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An energy balance under a conventional crop rotation system in northern Japan: Perspectives on fuel ethanol production from sugar beet

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Abstract

In the context of sustainable and less energy-dependent agricultural biomass production, an energy balance was developed for a conventional rotation of winter wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L. subsp. *vulgaris*), adzuki bean (*Vigna angularis* (Willd.) Ohwi & Ohashi) and potato (*Solanum tuberosum* L.) under the highly fuel-dependent and material-intensive farming systems in the Tokachi region of Hokkaido, northern Japan. As annual energy inputs, tractor operations, truck transportations and grain drying for adzuki bean and winter wheat consumed the equivalent of 6.09 and 11.50 GJ ha^{-1} $year^{-1}$ in fossil fuels, respectively. Input–output table estimates of the energy consumption resulting from the use of materials necessary to agricultural production (chemical fertilizers, biocides and agricultural machines) ranged between 11.01 ± 0.26 GJ ha^{-1} $year^{-1}$ for winter wheat and 24.38 ± 0.35 GJ ha^{-1} $year^{-1}$ for sugar beet. Thus, total annual energy inputs for fuel and materials consumed in cultivation and transportation steps amounted to 22.51 ± 0.26, 32.97 ± 0.35, 20.71 ± 1.58 and 24.44 ± 0.41 GJ ha^{-1} $year^{-1}$ for winter wheat, sugar beet, adzuki bean and potato production, respectively. Chemical fertilizer consumption contributed significantly to the energy use, representing 25–43% of the total energy inputs. Based on regional crop production statistics (1999–2003), total energy outputs as yield and crop residue biomass were estimated at 151.3 ± 18.1, 346.1 ± 17.9, 42.0 ± 18.1 and 163.8 ± 11.6 GJ ha^{-1} $year^{-1}$ for winter wheat, sugar beet, adzuki bean and potato production, respectively, resulting in regional conventional cropping energy output/input ratios of 6.72, 10.50, 2.03 and 6.70. Sugar beet is the most promising biomass-derived energy feedstock crop in this region, due to its high energy output/input ratio and net energy gain (energy output–input). However, for the full sugar beet-based bioethanol production system, a much lower energy output/input ratio and net energy gain were expected, given the greater energy inputs required in the transformation process. In addition to altering agronomic practices, transformation technologies less dependent on fossil fuels are crucial to developing sustainable bioethanol production systems in northern Japan.

Keywords: Bioethanol; Biomass production; Crop rotation; Energy balance; Fuel consumption

1. Introduction

Concerns regarding fossil energy conservation and mitigation of net greenhouse gas emissions have led to an increasing application of energy balances to a wide variety of crop production systems (Zentner et al., 1989; Conforti and Giampietro, 1997; Pimentel et al., 2005). In conventional systems, energy is primarily expended in fuel-consuming operations, such as running tractors, transporting farm products and materials by truck and drying grain (Smith, 1993; Koga et al., 2003). Energy is also expended through the significant fuel consumption involved in the manufacture and transport of input materials such as chemical fertilizers, biocides (herbicides, fungicides and insecticides) and agricultural machinery (Zentner et al., 1989; Hülsbergen et al., 2002). In light of the highly fuel-dependent and material-intensive nature of modern crop

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production systems, sustainable energy-saving protocols involving reduced tillage (Borin et al., 1997; Ozturk et al., 2006) and fertilization practices (Hülsbergen et al., 2002; Acaroğlu and Aksoy, 2005; Rathke and Diepenbrock, 2006) are being studied intensively.

Crop production can be viewed as the production of energy-rich materials through the process of photosynthesis (Calvin, 1974). Yield biomass is mainly targeted to human consumption and animal production, while crop residues are incorporated into soils or burned in the field. Recently, both yield and residue biomass components of crop production have generated growing attention for their potential as energy resources which can be called upon in an effort to decrease our dependence on fossil fuels and thus reduce net CO_2 emissions. Conversion to bioethanol of yield biomass from sugarcane (*Saccharum officinarum* L.), corn (*Zea mays* L.) and other cereal crops bearing a high concentration of sugars or starches is currently practiced in some countries (Macedo, 1998; Rosenberger et al., 2001; De Oliveira et al., 2005). Given crop residues' poor decomposability during energy transformation processes and the inherent difficulties in their recovery from the field, practical energy generation from them, other than by traditional combustion, is less common. Even though crop residues have a fundamental role in sequestering carbon in soil (Lal, 2005), they are deemed an unused energy resource, the use of which could contribute to reducing CO_2 emissions from fossil fuel burning (Peterson, 2006; Prasad et al., 2007).

Located in the northern part of Japan, the Tokachi region of Hokkaido prefecture is Japan's main crop production area, producing winter wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L. subsp. *vulgaris*), beans [adzuki bean – *Vigna angularis* (Willd.) Ohwi & Ohashi; kidney bean – *Phaseolus vulgaris* L.; soybean – *Glycine max* Merr.] and potato (*Solanum tuberosum* L.) in rotation. Agriculture here is conducted on a much larger scale than elsewhere in Japan, and a wide range of highly mechanized field management practices are used according to the crop type (Koga et al., 2003). Tillage, sowing or transplanting, basic fertilization, biocide spraying and harvesting constitute the most common tractor operations for these crops, while inter-row cultivation, additional fertilization and ridge construction differ according to the crop (Department of Agriculture, Hokkaido Government, 2000). In addition, agricultural materials such as chemical fertilizers and biocides are frequently and intensively employed to obtain high, stable yields. Highly mechanized, material-intensive modern crop production systems such as those implemented in the Tokachi region of Hokkaido may thus entail significant energy consumption. In the context of current flourishing bioethanol production in the world, in 2007, the Japanese Government launched a national project on bioethanol production from yield biomass, such as sugar beets and potatoes, produced in Hokkaido. Viable bioethanol production systems, suitable for Japanese conditions, are being sought.

As energy resources in Japan are limited, it is important to devise more energy-efficient and thus ultimately more sustainable agricultural production systems. An energy balance of conventional crop rotation systems in the Tokachi region of northern Japan was developed. Moreover, the possibility of fuel ethanol production from crops grown in Hokkaido was discussed on the basis of the energy balance and earlier studies.

2. Materials and methods

2.1. Energy inputs under conventional cropping systems

2.1.1. Energy inputs through fuel consumption

Tractor operations, truck transportation of materials and farm products, along with other fuel-consuming operations such as mechanical wheat grain drying, were included in the calculation of fuel consumption-associated energy inputs under conventional winter wheat, sugar beet, adzuki bean and potato production (Fig. 1). The extent of tractor operations for each crop was based on the recommendations of the Department of Agriculture, Hokkaido Government (2000), while the total diesel oil consumption for tractor operations was drawn from Koga et al. (2003). This calculation assumed the use of the most common tractor size and working width for each tractor operation. Therefore, no variations were evaluated for fuel consumption rates. The diesel oil consumption associated with hauling materials (e.g. seedlings, chemical fertilizers, lime) between farmhouse and field, and farm products between the field and their destination was based on the distances of 1 and 10 km, respectively (Koga et al., 2003). Among other fuel-consuming operations, gasoline was also used to broadcast snow-melting materials by snowmobile, and kerosene was consumed to dry wheat grain. In addition, electrical energy was consumed in drying wheat grain and raising sugar beet seedlings. Energy equivalents for diesel oil, gasoline and kerosene were 37.77, 34.59 and 36.74 MJ L^{-1}, respectively (Table 1; Greenhouse Gas Inventory Office of Japan, 2006). The consumption of each kWh electricity was equivalent to 3.6 MJ of energy input.

2.1.2. Energy inputs through material consumption

Energy consumption from the use of agricultural materials, chemical fertilizers, biocides and agricultural machines (mainly tractors and tractor implements) was estimated for Japanese conditions, using input-output tables (Table 1; Nansai et al., 2002). This table provides energy consumption rates for a wide range of products and services, which are calculated from the consumption of various types of energy necessary for their manufacture and transport. Energy consumption rates of 77.79, 47.62 and 48.57 kJ yen^{-1} were used in this study for fertilizers, biocides and agricultural machinery, respectively (Table 1). The rates for chemical fertilizers and biocides were