{1}$$

$$\text{Life cycle environmental impacts} = \mathbf{E}(\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{x} \tag{2}$$

where $\boldsymbol{I}$ is the identity matrix, the $(n+k)\times(n+k)$ matrix $\boldsymbol{A}$ is the technology matrix, the $(n+k)\times(n+k)$ matrix $(\boldsymbol{I}-\boldsymbol{A})^{-1} - \boldsymbol{I}$ is the total requirement coefficient matrix, $\hat{\boldsymbol{x}}$ is the diagonal matrix for the $(n+k)\times 1$ vector $\boldsymbol{x}$ indicating each sector's economic output, and the $m\times(n+k)$ matrix $\boldsymbol{E}$ indicates each sector's environmental impacts per unit of economic output with m standing for the number of types of environmental impacts.

The function unit was 1.6 million tonnes of ethanol, which was the amount of fuel ethanol produced in China in 2007 (RGCECER, 2009). Data used to construct the MUIO-LCA model were shown in Tables S1–S3 of the Supplementary Information (SI).

China's 2007 monetary input–output table (MIOT) was used to construct the MUIO-LCA model. The 135-sector Chinese 2007 MIOT was aggregated into a 45-sector format to be consistent with the Chinese environmental statistics (Table S5 in the SI). Moreover, the column named "Others" in final demands of Chinese MIOT is regarded as errors of different data sources (Liang and Zhang, 2011; Peters et al., 2007) and subtracted from final demands and total outputs when using each sector's total outputs to normalize the intermediate delivery matrix. For environmental matrix, each sector's environmental impacts included energy use, freshwater use, generation of solid wastes, global warming potential (GWP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), photochemical oxidation potential (POCP), acidification potential (AP), and eutrophication potential (EP). Detailed information regarding data sources could be found in the SI. In particular, data on the usage of energy sources and freshwater by agricultural sectors were aggregated in Chinese statistics. Those aggregated data were disaggregated based on their monetary outputs from Chinese statistics and enrgy and freshwater intensity from 2005 Chinese physical input-output table(Liang et al., 2011).

3. Results and discussion

3.1. Net energy yield, net global warming potential and net economic benefit

Net energy yield is defined as gross energy yield less life cycle energy use. Ethanol derived from starch-based and sugar-based feedstocks had negative net energy yields, while cellulosic bioethanol had positive net energy yields (Fig. 1). Energy yields of ethanol derived from switchgrass, cornstalk, wheat straw, wood chips, and scrap paper accounted for 225.6%, 181.9%, 106.2%, 216.5%, and 85.4% of their life cycle energy uses, respectively. Co-generated electricity from cellulosic ethanol accounted for 23.3–36.6% of its life cycle energy uses. If co-generated electricity is taken into account, energy yields of ethanol and electricity from switchgrass, cornstalk, wheat straw, wood chips, and scrap paper accounted for 258.3%, 212.2%, 135.1%, 253.2%, and 108.7% of their life cycle energy use, respectively.

Life cycle global warming potential minus direct CO_2 sequestrated in feedstock planting is defined as the net global warming potential. CO_2 sequestration is calculated by multiplying feedstock yields with CO_2 sequestration coefficients (Table S4 in the SI). Net global warming potentials of ethanol from 11 feedstocks were shown in Fig. 2. Ethanol derived from wheat grain, sugarcane, cassava, cornstalk, wheat straw, and wood chips had positive net CO_2 sequestration, accounting for 14.0%, 80.7%, 23.5%, 48.6%, 47.4%, and 85.0% of CO_2 sequestrated by each feedstock, respectively. Ethanol derived from the other five feedstocks had negative net CO_2 sequestration.

Defined as economic benefits of products (including co-products) less economic costs of both feedstock planting and ethanol production, net economic benefits of ethanol from 11 feedstocks were also shown in Fig. 3. Ethanol produced from corn grain, wheat grain and sugarcane had negative net economic benefits.

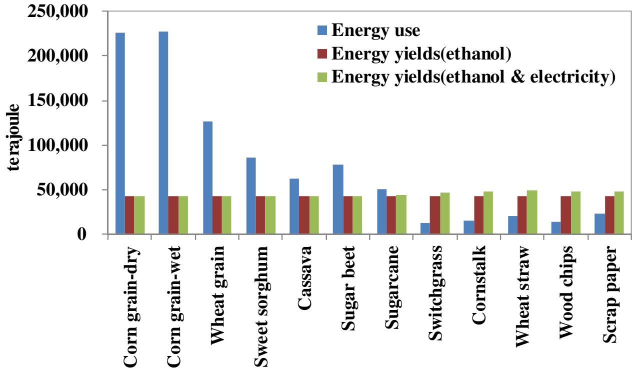


Fig. 1. Energy use and energy yields of ethanol from 11 feedstocks. The bar in color (🟦) indicates life cycle energy use of ethanol production. The bar in color (🟥) indicates energy value of ethanol produced from feedstocks, excluding co-generated electricity. The bar in color (🟩) indicates energy value of both ethanol produced from feedstocks and co-generated electricity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

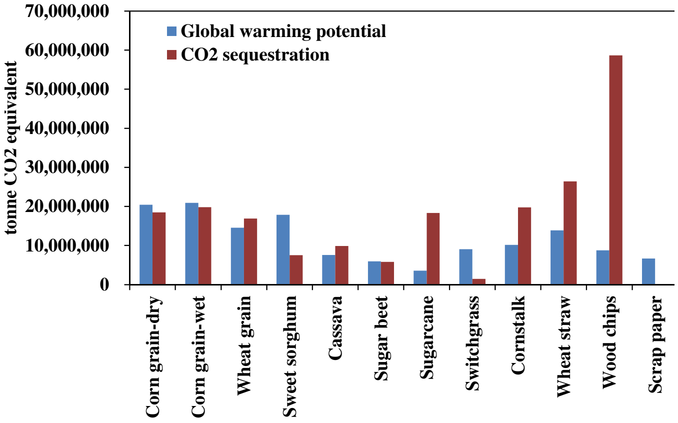


Fig. 2. Net global warming potentials of ethanol from 11 feedstocks. The bar in color (🟦) indicates life cycle global warming potential of ethanol production. The bar in color (🟥) indicates the amount of CO2 directly captured in feedstock planting stage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

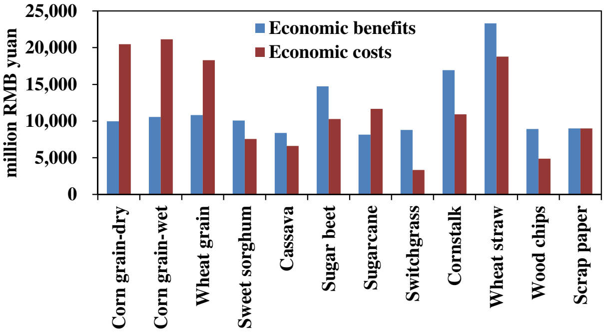


Fig. 3. Economic costs and benefits of ethanol from 11 feedstocks. The bar in color (🟦) indicates the sum of economic benefit of ethanol and that of co-products from feedstock planting and ethanol production. The bar in color (🟥) indicates economic cost of intermediate material inputs in feedstock planting and ethanol production. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Ethanol production from the other eight feedstocks had positive net economic benefits. Ethanol derived from cornstalk had the largest net economic benefit (6.0 billion RMB), accounting for 55.1% of its economic cost. On the contrary, ethanol derived from scrap paper had the least net economic benefit (18 million RMB), only accounting for 0.2% of its economic cost.

3.2. Life cycle environmental impacts and potential environmental problems

Life cycle environmental impacts of ethanol from 11 feedstocks were calculated using the MUIO–LCA model (Tables S6 and S7 in the SI). Corn grain-derived and wheat grain-derived ethanol had relatively less biomass use but more impacts on the other eleven categories. Sweet sorghum-derived ethanol had relatively high biomass use, GWP, POCP, AP, and EP. Cassava-derived ethanol had relatively large POCP and AP. Sugarcane-derived ethanol had relatively large biomass use. Sugar beet-derived ethanol had relatively large biomass use, HTP, FAETP, MAETP, and solid waste generation. Wheat straw-derived ethanol had relatively large freshwater use and GWP. Wood chips-derived ethanol had relatively large biomass use. Moreover, scrap paper-derived ethanol had relatively large HTP, FAETP, and MAETP.

Previous research mainly focuses on energy use, GWP, and freshwater use of fuel ethanol. However, only focusing on these three environmental impacts would lead to significant environmental problem shifting. According to results in Tables S6 and S7 in the SI, ethanol derived from sugar beet, sugarcane, cassava, switchgrass, cornstalk, wood chips, and scrap paper had relatively less energy use, GWP and freshwater use. Yet using sugar beet and scrap paper for ethanol production would lead to increasing HTP, FAETP, and MAETP. In addition, using cassava to produce ethanol would cause increasing POCP and AP.

3.3. Sensitivity analysis

Sensitivity analysis of main parameters influencing life cycle environmental impacts was show in Fig. 4. In general, parameters related to the feedstock planting stage had strong effects on freshwater use and EP. Parameters related to the ethanol production stage affected most environmental impact categories except biomass use and freshwater use. Material prices had strong effects on environmental impacts except biomass use and EP.

Efficiency improvement in feedstock planting (10%) had strong effects on freshwater use (8.4–9.9%) and EP (4.4–8.7%) for all feedstocks except for wood chips and scrap paper as they do not have planting stage. Moreover, efficiency improvement in planting of wheat grain and sweet sorghum could reduce GWP by 5.3% and 6.8%, respectively. Efficiency improvement in the planting of cellulosic feedstock could also reduce energy use, HTP, FAETP, MAETP, TETP, POCP, and AP.

Efficiency improvements in ethanol production (10%) from starch-based and sugar-based feedstocks could effectively reduce energy use (6.6–9.1%), GWP (3.1–6.7%), HTP (6.2–8.2%), FAETP (6.2–8.2%), MAETP (6.2–8.2%), TETP (6.9–8.5%), POCP (7.6–9.3%), and AP (7.5–9.1%). In addition, efficiency improvement in ethanol production had large effects on reducing EP of sugar beet-derived (5.6%) and sugarcane-derived (5.0%) ethanol as well as solid wastes of ethanol derived from sweet sorghum (8.2%), sugar beet (10.0%), and cassava (7.8%). Efficiency improvement in ethanol production could reduce GWP of cellulosic ethanol (5.8–9.1%). Moreover, efficiency improvement in ethanol production had strong effects on reducing EP of wood chips-derived ethanol (9.8%) and scrap paper-derived ethanol (9.1%).

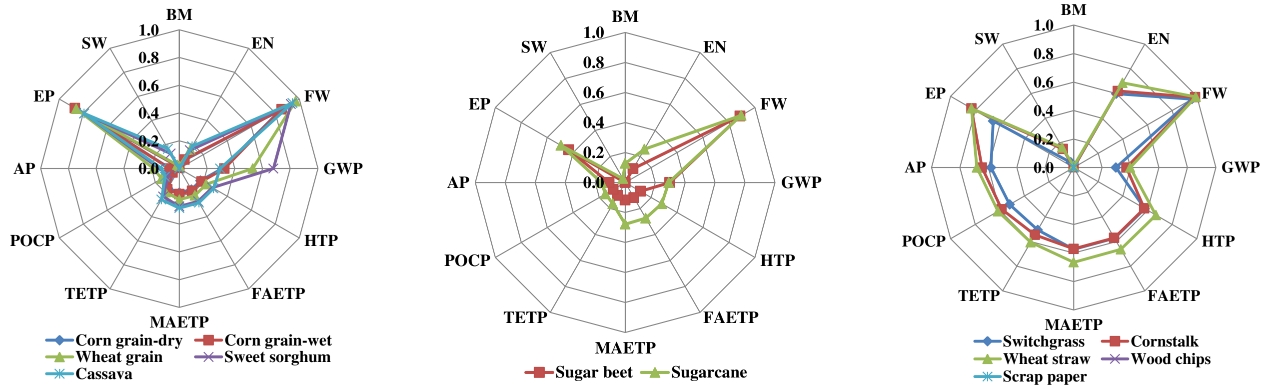
Material price reduction had strong effects on reducing energy use (6.1–10.0%), HTP (9.9–10.0%), FAETP (9.9–10.0%), MAETP (9.9–10.0%), TETP (9.9–10.0%), POCP (4.3–10.0%), and AP (4.2–10.0%) of ethanol from all feedstocks. In addition, material price reduction could effectively reduce freshwater use of wood chips-derived ethanol (9.7%) and scrap ethanol paper-derived (8.7%). Material price reduction also greatly reduced GWP of corn grain-derived ethanol and sugarcane-derived ethanol (7.1–8.4%). Moreover, material price reduction also decreased solid waste generation of sweet sorghum-derived ethanol (7.4%) and cassava-derived ethanol (7.4%).

3.4. Policy implications

Impact of biofuel production on food security has long been debated (Mueller et al., 2011; Pimentel et al., 2009; Young, 2009). Results in this study showed that ethanol derived from corn grain and wheat grain, two main food sources for human, had negative net energy yields, negative net economic benefits, and increased environmental impacts. In addition, corn grain-derived ethanol and wheat grain-derived ethanol have less potential to meet increasing transportation fuel demand (Hill et al., 2006). Therefore, it is obvious that corn grain and wheat grain are not suitable for feedstock of large-scale bioethanol production.

Although ethanol produced from sweet sorghum, cassava, and sugar beet had positive net economic benefits, it had negative net energy yields and significant environmental impacts such as

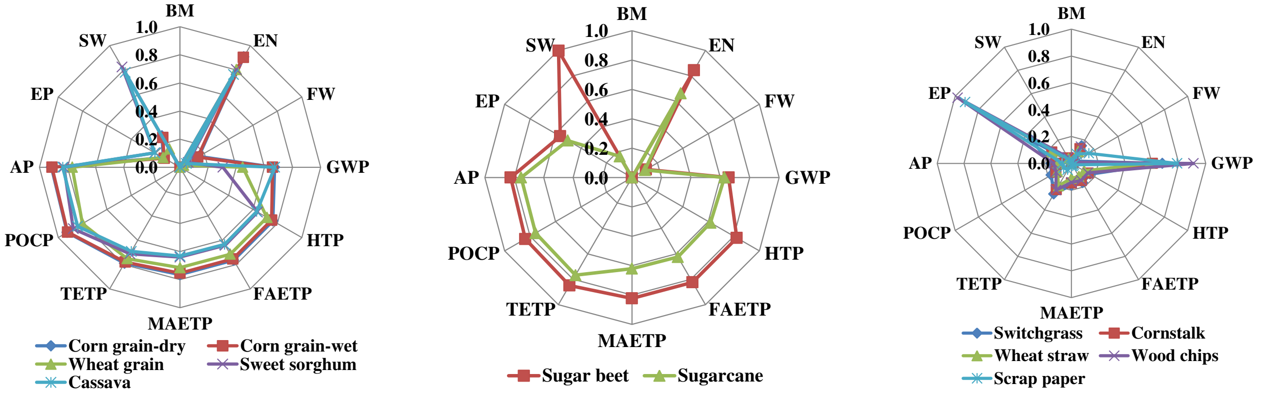
GWP, HTP, FAETP, MAETP, POCP, AP, EP, and solid wastes. Therefore, efficiency improvement in ethanol using these feedstocks should be encouraged. Potential problem shifting of using feedstocks to produce bioethanol should also be considered. Sugarcane-derived ethanol had less negative net energy yields and environmental impacts. According to the sensitivity analysis, efficiency improvement had strong effects on reducing environmental impacts of sugarcane-derived ethanol. Therefore, efficiency improvement through advancing bioethanol technology has great opportunities to improve net energy yields of sugarcane-derived



(a) Planting technologies improve by 10%: Starch-based feedstocks

(b) Planting technologies improve by 10%: Sugar-based feedstocks

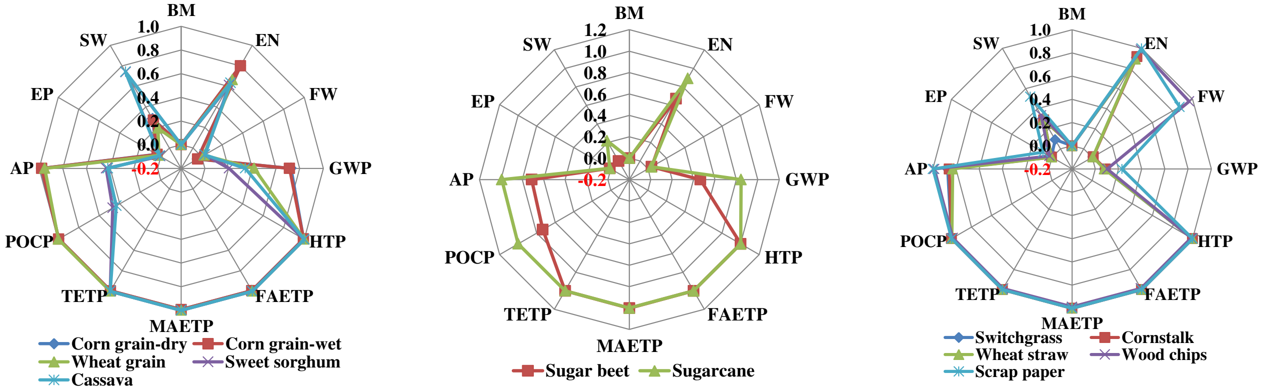
(c) Planting technologies improve by 10%: Cellulose-based feedstocks



(d) Ethanol production technologies improve by 10%: Starch-based feedstocks

(e) Ethanol production technologies improve by 10%: Sugar-based feedstocks

(f) Ethanol production technologies improve by 10%: Cellulose-based feedstocks



(g) Material prices decrease by 10%: Starch-based feedstocks

(h) Material prices decrease by 10%: Sugar-based feedstocks

(i) Material prices decrease by 10%: Cellulose-based feedstocks

Fig. 4. Sensitivity analysis of factors related to life cycle environmental impacts of ethanol. The abbreviations: BM indicates biomass use; EN indicates energy use; FW indicates freshwater use; GWP indicates global warming potential; HTP indicates human toxicity potential; FAETP indicates freshwater aquatic ecotoxicity potential; MAETP indicates marine aquatic ecotoxicity potential; TETP indicates terrestrial ecotoxicity potential; POCP indicates photochemical oxidation potential; AP indicates acidification potential; EP indicates eutrophication potential; and SW indicates solid wastes. (a) For example, shows that if planting technologies improve by 10%, global warming potential of wheat grain-derived ethanol will decrease by 5.3%. (d) For example, shows that if ethanol production technologies improve by 10%, global warming potential of wheat grain-derived ethanol will decrease by 4.5%. (g) For example, shows that if material prices decrease by 10%, global warming potential of wheat grain-derived ethanol will decrease by 4.2%.

ethanol. Government financial support is needed for more costly effective sugarcane-derived ethanol production due to its negative net economic benefits. In addition, using both sugarcane and sugarcane bagasse – co-product from sugarcane-derived ethanol production – to produce ethanol has better economic benefits than using only sugarcane (Dias et al., 2012). Thus, integrated ethanol production from both sugarcane and sugarcane bagasse should also be encouraged. Moreover, using these feedstocks for ethanol production likely leads to severe competition on crop land between ethanol production and food production. China now has over 100 million hectares of marginal lands that are not appropriate for food production. To avoid competing for crop land, bioethanol feedstocks should be cultivated on the marginal lands.

Cellulosic ethanol had positive net energy yields and also positive net economic benefits. Positive net economic benefits of scrap paper-derived ethanol, however, were nearly zero. Thus, governments could provide financial support for scrap paper-derived ethanol to make it economically feasible. Moreover, using cellulosic feedstock to produce ethanol can lead to significant environmental problem shifting. For example, developing wheat straw-derived ethanol may result in problems of increasing freshwater demands and GWP. Developing scrap paper-derived ethanol may lead to increasing HTP, FAETP, and MAETP. Therefore decision makers should pay special attentions on freshwater use, GWP, HTP, FAETP, and MAETP associated with cellulosic ethanol production. Wood chip-derived ethanol had significant life cycle biomass demand. If wood chips are from forest wood, wood chip-derived ethanol can accelerate deforestation. Thus, wood chips for ethanol production should be obtained from wood wastes in timber harvesting, wood processing, fruit trees pruning, and so on. In addition, most scrap paper is used for paper production. Using scrap paper for ethanol production can increase demands for crop straws and wood for paper production (Liang et al., 2011). Using crop straws for paper production competes with straw-derived ethanol, while using wood chips for paper production may compete with wood chip-derived ethanol or cause the acceleration of deforestation. Future work should focus on balancing ethanol and other pathways of using cellulosic feedstock. This requires considering a much wider range of impacts including biodiversity, land use changes, and ecosystem services.

Technology development should focus on processes identified as important by sensitivity analysis in this study. Developing wheat straw-derived ethanol could increase freshwater use and GWP. Technology development in wheat planting stage could offset freshwater demands of wheat straw-derived ethanol. Efficiency improvements in ethanol production stage could lower GWP for wheat straw-derived ethanol. The development of scrap paper-derived ethanol could increase HTP, FAETP and MAETP. Scrap paper-derived ethanol only had the ethanol production stage. Efficiency improvement for the production stage could not decrease HTP, FAETP, and MAETP to significant levels. The reduction of HTP, FAETP, and MAETP from scrap paper-derived ethanol mainly relied on price reduction of its intermediate material inputs which requires financial support by the government.

3.5. Potential feedstock supply in China

China will promote biofuel development in the next couple of years. Bioethanol is an important component in China's renewable energy strategy. In 2010, China produced 9.3 million tonnes of sugar beet and 110.8 million tonnes of sugarcane (NBS, 2011). Bioethanol derived from sugar beet and sugarcane can potentially substitute 8.4% of China's gasoline demand in 2010. In addition, China produced 224.9 million tonnes of cornstalk and 157.3 million tonnes of wheat straw in 2010. Ethanol derived from cornstalk and wheat straw has the potential of substituting 86.3% of China's gasoline demand in 2010.

3.6. Uncertainties and recommendations

Uncertainties of results in this study mainly come from uncertainties embodied with data. In this study, parameters are secondary data from experiments or on-site investigation reported in literature. Uncertainties associated with these studies are inherited in this study. Moreover, this study focuses on national average level, aiming to provide guidance for decision making at the national level. When life cycle impacts of ethanol production in a special region are analysed, parameters for production processes and the monetary input–output table should be obtained corresponding to that region.

Future work should focus on balancing pathways of utilizing cellulosic biomass. Moreover, biofuel production can potentially lead to indirect land use changes (Lapola et al., 2010) and significantly impact ecosystem services (Lal and Pimentel, 2009) such as deforestation and biodiversity loss. Thus, future work should also focus on impacts of biofuel development on land use change and ecosystem services. In addition, particular crops have different types of straws, such as *Leafstar* and *Koshihikari* for rice straws. Different types of straws usually have different economic, energy, and environmental performances (Roy et al., 2012). Further detailed comparisons among various types of straws should be conducted in future for ethanol production.

4. Conclusion

Corn grain and wheat grain had negative economic, energetic, and environmental performances. Sweet sorghum, cassava, sugar beet, and sugarcane had positive economic performance but negative energy and environmental performances. Technology development in ethanol production from these feedstocks should be encouraged to improve their energy and environmental performances, especially for sugarcane. Cellulosic feedstock had positive economic, energy, and environmental performances. Special attention should be paid to potentially increasing freshwater use, GWP, HTP, FAETP, and MAETP due to cellulosic ethanol production.

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Appendix A. Supplementary data

The Supplementary Information provided detailed information on three aspects: (1) data sources for the construction of columns representing each ethanol production stage. (2) The construction of environmentally-extended economic input–output model. (3) Results on life cycle environmental impacts of ethanol production from 11 feedstocks. Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2012.08.097.

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