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Evaluation of Global Energy Crop Production Potential up to 2100 under Socioeconomic Development and Climate Change Scenarios

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We evaluated the global technical potential of energy crop production up to the year 2100, maintaining consistency with agricultural land use change under three different socioeconomic development and climate change scenarios. Our evaluation shows that the energy potential will increase from 160 EJ yr⁻¹ in 2000 to 180-200 EJ yr⁻¹ by 2050, and to 220-270 EJ yr⁻¹ by 2100, reflecting the increase in the potential land area for energy crops. The upper limits of the aforementioned potential correspond to the scenario with low population growth and high economic growth, while the lower limits correspond to the scenarios with moderate economic and population growth. It was clearly demonstrated that differences of socioeconomic development substantially impact the evaluation results, while differences in the level of global warming have little impact on the results. Furthermore, it is shown that land having relatively high crop yields and high land accessibility will be limited and concentrated in some developing regions such as Africa and Latin America.

世界の2100年までのエネルギー作物の技術的ポテンシャルを、異なる3つの社会経済発展・気候変動シナリオに対し、農業土地利用変化との整合性を考慮の上評価した。それによると、エネルギー作物のポテンシャルは、利用可能と考えられる土地面積の増大を反映し、2000年の160 EJ yr⁻¹から、2050年に180-200 EJ yr⁻¹、2100年に220-270 EJ yr⁻¹まで増大する。この上限値は低位人口・高位経済成長シナリオに、また、下限値は中位人口・中位経済成長シナリオに対応する。分析により、ポテンシャル値は、社会経済発展の違いに大きく依存する、一方、地球温暖化のレベルの違いにはあまり依らない事が示された。さらに、作物単収が高く、アクセスが良いと考えられる土地は限られ、アフリカや中南米等一部の発展途上地域に集中している事が示された。

Key Words

Energy crop, Food and water, Land use, Socioeconomic development, Climate change

1. Introduction

Biomass is the primary source of food and fodder, and it also plays a role as an energy source. Biomass provided about 10% (about 50 EJ) of global total primary energy supply (TPES) in 2008¹⁾. Most of this was utilized for traditional styles of cooking, space heating, and lighting in developing countries, while modern-style use of electricity, heat, and transportation accounted for no more than 11 EJ (2% of TPES). In the future, biomass energy utilization, and especially modern-style utilization, is projected to increase over time due to an increase in energy demand, technological progress with modern bioenergy, and other factors. For example, a study using models²⁾ projected that deployment of modern bioenergy would amount to 5-130 EJ

yr⁻¹ (1%-13% of TPES) in 2050 and 70-230 EJ yr⁻¹ (5%-17% of TPES) in 2100 under baseline scenarios, in which no specific policies for climate change mitigation were assumed. Under climate policy scenarios, the share accounted for by modern bioenergy is even larger, to substitute fossil fuels and to mitigate CO₂ emissions. For scenarios in which a CO₂-equivalent atmospheric concentration of 450 ppm is attained in 2100, the estimated deployment of the modern bioenergy would amount to 15-250 EJ yr⁻¹ (3%-37% of TPES) in 2050 and 210-330 EJ yr⁻¹ (23%-50% of TPES) in 2100. Furthermore, model projections suggested that constraints on global bioenergy supply would notably affect the cost of mitigating climate change³⁾.

From the viewpoint of sustainable bioenergy use, it is important to avoid competition with food production and environmental conservation needs. The bioenergy

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potential taking these issues into account is often called the ‘technical potential’, and a number of projections have been conducted. However, the projections vary widely depending on background assumptions regarding food demand, progress with agricultural productivity, types of energy crops, preference regarding environmental conservation, land categories, and other factors. According to a literature review by Offermann *et al.*⁴⁾, the technical potential in 2050 was evaluated in the range of 0–1,272 EJ yr⁻¹ for energy crop production in surplus agricultural land and degraded land, and 62–325 EJ yr⁻¹ for residuals (originating from forestry, agriculture, and organic wastes). Dornburg *et al.*⁵⁾ stated, based on model and literature assessment, that the upper bound for the technical potential in 2050 is about 500 EJ yr⁻¹, with such potential consisting of 120–330 EJ yr⁻¹ from energy crop production, about 100 EJ yr⁻¹ from residuals, and about 70 EJ yr⁻¹ from surplus forest (forest unutilized for conventional industrial roundwood production). Meanwhile, most studies have focused on the potential in 2050, even as the requirement for bioenergy is expected to increase over time during this century, particularly if extensive CO₂ emission reduction will be required.

In this study, we focused on the potential of energy crop production, since it is expected to account for a large share of bioenergy potential and to have a substantial impact on strategies for effective energy supply. We evaluated the global technical potential of energy crop production up to 2100. Three different socioeconomic development and climate change scenarios were adopted for the evaluation, to clarify impacts on the potential evaluation caused by different assumptions regarding these factors.

2. Methodology

2.1 Procedure of model analysis

An agro-land model⁶⁾ was utilized to evaluate the technical potential, maintaining consistency with agricultural land use changes under socioeconomic development and climate change scenarios. It is basically a grid-based model with the spatial resolution of 15 minutes × 15 minutes, although the modules for food demand and management factor have 32 regions; for the locations of the regions, refer to Fig. A1 in the Appendix. It is integrated with a water supply-demand model as shown in Fig. 1, and it enables the consideration of water availability.

First in the analysis, the food demand is calculated based on per-capita dietary energy demand and population. The dietary energy demand is converted to demand for food crops (wheat, rice, maize, sugar cane, soybeans, oil palm fruit, rapeseed, and others). Moreover, the yields of the food crops are evaluated considering not only the

Fig. 1 Framework of the agro-land model (* The land cover is divided into major land types such as rainforest, other forests, arable land, grassland (including scrub/wood land), pasture, barren land, and so on. It was constructed based on a land cover map for around the year 2000^{7) ~ 9)}. Protected areas are based on a map developed by IIASA¹⁰⁾. Only arable land is allowed to be expanded when additional land is required for food production^{6) 11)})

productivity improvement resulting from technological progress associated with economic growth, but also impacts due to climate change. Impacts due to climate change are taken into account through changes in potential production, which can be calculated using the information on crop characteristics provided in the GAEZ model¹²⁾. Adaptations such as planting time shift and variety change are also taken into account in the calculation of potential production. Next, cropland for food crop production is preferentially allocated to arable land with higher crop productivity to meet the crop demand in each of the regions. This represents an implicitly cost-effective process of land choice, although the agro-land model does not have modules for production cost or crop prices. Fallow land is estimated by subtracting cropland required for food production from arable land. Then, solely fallow land and grassland are adopted as candidate land for energy crop production to avoid conflict with food production. These areas do not include forests and protected areas; therefore, concerns regarding CO₂ emissions and biodiversity loss are minimal. After this, water-stressed basins, which are estimated based on a certain criterion ($0.4 \leq$ the annual water withdrawal-to-availability ratio¹³⁾) are excluded from candidate land. Finally, we focus on land satisfying certain conditions for

Table 1 Categorization of land for energy crop production

Category	Yield	Land accessibility
1	$\geq 20 \text{ DW-t/ha/yr}^a$	$> 1 \text{ person/km}^2^d$
2	$20 \text{ DW-t/ha/yr}^a > \& \geq 12 \text{ DW-t/ha/yr}^b$	
3	$12 \text{ DW-t/ha/yr}^b > \& \geq 6 \text{ DW-t/ha/yr}^c$	
4	$\geq 6 \text{ DW-t/ha/yr}^c$	$1 \text{ person/km}^2^d \geq \& > 0.1 \text{ person/km}^2^e$

a, b, c: The numerical values were assumed based on maximum, mean, and minimum yields of lignocellulosic energy crops on experimental farms, respectively^{15) 16)}

d: The same value was adopted as that used for estimating potentially available arable land¹¹⁾

e: A value one order smaller than that for categories 1, 2, and 3 was assumed to take into account the possible cultivation of perennial grass and woody biomass even on land with low accessibility

energy crop yield and land accessibility of candidate land, and we calculate the available energy based on the crop production on such land.

Selection of energy crop type will vary by region depending on policies on land use, agriculture, etc. In this study, we left the type unspecified to focus on potential amounts, and we estimated energy crop production based on NPP (Net Primary Production) calculated based on annual mean temperature and annual precipitation¹⁴⁾, assuming average carbon content of 50%. Constraints on crop production due to terrain slope were taken into account based on Fisher *et al.*¹²⁾ To convert crop production weight to energy amount, 15 GJ/DW (dry weight)-t was adopted, as a heating value per unit production.

Annual and monthly climate including temperature, precipitation, etc. was estimated from the projections by atmosphere-ocean coupled general circulation models (AOGCMs) and global mean temperature (GMT) change scenarios, based on a pattern-scaling method. These calculations are carried out for every decade from 2000 to 2050, and for the years 2070 and 2100 as time points.

The four categories shown in Table 1 were assumed for potentially available land for energy crop production based on crop yield and land accessibility. As a proxy for land accessibility, population density⁶⁾ was adopted.

2.2 Scenarios

Three scenarios related to socioeconomic development and climate change, A-Base, A-CP3 and B-Base, were adopted from the alternative scenarios that had been developed and had been assessed quantitatively by Akimoto *et al.*¹⁷⁾ from the viewpoint of climate stabilization and sustainable development. In the A-Base scenario, a world

with moderate growth of population and per capita GDP and no specific policy for climate change mitigation is illustrated; in the A-CP3 scenario, it is assumed that the population and per capita GDP are same as those for the A-Base scenario, but climate change is mitigated so that the GMT increase is expected to be below about 2°C relative to the pre-industrial level; and in the B-Base scenario, a world with low population growth, high per capita GDP growth, and no intervention on climate are illustrated. The global population and per capita GDP for the A-Base and A-CP3 scenarios are almost consistent with those for the SRES-B2 scenario¹⁸⁾. The global population for the B-Base scenario corresponds to that for the SRES-B1 scenario¹⁸⁾, although the per capita GDP for the former scenario is somewhat lower than that for the later scenario. The data on the population and GDP for the A-Base and B-Base scenarios, as well as that for greenhouse gas (GHG) emissions for the A-Base scenario, can be obtained from the RITE web site¹⁹⁾. There was little difference in the GMT increase between the A-Base and B-Base scenarios, since their GHG emissions were much the same, and the GMT increase for these scenarios is approximately 4°C by 2100. As the AOGCM data, the projection by MIROC3.2 (Medres)²⁰⁾ was adopted. Sensitivity analysis for inter-AOGCMs differences remains to be addressed.

It was estimated that the global dietary energy demand in the A-Base and A-CP3 scenarios would increase up to 170% of that in 2000 by 2050. It was estimated that after 2050, the rate of increase would slow down due to slowing population and per capita demand growth. In the B-Base scenario, global dietary energy demand will be lower than it would be in either the A-Base or the A-CP3 scenario, mainly due to low population growth, and it will decrease after 2050. The demand in 2050 and 2100 will be 160% and 140% of that in 2000, respectively.

3. Results

3.1 Technical potential under the A-Base scenario

Fig. 2 shows estimated global land areas by major land type for the A-Base scenario. The area of cropland required for food production will increase from 1,200 million ha in 2000 to 1,400 million ha by 2050 due to the food demand increase, the rate of which exceeds the rate of crop yield increase in regions such as West Africa. After that, the area will decrease due to the slowing down of the food demand increase together with a continuous increase in crop yield. The fallow land area will increase gradually, owing to improvement in food crop productivity, the rate of which exceeds the rate of food demand increase in regions such as East Europe, Russia, China, and India. Global

Fig. 2 Global land areas by major land type for the A-Base scenario

grassland was estimated to amount to about 2,200 million ha in 2000, and to decrease to about 2,100 million ha by 2100 due to land use changes to cropland.

Fig. 3 shows distribution of fallow land and grassland estimated as being potentially available for energy crop production in 2050 for the A-Base scenario. The available fallow land is in some grids for East Europe, Russia,

China, and elsewhere. In Western Africa, grassland will predominate as available land, since almost all the arable land will be required for food crop production. It should be noted that the most of the available land (including fallow land and grassland) in Africa, Latin America, Southeast and South Asia, and East Asia is category 1 or 2 land, while the most of the available land in East Europe and Russia is category 3 or 4 land.

3.2 Comparisons among scenarios

Fig. 4 shows the total potential land area worldwide and the energy potential from energy crop production on land for the three scenarios. In the A-Base scenario, the potential area will be around 1,000 million ha by 2050, and it will increase to 1,200 million ha by 2100, mainly reflecting an increase in fallow land. There is little difference in potential area between the A-Base and A-CP3 scenarios. In the A-CP3 scenario, less cropland will be required for food production (by 50 million ha in 2050) than in the A-Base scenario, owing to alleviation of the negative impacts of

Fig. 3 Distribution of land estimated as potentially available for energy crop production in 2050 for the A-Base scenario

Fig. 4 (a) Potential land area and (b) global energy potential by land category for the three scenarios

global warming. Therefore, there will be slightly more fallow land (by about 40 million ha in 2050) than in the A-Base scenario. However, this increase in fallow land will rarely contribute to the potential land area, since most of it will be excluded from the candidate land for energy crop production due to constraints on the water availability. Furthermore, some of the grassland estimated as potentially available for energy crop production in the A-Base scenario is excluded in the A-CP3 scenario, since expected increases in water availability and/or crop yield due to climate change are reduced under the A-CP3 scenario in some regions such as Asia and Russia. In the B-Base scenario, the potential area will be larger than those in the A-Base and the A-CP3 scenarios, since there is expected to be conspicuously more fallow land (by about 170 million ha in 2050, compared to fallow land in the A-Base scenario) due to the substantially lower food demand. Technical energy potential from energy crop production on the land will increase reflecting the increase in the potential area under all of the scenarios; it is expected to be 180-200 EJ yr⁻¹ in 2050, and to be 220-270 EJ yr⁻¹ in 2100.

A comparison of estimated energy potential figures by region for 2050 among those of the different scenarios and those of other recent studies using grid-based models^{1) 21)} is shown in Fig. 5. The amounts of estimated energy potential were aggregated into seven regions; for such seven regions, refer to Table A1 in the Appendix. Among the three scenarios adopted in this study, the B-Base scenario has the highest potential for all of the regions, while the lowest potential is estimated in the A-Base or the A-CP3 scenario. There is not much difference between the A-Base and A-CP3 scenarios for most regions. Comparisons between our estimates and those of the recent studies show that they do not agree very well. Our estimates of the energy potential for Latin America, Asia, and Europe, FSU are

greater than those of the other studies, while our estimates for North America and Oceania are lesser than those of the other studies. Differences in assumptions regarding socioeconomic development, climate change, environmental constraints, types of energy crops, etc. may cause such differences. Further research is necessary to narrow the gaps.

We evaluated the potential for the B-CP3 scenario, in which socioeconomic development is same as that for the B-Base scenario and the GMT increase is below about 2 °C. The results, not shown in this paper, differed very little from those of the B-Base scenario.

For the year 2050, the total technical potential of bioenergy is estimated at about 350-370 EJ yr⁻¹, when the potential energy from residuals (about 100 EJ yr⁻¹)⁵⁾ and that from surplus forest (about 70 EJ yr⁻¹)⁵⁾ are added to that from energy crop production (180-200 EJ yr⁻¹) evaluated in this study. This total amount of technical potential seems to satisfy the total bioenergy requirement for achieving the low CO₂ atmospheric concentration of 450 ppm (about 55-290 EJ yr⁻¹, an estimate based on 15-250 EJ yr⁻¹ for modern bioenergy and 40 EJ yr⁻¹ for traditional bioenergy; for these numerical values, refer to Chapter 1). However, it should be noted that the potentially available land for energy crop production with relatively high crop yield and high land accessibility will be concentrated in some developing regions and limited as shown in Figs. 3 and 4. These results imply that the deployment of bioenergy may not be so straightforward, despite the large total technical potential.

4. Conclusions

We evaluated global technical potential by energy crop production up to 2100, maintaining consistency with agricultural land use change under socioeconomic development and climate change scenarios. Our evaluation

Fig. 5 Comparisons of energy potential by region with recent studies for the year 2050 (* Based on Table 2 of van Vuuren *et al.* 21), ** Based on Table 2.3 of Chum *et al.* 11)

shows that the area of potentially available land for energy crop production will increase from 900 million ha in 2000 to 1,000-1,100 million ha by 2050, and to 1,200-1,400 million ha by 2100. The energy potential will increase from 160 EJ yr⁻¹ in 2000 to 180-200 EJ yr⁻¹ by 2050, and to 220-270 EJ yr⁻¹ by 2100, reflecting the increase in the potential area. The upper limits of these potential correspond to the scenario with low population growth and high economic growth, while the lower limits correspond to the scenarios with moderate growth of population and economy. It was clearly demonstrated that differences of socioeconomic development substantially impact the evaluation results, while differences in the level of global warming have little impact on the results. Furthermore, it is shown that the potentially available land for energy crop production with relatively high crop yield and high land accessibility will be limited and concentrated in some developing regions such as Africa and Latin America. This situation makes us apprehend that the economic bioenergy potential may not be sufficient to satisfy requirements, and further study in this area will be required.

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Appendix

Fig. A1 The locations of the 32 regions in the world

Table A1 Correspondence between the 32 regions and the 7 regions

32 regions		7 regions			
NOA	North Africa	Africa	WEP	Western Europe	Europe, FSU
SOA	South Africa		RUS	Russia	
SEA	South East Africa		AIS	Annex I of FUSSR	
OSA	Other S. S. Africa		OFS	Other FUSSR	
MEX	Mexico	Latin America	EEP	Eastern Europe	N. America
BRA	Brazil		USA	United States	
PUA	Paraguay, Uruguay, Argentina		CAN	Canada	
OSM	Other South America		ANZ	Oceania	
JPN	Japan	Asia	IRN	Iran	M. East
CHN	China		ARP	Arabian Peninsula	
MDK	Mongolia, North Korea		TUR	Turkey	
CLV	Cambodia, Laos, Viet Nam		OME	Other Middle East	
KOR	South Korea				
MSB	Malaysia, Singapore, Brunei				
IDS	Indonesia				
THI	Thailand				
PHI	Philippines				
IND	India				
APS	Afghanistan, Pakistan				
OTA	Other Asia				