1 Life Cycle Assessment of Common Reed (*Phragmites australis* (Cav)
2 *Trin. ex Steud*) Cellulosic Bioethanol in Jiangsu Province, China

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ABSTRACT: Common reed (*Phragmites australis* (Cav) Trin. ex Steud) at wetlands is a natural resource in Jiangsu Province, China. Proper application of common reed could supplement bioenergy feedstocks and encourage wetlands conservation in this area. In this study, common reed and soil samples from wetlands near to farm, coastline and for wastewater treatment were collected. Potential bioethanol yield was estimated based on biomass yield and bioethanol production, and a life cycle assessment (LCA) model was built to analyze environmental performance of common reed bioethanol. The dry biomass yield of common reed was in the range of 3.8 – 36 Mg ha⁻¹, and location was the significant factor on biomass yield. Soil pH and available N content had positive impacts on yields of biomass and bioethanol; higher glucan content was detected in stem than in leaf and flower, while ash and klason lignin contents were higher in leaf than in stem and flower. The results indicated that wetlands with high available N content were very suitable for common reed growth, and stem fraction was better than leaf for bioethanol production. Based on LCA model calculation, the net energy and ratio of energy efficiency were compatible to bioethanol from switchgrass and rice straw, and the greenhouse gases (GHG) emission intensity and eutrophication potential were 15 gCO_{2,eq} MJ⁻¹ and -1.1 gPO₄³⁻_{eq} MJ⁻¹. The results indicate that common reed is a sustainable and renewable resource for bioethanol production, especially those grown on wetlands near to farmland in Jiangsu Province, China.

Keywords: bioethanol; common reed; energy efficiency; eutrophication potential; greenhouse gases emission

1. Introduction.

Jiangsu Province is located at the Eastern of China, in a zone of subtropical monsoon climate, where there are plenty of wetlands along brooks near to farmlands, lakes, and ocean coastlines. Soils of wetlands are either permanently or periodically saturated with water, playing pivotal roles in environmental protection, including ecological balance, wildlife habitat, and abundant nutrients (N/P) sustaining [1]. However, economic development and population pressure always override wetland protection, which cause approximately 364,000 km² wetlands irreversibly disappearing in the last two decades [2]. Due to limited agricultural farms, wetlands, especially those near to farmlands, are converted into farmlands or ponds for aquaculture in Jiangsu Province, which can increase the risk of surface water eutrophication. Developing a sustainable application of wetland plants is benefit for wetlands conservation.

Common reed (*Phragmites australis* (Cav) Trin. ex Steud) is a native perennial plant growing at wetlands in Jiangsu Province, which is usually used as household feedstock, for thatching roof and basking mat, etc. Harvesting common reed from banks near to farmlands is a tradition in Jiangsu Province to maintain stream clean and prevent stream from paludification. Previous research of Sun [3] showed that wetland with harvesting common reed annually had better ability in N/P removal than that without harvesting.

Common reed feedstock can also be applied for paper [4], construction material, electricity [5] and bioethanol. Based on the previous research of Gao et al. [6], bioethanol application of rice and wheat straws was better than the applications of corrugated paper, combined heat and electricity and medium density fiberboard in environmental aspects. Only 0.22×10^6 gCO_{2,eq} per 700 kg rice straw bale would be

emitted from bioethanol application and the renewability indicator (*RI*) was high to 47.7 %, while corrugated paper application would emit 3.06×10^6 gCO_{2,eq} per 700 kg bale and *RI* was only 11 %, respectively, in which *RI* was the ratio between the total input renewable energy to the total input energy. Emergy was the total embodied energy in one product.

Common reed has high contents of cellulose (33-36 %) and hemicelluloses (20-22 %) [7], which can be hydrolyzed into monosugars and then fermented into bioethanol. There were studies about pretreatments effects on common reed for bioenergy [8], after which monosugar conversions of structure glucan and xylan could be improved from about 25 % to 87 % and 71 %, respectively. However, there was limited research about environmental effects of common reed bioethanol analyzed through life cycle assessment (LCA), including greenhouse gases (GHG) emission, energy efficiency, eutrophication impact.

The primary objectives of this study were to: 1) analyze of sugar compositions in common reeds at different environments; 2) examine effects of environment factors on potential bioethanol yield; 3) analyze environmental behavior of common reed bioethanol through an LCA model, including GHG emission intensity, total nonrenewable energy efficiency and eutrophication potential, etc. It was the first time that we combined area survey, lab experiments and an LCA model together to compare effects of location and soil properties on the possibility of common reed bioethanol application, and concern its environmental sustainability. The development of common reed bioethanol would bring profit to local people, which would further stimulate them to preserve wetlands growing common reed instead of aquaculture or farming.

2. Methods

2.1. Sampling locations

The two-year study was conducted in 2012 and 2013 at three counties in Jiangsu Province, China, including Haimen (Nantong county, N 31.88, E 121.12), Sihong (Suqian county, N 33.39, E 118.29), Sheyang (Yancheng county, N 33.61, E 120.48). Four wetlands were chosen in each county, including those brook banks near to farmlands, conservation areas near to lakeshores/seashores or a former constructed wetland for wastewater treatment. Four sampling sites were setup randomly in each wetland, and 5 plants and 5 soil samples at 0-20 cm depth were collected at each sampling sites. All sampling sites were 2 m away from outside or in the middle of the wetlands and there was 50 m apart between two sampling sites in each selected wetland. Stand density of common reed in 1 m² around the sampling site was counted to calculate biomass yield (Table 1). The common reed at these three locations dried at the end of November, and all samples were collected within two weeks. The weather conditions in year 2012 and 2013, including total monthly precipitation and average monthly temperature, were obtained from Jiangsu meteorological information center, and average values in the recent decade (2003-2012) at these three locations were presented in Table 1.

Table 1. Site information of three locations

2.2. Soil and plant sample preparation

The soil samples were crashed and dried in hood till no moisture losing at 25 °C, then they were passed through a 100 mesh sieve. The plant samples were hand separated as stem, leaf and flower fractions and then weighted, and all plant samples were placed in 60-72 °C oven to determine moisture content, which would be used to calculate the yield of dry biomass (Y_{db} , Mg ha⁻¹). Then plant samples were chopped into 3 mm pieces and stored at 4 °C for later analysis. The pH of soil samples were

measured by pH meter (Thermo Scientific Orion 5-star, Beverly, MA), contents of soil organic carbon (SOC) and available N were measured in the Soil Analysis Laboratory at Institute of Soil Sciences, CAS (Table 1), the information of detail methods could be found in supplemental materials Text S1.

2.3. Composition analysis

Compositions of common reed fractions (stem, leaf and flower), including ash, polysaccharide (glucan, xylan or arabinan), and klason lignin (acid-insoluble lignin), were analyzed following standard methods outlined by the National Renewable Energy Laboratory standard protocols LAP 002, 003 and 005 [9]. In brief, ash content of dried biomass was obtained by burning and baking plant sample in a 575°C muffle oven for 6 h. Acid hydrolysis was used to analysis polysaccharide contents in fractions, in which 3 mL 72% (w/w) H₂SO₄ was added into 100 mL autoclavable high-pressure tube (Chemglass Life Science Inc., Vineland, NJ) with 0.3 g common reed fraction. The mixture was continuous horizontally shaken for 1 h at 30°C, added 84 mL distilled water, and then the mixture tube was autoclaved at 121°C for 1 h. The supernatant was removed by filtration to obtain klason lignin, and 1 mL supernatant was passed through a 0.22 μm syringe filter (Millipore Inc., Billerica, MA) for monosaccharide analysis.

The contents of polysaccharides from cellulose and hemicelluloses were calculated based on monosaccharide concentrations after acid hydrolysis, following equation 1:

$$PS = \frac{C \times V \times 1000}{R \times W \times (1 - m)} \quad (1)$$

where PS (g kg⁻¹ dry biomass) was glucan, xylan or arabinan content in dry biomass, C (g L⁻¹) was the concentration of glucose, xylose or arabinose in supernatant after

acid hydrolysis, V (0.087 L) was the total volume of acid hydrolysis, and R was the stoichiometric ratio of molecular weight glucose to glucan (1.11 g g⁻¹), xylose to xylan (1.136 g g⁻¹) or arabinose to arabinan (1.136 g g⁻¹), W (g) and m (%) are the added biomass's weight and moisture fraction before acid hydrolysis. The value of m was the weight loss after putting biomass into an oven at 105 °C for at least 2 h.

2.4. High-performance liquid chromatography (HPLC)

After acid hydrolysis, 20 μ L supernatant was analyzed by direct injection onto a 25 cm $\times$ 4.6 mm SUPELGOGEL H (5 μ m) column in an Agilent 1260 high performance liquid chromatography (HPLC) with an Agilent 1260 Refractive Index Detector. The mobile phase was an isocratic 5 mM sulfuric acid at a flow rate of 0.2 mL min⁻¹ with a 15 min run at 35 °C. External standards were employed for glucose, xylose or arabinose using 4-point calibration curves. The detection limit for sugars by HPLC was 0.5 mg L⁻¹ based on the lowest concentration of the calibration curve.

2.5. Estimation of bioethanol yield

In this study, modified alkali pretreatment [10] was conducted to common reed fractions, detail information could be found in the supplemental materials (Text S2). The ethanol production ($E_{\text{prod,wh}}$, L kg⁻¹) of whole plant was estimated [11] by the contents of glucan and xylan in whole-plant common reed and their enzymatic hydrolysis conversions, as equation 2:

$$E_{\text{prod,wh}} = 0.48 \times PS_{\text{glc,wh}} \times Glu_{\text{conversion,wh}} + 0.29 \times PS_{\text{xyl,wh}} \times Xyl_{\text{conversion,wh}} \quad (2)$$

where $PS_{\text{glc,wh}}$ (36.47 g kg⁻¹ dry biomass) and $PS_{\text{xyl,wh}}$ (16.23 g kg⁻¹ dry biomass) were glucan and xylan contents in the whole plant of common reed, $Glu_{\text{conversion,wh}}$ and $Xyl_{\text{conversion,wh}}$ were conversions (Table S3) of glucan and xylan to glucose and xylose in enzymatic hydrolysis at 6% biomass loading.

The bioethanol yield (Y_{ethanol} , L ha⁻¹) was estimated by biomass yield (Y_{db} , Mg ha⁻¹) and $E_{\text{prod,wh}}$ (L kg⁻¹) as equation 3:

$$Y_{\text{ethanol}} = Y_{\text{db}} \times E_{\text{prod,wh}} \times 1000 \quad (3)$$

2.6. Statistical analysis

Analysis of variance (ANOVA) was employed to determine the significant factors ($p < 0.05$), including soil pH, soil organic carbon (SOC), soil available N content, average monthly temperature and total monthly precipitation, on fraction ratio (f_i), composition of fractions, yield of dried biomass (Y_{db}), and ethanol yields (Y_{ethanol}).

A linear mixed model was also applied to study location and year effects, as follows:

$$\gamma_{jk} = \mu + L_j + W_j + Y_k + L_j \times Y_k + e_{jk} \quad (4)$$

where γ was the response variable, including the fraction ratio of flower, leaf or stem, composition of fractions, biomass yield, or ethanol yield, μ was the grand mean of γ , L (j = Haimen, Sihong, or Sheyang) and Y (k = 2012 or 2013) were the fixed effects of location and year, W was the random effect of wetland, $L \times Y$ was the interaction effect between year and location, and e was the residual. The analysis was conducted with a PROC MIXED model in SAS 9.3 (SAS Institute, Cary, NC) at $p < 0.05$ level.

2.7. Life cycle assessment (LCA) model for common reed bioethanol

2.7.1. System boundary and description

A gate-to-gate LCA model of common reed bioethanol was constructed with the software of Gabi 6.0 (PE International, Stuttgart, Germany) [12] in conjunction with the EcoInvent Database 2.0 [13]. The system boundary could be found in Fig. 1. Because common reed was a perennial plant and naturally occurring in wetland, extra

agricultural work and fertilizer were not needed in the growth stage, which were not included in the system. Harvest tools, infrastructures and facilities were assumed to be already built, which were not included either. The harvested common reed would be packed as a 700 kg bale and transported. The transport distance of a round-trip from field to bioethanol plant was 50 km with a tractor powered with diesel (Table S1).

Fig 1. A gate-to-gate system for the evaluation of the common reed bioethanol.

The feedstock would be chopped (Table S2) and pretreated first, then processed enzymatic hydrolysis and fermentation with engineered *S. cerevisiae*, such as LNH-ST 424A [14, 15], which could use glucose and xylose to produce ethanol. The lignin, a left part of biomass after hydrolysis and fermentation, would be dried and pelleted to produce electricity, partial of which would be reused in biorefinery plant and extra electricity would be exported as a co-product of the system. The product ethanol was 99.7 % pure after distillation. Wastewater would be treated with the sewage treatment class 2 and recycled in the bioethanol production process. The processes from harvesting to ethanol distillation selected in this LCA model could be found in Fig. S1 and S2. The function unit was 1 L bioethanol.

Because no real industrial data about ethanol production from common reed could be obtained, ethanol production in laboratory-scale was used in this study, which was probably overestimated ethanol production at commercial-scale considering more complex fermentation environments in a larger scale bioethanol biorefinery. A sensitivity analysis was conducted after building an LCA model, and detail information could be found in supplemental materials Text S3.

2.7.2. Net energy and energy efficiency.

In this study, total nonrenewable input energy (ΣE_I , MJ L⁻¹) was calculated through LCA model, including nonrenewable energy from crude oil, hard coal,

lignite, natural gas, uranium, light fuel oil, electricity, low-sulfur diesel and energy in organic substances during the processes. The lower heating values (*LHV*) of resources and organic chemicals were used in calculation [16]. The total output energy (ΣE_O , MJ L⁻¹) included energy in ethanol and co-product electricity. Net energy ($\Delta E = \Sigma E_O - \Sigma E_I$, MJ L⁻¹) was defined as the difference between ΣE_O and ΣE_I for 1 L ethanol production in the LCA model. The energy efficiency ($r_{en} = \Sigma E_O / \Sigma E_I$, MJ MJ⁻¹) was defined as the ratio of ΣE_O to ΣE_I [17].

2.7.3. Global warming potential

Global warming potential was calculated based on the CML characterization method [18]. Because biogenic GHG emission was climate neutral, only GHG emissions from fossil fuel and other non-renewable resources were counted in calculation. As bioethanol would replace gasoline as transportation fuel, the GHG emission intensity (GHG_{int} , gCO_{2,eq} MJ⁻¹) of common reed bioethanol was calculated, as equation 5 follows:

$$GHG_{int} = \frac{GHG_{total} - GHG_{credit}}{LHV_{ethanol}} \quad (5)$$

where GHG_{total} was the total GHG emission excluding biogenic GHG emission for producing 1 L bioethanol and $LHV_{ethanol} = 21.7$ MJ L⁻¹ [16], and GHG_{credit} was the saved GHG emission from coproduct electricity 0.20 MJ L⁻¹ (277 gCO_{2,eq} MJ⁻¹ for coal fired power plants) [19].

2.7.4. Eutrophication potential

The eutrophication potential (*EP*) of common reed bioethanol was calculated with the method developed by Heijungs et al. [20], in which the equivalency factor was set to aggregate nitrogen and phosphorus emitted into water, which would cause

phytoplankton over growth. The equivalency factors [20] of N, NO_3^- and NH_4^+ for eutrophication were 0.42, 0.10 and 0.33 gPO_4^{3-} eq.

3. Results and Discussion

3.1. Site description and dry biomass yield

Common reed would sprout at March, bloom at October and dry at the end of November at the three locations. There is plentiful precipitation (1007.5 ± 10.6 mm) at the three locations and the average temperature is 15.1 ± 0.9 °C from March to November in the recent decade (Table 1). The average temperature in 2013 was $0.47 - 0.63$ °C higher than that in 2012 at the three locations; the total precipitations of Sihong and Sheyang in this period in 2013 were 403 mm and 136 mm less than those in 2012, respectively, while the precipitation of Haimen was 118 mm more in 2013 than in 2012. The values of Y_{db} were in the range of $3.8 - 36.0 \text{ Mg ha}^{-1}$, which were consistent with the reported values [8, 21] and similar to the yields of switchgrass [17].

Location was a significant factor ($p < 0.05$) for common reed Y_{db} in the study years. The average biomass yields of Haimen ($Y_{\text{db}} = 20.8 \pm 8.2 \text{ Mg ha}^{-1}$) and Sheyang ($Y_{\text{db}} = 15.9 \pm 4.1 \text{ Mg ha}^{-1}$) were much higher than that of Sihong ($Y_{\text{db}} = 9.3 \pm 5.0 \text{ Mg ha}^{-1}$). Further statistical analysis showed soil pH and available N content were significant factors ($p < 0.05$) on Y_{db} . Higher soil pH would have higher Y_{db} in the pH range of 7.19 – 8.47. The locations of Haimen ($\text{pH} = 8.13 \pm 0.20$) and Sheyang ($\text{pH} = 8.28 \pm 0.21$) were near to coastline of ocean, while sites at Sihong ($\text{pH} = 7.81 \pm 0.31$) was near to lake bank (Hongze lake). In the research of Shi [22], soil salination would affect the levels of common reed's DNA methylation, which could cause differences among populations of common reed at different locations. The result in this study was different from the reported data of Gong et al [23], where they found soil salination,

pH and water content would limit common reed growth in arid area, because water uptake would be impacted. However, common reed in this study grew at wetlands, and there was no problem in water uptaking. Aquatic common reed has higher growth rate than terrestrial common reed and more responsive to soil available N and P changes [24]. Soil samples in Haimen and Sheyang also have higher available N content than soils in Sihong. Higher soil available N content would improve Y_{db} and decrease flower fraction ratio in whole plant (Fig 2), which had also been observed in other plants [25, 26]. However, temperature, precipitation, SOC, and soil application type had limited effects on Y_{db} of common reed. More studies were required to confirm this result. The results indicated that common reed grown near to farmland was very suitable for bioethanol production.

Fig 2. Effects of soil available N on a) common reed biomass yield and b) flower ratio.

3.2. Fraction composition and ethanol yield prediction

Fraction ratios of flower, leaf and stem (Table 2) in the whole plant were in the ranges of 2.34 – 15.35 %, 11.60 – 35.08 %, and 59.20 – 86.06 %, respectively, which were consistent with the previous research of Li et al. [24]. In this study, location had no significant effect on fraction ratios and fraction compositions, including common reed grown at wastewater treatment wetland. This result was consistent with the results of Li et al [24], in which they found similar biomass allocation patterns among different environments, including aquatic and terrestrial common reed.

Table 2. Mass fractions of stem, leaf and flower in common reed and their compositions

Glucan content was significantly higher in stem fraction than those in leaf and flower fractions, ash and klason lignin contents were significantly higher in leaf than

those in stem and flower fractions (Table 2). Klason lignin and ash were proved to obstruct monosaccharide's hydrolysis and fermentation [27]. No significant difference of xylan and arabinan contents was observed among leaf, stem and flower fractions in this study. The xylan content in common reed was lower than that in corn cob (308 g kg^{-1}) and stover (230 g kg^{-1}) but the content of arabinan was higher than that in corn cob (39 g kg^{-1}) and stover (39 g kg^{-1}) [11]. The contribution of leaf bioethanol to the whole-plant bioethanol was in the range of 4-51%. Based on pretreatment and enzymatic hydrolysis data (Table S3), the recovery ($77 \pm 3 \%$) and polysaccharide conversions of stem ($> 83 \pm 8 \%$) was much better than leaf and flower fractions. The results indicated that stem was more suitable for bioethanol production than leaf and flower.

The values of Y_{ethanol} ($890 - 7580 \text{ L ha}^{-1}$) were estimated following equation 3, and $E_{\text{prod,wh}}$ (0.17 L kg^{-1}) of whole-plant common reed was lower than the reported values (16.5 g and 15.8 g ethanol per 100 g dry biomass) of Cotana et al [28] because of different pretreatment methods. Based on statistical analysis, Y_{ethanol} values from common reed at Haimen and Sheyang were significantly higher than those at Sihong due to higher biomass yields (Table 1). The highest Y_{ethanol} was located at Haimen block 1 in 2012, a brook bank wetland near to a farmland; the lowest Y_{ethanol} was found at Sihong block, an abandoned constructed wetland for wastewater treatment. Based on the linear mixed model (SAS 9.4), the values of Y_{ethanol} were linear correlated ($R^2 = 0.4$) with soil available N content (Fig 3). This result indicated that the wetlands with high available N content were very suitable for common reed growth as a bioenergy feedstock, and at the same time the wetlands could serve as buffer zones to reduce N/P in runoff [3, 29]. Harvesting common reed in winter could enhance N/P remove efficiency, because land cleaning could create more aerobic

condition and improve microbial activity of denitrification [3]. However, harvesting common reed could disturb wetland environment, which also served as habitats of wild animals.

Fig 3. Effects of soil available N on common reed ethanol yield.

3.3. Energy efficiency of common reed bioethanol

Because common reed was naturally occurring at wetlands, no agriculture activity was involved in common reed growth. The value of ΣE_I for common reed bioethanol was 4.19 MJ L^{-1} , which was only one quarter of sweet sorghum bioethanol [30]. The value of net energy ($\Delta E = 17.7 \text{ MJ L}^{-1}$) was similar to bioethanol from corn stover, rice straw, wheat straw and switchgrass (Table 3), and the value of r_{en} (5.22) was 2.0 – 2.9 times of bioethanol from corn stover, similar to rice, wheat straw, but lower than switchgrass bioethanol (Table 3). The difference between common reed bioethanol and switchgrass bioethanol [17] was from co-product credit, export electricity was 0.20 MJ L^{-1} in this study while 4.8 MJ L^{-1} in their study. The average export electricity (0.29 MJ L^{-1}) was reported in the research of Kumar and Murthy [31] with four biomass pretreatments, including diluted acid, diluted alkali, hot water and steam explosion, which was similar to this study.

Table 3. Comparisons of composition and energy efficiency among different biomass feedstocks

Based on the results of the LCA model (Fig 4a), auxiliary materials in ethanol biorefinery processes, such as calcium chloride, sodium chloride, ammonium, sulfuric acid, etc, contributed the most (61 %) to ΣE_I ; harvest, bale and transport contributed 29 %; natural gas in ethanol biorefinery processes contributed 7.8 %. These results were comparable with the research of Sinistore et al [39]. The results indicated that improving biorefinery could greatly save the nonrenewable energy input.

Fig 4. Results of LCA model in this study, a) nonrenewable energy input of each process, b) GHG emission of each process in the system.

3.4. GHG emissions of common reed bioethanol

Excluded biogenic GHG, the total emitted GHG estimated through the LCA system was $380 \text{ gCO}_{2,\text{eq}} \text{ L}^{-1}$, which was compatible with the research of Sinistore et al [39]. Based on LCA calculation (Fig. 4b), auxiliary material, ethanol fermentation and natural gas in biorefinery processes contributed the most (85 %) to the total GHG emission, and the processes of harvest, bale and transport contributed 13 % to the total GHG emission.

If the credits of co-product electricity were considered, the value of common reed ethanol GHG_{int} was $15 \text{ gCO}_{2,\text{eq}} \text{ MJ}^{-1}$, which was compatible with the values of bioethanol from other cellulosic feedstocks (Table 3) and much lower than whole-plant corn ethanol ($59 - 99 \text{ gCO}_{2,\text{eq}} \text{ MJ}^{-1}$) [40].

3.5. Eutrophication potential

Based on LCA model calculation, *EP* of common reed bioethanol was $0.712 \text{ gPO}_4^{3-\text{eq}} \text{ L}^{-1}$, and 88 % was from bioethanol biorefinery, including the distillery process, added maize starch, ammonia, sulfuric acid, *ect.*, which was consistent with the results of Borrion et al. [41]

At the same time, common reed could effectively remove N and P from soil and runoff during the growth stage, and the removal rates were related with N and P concentrations in water, retention time of runoff, and density of common reed in wetland. Based on previous researches [42, 43], the remove rates of N and P were in the ranges of 14 - 98 % and 52 - 99 %. The research of Wu et al. [29] indicated the average values of N and P stored in above ground parts of common reed were $13.5 \pm 2.2 \text{ g m}^{-2}$ and $0.99 \pm 0.29 \text{ g m}^{-2}$ at the end of October. If all above ground biomass

(15.0 Mg ha⁻¹) was harvested for bioethanol, the removed N and P could be used to calculate reduced *EP* and the value was 24.2 gPO₄³⁻eq L⁻¹, which was much higher than the value of *EP* produced during bioethanol processes. The final *EP* value of common reed bioethanol indicated encourage this application is beneficial in reducing water eutrophication. At the same time, proper application of wetland plants would be helpful in wetland conservation.

3.6. Sensitivity Analysis

A sensitivity analysis was conducted in this study (Text S3 in supplemental materials) to test model stability. The results showed that ΣE_L , GHG_{int} and *EP* in the LCA model were stable with the change values ($\pm 30\%$) of natural gas usage, bale weight, transport distances from farm to plant, and the degrees of sensitivity S_{ij} were < 0.05 (equation S1 in supplemental materials). However, they were sensitive to E_{prod} , and the values of S_{ij} were 0.27, -0.13, 0.25, respectively, which indicated the values of ΣE_L , GHG_{int} and *EP* in the LCA model were mainly from the process of ethanol production.

4. Conclusions.

Due to high-density population and arable land limitation, wetland shrinking is a confronted challenge to the world. As a natural specie in wetlands, common reed grows well in China, especially in Jiangsu Province. Developing an application strategy of common reed will be helpful in conserving wetlands. The results in the study showed common reed grew well in soils with higher available N content, and location had limited influence on common reed polysaccharide compositions. High glucan and xylan contents were detected in common reed, which made it a good candidate for bioethanol feedstock. Based on the LCA model, about 70 % of ΣE_L was from biorefinery processes. Bioethanol application could produce positive net energy,

and the values of r_{en} and GHG_{int} were comparable to those of switchgrass bioethanol; the negative value of EP indicated encouraging bioethanol application of common reed could benefit for water quality. Different results may be obtained at the scales of bioethanol data collection [44]. Based on previous research of rice straw bioethanol application, the common reed bioethanol would made a profit of \$38.6 per 700 kg bale if the price of common reed biomass was 250 Yuan Mg^{-1} and \$1 = 6.5 yuan (Chinese currency), which made this application considerable for investigators and stakeholder [6]. Optimizing fermentation conditions for common reed ethanol production should be done in the future, which would greatly impact GHG emission, energy efficiency and eutrophication potential. Our finding implied that common reed would supplement agriculture residues (wheat straw, rice straw and corn stover) as renewable bioenergy feedstocks. However, harvesting common reed growing in the reserved area should be prohibited, which provides many ecosystem services in the wetlands, especially to fauna, such as migrating avian species in Jiangsu Province.

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428 Figures

429 Fig 1. A gate-to-gate system for common reed cellulosic bioethanol.

430 Fig 2. Effects of soil available N on a) common reed biomass yield and b) flower
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432 Fig 3. Effects of soil available N on common reed ethanol yield.

433 Fig 4. Results of LCA model in this study, a) nonrenewable energy input of each
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578 Fig 1. A gate-to-gate system for common reed cellulosic bioethanol.

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582 Fig 2. Effects of soil available N on a) common reed biomass yield and b) flower
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587 Fig 3. Effects of soil available N on common reed ethanol yield.

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Fig 4. Results of LCA model in this study, a) nonrenewable energy input of each process, b) GHG emission of each process in the system.

Table 1.

Weather conditions and soil properties at three sampling locations.

	Haimen		Sihong		Sheyang	
T_{av}^b (°C)	15.9		15.2		14.1	
P_{total}^c (mm)	997		1000		1015	
	2012	2013	2012	2013	2012	2013
SOC (%)	1.29 ± 0.29	1.28 ± 0.25	0.92 ± 0.46	0.91 ± 0.34	0.97 ± 0.60	1.03 ± 0.13
pH	8.24 ± 0.10	8.01 ± 0.21	7.69 ± 0.23	7.94 ± 0.16	8.19 ± 0.30	8.35 ± 0.03
N (g kg ⁻¹)	41.5 ± 3.4	22.5 ± 3.3	19.0 ± 3.8	26.2 ± 6.2	22.3 ± 6.9	26.5 ± 4.1
Y_{db}^d (Mg ha ⁻¹)	25.5 ± 8.5	21.1 ± 10.5	8.6 ± 2.6	9.5 ± 5.1	18.2 ± 2.0	13.6 ± 6.2
$Y_{ethanol}^e$ (L ha ⁻¹)	5400 ± 1800	4400 ± 2200	1800 ± 600	2100 ± 1300	3900 ± 400	2800 ± 1300

^a Haimen, N 31.88, E 121.12; Sihong, N 33.39, E 118.29; Sheyang, N 33.61, E 120.48;^b Average annual temperature of 2003-2012;^c Total annual precipitation of 2003-2012;^d Dry biomass yield;^e Estimated bioethanol yield.

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Table 2.

Fraction ratios of stem, leaf and flower in common reed and their compositions.

Location ^a	Flower (%)		Leaf (%)		Stem (%)	
	2012	2013	2012	2013	2012	2013
Haimen	2.34	5.72	11.60	35.08	86.06	59.20
Sihong	15.35	13.82	14.20	28.59	70.45	57.59
Sheyang	8.18	6.86	12.44	32.83	79.38	60.30
Compositions (g kg ⁻¹ dry biomass) in flower, leaf and stem						
Glucan	278 ± 29		280 ± 21		365 ± 29	
Xylan	164 ± 19		139 ± 36		156 ± 39	
Arabinan	11.0 ± 3.3		10.8 ± 5.1		5.9 ± 4.8	
Klason lignin ^b	253 ± 28		297 ± 41		272 ± 40	
Ash	64.6 ± 16.4		140 ± 41		45.3 ± 13.0	

^a Haimen, a city in Nantong, Jiangsu Province; Sihong, a city in Suqian, Jiangsu Province; Sheyang, a city in Yancheng, Jiangsu Province.

^b Acid insoluble lignin.

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Table 3.

Comparisons of composition and energy efficiency among different biomass feedstocks.

	common reed ^a	common reed ^b	corn stover ^c	rice straw ^d	wheat straw ^e	switchgrass ^f
	g kg ⁻¹ dm					
Glucan	337 ± 29	327 ± 25	388	347 ± 11	302 - 448	285 ± 4
Xylan	150 ± 24	181 ± 22	230	151 ± 2	187 - 236	198 ± 3
Klason lignin	282 ± 37	220 ± 20	180	191 ± 10	140 - 242	167 ± 8
	L kg ⁻¹ dm					
$E_{\text{prod,wh}}$	0.17 ^g	0.22	0.20	0.27	0.25- 0.36	0.25
	Life cycle energy efficiency of bioethanol production					
ΔE (MJ L ⁻¹) ^h	17.7	-- ^j	22.0 - 32.0 ^k	17.6	17.7	22.8 ^l
r_{en} (MJ MJ ⁻¹) ⁱ	5.22	--	1.8 - 2.6 ^k	4.60	5.74	8.2
GHG _{int} (gCO _{2,eq} MJ ⁻¹)	15	--	15 - 30 ⁿ	14	13	11

^a Data from this study;^b Reference [7];^c Reference [10];^d References [6, 31, 33];^e Reference [6, 34];^f References [18, 35];^g Predicted ethanol production, estimated with 6 % solid loading enzymatic hydrolysis;^h Net energy gain, which is defined as the gained energy between the total output energy and the total input nonrenewable energy;ⁱ The net energy ratio, which is defined as the ratio between the total output energy and the total input nonrenewable energy;^j No data;^k Reference [36];^l References [37];ⁿ Reference [38]

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