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# Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model

Hiromi Yamamoto[a,*], Junichi Fujino[b], Kenji Yamaji[c]

[a] *Socioeconomic Research Center, Central Research Institute of Electric Power Industry, 1-6-1 Otemachi, Chiyoda-ku, Tokyo 100-8216, Japan*

[b] *Global Warming Response Team, Global Environment Division, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-0053, Japan*

[c] *Department of Advanced Energy, School of Frontier Sciences, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

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**Abstract**

The purpose of this study is to evaluate the global bioenergy potential in the future using a multi-regional global-land-use-and-energy model (GLUE-11). The model covers a wide range of biomass flow including food chains from feed to meat, paper recycling, and discharge of biomass residues.

Through a set of simulations, the following results are obtained. (1) Supply potential of energy crops produced from surplus arable land will be available in North America, Western Europe, Oceania, Latin America, former USSR and Eastern Europe. However, the potential of energy crops will be strongly affected by the variation of parameters of food supply and demand such as animal food demand. (2) Bioenergy supply potential of biomass residues will be stable against a change of a food demand parameter. The ultimate bioenergy supply potential of biomass residues will be 265 EJ/year in the world in 2100. The practical potential of biomass residues in the world will be 114 EJ/year, which is equivalent to one-third of the commercial energy consumption in the world in 1990. (3) Concerning land uses, the global mature forest area will decrease by 24% between 1990 and 2100, because of growth of both population and wood biomass demand per capita in the developing regions. The mature forest, especially, will disappear by 2100 in some developing regions, such as Centrally Planned Asia, Middle East and North Africa, and South Asia. 

*Keywords:* Bioenergy supply potential; Land use competitions; Biomass flow; Model analysis; Bioenergy in the future

## 1. Introduction

Bioenergy is expected to become one of the key energy resources in the future because bioenergy, if maintained adequately, is renewable and free from net $CO_2$ emissions.

However, there are different outlooks on the bioenergy supply potential in the future. For example, in the Second Assessment Report of the Intergovernmental Panel on Climatic Change published in 1996 [1], bioenergy is considered the most important energy resource in the future. On the other hand, at the

* Corresponding author. Tel.: 81-3-3201-6601; fax: 81-3-3287-2805.

*E-mail address:* yamamoth@criepi.denken.or.jp (H. Yamamoto).

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World Food Summit held by the United Nations Food and Agriculture Organization in 1996 [2], reduction of starvation population was discussed, but neither surplus arable land use nor bioenergy supply was talked about.

We note the following two points as the reasons for the difficulty to evaluate the bioenergy supply potential. First, biomass is used not only for energy but also for food and materials. Since the area to produce biomass is limited, we need to analyze land use competitions in order to evaluate the bioenergy supply potential. Second, biomass is utilized through complicated processes such as harvest, conversion, consumption, and recycling. Biomass residues including by-products and wastes, which are discharged at various processes of biomass utilization, can be used for energy.

In order to evaluate such bioenergy resources comprehensively and systematically, we developed a global-land-use-and-energy model (GLUE) considering land use competition and overall biomass flow including those of biomass residues. We reported analyses using the model in Refs. [3–6]. GLUE, which is a model with two regions, is adequate to grasp biomass supply and demand, bioenergy supply potential, and land use changes in the world; however, it is not enough to catch their regional aspects.

The purpose of this paper is to evaluate the multi-regional bioenergy potential of energy crops and biomass residues in the future. For the purpose we modified the two-region model (GLUE) into a model in which the world is divided into 11 regions (GLUE-11) [7]. We also prepared the multi-regional data for the modified model.

The following four sections show the outline of GLUE-11, data, simulation results, and conclusions, respectively.

## 2. Multi-regional global-land-use-and-energy model (GLUE-11)

### 2.1. Outline of GLUE-11

In this section, we explain the outline of the multi-regional global-land-use-and-energy model (GLUE-11). We focus especially on the differences between GLUE-11 and the two-region global model (GLUE) [3].

Table 1
Regions in the model (GLUE-11)

| No. | Regions |
|---|---|
| 1 | North America |
| 2 | Western Europe |
| 3 | Japan |
| 4 | Oceania |
| 5 | Centrally Planned Asia |
| 6 | Middle East and North Africa |
| 7 | Sub-Sahara Africa |
| 8 | Latin America |
| 9 | Former USSR and Eastern Europe |
| 10 | Southeast Asia |
| 11 | South Asia |

#### 2.1.1. Regions in the model

We divide the world into 11 regions (Table 1) in order to analyze land use competitions and bioenergy supply potential regionally.

#### 2.1.2. Model structure

GLUE-11 consists of two sectors (a food sector and a forest sector) and describes land use competition among various uses for biomass applications such as paper, timber, food, feed, and energy (Fig. 1). The model covers a wide range of land uses and biomass flow including food chains from feed to meat, paper recycling, and discharge of biomass residues (Figs. 2 and 3). In this study, biomass is divided into four kinds (primary, intermediate, final, and scrap). ‘Primary biomass’ is defined as the form of biomass just harvested from the land or harvested from the water; ‘final biomass’ is the form of biomass supplied to final consumers (Figs. 2 and 3).

In the model, we consider four kinds of land uses namely, forest (including woodlands), arable land (including permanent crop land), pasture, and other land, following the FAO definition [8]. The forest area in the model is divided into two kinds of areas: mature forest area and growing forest area. We assume that the growing forest grows for decades with the associated absorption of carbon and then changes to the mature forest in which the speed of carbon absorption balances that of carbon emission caused by dead biomass (see Section 3.2.2). In addition, we assume

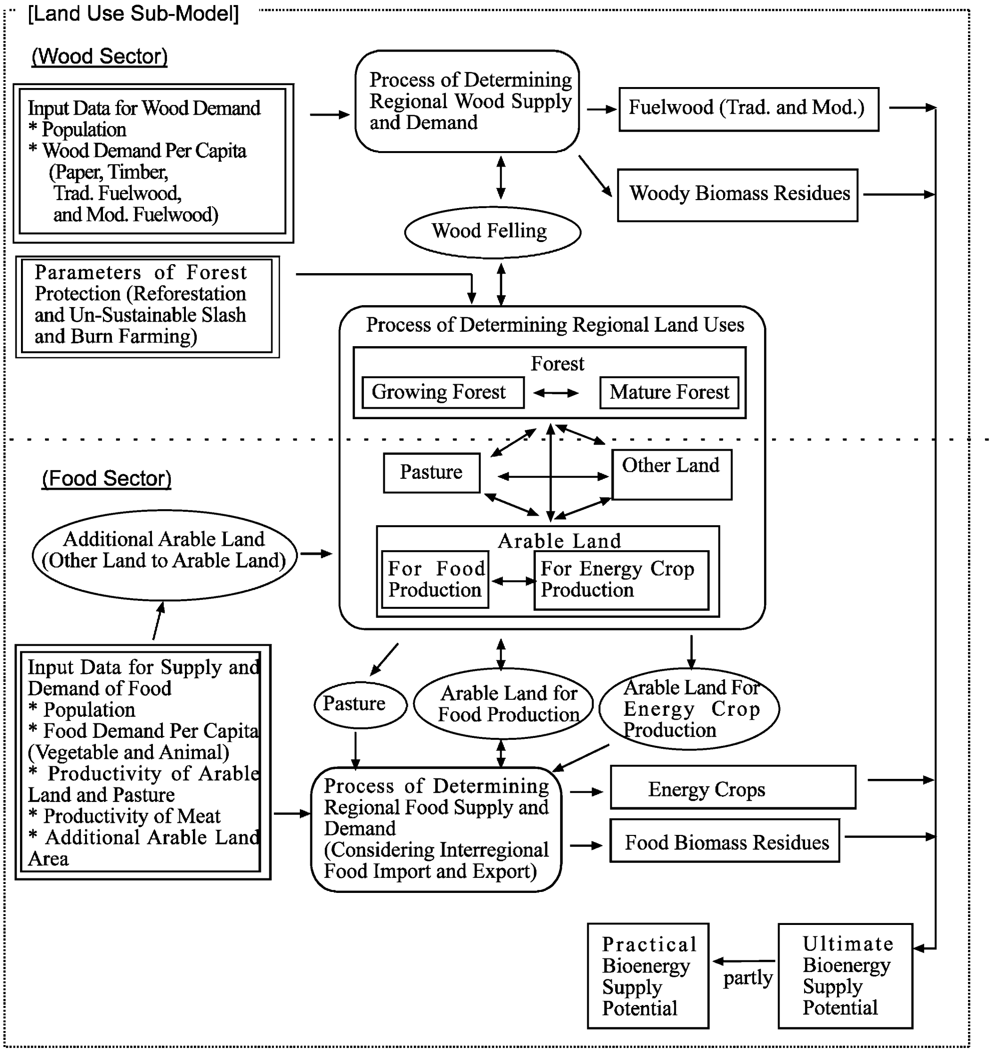


Fig. 1. Structure of the model.

that we will cut trees only in the mature forest area considering sustainable forest management.

The model evaluates the bioenergy supply potential of energy crops, fuelwood, and biomass residues.

### 2.1.3. Simulation period

The model calculates bioenergy potential from 1961 to 1990 based on the past records and that from 1990 to 2100 based on the data explained in the next section, with a one-year time step.

### 2.2. Outline of calculation procedures of GLUE-11

The outline of calculation procedures of the model is as follows:

1. Each kind of final biomass demand (shown in Figs. 2 and 3) is calculated from population (exogenous) and biomass demand per capita (exogenous).
2. The model calculates biomass demand following the biomass flow in Figs. 2 and 3 upstream, namely,

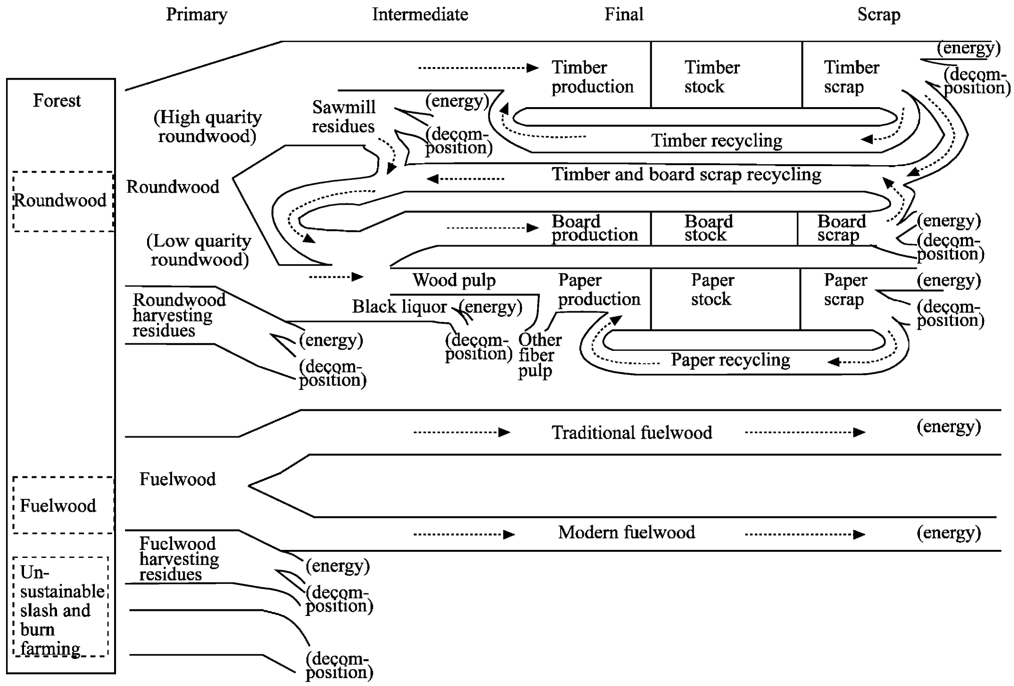


Fig. 2. Wood biomass flow in the model. The widths of the arrows are not representative of the magnitude of the flow.

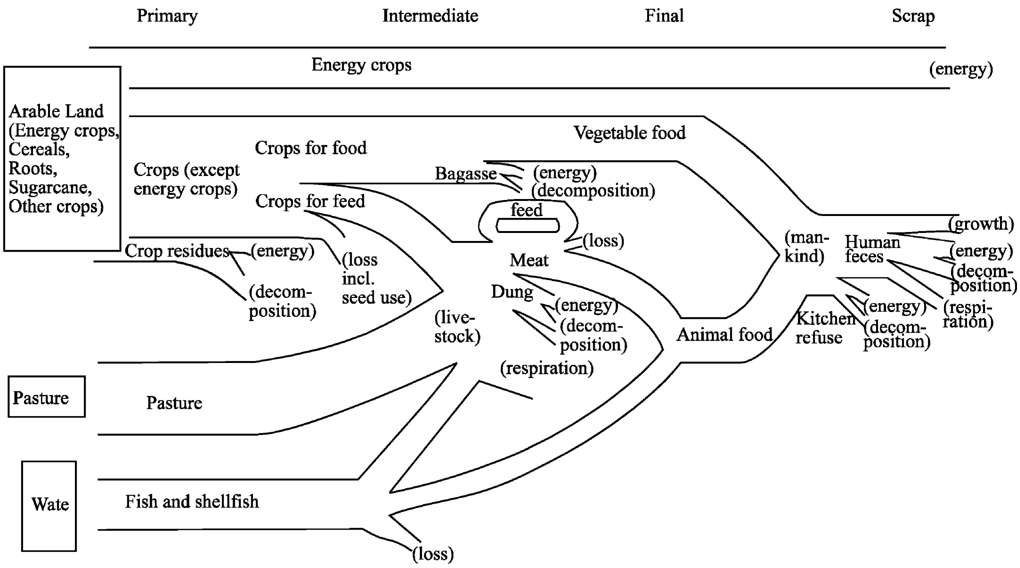


Fig. 3. Food biomass flow in the model. The widths of the arrows are not representative of the magnitude of the flow.

from the final biomass demand through intermediate to primary biomass; then, the model determines import and export of biomass (see Appendix A).

3. The model calculates demand for land. When land shortage occurs, the model revises biomass consumption following the downstream biomass flow

in Figs. 2 and 3 from primary through intermediate to final biomass (see Appendix A).

### 2.3. Definition of bioenergy supply potential

In this study, we define two terms, which are 'ultimate' and 'practical', for evaluation of the bioenergy supply potential.

#### 2.3.1. Bioenergy potential of biomass residues

We define 'ultimate' and 'practical' bioenergy supply potential of biomass residues as follows:

(ultimate bioenergy supply potential)

= (all the discharged biomass residues)

(1 − material-recycling ratios),

(practical bioenergy supply potential)

= (all the discharged biomass residues)

(practical usable ratios

−material-recycling ratios).

We assume that the practical usable ratios are the realistic maximum ratios of energy use of biomass residues, i.e. excluding ratios of collection loss and some kinds of cascaded-recycling uses such as fertilizer use and agricultural material use. Besides, we consider material-recycling ratios of timber scrap (including board scrap), sawmill residues, and paper scrap, which are specified in the wood biomass flow (Fig. 2).

#### 2.3.2. Modern fuelwood and energy crops

In this study we divide fuelwood into two kinds: traditional fuelwood and modern fuelwood. We assume that traditional fuelwood is mainly used for small and low-efficient equipment (such as cooking stoves) in households. We assume that modern fuelwood as well as energy crops is mainly used or converted with modern and high-efficient equipment (such as power plants and liquefaction plants) [3].

Traditional fuelwood is the sum of fuelwood and charcoal in FAO statistics [8]. We assume that modern fuelwood is a product of energy plantation in forest area without planting short rotation coppice such as hybrid poplar and willow. We assume that modern fuelwood is produced in some-decade-rotation between planting and felling processes (see Table 5). In this study, we assume that short rotation coppice is categorized not in forestry but in energy crops produced from surplus arable land.

In this study, we estimate the ultimate bioenergy potential of modern fuelwood as the mature forest areas in 2100 (the final year of the simulation) multiplied by the biomass accumulation rates of the forest.

The biomass accumulation rate in forest is defined as a rate of net primary product (*NPP*) minus rates of natural biomass death and forest thinning. In other words, the potential of modern fuelwood excludes bioenergy potential of forest thinning.

We defined 'ultimate energy potential' of energy crops as the area of surplus arable land (see Section A.2) multiplied by the productivity of energy crops (see Section 3.2.2).

In this study, we do not evaluate the bioenergy potential from pasture, other land (such as desert, tundra, and residential area), and the water (the sea and fresh water) numerically. The reasons are as follows: (1) The great portion of biomass production (except feed use) must be reserved for natural fertilizer in pasture area [3] (see Section 4.5). (2) The productivity of biomass on other land is small. (3) Fishery catch has already hit the ceiling [9]. (4) It is considered that bioenergy production from the water (such as giant kelp) is difficult for reasons of high costs [10].

## 3. Biomass-related data

First, we analyze the relations between final biomass demand and *GDP*. Based on the analysis of the biomass demand and *GDP*, we explain the main data settings for GLUE-11.

### 3.1. Relations between final biomass demand and GDP

We analyze cross-sectional relations between final biomass demand per capita and $GDP_{\mathrm{ppp}}$ (purchasing power parity) per capita in 1990.

In this study the world is divided into 11 regions (Table 1). Final biomass consumption is divided into five categories: timber (including board), paper,

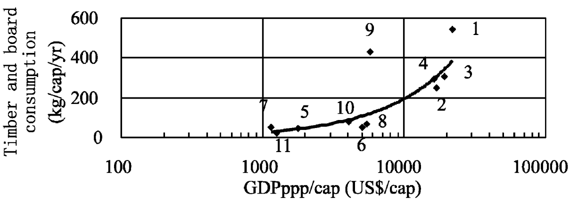


Fig. 4. Timber (including board) consumption and $GDP_{ppp}$ (in 1990). The data are based on Refs. [11,12]. The regions are mentioned in Table 1.

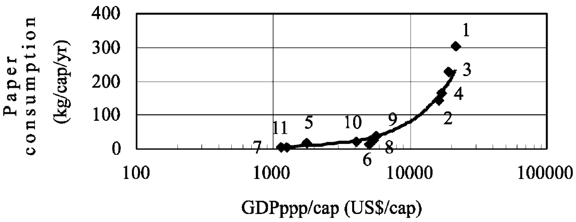


Fig. 5. Paper consumption and $GDP_{ppp}$ (in 1990). The data are based on Refs. [11,12]. The regions are mentioned in Table 1.

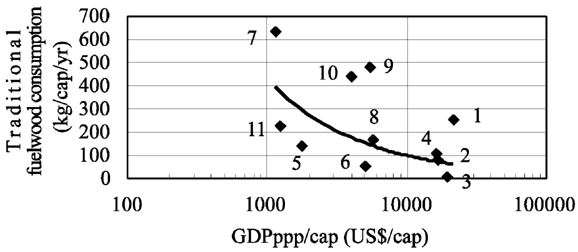


Fig. 6. Traditional fuelwood consumption and $GDP_{ppp}$ (in 1990). The data are based on Refs. [11,12]. The regions are mentioned in Table 1.

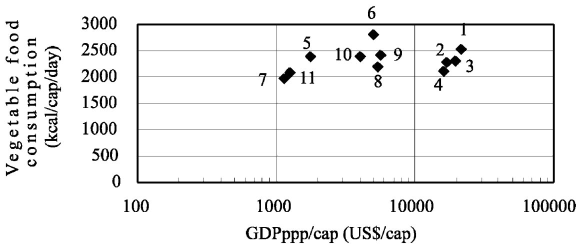


Fig. 7. Vegetable food consumption and $GDP_{ppp}$ (in 1990). The data are based on Refs. [11,12]. The regions are mentioned in Table 1.

traditional fuelwood, vegetable food, and animal food (Figs. 2 and 3). We take timber and board (consisting of particleboard and fiberboard) in the aggregate because timber and board can substitute each other. Besides, we neglect the modern fuelwood demand in 1990 because most of the modern woody fuel is not modern fuelwood but woody biomass residues such as sawmill residues and black liquor currently (see Section 2.3.2).

Fig. 4 shows the timber consumption compared with the $GDP_{ppp}$. The figure shows that the timber consumption in North America is twice as much as the average consumption in the other developed regions. In addition, the timber consumption per $GDP_{ppp}$ in former USSR and Eastern Europe is above the regression curve in the figure.

Fig. 5 shows the paper consumption compared with the $GDP_{ppp}$. The figure shows that the plotted data are along the least-squares curve under constant elasticity. In particular, the paper consumption in North America is 50% larger than the average consumption in the other developed regions.

Fig. 6 shows the traditional fuelwood consumption compared with the $GDP_{ppp}$. The figure shows that the consumption of traditional fuelwood in Sub-Sahara Africa, Southeast Asia, and Latin America is larger than 400 kg biomass/capita/year. In addition, the consumption in North America, where huge forest resources are available, is 260 kg biomass/capita/year and is three times as much as the average consumption in the other developed regions.

Fig. 7 shows the vegetable food consumption compared with the $GDP_{ppp}$. The figure shows that there is little difference between the vegetable food consumption in the developed regions and that in the developing regions. However, the consumption in the lowest income regions such as Sub-Sahara Africa and South Asia is lower than that in the other regions.

Fig. 8 shows the animal food consumption compared with the $GDP_{ppp}$. The figure shows that there is a correlation of animal food consumption with $GDP_{ppp}$. For example, the animal food consumption per $GDP_{ppp}$ in Southeast Asia, Middle East and North Africa, and Japan is below the regression curve in the figure. On the contrary, the animal food consumption per $GDP_{ppp}$ in Centrally Planned Asia is above the regression curve in the figure. While the $GDP_{ppp}$ in Centrally Planned Asia is more than half of that in

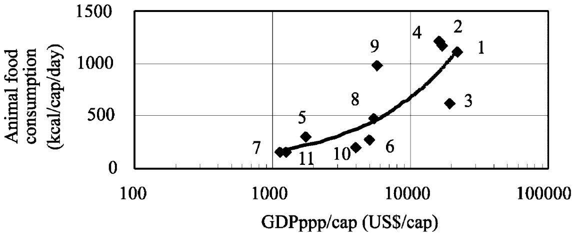


Fig. 8. Animal food consumption and $GDP_{\text{ppp}}$ (in 1990). The data are based on Refs. [11,12]. The regions are mentioned in Table 1.

Southeast Asia, the animal food consumption in the former is 1.5 times as much as that in the latter.

### 3.2. Data for GLUE-11

We prepare multi-regional data for a reference case (Case A) in GLUE-11. We set the data on the basis of the analyses in Section 3.1 and middle or reference projections in the World Bank [13], IPCC [14,15], and other references [16,17]. The details of these data are described in Ref. [7].

In addition, we set a comparative case (Case B) called a high animal food demand case in Centrally Planned Asia, considering the analysis of the biomass supply and demand (see Section 3.1). The data without specification means the data in the reference case (Case A) in the following explanation.

#### 3.2.1. Biomass demand data

Biomass demand data consist of population and biomass demand per capita.

*3.2.1.1. Population.* We set the population data according to the middle scenario of the World Bank where the global population will increase to 11.5 billion in 2100 (Table 2) [13].

Table 2
Population scenario (in millions)[a]

| | 1990 | 2050 | 2100 |
|---|---|---|---|
| North America | 277 | 369 | 379 |
| Western Europe | 361 | 343 | 327 |
| Japan | 124 | 115 | 107 |
| Oceania | 27 | 36 | 37 |
| Centrally Planned Asia | 1242 | 1715 | 1799 |
| Middle East and North Africa | 300 | 796 | 961 |
| Sub-Sahara Africa | 527 | 1808 | 2443 |
| Latin America | 448 | 829 | 910 |
| Former USSR and Eastern Europe | 429 | 512 | 537 |
| Southeast Asia | 372 | 684 | 765 |
| South Asia | 1190 | 2441 | 2791 |

[a]The scenario is based on the middle scenario in Ref. [13].

*3.2.1.2. Biomass demand per capita.* Based on the analyses in Section 3.1, we derived long-term biomass demand scenarios for the model.

First, we assume that all the biomass demand per capita in the developed regions will be constant at the level in 1990. Next, we assume that the biomass demand per capita in the other regions will increase as $GDP_{\text{ppp}}$ per capita increases. Specifically we assume the function as follows:

$$(\text{biomass demand per capita}) = a(GDP_{\text{ppp}}\ \text{per capita})^b.$$

We estimate the values of $a$ and $b$ using two figures such as the point in 1990 and the upper limit shown in Table 3. The $GDP_{\text{ppp}}$ scenario is based on IS92a that is a reference scenario of IPCC [15].

In addition, we assume that the demand per capita will not exceed the upper limits (shown in Table 3). The upper limits are set using the analyses in Section 3.1. For example, the upper limit of the wood biomass per capita is the average of those in the developed regions except North America (Table 3).

However, the long-term prospect of biomass demand contains substantial uncertainty. Thus, we prepare a comparative case and conduct scenario analyses. We choose animal food demand in Centrally Planned Asia as a variant parameter in the comparative case (Case B) (see Section 3.1). The upper limit of the animal food demand per capita in Centrally Planned Asia is the same as that in Japan in Case A; on the other hand, it is the average of those in the developed regions except Japan in Case B (Table 3).

In addition, we assume that no modern fuelwood will be introduced in both cases considering natural forest protection.

#### 3.2.2. Biomass supply data

Biomass supply data comprise the data of land use and productivity. The details of these data are also described in Ref. [7].

Table 3
Upper limits of biomass demand per capita in scenarios of GLUE-11 (in developing regions and former USSR and Eastern Europe)[a]

| | Kinds of biomass | Upper limits |
|---|---|---|
| 1. | Paper, timber and board, trad. fuelwood | The average of the developed regions except North America |
| 2. | Vegetable food | The average of the developed regions |
| 3. | Animal food (regionally) | |
| | Former USSR and Eastern Europe and Latin America | The average of the developed regions except Japan |
| | Middle East and North Africa, Sub-Sahara Africa, Southeast Asia, and South Asia | The value of Japan |
| Case A | Centrally Planned Asia | The value of Japan |
| Case B | Centrally Planned Asia | The average of the developed regions except Japan |

[a]Case A is a reference case; Case B is a high animal food demand case in Centrally Planned Asia. The data without the cases are common data. We assumed the values of the upper limits considering the analysis in Section 3.1.

Table 4
Additional arable land converted from fallow land and degraded land (in Mha)[a]

| | By 2025 | By 2050 | By 2100 |
|---|---|---|---|
| North America | 38 | 38 | 38 |
| Western Europe | 30 | 30 | 30 |
| Japan | 0 | 0 | 0 |
| Oceania | 0 | 0 | 0 |
| Centrally Planned Asia | 25 | 50 | 50 |
| Middle East and North Africa | 0 | 0 | 0 |
| Sub-Sahara Africa | 51 | 101 | 249 |
| Latin America | 78 | 156 | 188 |
| Former USSR and Eastern Europe | 0 | 0 | 0 |
| Southeast Asia | 6 | 11 | 11 |
| South Asia | 27 | 53 | 53 |
| World | 254 | 439 | 619 |

[a]The data are based on Refs. [16,18]. The table shows area of conversion from other land (fallow land, degraded land, and semi-desert) to arable land. It is assumed that the conversion will start in 2000 and that the conversion from semi-desert to arable land will start in 2050. It is assumed that the data will change linearly between the values shown in the table.

*3.2.2.1. Land use changes.* It is assumed that fallow land (at 70 Mha in all the developed regions) will be changed to arable land in the developed regions, and degraded land (at 550 Mha in all the developing regions) will be added to arable land in the developing regions (Table 4) following Refs. [16,18]. We assume that the fallow land and the degraded land are included in 'other land' [8] (see Section 2.3).

Perfect reforestation, which fulfills no unsustainable slush-and-burn farming and 100% reforestation, has already been achieved in the developed regions and it is assumed that it will be achieved in the developing regions in 2025 [3].

*3.2.2.2. Productivity of biomass.* Concerning wood biomass, we assume that the biomass accumulation rate of growing forest ranges from 3.1 AD-t (air-dry tons of biomass)/ha/year (in former USSR and Eastern Europe) to 17.0 AD-t/ha/year (in Southeast Asia and Latin America) (Table 5) [7,19].

Concerning food biomass, we assume that the values of productivity of arable land are set on the basis of Ref. [17]. The values in 2100 will be constant (in Japan) and will be three times (in South Asia) as much as those in 1990 (Table 6). We assume that the regional productivity of energy crops follows the productivity in Ref. [16] and will reach 300 GJ/ha/year in each region in 2050 [16]. We assume that the productivity of energy crops will be constant in and after 2050. We assume that the catches of fishery products will be constant at the levels in 1990 [9]. In addition, we assume that livestock conversion ratios from feed to meat in energy units will increase from 11% in 1990 to 13% in 2100 in former USSR and Eastern Europe and the developed regions except Japan and will increase from 9% in 1990 to 13% in 2100 in the developing region. We assume that the ratio will be constant at 21% in Japan [7]. The high ratio in Japan is because most livestock are maintained quite efficiently and because of the unavailable data such as those concerning import of feed pasture or live livestock [7].

Table 7 shows discharge rates and practical energy usable ratios of biomass residues and shows material-recycling ratios of timber scrap, sawmill

Table 5
Forest parameters (biomass stocks, growing periods, and storage speeds)[a]

| Regions | Mature forest (t-C/ha) | Growing period (year) | Accumulation speed of growing forest (t-C/ha/year) |
|---|---|---|---|
| North America | 100 | 50 | 2.00 |
| Western Europe | 100 | 50 | 2.00 |
| Japan | 115 | 40 | 2.88 |
| Oceania | 115 | 40 | 2.88 |
| Centrally Planned Asia | 115 | 40 | 2.88 |
| Middle East and North Africa | 115 | 40 | 2.88 |
| Sub-Sahara Africa | 133 | 30 | 4.42 |
| Latin America | 150 | 20 | 7.50 |
| Former USSR and Eastern Europe | 85 | 60 | 1.41 |
| Southeast Asia | 150 | 20 | 7.50 |
| South Asia | 133 | 30 | 4.42 |

[a]The data on biomass stocks and growing period are based on Refs. [19,20]. 1 t-C of roundwood is equal to 2.4 AD-t (air-dry tons of biomass) and 1 AD-t is equal to 15 GJ.

Table 6
Indices of productivity of arable land (1.0 in 1990)[a]

| | 1990 | 2000 | 2050 | 2100 |
|---|---|---|---|---|
| North America | 1.00 | 1.18 | 1.67 | 1.72 |
| Western Europe | 1.00 | 1.18 | 1.45 | 1.57 |
| Japan | 1.00 | 0.96 | 1.02 | 0.99 |
| Oceania | 1.00 | 1.20 | 1.67 | 1.84 |
| Centrally Planned Asia | 1.00 | 1.22 | 1.50 | 1.93 |
| Middle East and North Africa | 1.00 | 1.20 | 1.41 | 1.67 |
| Sub-Sahara Africa | 1.00 | 1.13 | 1.50 | 1.73 |
| Latin America | 1.00 | 1.19 | 2.14 | 2.95 |
| Former USSR and Eastern Europe | 1.00 | 1.15 | 1.84 | 2.12 |
| Southeast Asia | 1.00 | 1.30 | 2.00 | 2.81 |
| South Asia | 1.00 | 1.31 | 2.34 | 2.98 |

[a]The data are based on Ref. [17]. It is assumed that these data will change linearly.

residues, and paper scrap (see Section 2.3.1). As to all the other parameters such as conversion ratios of wood-to-pulp and sugarcane-to-sugar, we assume that they will be constant at the levels in 1990 [7].

## 4. Simulation results

We conduct simulations using GLUE-11 and analyze the simulation results such as bioenergy supply potential and land uses. Then, we compare our results with other studies.

### 4.1. Supply potential of energy crops

In Case A (the reference case) there will be supply potential of energy crops produced from surplus arable land in North America, Western Europe, Oceania, Latin America, and former USSR and Eastern Europe. The bioenergy supply potential in the world will be 110 EJ/year in 2050 and 22 EJ/year in 2100 (Fig. 9).

The reasons for the decrease of the potential between 2050 and 2100 are as follows. We assume that crop productivity will mature in the world but animal food demand per capita would grow continuously in the developing regions after 2050 (see Section 3.2). Therefore, the increase of the food demand will exceed the increase of the food supply in the world, and the supply potential of energy crops will decrease between 2050 and 2100.

In Case B (high animal demand in Centrally Planned Asia), the world food demand will be eventually larger than the food supply. Thus, there will be no supply potential of energy crops in the world in 2100 (Fig. 9).

In conclusion, energy crops produced from surplus arable land will be produced potentially in Latin America, former USSR and Eastern Europe, and the developed regions excluding Japan, but the supply potential of energy crops will be vulnerable to the variation of the parameters of food supply and demand.

Table 7
Discharge rates, practical usable ratios, and material-recycling ratios of biomass residues[a]

| | Discharge rates of residues | Energy use ratios (before 2000) | Practical usable ratios (after 2050) | Material-recycling ratios (after 2050) |
|---|---|---|---|---|
| *Wood biomass* | | | | |
| Industrial roundwood harvesting residues | 0.51 t/t wood stock | 0.00 | 0.50 | |
| Fuelwood harvesting residues | 0.36 t/t wood stock | 0.00 | 0.00 | |
| Black liquor | 0.44 J/J roundwood input | 1.00 | 1.00 | |
| Sawmill residues | 0.49 J/J roundwood consumption (in developed)<br>0.34 J/J roundwood consumption (in developing) | 0.00 | 0.75 | 0.00 |
| Paper scrap | 0.26 t/t paper stock/year[b] | 0.00 | 0.75 | 0.65[c] |
| Timber scrap (inc L board scrap) | 0.03 t/t timber stock/year[b] | 0.00 | 0.75 | 0.00 |
| *Food biomass* | | | | |
| Cereal harvesting residues | 1.3 t/t harvested cereals | 0.00 | 0.25 | |
| Sugarcane harvesting residues | 0.150 t/t harvested sugarcane | 0.00 | 0.67 | |
| Bagasse | 0.283 t/t harvested sugarcane | 1.00 | 1.00 | |
| Animal dung | 0.3 J/J feed consumption | 0.00 | 0.25 | |
| Kitchen refuse | 0.2 J/J food consumption | 0.00 | 0.75 | |
| Human faeces | 0.2 J/J food consumption | 0.00 | 0.25 | |

[a]The data are based on Renewable-intensive Global Energy Scenario (RIGES) [16] and our study [3,21]. We assume that the use ratios will increase from the ratios before 2000 to practical usable ratios until 2050; the ratios will be constant after 2050.
[b]The discharge rates are based on Ref. [21].
[c]The material-recycling ratios of paper scrap before 2050 are different in each region, and they are shown in Ref. [7].

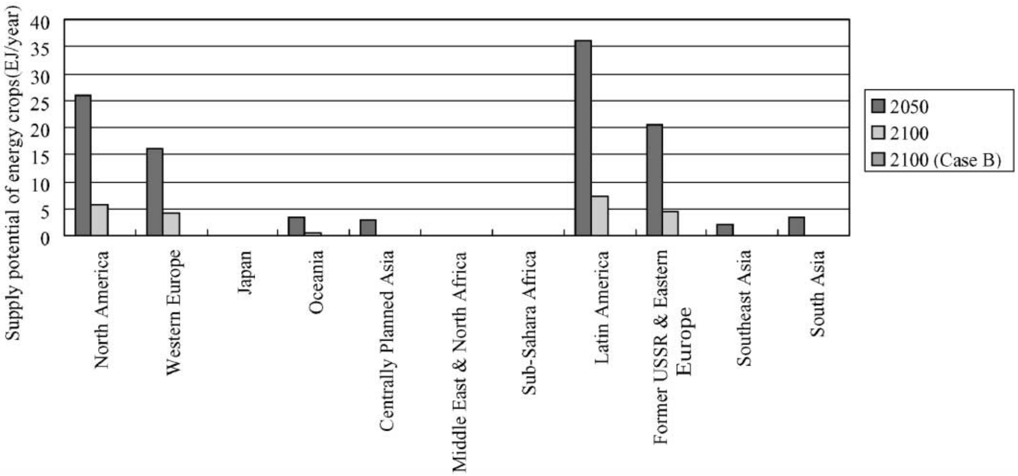


Fig. 9. Supply potential of energy crops. The potential in Case B (high animal demand in Centrally Planned Asia) will be zero in 2100.

## 4.2. Bioenergy supply potential of biomass residues

### 4.2.1. Values of bioenergy supply potential

Ultimate bioenergy supply potential of biomass residues will increase from 84 EJ/year in 1990 to 265 EJ/year in 2100 in the world in the reference case (Case A), following the increase of biomass consumption in the future.

The values of the potential will be large as shown in Fig. 10 in North America, Centrally Planned Asia, Latin America, and South Asia which will be major consumers or exporters of biomass. The values

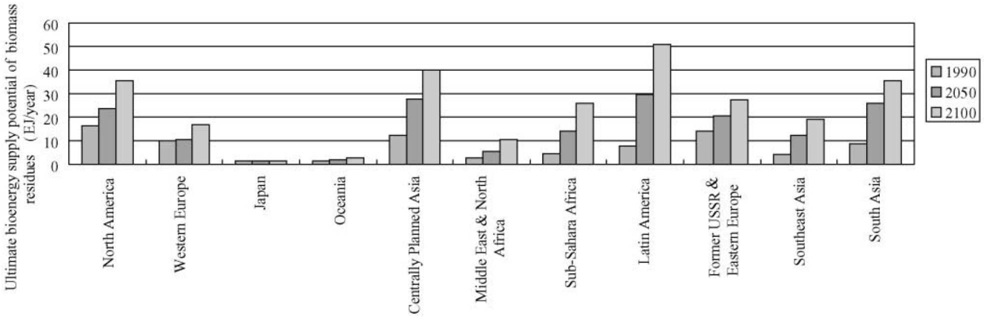


Fig. 10. Ultimate bioenergy supply potential of biomass residues.

of the potential in those regions will be larger than 30 EJ/year in 2100.

Cereal-harvesting residues will take the highest share at 42% of the total residue potential in the world in 2100. Besides, industrial roundwood felling residues, timber scrap, and animal dung will take large shares, above 10% each (Fig. 11).

Practical bioenergy supply potential of biomass residues will be 72 EJ/year in 2050 and 114 EJ/year in 2100 in the world. The potential in North America, Centrally Planned Asia, and Latin America will be larger than 15 EJ/year in 2100 for each of the regions (Fig. 12).

### *4.2.2. Robustness of bioenergy supply potential of biomass residues*

The global ultimate bioenergy supply potential of biomass residues in Case B (high animal food demand case in Centrally Planned Asia) in 2100 will be 272 EJ/year and 3% larger than that in Case A (the reference case). Thus, the potential of biomass residues is more stable than that of energy crops (see Section 4.1).

### *4.2.3. Bioenergy supply potential per capita*

The values of bioenergy supply potential per capita of biomass residues are shown in Figs. 13 and 14.

The values of the ultimate bioenergy supply potential per capita of biomass residues in North America, Oceania, and Latin America will be larger than those in the other regions. The values of the potential per capita in the former regions will be larger than 100 GJ/capita/year in 2100. Those values will be larger than 2/3 of the primary energy consumption per capita in Japan in 1990.

On the other hand, the ultimate bioenergy supply potential per capita of biomass residues in the other regions will be lower than 65 GJ/capita/year in 2100. Especially, the value in Japan, which will be 12 GJ/capita/year in 2100, will be the lowest of all the regions. This is because Japan will continue to be an importer of wood and food, and because most of the wood felling residues and food harvesting residues will be produced not in Japan but in the biomass exporting regions. However, the potential of biomass residues in Japan will be equivalent to 8% of the commercial energy consumption in Japan in 1990. The potential exceeds the consumption of hydroelectric power in Japan in 1990.

The practical bioenergy supply potential per capita of biomass residues will be large in North America (at 44 GJ/capita/year), Oceania (at 33 GJ/capita/year), and Latin America (at 22 GJ/capita/year). On the other hand, the potential per capita of biomass residues will be lower than 10 GJ/capita/year in Japan, Middle East and North Africa, Sub-Sahara Africa, and South Asia.

## *4.3. Land use changes and bioenergy supply potential of forest*

### *4.3.1. Land use changes*

The total area of the forest (comprising the mature forest and the growing forest) will be stable in each region, since we assume that perfect reforestation has been achieved in the developed regions and will be achieved in the developing regions after 2025.

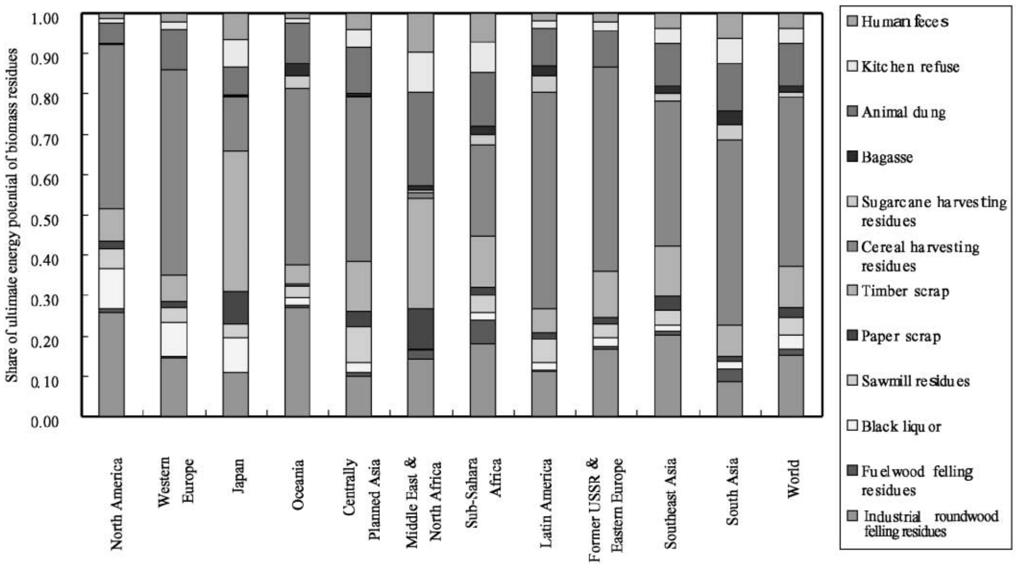


Fig. 11. Share of ultimate bioenergy supply potential of biomass residues (in 2100).

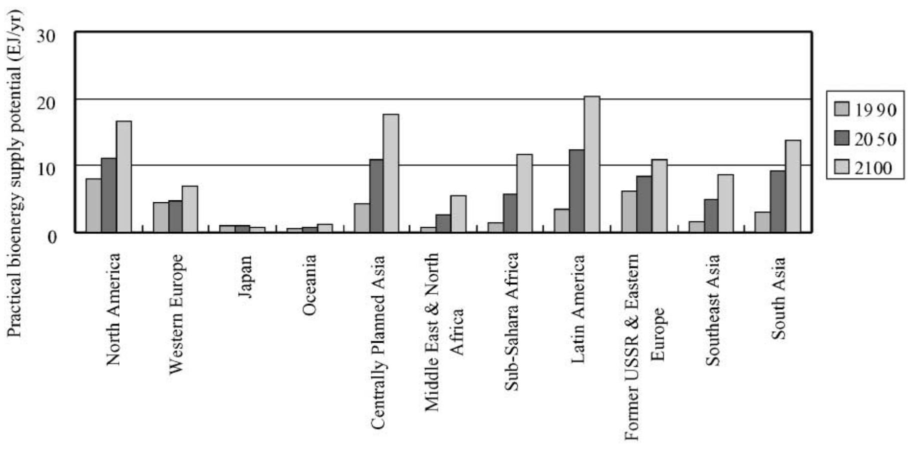


Fig. 12. Practical bioenergy supply potential of biomass residues.

However, the shares of the forest area will continue to change. The mature forest area will decrease and the growing forest area will increase (Fig. 15). This is because the demand for wood biomass will increase rapidly in the developing regions (see Section 3.2.1). The global mature forest area will decrease by 24% from 3050 Mha in 1990 to 2330 Mha in 2100. Especially, the mature forest areas in Centrally Planned Asia, Middle East and North Africa, and South Asia will disappear by 2100 (Fig. 15). Here we confirm that no introduction of modern fuelwood is assumed in this study (see Section 3.2.1) [3,7].

#### *4.3.2. Bioenergy supply potential of modern fuelwood*

It is estimated that the ultimate bioenergy supply potential of modern fuelwood from the forest area will be 379 EJ/year in the world (Fig. 16) (see

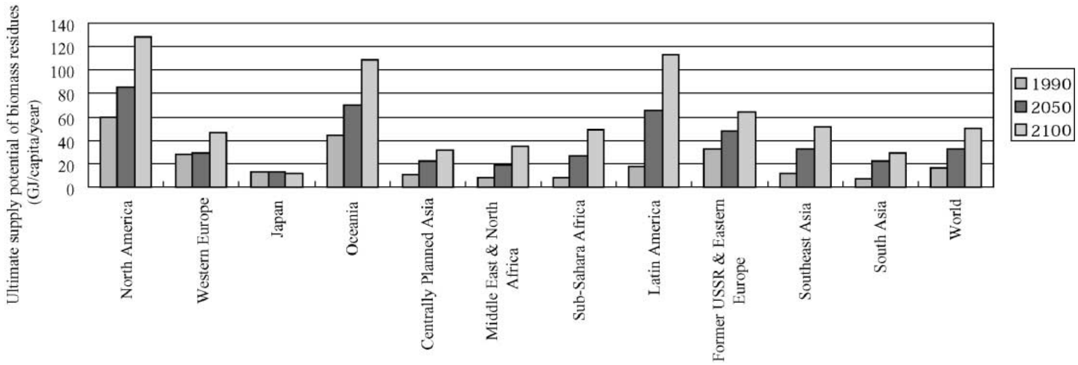


Fig. 13. Ultimate bioenergy supply potential of biomass residues (per capita). For reference, values of primary commercial energy consumption are 321 GJ/capita/year in North America, 150 GJ/capita/year in Japan, 36 GJ/capita/year in Latin America, and 25 GJ/capita/year in Centrally Planned Asia in 1990 [22–24].

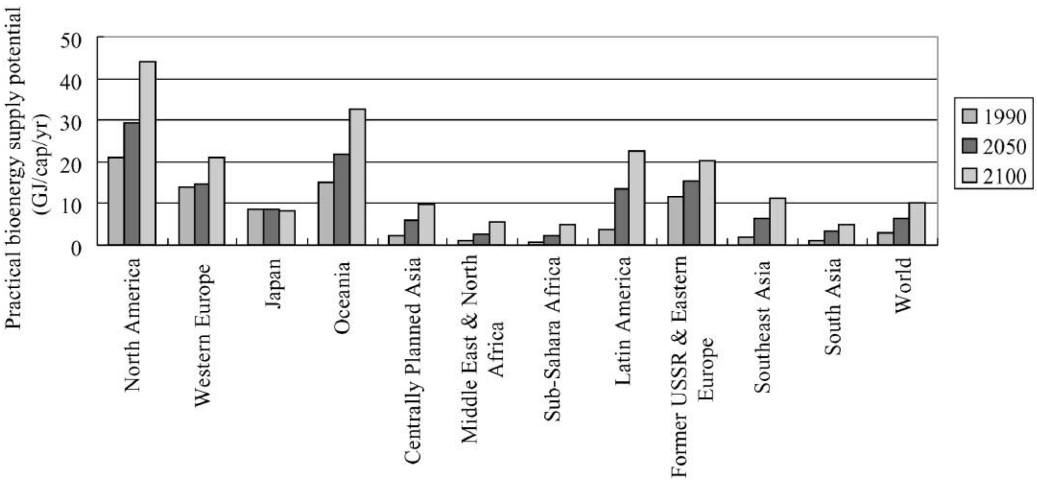


Fig. 14. Practical bioenergy supply potential of biomass residues (per capita). For reference, values of primary commercial energy consumption are 321 GJ/capita/year in North America, 150 GJ/capita/year in Japan, 36 GJ/capita/year in Latin America, and 25 GJ/capita/year in Centrally Planned Asia in 1990 [22–24].

Section 2.3). Especially, the potential in Latin America will be 199 EJ/year, which will be more than half of the global potential. On the other hand, the potential in Sub-Sahara Africa will be 75 EJ/year and the second largest in all the regions. The potential in Western Europe, Japan, Centrally Planned Asia, Middle East and North Africa, and South Africa will be 0–6 EJ/year, since the mature forest areas in those regions will be small.

We should be cautious in estimating the practical supply potential of modern fuelwood. This is because the global mature forest area will decrease by 24% between 1990 and 2100 even without modern fuelwood introduction, and because there is a strong public opinion against the use of mature forest to reserve the bio-diversity in natural forests.

### 4.4. Comparison with IEA estimation

We compare the bioenergy supply potential of biomass residues calculated by GLUE-11 with the

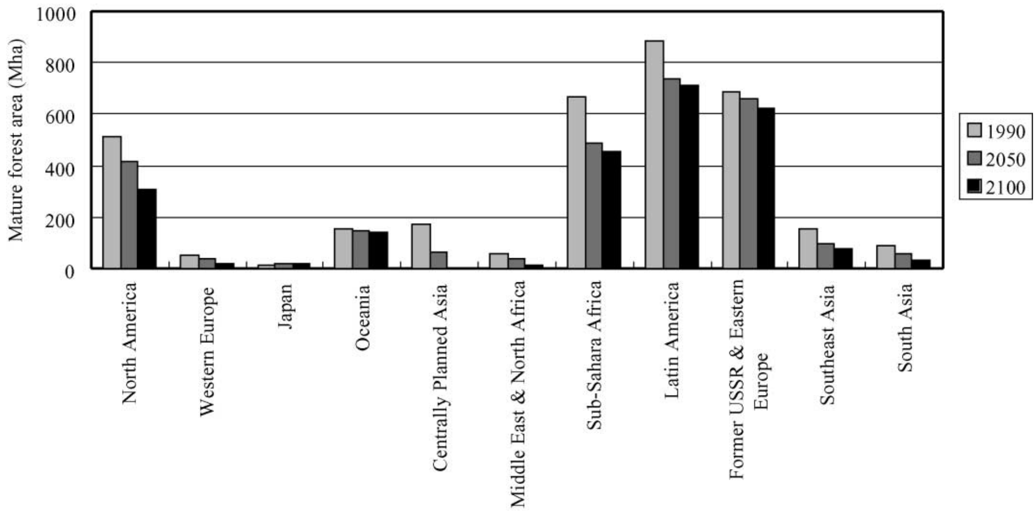


Fig. 15. Changes of mature forest area.

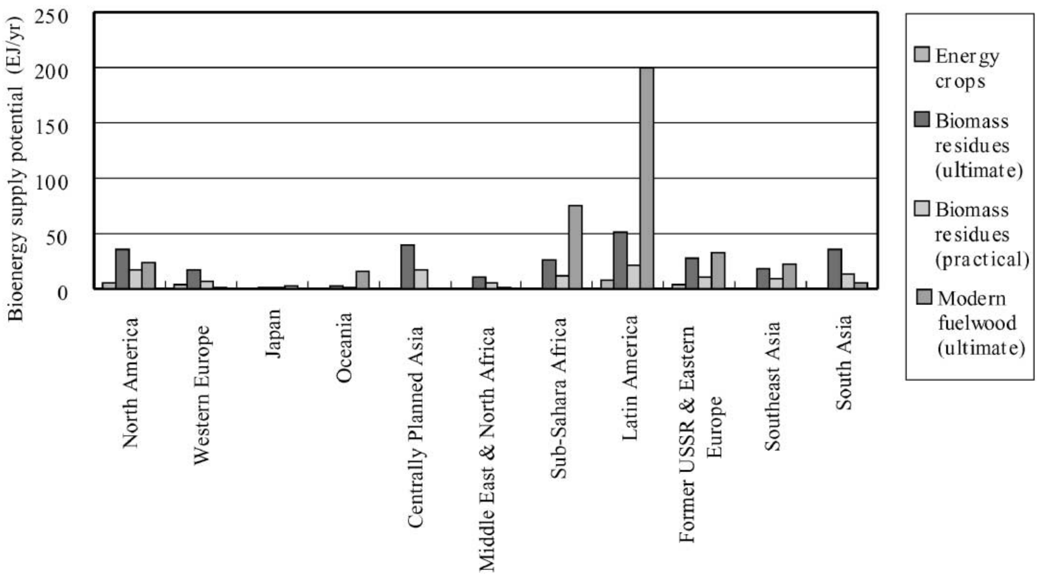


Fig. 16. Bioenergy supply potential of energy crops, biomass residues, and modern fuelwood (in the reference case) (in 2100).

bioenergy consumption of biomass residues estimated by IEA in 1996 [22–24].

The values of the practical supply potential in 1990 estimated by GLUE-11 are 3–10 times as much as the values of the consumption estimated by IEA in the developed regions and former USSR and Eastern Europe (Fig. 17). This is probably because there is much unused energy potential of biomass residues in those regions.

On the other hand, the values of the practical bioenergy supply potential by GLUE-11 are close to the values of the consumption by IEA in the developing

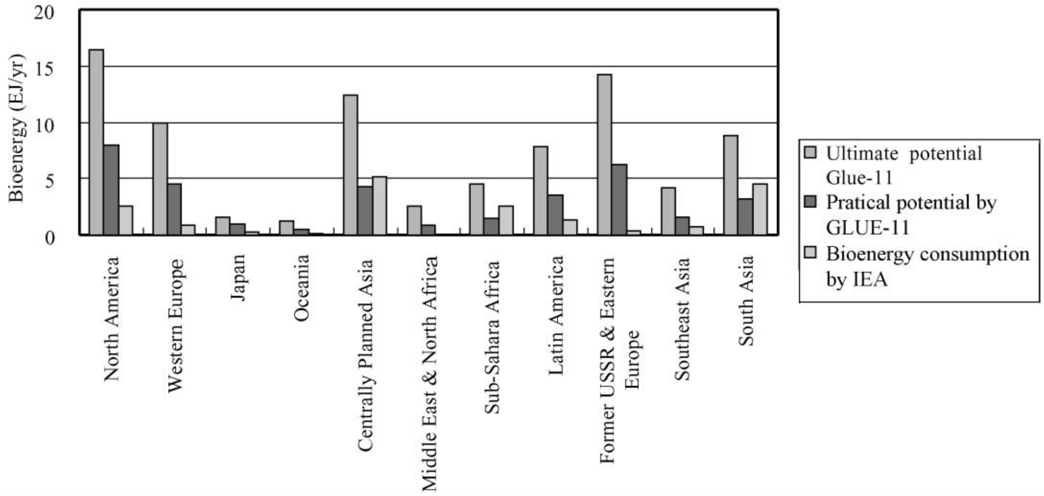


Fig. 17. Bioenergy supply potential (calculated by GLUE-11 in 1990) and bioenergy consumption (estimated by IEA in 1996) of biomass residues.

regions (Fig. 17). Besides, the former are less than the latter in Centrally Planned Asia, Sub-Sahara Africa, and South Asia. It suggests that biomass residues have already been intensively used for energy in those developing regions.

However, there is no region where the values of the consumption by IEA exceed the ultimate bioenergy supply potential estimated by GLUE-11. Therefore we consider that the values by GLUE-11 and by IEA are in a rational range. In addition, Ref. [24] mentions that the values by IEA are not accurate in the developing regions. We will be able to evaluate the bioenergy supply potential of biomass residues more accurately, if we compare the internal data of GLUE-11 with those of IEA (Table 8).

### 4.5. Discussion

We compare this study (GLUE-11) with other studies that evaluated the bioenergy supply potential. The studies are those of Hall [25], Dessus et al. [26], Johansson et al. [16], Alcamo et al. [17], IPCC [1], and Fischer et al. [27].

First, Hall led the bioenergy potential analysis. He estimated the potential of recoverable biomass residues in 82 regions in 1991 at 87 EJ/year altogether. He did not estimate the practical supply potential of energy crops and modern fuelwood, and the bioenergy supply potential in the future.

Next, we compare our study with the studies that evaluated the potential of energy crops, modern fuelwood, and biomass residues in the future.

The supply potential of energy crops ranges between 110 and 207 EJ/year in 2050 and between 22 and 229 EJ/year in 2100. Among the studies, only Fischer et al. evaluated the bioenergy potential produced not from surplus arable land but from pasture. Only Alcamo et al. and GLUE-11 specified overall parameters of food supply and demand that should be the basis of the calculation of the potential of energy crops. In addition, only GLUE-11 mentioned that bioenergy supply potential of energy crops would be vulnerable to the parameters of food supply and demand.

The practical supply potential of modern fuelwood was estimated only in RIGES, Dessus et al., and Fisher et al. and not in the other studies. This is probably because the introduction of modern fuelwood may cause the decrease in natural forest that is essential for the preservation of bio-diversity. In GLUE-11, we did not evaluate the practical potential but only the ultimate potential. In addition, we mentioned that the global mature forest area would decrease by 24% between 1990 and 2100 even if we assumed no introduction of modern fuelwood.

Table 8
Outline of studies of bioenergy supply potential

| | Evaluation period | Year | Regions | Energy crops (EJ/year) | Modern fuelwood (EJ/year) | Biomass residues (EJ/year) | Total (EJ/year) |
|---|---|---|---|---|---|---|---|
| Hall[a] | 1991 | 1991 | 82 | — | — | 87 | — |
| Dessus et al.[b] | 1985–2020 | 2020 | 10 | 15 | 65 | 26 | 106 |
| Johansson et al.[c] | 1985–2050 | 2050 | 10 | 128 | 10 | 68 | 206 |
| Alcamo[d] | 1990–2100 | 2050 | 13 | — | — | 74 | 74 |
| | | 2100 | | — | — | 208 | 208 |
| IPCC-BI[e] | 2025–2100 | 2050 | 7 | 135 | — | 48 | 183 |
| | | 2100 | | 229 | — | 96 | 325 |
| Fischer et al.[f] | 1990–2050 | 2050 | 11 | 147–207 | 91–110 | 132–135 | 370–453 |
| GLUE-11[g] | 1961–2100 | 2050 | 11 | 110 | (378) | 72 | 182 |
| | | 2100 | | 22 | (378) | 114 | 136 |

[a] In Ref. [25].
[b] In Ref. [26].
[c] In Ref. [16]. RIGES is the abbreviation of Renewable-Intensive Global Energy Scenario.
[d] In Ref. [17]. CWS is the abbreviation of Conventional Wisdom Scenario.
[e] In Ref. [1]. BI is the abbreviation of biomass-intensive variant.
[f] In Ref. [27]. The bioenergy potential of energy crops is not the potential of surplus arable land but that of pasture.
[g] GLUE calculated not the practical supply potential but the ultimate supply potential concerning modern fuelwood, so we put the figure in parentheses. We mentioned that the potential of energy crops would be vulnerable to the variation of the parameters of food supply and demand [3].

The practical supply potential of biomass residues ranges between 48 and 135 EJ/year in 2050 and between 96 and 208 EJ/year in 2100, in the studies. However, only GLUE-11 calculated the potential based on the concept of the overall biomass flow.

Consequently, the studies vary in the bioenergy supply potential, especially in the potential of energy crops. We consider that the bioenergy supply potential in GLUE-11, which specified biomass supply and demand parameters and considered the overall biomass flow, can be a baseline to discuss its potential furthermore.

## 5. Conclusions

In this study, we developed a multi-regional global-land-use-and-energy model (GLUE-11) considering land use competitions and overall biomass flow, in order to evaluate the bioenergy supply potential comprehensively and systematically. We prepared biomass-related data for the model and conducted simulation analyses using the model.

Through a set of simulations using the model and the data, the following results were obtained. (1) Supply potential of energy crops produced from surplus arable land will be available in North America, Western Europe, Oceania, Latin America, and former USSR and Eastern Europe. However, the potential of energy crops will be strongly affected by the variation of the parameters of food supply and demand such as animal food demand. (2) Bioenergy supply potential of biomass residues will be stable against changes of food demand parameters. The ultimate bioenergy supply potential of biomass residues will be 265 EJ/year in the world in 2100. The practical potential of biomass residues in the world will be 114 EJ/year, which is equivalent to one-third of the commercial energy consumption in the world in 1990. The potential per capita of the biomass residues will be large especially in biomass exporting regions, such as North America, Latin America, and Oceania. (3) Concerning land uses, the global mature forest area will decrease by 24% between 1990 and 2100, because of the growth of both population and wood biomass demand per capita in the developing regions. The mature forest especially will disappear by 2100 in some developing regions, such as Centrally Planned Asia, Middle East and North Africa, and South Asia. The ultimate bioenergy supply potential in the global forest will be estimated at 379 EJ/year. However, the potential will be strongly limited by the public concern about the use of natural forest.

## Appendix A. Import and export of biomass and treatment of land shortage

The following explanations are the supplementary explanations of Section 2.2.

### *A.1. Each kind of biomass except cereals and energy crops*

Concerning each kind of biomass except cereals and energy crops, we assume that the import regions and the export regions of the biomass in 1990 [11] will continuously be the import regions and the export regions, respectively, throughout the simulation period.

The model calculates import of each kind of biomass:

$$IMP(a,i) = DEM(a,i)CIMP(a,i), \tag{A.1}$$

where $a$ denotes the kind of biomass excluding cereals and energy crops, $i$ the import regions, *IMP* the import of biomass, *DEM* the biomass demand, and *CIMP* the biomass import ratios (import per demand; assumed constant at 1990 levels).

$$DDS(a,i) = DEM(a,i) - IMP(a,i), \tag{A.2}$$

where *DDS* is the demand of domestic supply of biomass.

Concerning industrial roundwood, the demands will exceed the supplies in some regions where mature forest area will disappear. If it happens, we use formulas (3) and (4) instead of formulas (1) and (2) and calculate the additional import requirements:

$$ADIMP(r,i) = DDS(r,i) - AMF(i)PB(r,i), \tag{A.3}$$

where $r$ is the industrial roundwood, *AMF* the available area for felling of industrial roundwood, *PB* the productivity of biomass (exogenous), and *ADIMP* the additional import requirements.

$$DDS(r,i) = DEM(r,i) - IMP(r,i) - ADIMP(r,i). \tag{A.4}$$

The model calculates the global sum of import and export of each biomass.

$$EXPW(a) = IMPW(a) = \sum_i (IMP(a,i) + ADIMP(a,i)), \tag{A.5}$$

where *EXPW* is the global total of biomass export, and *IMPW* the global total of biomass import. Then, the export of biomass for each region is calculated as follows:

$$EXP(a,j) = EXPW(a)CEXP(a,j), \tag{A.6}$$

where $j$ is the biomass export regions, *EXP* the export of biomass, and *CEXP* the biomass export shares (regional export per *EXPW*; assumed constant at 1990 levels).

The total production requirement of domestic biomass in the export region is calculated as follows:

$$DDS(a,j) = DEM(a,j) + EXP(a,j). \tag{A.7}$$

In each export region, the actual total production of industrial roundwood does not exceed the domestic supply potential in the simulations in this study. Namely, the following formula is satisfied:

$$DDS(a,j) < AMF(j)PB(a,j). \tag{A.8}$$

### *A.2. Cereals and energy crops*

The global sum of supply and demand of cereals is calculated as follows:

$$DEMW(c) = \sum_m DEM(c,m), \tag{A.9}$$

$$SUPW(c) = \sum_m ACE(c,m)PB(c,m), \tag{A.10}$$

where $m$ denotes all regions, *DEMW* the global sum of demand of cereals; *SUPW* the global sum of supply potential of cereals, and *ACE* the available land to produce cereals or energy crops.

If *SUPW* exceeds *DEMW*, the following formulas from (11) to (17) are adopted. For import regions of cereals:

$$IMP(c,i) = DEM(c,i) - ACE(i)PB(c,i), \tag{A.11}$$

$$AC(i) = ACE(i), \tag{A.12}$$

$$AE(i)=0, \quad (A.13)$$

$$EXPW(c)=IMPW(c)=\sum_i IMP(c,i), \quad (A.14)$$

where $c$ represents the cereals, $i$ the import regions of cereals, $AC$ the area to produce cereals, and $AE$ the area to produce energy crops (namely surplus arable land).

For export regions:

$$EXP(c,j)=EXPW(c)(ACE(j)PB(c,j)-DEM(c,j)) \Big/ \sum_j (ACE(j)PB(c,j)-DEM(c,j)), \quad (A.15)$$

$$AC(j)=(DEM(c,j)+EXP(c,j))/PB(c,j), \quad (A.16)$$

$$AE(j)=ACE(j)-AC(j), \quad (A.17)$$

where $j$ is the export regions of cereals.

On the contrary, if $DEMW$ exceeds $SUPW$, we adopt the following formulas from (18) to (22) instead of the above formulas from (11) to (17):

$$AC(m)=ACE(m), \quad (A.18)$$

$$AE(m)=0, \quad (A.19)$$

where $m$ denotes all regions.

$$EXP(c,j)=ACE(c,j)PB(c,j)-DEM(c,j), \quad (A.20)$$

$$IMPW(c)=EXPW(c)=\sum_j EXP(c,j), \quad (A.21)$$

$$IMP(c,i)=IMPW(c)(DEM(c,i)-ACE(i)PB(c,i)) \Big/ \sum_i (DEM(c,i)-ACE(i)PB(c,i)). \quad (A.22)$$

The model does not adjust either demand or supply of food in the case when $DEMW$ exceeds $SUPW$, but merely calculates the amount of the food shortage in those regions as follows [3]:

$$STC(c,i)=DEM(c,i)-ACE(i)PB(c,i)-IMP(c,i), \quad (A.23)$$

where $STC$ is the shortage of cereals.

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