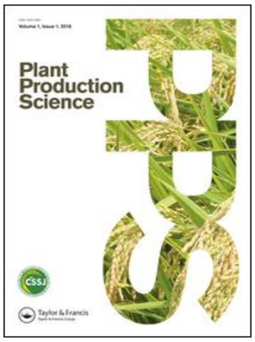


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# Energy Crops for Sustainable Bioethanol Production; Which, Where and How?

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**Abstract: Bioethanol is gathering attention as a countermeasure to global warming and as an alternative energy for gasoline. Meanwhile, due to the synchronous increase in bioethanol production and grain prices, the food-fuel competition has become a public issue. It is necessary to see the issue objectively and to recognize that the real background is the change in allocation of limited resources such as farmland and water. In this review, we discuss which, where and how energy crops should be grown to establish a sustainable bioethanol production system. Several combinations of crops, areas and cultivation methods are recommended as a result of a survey of the bioethanol production system with various energy crops. In tropical and subtropical regions, sugarcane can be grown in agricultural and/or unused favorable lands. In other regions, cellulosic energy crops can be grown in abandoned and marginal lands, including lands contaminated with inorganic pollutant like heavy metals and some detrimental minerals. There also is the possibility that, for Japan and other Asian countries, rice can be grown as an energy crop in unused lowland paddy field. Regarding cultivation way, energy saving is beneficial for bioethanol production systems irrespective of energy efficiency. On the other hand, effective energy input should be considered for the systems with higher energy efficiency when available land area is limited. Exploring and developing new energy crops and varieties, which show higher biomass productivity and stress tolerances under marginal conditions, are necessary for sustainable bioethanol production because energy crop production would be restricted mostly to marginal areas in future.**

**Key words: Bioethanol, Biomass, Energy crop, Energy efficiency, Sustainability.**

Biofuel made from plant biomass is recently gaining attention as a countermeasure to global warming and as an alternative to petrol. Biomass can be defined as "renewable and organisms-originated organic materials excluding fossil resources". For example, plants, food waste, excretory substance of livestock, woody materials and used paper are listed as biomass. Biofuel is defined as liquid, solid and gaseous fuels derived from biomass. The major examples of biofuel are bioethanol from maize grain or sugarcane, biodiesel from seeds of rape or sunflower, and methane gas from excretory substances of livestock.

Biofuels commonly have several advantages as a countermeasure against global warming and as an alternative energy; (1) renewable, (2) carbon-neutral (to avoid an increase of carbon concentration in atmosphere because carbon released from biofuels is offset by prior carbon sequestration by its raw material plants), and (3) biomass are widely distributed unlike petrol. In addition to these common advantages, each biofuel has own characteristics. For example, biogas can be produced from relatively simple and small systems with higher energy yield (e.g. Mshandete and Parawira, 2009). This review focuses is on bioethanol which has a quite important advantage when mixed with gasoline. The advantages of bioethanol and the social conditions have been encouraging many countries to produce and utilize bioethanol. Bioethanol production in the world has been rapidly increasing from about 3,000 million kL in 2,000 to about 6,300 million kL in 2007 (F.O. Licht, 2007).

Bioethanol is usually classified into 3 types depending on the type of raw material. The first one is bioethanol derived from sugar-based materials such as sugarcane and sugar beet. The second one is derived from starch-based materials such as grains of maize and wheat, and root and tuber crops. The third one, so-called cellulosic bioethanol or second generation bioethanol, is made from cellulosic materials including crop residue (e.g. rice straw and maize stover) and woody materials.

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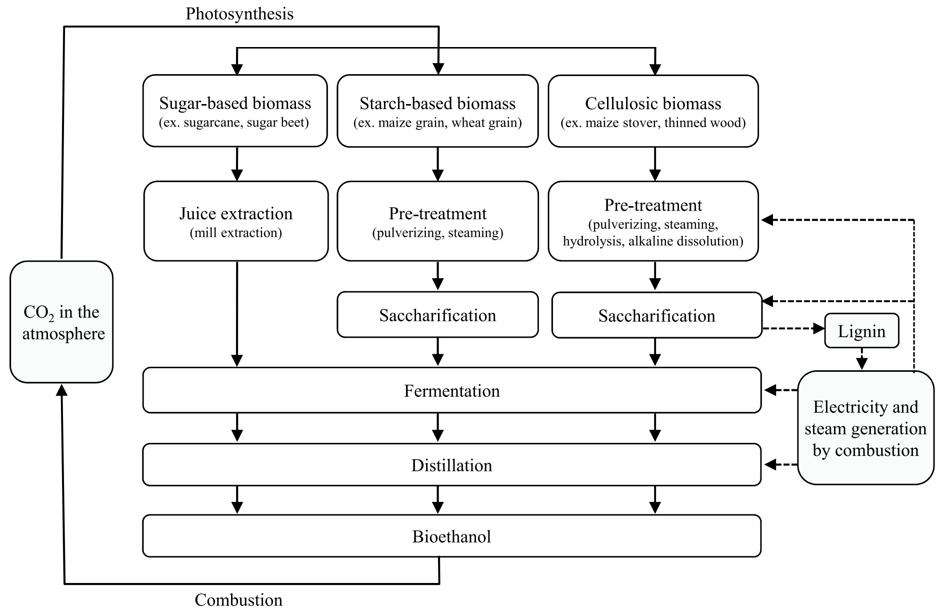


Fig. 1. Production processes of bioethanol from 3 types of raw materials.

The major leading countries of bioethanol production, USA and Brazil, have mainly been using maize and sugarcane, respectively, as materials for bioethanol production. Especially, in the USA, recently bioethanol production from maize grain has rapidly increased with an annual increase rate during 1998 to 2006 of 12.9%, while bioethanol production from sugarcane in Brazil during the same period increased at an annual rate of 1.7%. The promotion of bioethanol production in the USA has increased the demand for maize as material for bioethanol instead for food and forage. Because the amount of bioethanol production and the market grain prices increased synchronously, bioethanol was highly-publicized as the cause of the rise in grain prices. This is the issue of so-called "food-fuel competition". However, thinking objectively, there are many other relevant factors behind the increase in grain prices; for example the drought-caused failure of wheat production in Australia, the influx of speculative money in the grain market, the spike in oil price, and the rapid growth of world population. Therefore, including these factors, some studies were conducted to evaluate the significance of biofuel production on grain prices; Mitchell (2008) estimated that 70-75% of the increase in food prices was ascribable to biofuels and related consequences such as low grain stocks and land use changes. In contrast, the former Secretary of Agriculture of USA indicated that the production of bioethanol accounted for only 2-3% of the increase in food prices. Rosegrant (2008) reported that the increased biofuel demand accounted for 30% of the increase in grain prices and it had the biggest impact on the price of maize.

The estimated significance of bioethanol production might vary depending on the method of analysis, standpoint of analyst, and other factors. Meanwhile, we believe that all these estimations have failed to realize the underlying problem of food-fuel competition. The real background of this issue is not only the direct competition in the utilization of food and forage crops as materials for bioethanol, but also the indirect competition such as for allocation of limited resources (farmland, irrigation water, fertilizer and fossil energies) for food, forage and energy crops. The latter indirect competition may be an issue which would greatly increase its influence on grain prices in future. Recently, the interest of many countries is shifting from sugar- or starch-derived bioethanol to a cellulosic one in order to prevent food-fuel competition. Sometimes, in these countries, it is recognized that there will not be any food-fuel competition if bioethanol is produced from non-food cellulosic biomasses. However, it is necessary to realize the latent importance of the indirect competition. From these viewpoints, current systems of biomass production for bioethanol should be carefully reexamined. In this context, we will discuss which, where and how energy crops should be grown for sustainable production of bioethanol.

## 1. Which energy crops should be grown?

Bioethanol is classified into 3 types depending on the raw material, and the process of conversion from the raw material to ethanol can be classified accordingly (Fig. 1). Bioethanol production from sugar-rich biomasses such as sugarcane and sugar beet is the simplest process since the extracted sugar juices can be directly fermented to produce ethanol. Starch-derived bioethanol made from biomasses such as maize and wheat, require saccharification

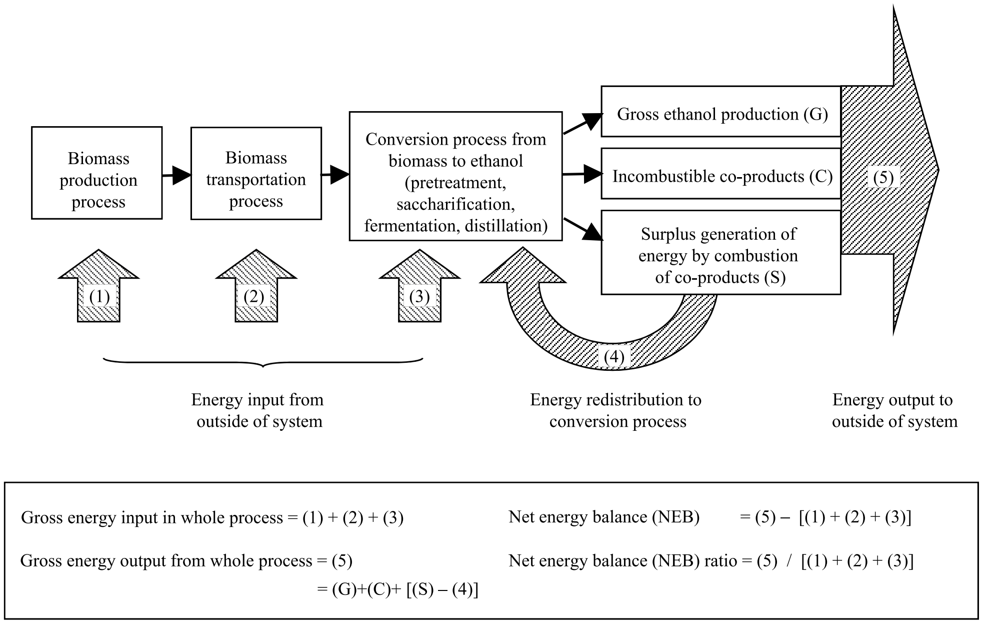


Fig. 2. Energy flow in a whole system of bioethanol production.

of starch to sugars before the fermentation process. In addition, the grains are pulverized and steamed to accelerate saccharification. Therefore, bioethanol made from starch generally requires more energy input than that made from sugar. The third type is cellulosic bioethanol. Even more energy input will be needed to soften cellulosic materials such as by acidic hydrolysis after the pulverization and steaming before the saccharification process. On the other hand, lignin, a main co-product in the conversion of cellulosic biomasses, can be burned to generate electricity and steam. This combustion of lignin contributes to reduction of fossil energy input in the production of cellulosic bioethanol. Additionally, technologies to convert cellulosic biomasses to bioethanol are being further developed for commercial production. When we discuss which energy crops to be grown, these differences in conversion process should be considered as well as productivity and other characteristics of candidate energy crops.

**(1) Conventional energy crops**

As already mentioned, bioethanol has been produced from crops with high sugar or starch contents, such as sugarcane and maize, but the food-fuel competition and also low energy efficiency are of growing concern.

Figure 2 shows the energy flow in a whole system of bioethanol production. The gross energy input means the sum of fossil energy required in the whole bioethanol production system including production, transportation and conversion of biomass. The gross energy output, usually, includes the energy of produced ethanol and co-produced materials which could be supplied outside of the system. For example, distillers grain, which is co-produced with maize-derived bioethanol, could displace animal feed. On the other hand, if combustible co-products are energetically recycled within the system (like the combustion of sugarcane bagasse to generate electricity and steam), it contributes to decrease fossil energy input in conversion process. The net energy balance (NEB) is the difference between output and input energies, and the NEB ratio is the ratio between them (Fig. 2). The NEB ratio is often adopted to indicate energy efficiency of the whole system of biofuel production (e.g. Tilman et al., 2006).

According to the Department of Energy (DOE) in USA, the NEB in the whole system of bioethanol production from maize is currently positive (Lavigne and Powers, 2007). However, the energy efficiency of the system is reported to be low; as expressed by the typical NEB ratio of 1.34 (Shapouri et al., 2002), although it is possible to increase the NEB ratio by the development of agricultural and conversion technologies (e.g. better maize variety, improvement of efficiency in fertilizer use, recycling yeast and enzyme in the conversion process, appropriate co-products management).

Bioethanol from sugarcane in Brazil, in contrast, has an excellent NEB ratio of 8.3 in 2002 (Macedo et al., 2004), and it has been further improved to 9.3 in 2005/2006 on average (Macedo et al., 2008). This excellent NEB ratio is based on easy-fermentable sugar for material as well as reuse of the co-product as an energy source for the conversion process. Thus, sugarcane has been recognized as one of the best biomasses for bioethanol production, especially in tropical and subtropical regions where sugarcane can thrive. Most countries, however, are located in the mid- to high-latitudes where meteorological conditions are not always suitable for growing sugarcane

Table 1. Summary of previously reported biomass productivity of cellulosic energy crops.

| | Yield ($t\ DM\ ha^{-1}$) | Site | References |
|---|---|---|---|
| Napier grass | 93 | El Salvador | Watkins and Lewy-van Severen (1951) |
| | 85 | Puerto Rico | Vicent-Chandler et al. (1959) |
| | 67 | Okinawa(Japan) | Kitamura et al. (1982) |
| | 23 | Northern Germany | El Bassam (1998) |
| *Erianthus* spp. | 40–60 | Florida (USA) | Mislevy et al. (1997) |
| Sorghum | 19–47 | Southern Italy | El Bassam (1998) |
| | 22–33 | Central Greece | El Bassam (1998) |
| | 10 | Virginia(USA) | Worley et al. (1992) |
| *Miscanthus* spp. | 40 | China | El Bassam (1998) |
| | 15–26 | Italy | Ercoli et al. (1999) |
| | 18 | Southwestern Germany | Boehmel et al. (2008) |
| | 12 | Konya(Turkey) | Acaroğlu and Aksoy (2005) |
| Switchgrass | 7–35 | Alabama(USA) | Sladden et al. (1991) |
| | 13–21 | Southeastern USA | Parrish et al. (1997) |
| | 10–11 | Virginia(USA) | Parrish et al. (1993) |
| Reed Canarygrass | 11–19 | Sweden | Mediavilla et al. (1993; 1994; 1995) |

due to lower temperatures and/or less precipitation. In these areas sugar beet and sweet sorghum are recognized as a possible raw material for production of bioethanol because they can produce much sugar even in cooler climates. However, the energy efficiency in the system of bioethanol production from sugar beet is lower than that from sugarcane; the NEB ratio for sugar beet-derived bioethanol is reported to be 1.22 (Koga, 2008) and 1.60 (Malça and Freire, 2006). Bioethanol production from sweet sorghum also has a low NEB ratio because of low sugar yield per unit biomass yield (Worley et al., 1992; Monti and Venturi, 2003). Therefore, development of better raw materials for bioethanol production is important in these areas.

**(2) Cellulosic energy crops**

Recent technological developments to convert cellulosic biomasses to ethanol have identified many plants as possible sources of bioethanol. Various kinds of plants have already been listed as cellulosic energy crops (e.g. El Bassam, 1998) including some well-known ones like napier grass (*Pannisetum purpureum* Schumach), switchgrass (*Panicum virgatum* L.) and reed canary grass (*Phalaris arundinacea* L.). Such cellulosic energy crops usually have greater biomass productivity (Table 1). Higher tolerance against diseases and pests, and vigorous growth even in low fertility or stressed conditions are also expected for these energy crops. These characteristics help to produce much more biomass per unit land area and unit energy input. In the USA, switchgrass is gaining attention as a promising cellulosic energy crop, and studies on its breeding and cultivation have been conducted through projects such as the Bioenergy Feedstock Development Program sponsored by the DOE. In the southern USA, similar studies have been done on other tropical grasses such as napier grass, bermudagrass (*Cynodon dactylon* (L.) Pers) and bahiagrass (*Paspalum notatum* Flugge). In the European Union (EU), *Miscanthus* spp., giant reed (*Arundo donax* L.) and reed canary grass, which have higher biomass productivity and lower energy demands in cultivation, are considered as possible cellulosic energy crops. In Japan, *Miscanthus* spp. is considered as a potential cellulosic energy crop for mid to northern regions. In addition, *Erianthus* spp. for southern to mid regions is being considered.

Recent technological developments in making ethanol from cellulosic biomass have also identified crop residues as an ethanol source. Most of the crop residues have been unused, for example, around 90% of maize stover is unused and remains in the field (Kim and Dale, 2004a). Because tremendous amounts of crop residues are annually produced in the world (Kim and Dale, 2004a), it is logically to use them as materials of bioethanol. In fact, utilization of maize stover for bioethanol production has been actively studied in the USA (Sheehan et al., 2004; Varvel et al., 2008). However, utilization of crop residues should be carefully considered because they are well-known to be important to maintain sustainability of crop production through prevention of soil degradation, improvement of soil water balance, maintenance of soil organic carbon content and so on (e.g. McAloon et al., 2000; Wilhelm et al., 1986; Allmaras et al., 2000; Clapp et al., 2000). When utilization of crop residues is planned, it is important to pay attention to detailed social and

Table 2. Reduction of greenhouse gases (GHGs) by utilization of various bioethanol instead of energy-equivalent gasoline.

| | GHGs reduction (%) | References |
|---|---|---|
| Maize grain | 18 | Farrell et al. (2006) |
| | 12 | Hill et al. (2006) |
| Wheat grain | 49 | Commission of the European Communities (2006) |
| Sugarcane | 85–90 | Smeets et al. (2006) |
| | 89 | Commission of the European Communities (2006) |
| Sugar beet | 40 | Commission of the European Communities (2006) |
| Wheat straw | 91 | Commission of the European Communities (2006) |
| Maize stover | 106[1)] | Sheehan et al. (2004) |
| Switchgrass | 94 | Schmer et al. (2008) |

[1)]In Sheehan et al. (2004), co-produced lignin could provide more than enough energy for conversion process and this surplus energy output contributed greatly to reduction of GHGs.

environmental situations in each region (Wilhelm et al., 2004). For example, crop residues are burnt worldwide including the USA, India, China (e.g. McCarty et al., 2009), and this has been found to significantly increase aerosol and greenhouse gases (GHGs) in ambient air (Mittal et al., 2009; Yang et al., 2008). In other cases like eastern Corn Belt in USA, where soils are often wet after harvest, possibility of soil compaction caused by cattle grazing of residues remained in the field is one of the concerns from the viewpoint of soil conservation (Sulc and Tracy, 2007). In areas where rice production is dominant, incorporation of rice straw into lowland paddy fields might cause an increase in methane emission (e.g. Fumoto et al., 2008). In these regions, the best use of the crop residues should be actively discussed, and utilization of residues for cellulosic bioethanol might be suitable in many cases.

When bioethanol is produced, the NEB in the system must be positive as mentioned above. In the system using cellulosic energy crops, generation of electricity and steam by combusting co-produced lignin can significantly improve the NEB. Additionally, the energy requirement for growing cellulosic energy crops is much lower compared to those for food crops (see section 3). Consequently, the NEB in cellulosic bioethanol production system is expected to be positive and the NEB ratio is much higher than those of starch-derived bioethanol systems. For example, the NEB ratio in switchgrass bioethanol system is expected to be 5.4 (Schmer et al., 2008). This indicates that cellulosic energy crops would be more suitable as raw materials for bioethanol compared to conventional energy crops other than sugarcane.

## 2. Where should energy crops be grown?

It is not so easy to answer the question where energy crops should be grown. We have to consider emission of GHGs as well, because one of the most important motivations for bioethanol production. Not only $CO_2$ but also other gasses such as $N_2O$ emitted during biomass production process should be considered (e.g. Renouf et al., 2008). There have been many analyses to estimate how much GHGs could be reduced when bioethanol is used instead of gasoline (Table 2). Efficiency of GHGs reduction largely depends on both the amount of energy input required for bioethanol production system and the proportion of renewable energy input to total energy requirement. These factors are affected by the type of energy crops utilized.

Recently, Searchinger et al. (2008) and Fargione et al. (2008) raised fundamental doubts concerning the reduction of GHGs by bioethanol utilization, because previous analyses did not consider the influence of land use changes accompanying biomass production. An increase in bioethanol production would accelerate clearing of forests and grasslands directly by the enlargement of energy crops field, or indirectly by land reclamation of farmland for energy crops production. Land clearing induces emission of carbon stored in wood and grass to the atmosphere. Even when forest and grassland plants are harvested for bioethanol production, it is not carbon neutral because carbons stored in forest and grassland are very stable just as fossil fuels stored in deep soil layers. Taking these direct and indirect land use changes into account, GHGs emission were estimated to be increased by bioethanol utilization (Searchinger et al., 2008; Fargione et al., 2008). Thus, it is necessary to use bioethanol for a long period to offset this GHGs unbalance. The time required to offset GHGs unbalance varies depending on the materials for bioethanol; Fargione et al. (2008) estimated that maize-derived bioethanol produced after clearing grassland in the central USA is required to be utilized for 93 years to offset the GHGs emission. When sugarcane is grown for bioethanol production in tropical grassland, the offset time is relatively short because sugarcane is a highly efficient material for bioethanol (4 and 17 years estimated by Searchinger et al. (2008) and Fargione et al. (2008), respectively). This

Table 3. Summary of previous studies on fossil energy input and dry biomass yield in various energy crops production.

| | Energy input (MJ ha$^{-1}$)[1] | | | | | Dry biomass yield[2] (t DM ha$^{-1}$) | Energy imput per unit yield (MJ t$^{-1}$ DM) | References |
|---|---|---|---|---|---|---|---|---|
| | Fertilizer | Fuel | Chemicals | Others | Total | | | |
| *Conventional energy crops* | | | | | | | | |
| Sugarcane | 5065 | 2619 | 829 | 2683 | 11196 | 19.23 | 582 | Macedo et al. (2004) |
| Sugar beet | 14060 | 7290 | 4600 | 5720 | 31670 | 14.50 | 2184 | Koga (2008) |
| | 6700 | 15000 | 160 | 2030 | 23890 | 11.00 | 2172 | Börjesson (1996) |
| Sorghum (Sweet sorghum) | 5441 | 3442 | 197 | 5633 | 14713 | 10.20 | 1442 | Worley et al. (1992) |
| | 5510 | 8490 | 399 | 1506 | 15905 | 21.49 | 740 | Monti and Venturi (2003) |
| Maize grain | 13759 | 5899 | 3771 | 10571 | 34001 | 7.37 | 4613 | Pimentel and Patzek (2005) |
| | 16097 | 7539 | 1412 | 1545 | 26593 | 7.75 | 3431 | Kim and Dale (2004b) |
| | 7085 | 7171 | 1097 | 3022 | 18375 | 6.67 | 2755 | Shapouri et al. (2002) |
| | 8452 | 6454 | 770 | 3228 | 18905 | 7.48 | 2527 | Graboski (2002) |
| Rice grain | 6560 | 13261 | 4910 | 23292 | 48023 | 7.01 | 6851 | Saga et al. (2008) |
| Wheat grain | 4550 | 2693 | 88 | 1426 | 8757 | 1.91 | 4585 | Piringer and Steinberg (2006) |
| | 6900 | 4200 | 120 | 6400 | 17620 | 5.10 | 3455 | Börjesson (1996) |
| | 7815 | 4300 | 1045 | 1526 | 14686 | 7.53 | 1950 | Richards (2000) |
| Potato | 8300 | 17000 | 360 | 15300 | 40960 | 7.70 | 5319 | Börjesson (1996) |
| | 6190 | 9210 | 3200 | 4470 | 23070 | 8.85 | 2607 | Koga (2008) |
| *Cellulosic energy crops* | | | | | | | | |
| Switchgrass | 5260 | 5860 | 0 | 2790 | 13910 | 9.00 | 1546 | Turhollow and Perlack (1991) |
| | 3352 | 4190 | 1257 | 2828 | 11627 | 8.50 | 1368 | Pimentel and Patzek (2005) |
| | 7511 | 3358 | 253 | 517 | 11639 | 9.01 | 1292 | Kim and Dale (2004b) |
| | 3625 | 979 | 435 | 399 | 5438 | 7.10 | 766 | Schmer et al. (2008) |
| *Miscanthus* spp. | 4710 | 1030 | 0 | 5052 | 10792 | 13.19 | 818 | Acaroğlu and Aksoy (2005) |
| | 7470 | 3886 | 96 | 3506 | 14958 | 20.00 | 748 | Lewandowski et al. (1995) |
| | 11970 | 3979 | 0 | 1911 | 17860 | 28.13 | 635 | Ercoli et al. (1999) |
| Reed canarygrass | 5500 | 3500 | 30 | 940 | 9970 | 6.50 | 1534 | Börjesson (1996) |
| Sorghum (Fiber sorghum) | 8870 | 5010 | 1820 | 3810 | 19510 | 13.30 | 1467 | Turhollow and Perlack (1991) |
| | 5510 | 8490 | 399 | 1506 | 15905 | 18.71 | 850 | Monti and Venturi (2003) |

[1] In studies by Shapouri et al. (2002), Richards (2000), Börjesson (1996), Turhollow and Perlack (1991), Kim and Dale (2004b), Acaroğlu and Aksoy (2005) and Ercoli et al. (1999), all or a part of calculation of fossil energy input from the higher heating value.

[2] If there is no indication of moisture contents of maize and wheat grains, and switchgrass in each reference, their moisture contents were assumed to be 15%. For sugarcane, dry matter yield was calculated based on fresh matter yield, sucrose and fiber contents in unit fresh matter yield as reported by Macedo (2004). For *Miscanthus* spp. reported by Acaroğlu and Aksoy (2005) and fiber sorghum by Turhollow and Perlack (1991), moisture content was assumed to be 40% and 33%, respectively, from the harvested season.

estimation indicates that sugarcane is one of the most promised energy crops in tropical and subtropical regions. When other energy crops are grown for bioethanol, the offset time would be several decades or more than 100 years.

Therefore, cultivating areas of energy crops should be restricted to lands currently under fallow or not expected to be used for food and feed production, such as abandoned agricultural land or marginal degraded land. According to Campbell et al. (2008), the global area of abandoned agricultural land is estimated to be 385-472 million ha, and 1.6-2.1 billion t of dry biomass (which is equivalent to 32-41 EJ of energy) could be produced there. This indicates that energy crop production in these areas could be beneficial. It is also expected that highly productive energy crops could shorten the offset time of GHGs unbalance caused by clearing these lands. On the other hand, excellent tolerance against various stresses will be necessary to ensure high and stable productivity under marginal environments.

From these points of view, a new approach can be proposed. The approach is to grow energy crops in areas that can not be used for food production due to contamination of inorganic pollutant like heavy metals and some minerals like boron and sodium (e.g. Jadia and Fulekar, 2009). In fact, land pollution by heavy metals and salts is a global issue and a great deal of land is contaminated. More than 100,000 ha of cropland and 55,000 ha of pasture in the USA, 1.4 million sites in Western Europe, one-sixth of arable land (about 20 million ha) in China, many sites in India, Pakistan, Bangladesh and so on are affected by heavy metals (Lone et al., 2008), and 77 million ha of cultivated areas in the world were affected by salt (Tester and Davenport, 2003). When energy crops are grown in such areas, not only higher biomass productivity but also higher accumulation capacity of contaminants and tolerance against them will be required. Some trials have already been launched or proposed using poplar, short-rotation willow, oil-seed rape, maize and wheat as energy crops (Robinson et al., 2007; Volk et al., 2006; Van Ginneken et al., 2007). When energy crops are grown in abandoned contaminated areas, the food-fuel competition could be avoided. Furthermore, if the energy crops could absorb heavy metals from soil, it would contribute to changing non-arable land into arable land. In addition, additional GHGs emission due to land use changes would be cancelled out in a short period because carbon stored by natural vegetations in such areas is generally small. Cellulosic energy crops would be suitable for this purpose because they might show relatively higher stress tolerance and higher biomass productivity even in such conditions. Conventional starch-based energy crops would not be suitable for these areas because their stress tolerance are expected to be lower compared to cellulosic ones, and co-products such as distillers grains could not be used as animal feed due to toxicity of heavy metals remaining in them.

## 3. How should energy crops be grown?

One of the most fundamental issues in growing energy crops for bioethanol is to increase energy efficiency, i.e. biomass production per unit fossil energy input and GHG emission. Based on previous studies, in the production process of conventional energy crops (other than sugarcane and sweet sorghum), the fossil energy input per unit biomass yield (MJ $t^{-1}$ dry matter) is suggested to be relatively high (Table 3). This is partly because; (1) only easily fermentable parts (e.g. grains) are considered as yield and remaining cellulosic parts as unusable residues, and (2) conventional energy crops were also food crops and maximization of productivity of edible parts has been the most important breeding objective regardless of the extent of the energy input. On the other hand, fossil energy input per unit biomass yield in production process of cellulosic energy crops would be often lower than those of conventional ones, as revealed in Table 3. Briefly, production of 1 t dry biomass requires 2,000-4,000 MJ of fossil energy input for conventional energy crops other than sugarcane, whereas 600-1,600 MJ for cellulosic ones. This result is ascribable to higher biomass productivity of cellulosic energy crops under less energy input (less fertilizer and agrichemicals). Growing perennial energy crops such as switchgrass and *Miscanthus* spp., which do not need tillage and sowing (or planting) except for the first year, will also reduce fossil fuel consumption for agricultural machinery. This is one of the reasons why perennial grasses are well studied in the USA and the EU as candidates for energy crops (Lewandowski et al., 2003). However, productivity of cellulosic energy crops are expected to decrease in future, because their production would be restricted to degraded areas like abandoned agricultural or marginal lands as mentioned above. Therefore, improving cellulosic energy crops with further tolerance for various stresses should be of growing importance.

To increase biomass production per unit fossil energy input, minimizing fossil energy input and maximizing biomass production should be attempted in harmony with each other. There have already been several methods for saving fossil energy input by adopting traditional techniques such as inter- or mixed-cropping, crop rotation, water harvesting, minimum and no tillage. These techniques generally have less negative effects on the environment. Especially, inter- or mixed-cropping with legumes is an effective technique to reduce nitrogen fertilizer which needs a larger fossil energy input in manufacturing. Inter- or mixed-cropping is based on beneficial interaction of plant functional groups such as gramineous and leguminous plants. Tilman et al. (2006) presented a unique system for biomass production with lower fossil energy input based on the beneficial interaction. They cultivated 1 to 16 plant species in various combinations on agriculturally degraded and abandoned nitrogen-poor sandy soil, and demonstrated that higher biomass productivity was achieved as plant diversity (number of plant species in the community) increased. The NEB ratio of bioethanol production system from such mixed vegetation was reported to be beyond 5.4.

To discuss the effectiveness of energy saving in the biomass production process, we organized previous studies with various energy crops and estimated energy balances in possible bioethanol production systems (Table 4). As shown in Table 4, in bioethanol production systems with conventional energy crops other than sugarcane, fossil energy input in the biomass production process usually occupies 20-40% of that for the whole system. In contrast, it occupies 50-80% of the cellulosic bioethanol production system (Table 4). This is due to the lower fossil energy requirement in the conversion process of cellulosic

Table 4. Estimation of ethanol productivity and NEB ratio in whole system of bioethanol production from various energy crops.

| | Fresh biomass yield[1)] (t FM ha$^{-1}$) | Dry biomass yield[1)] (t DM ha$^{-1}$) | Conversion efficiency[2)] | Estimated ethanol yield[3)] (kL ha$^{-1}$) | Energy input (GJ ha$^{-1}$) Biomass production[4)] | Biomass transportation[5)] | Conversion to ethanol[6)] | Estimated NEB ratio[3,7)] |
|---|---|---|---|---|---|---|---|---|
| *Conventional energy crops* | | | | | | | | |
| Sugarcane | 68.7 | 19.2 | 86 L t$^{-1}$ FW | 5.9 | 11.2 | 5.9 | 3.4 | 6.69 |
| Sugar beet | 58.1 | 14.5 | 109 L t$^{-1}$ FW | 6.3 | 31.7 | 5.0 | 76.4 | 1.19 |
| | 45.8 | 11.0 | 109 L t$^{-1}$ FW | 5.0 | 23.9 | 3.9 | 60.3 | 1.20 |
| Sorghum (Sweet sorghum) | 42.0 | 10.2 | 34 L t$^{-1}$ FW | 1.4 | 14.7 | 3.6 | 25.6 | 0.70 |
| | 95.5 | 21.5 | 59 L t$^{-1}$ FW | 5.7 | 15.9 | 8.1 | 75.1 | 1.21 |
| Maize grain | 8.7 | 7.4 | 380 L t$^{-1}$ FW | 3.3 | 34.0 | 0.7 | 43.2 | 1.08 |
| | 9.1 | 7.8 | 380 L t$^{-1}$ FW | 3.5 | 26.6 | 0.8 | 45.5 | 1.21 |
| | 7.8 | 6.7 | 380 L t$^{-1}$ FW | 3.0 | 18.4 | 0.7 | 39.2 | 1.31 |
| | 8.8 | 7.5 | 380 L t$^{-1}$ FW | 3.3 | 18.9 | 0.8 | 43.9 | 1.34 |
| Rice grain | 8.3 | 7.0 | 434 L t$^{-1}$ FW | 3.6 | 48.0 | 0.9 | 53.7 | 0.74 |
| Wheat grain | 2.2 | 1.9 | 350 L t$^{-1}$ FW | 0.8 | 8.8 | 0.2 | 14.4 | 0.79 |
| | 6.1 | 5.1 | 350 L t$^{-1}$ FW | 2.2 | 17.6 | 0.5 | 39.5 | 0.87 |
| | 9.0 | 7.5 | 350 L t$^{-1}$ FW | 3.1 | 14.7 | 0.8 | 57.6 | 1.00 |
| Potato | 35.0 | 7.7 | 462 L t$^{-1}$ DW | 3.6 | 41.0 | 3.0 | 41.7 | 0.88 |
| | 38.8 | 8.9 | 462 L t$^{-1}$ DW | 4.1 | 23.1 | 3.3 | 47.9 | 1.17 |
| *Cellulosic energy crops* | | | | | | | | |
| Switchgrass | 10.6 | 9.0 | 380 L t$^{-1}$ DW | 3.4 | 13.9 | 0.9 | 3.7 | 3.92 |
| | 10.0 | 8.5 | 380 L t$^{-1}$ DW | 3.2 | 11.6 | 0.9 | 3.5 | 4.29 |
| | 10.6 | 9.0 | 380 L t$^{-1}$ DW | 3.4 | 11.6 | 0.9 | 3.7 | 4.47 |
| | 8.4 | 7.1 | 380 L t$^{-1}$ DW | 2.7 | 5.4 | 0.7 | 2.9 | 6.31 |
| *Miscanthus* spp. | 22.0 | 13.2 | 380 L t$^{-1}$ DW | 5.0 | 10.8 | 1.9 | 5.4 | 5.88 |
| | 25.0 | 20.0 | 380 L t$^{-1}$ DW | 7.6 | 15.0 | 2.1 | 8.2 | 6.37 |
| | 59.8 | 28.1 | 380 L t$^{-1}$ DW | 10.7 | 17.9 | 5.1 | 11.5 | 6.57 |
| Reed canarygrass | 7.7 | 6.5 | 380 L t$^{-1}$ DW | 2.5 | 10.0 | 0.7 | 2.7 | 3.94 |
| Sorghum (Fiber sorghum) | 39.1 | 13.3 | 380 L t$^{-1}$ DW | 5.1 | 19.5 | 3.3 | 5.5 | 3.79 |
| | 83.2 | 18.7 | 380 L t$^{-1}$ DW | 7.1 | 15.9 | 7.1 | 7.7 | 4.91 |

1) Fresh and dry matter yields were calculated based on moisture content of raw materials as described in footnote of Table 3.

2) Conversion efficiencies were adopted from each reference. If there was no description in original reference, reasonable values were adopted from relevant references as follows; Koga (2008) for sugar beet, Kim and Dale (2005) for maize grain, Richards (2000) for wheat grain, Schmer et al. (2008) for cellulosic energy crops. For potato, data from study on ethanol conversion from cassava (Leng et al., 2008) was adopted because we could not find any other relevant references.

3) Some estimated ethanol yield may not be the real product of conversion efficiency and fresh or dry matter yields due to rounding of values in columns. This is similar to calculation of NEB ratio.

4) Data are similar to Table 3.

5) Distance of transportation from farm to conversion plant was assumed to be 40 km for all energy crops, and double wagon truck (see Macedo et al., 2004) was assumed to be employed for transportation.

6) Fossil energy input in conversion processes were calculated according to same references adopted to calculation of conversion efficiency. For sugarcane and sorghum, co-produced bagasse (50% water content, 7.53 MJ kg$^{-1}$) was assumed to be combusted in conversion plant for production of electricity and steam.

7) In the calculation of NEB ratio, lower heating value of ethanol (21.2 MJ L$^{-1}$) was adopted for all energy crops. Surplus production of electricity from bagasse combustion was also taken into account as according to Macedo et al. (2004).

biomass with the combustion of co-produced lignin. In the case of bioethanol production from sugarcane, biomass production process may occupy 50-60% of fossil energy input to the whole system and this is also due to combustion of co-produced bagasse (Macedo et al., 2004). Reducing the fossil energy input to biomass production

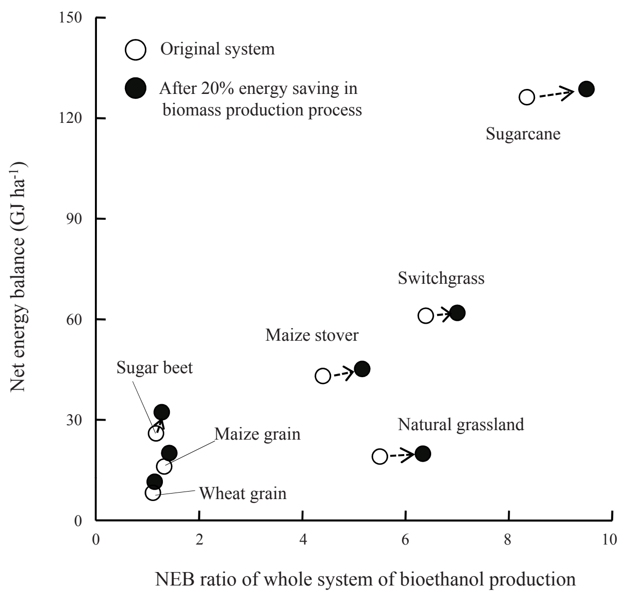


Fig. 3. Effects of 20% energy saving in the biomass production process on NEB ratio and NEB in typical bioethanol production systems with different raw materials.

Explanations: The data used for estimation was adopted from relevant references; Macedo et al. (2004) for sugarcane, Koga (2008) for sugar beet, Richard et al. (2000) for wheat grain with straw ploughed in, Shapouri et al. (2002) for maize grain, Schmer et al. (2008) for switchgrass, Sheehan et al. (2004) for maize stover and Tilman et al. (2006) for natural grassland.

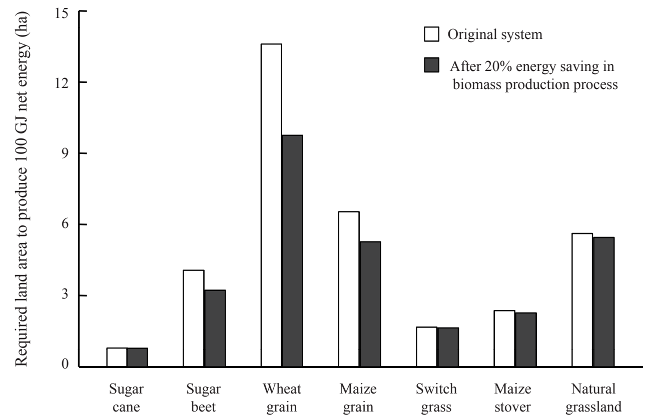


Fig. 4. Effects of 20% energy saving in the biomass production process on land area required to produce 100 GJ net energy in typical bioethanol production systems with different raw materials.

Explanation: The data for estimation was adopted from the same references as listed in Figure 3.

process 20%, would be equal to saving more than 10-16% energy in the whole system of cellulosic and sugarcane bioethanol production, but only 4-8% saving for starch-derived bioethanol. Thus, energy saving in the biomass production process will improve the NEB ratio in cellulosic and sugarcane bioethanol production systems more effectively than in starch-derived systems.

On the other hand, maximizing biomass production will also be important. Namely, there are many cases in which biomass production per unit fossil energy input could be increased by well-directed energy input rather than by excessive energy saving. In addition, the increase in biomass production per unit land area decreases the energy requirement for biomass harvesting and gathering. Simulation analysis using models will be helpful to check the optimal balance between fossil energy input and biomass productivity. Previous studies on optimization of agricultural management will also help to estimate effective energy input (Shapiro and Wortmann, 2006; Arregui and Quemada, 2008; Stevens et al., 2007; Fereres and Soriano, 2006), though each environmental situation has to be considered.

The priority of energy saving and effective energy input changes depending on the situation surrounding each bioethanol production system, especially in the land area available for biomass production. As shown in Figure 3, energy saving contributes little to the improvement of the NEB ratio in bioethanol production systems which originally have lower NEB ratios (e.g. for sugar beet, maize and wheat), but greatly in the systems with higher NEB ratios. The increase in NEB results in a decrease in the land area required for producing a certain amount of energy. When energy input is saved by 20% in the biomass production process, the land area required to produce 100 GJ of net energy is expected to decrease by 20, 19 and 28% in bioethanol production systems with sugar beet, maize grain and wheat grain, respectively (Fig. 4). In contrast, for systems with sugarcane and cellulosic energy crops, energy saving in the biomass production process could improve the NEB ratio greatly (Fig. 3), but has little effect on the required land area (Fig. 4). Therefore, it is suggested that; (1) energy saving in the biomass production is beneficial for the system with a lower NEB ratio especially when available land area is limited, (2) energy saving in the conversion and transportation processes is more effective to improve energy efficiency of the whole system with a lower NEB ratio, (3) energy saving in the biomass production process can improve energy efficiency of the system with a higher NEB ratio, and (4) effective energy input rather than excessive energy saving in the biomass production process is realistic for systems with higher NEB ratios when NEB is relatively low and/or available land area is limited. For instance, the system proposed by Tilman et al. (2006) does not have high biomass productivity but has a higher NEB ratio due to considerable energy saving. This system would require a large area for biomass production to generate a certain amount of bioethanol. In general, such a system has already been attempted to improve its NEB ratio and further saving of energy input might be often be difficult. Therefore, effective energy input should be taken into account to establish more efficient and sustainable system for bioethanol production with beneficial land utilization.

## 4. Bioethanol from rice plants grown in abandoned lowland paddy fields in Japan

Current technological developments to convert cellulosic biomass to ethanol have provided a new concept to utilize whole rice crop as energy crop. There are several trials to grow various rice varieties with very large total biomass as an energy crop for whole crop utilization in abandoned and unused lowland paddy fields.

Rice is a self-sufficient cereal crop in Japan but rice consumption per person has been gradually decreasing to around 60 kg per year. The Japanese government has forced farmers not to grow rice beyond necessity to prevent overproduction, and this has induced a continuous increase in abandoned or fallow lowland paddy fields. Although alternative crops such as wheat and soybean are encouraged to be grown there, their productivity is lower than those grown in upland fields due to poor drainage in lowland paddy fields.

The area of abandoned lowland and upland fields in Japan increased by nearly 80% from 217,000 ha in 1990 to 386,000 ha in 2005 (Ministry of Agriculture, Forestry and Fisheries, 2006). Statistics from the Japanese government (Ministry of Agriculture, Forestry and Fisheries, 2000) suggest that 40% of the abandoned fields are lowland paddy fields, and 20% of which (31,000 ha) is immediately available for rice production. In addition, there are 117,000 ha of fallowed lowland paddy fields. Consequently, it was estimated that nearly 150,000 ha of lowland paddy field, which is equivalent to about 6% of total area of lowland paddy field in Japan, is currently unused but is available for growing rice (Shiotsu et al., 2008).

Saga et al. (2008) estimated productivity of bioethanol from particular rice varieties to feed animals. They estimated that yields of grain, straw and husk are 7.0, 8.4 and 1.5 t $ha^{-1}$, respectively, and that totally 7.1 kL $ha^{-1}$ in total of starch-based and cellulosic bioethanol can be produced. Based on our estimation, the NEB ratio of the system is 1.1, although it can be improved up to about 1.6 by saving fossil energy for growing rice, for example, direct seeding, saving pesticide and shortening grain drying (Saga, 2008). Technical improvement in the conversion process of cellulosic biomass will also increase the NEB ratio in near future. If grains of rice were converted to bioethanol, and straw and husks were combusted in the conversion process for generation of electricity and steam, about 3.6 kL $ha^{-1}$ of bioethanol would be produced with an NEB ratio of 3.5. Therefore, there is the potential to produce around 0.5-1 million kL of bioethanol from currently unused lowland paddy field which if high-yielding rice varieties were grown as energy crops. The Japanese government plans to supply annually 6 million kL bioethanol by 2030, and utilization of whole rice crop as energy crop would contribute significantly to achieve this objective.

The bioethanol production from rice grown in unused lowland paddy fields in Japan has several advantages (Morita, 2008). Utilization of bioethanol is, of course, one of the countermeasures against global warming and could be utilized as an alternative to petrol. In addition, harvesting rice straw for ethanol production could reduce methane emission from straws incorporated into lowland paddy fields (Fumoto et al., 2008). Bioethanol production in abandoned paddy field does not cause additional GHGs emission due to land use changes, but more likely contributes to preservation of multi-functionality of paddy field including flood control, groundwater recharge, landslide prevention, and contribution to biodiversity (Matsuno et al., 2006). It is important to consider rice production in lowland paddy field systems itself as highly sustainable.

The biggest advantage of this system is to strengthen Japan's food security via an increase in efficiency of agricultural land use. If lowland paddy fields are left unused, they will gradually lose productivity and result in an unusable field after several years. If rice is grown as an energy crop, unused or abandoned paddy fields could be conserved under a sustainable condition. However, utilization of rice as an ethanol source might be criticized as one of the factors causing the food-fuel competition. Actually, in our estimation, more than 1 million t of rice grain could be newly produced from the 150,000 ha of unused paddy field. However, if the normal rice variety for human consumption is used, rice production would be only about 0.85 million t. This amount is less than 3% of the world rice trade (about 30 million t) and about 0.2% of world rice production (more than 400 million t). Therefore, utilization of whole crop rice in the unused paddy field in Japan might have little effect on the market price of rice. In addition, even if such rice was exported as food, it is difficult to improve the condition of world rice market because rice production in Japan requires high costs, resulting in higher market price compared to the global average. To reduce the amount of minimum access of rice of the Japanese government (0.77 million t) might be rather effective in improving the international supply-demand condition of rice, although it is quite a difficult political issue. Finally, production of rice-derived bioethanol in Japan should be considered as issues of food and energy securities and have little possibility to cause the food-fuel competition.

## 5. Future research directions

The most important point for establishing any bioethanol system is the sustainability of the system

Table 5. Guideline for future energy crop production for bioethanol.

| | Where? | | | | |
|---|---|---|---|---|---|
| | Agricultural land or unused favorable land | | Abandoned agricultural land and marginal land | | |
| | Tropical or subtropical regions | Other regions | Contaminated areas | Low fertility areas | Saline or acidic areas |
| Which? | Sugarcane | Food crops (residues can be used) | Cellulosic energy crops | Cellulosic energy crops (food crops if needed) | Cellulosic energy crops (including natural grasses) |
| How? | Effective energy input / energy saving (depends on land availability) | Effective energy input | Effective energy input | Energy saving/effective energy input (depends on land availability) | |
| Keywords for future research | (1) Sustainable management<br>(2) More productive crop varieties<br>(3) Sustainable harvest of crop residue in each region<br>(4) Life cycle assessment for energy balance and various GHGs emission | | (1) Energy saving agricultural practices<br>(2) New energy crops and better varieties with high productivity and tolerance against stress (including metal and salt toxicities)<br>(3) Material circulation to ensure system sustainability<br>(4) Efficient harvesting techniques for low density biomass<br>(5) Efficient harvesting techniques in poor ground conditions | | |

Table 6. Possible application of guideline of future energy crop production to current Japanese situation.

| | Where? | | | | |
|---|---|---|---|---|---|
| | Agricultural land or unused favorable land | | Abandoned agricultural land and marginal land | | |
| | Southwestern regions (Kyushu and Okinawa) | Other regions | Contaminated field (e.g. industrial areas) | Abandoned field (lowland/upland) | Seashore or volcanic areas |
| Which? | Sugarcane (molasses can be used) | Rice, wheat (straws and husks can be used) | Perennial grasses such as *Miscanthus* spp. for north and *Erianthus* spp. for south regions | High yielding rice varieties for lowland paddy field/ sugar beet, sorghum and wheat for upland field | Natural vegetation or perennial grasses like *Miscanthus* spp. |
| How? | Effective energy input | Effective energy input | Effective energy input | Energy saving | Energy saving |

(Robertson et al., 2008) and from this viewpoint we have to consider the following fundamental questions; which, where and how energy crops should be grown. To answer the questions, detailed life cycle assessment (LCA) focusing on energy and GHGs balances is required first rather than analyses of the economic situation which changes depending on various factors including the price of oil. Although several LCA studies have already been conducted (e.g. Renouf et al., 2008; Davis et al., 2009), the future direction of energy crop production has not been discussed in detail. Therefore, in this review, we discussed which, where and how energy crops should be grown (Table 5). We recommend the use of; (1) sugarcane in agricultural land and/or unused favorable land in tropical and subtropical regions, (2) cellulosic energy crops including natural vegetation in abandoned and marginal lands, and (3) rice in unused lowland paddy field (mainly for Japan or other Asian countries). Regarding the question of how; (1) energy saving is beneficial for systems with lower NEB ratio, (2) energy saving is also beneficial for systems with higher NEB ratio when available land area is not limited, and (3) effective energy input should be considered for the systems with higher NEB ratio when the available land area is limited. These recommendations might be used as a guideline for future energy crops production in each particular region. One of the possible applications of the guideline for Japan was suggested in Table 6. Of course, it is necessary to conduct final LCA studies and periodical inspections before and after the implementation of energy crops production in each particular region.

The actual background of the issue concerning bioethanol systems is the competition for limited resources such as land, water, fertilizer and fossil energies. Especially the competition for land for growing energy crops is already a serious issue and we have to use non-arable land where many biotic and abiotic stresses exist. This is the reason why we have to explore and/or generate new energy crops (or varieties) with strong tolerance for various stresses. Limitation of energy in the future must be considered to establish sustainable bioethanol systems, and energy crops have to be grown to yield a larger biomass with less energy input. Both of them are old and new subjects in crop science that remain to be solved.

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