Cost and Greenhouse Gas (GHG) Emission Analysis of a Growing, Harvesting, and Utilizing System for Willow Trees Aimed at Short Rotation Forestry (SRF) in Japan

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A system for growing, harvesting, and utilizing willow trees aimed at short rotation forestry (SRF) was designed in northern Japan, and the system was evaluated from the viewpoints of cost economy and greenhouse gas (GHG) emission based on a life cycle assessment (LCA) method. The willows were assumed to be grown intensively in 200 ha of idle land in the test area, harvested using a sugarcane harvester, and utilized for heat energy through the burning of wood chips directly in a biomass boiler. As a result, the cost of willow was 180.64 US$/dry-t, which was more than the cost of forest biomass such as logging residues and thinned trees, while willow chips were less expensive than heavy oil in terms of their price per calorific value. On the other hand, the GHG emission of willow was 6.633 kgCO2eq/GJ, less than one-tenth that of heavy oil. Therefore, it is suggested that substituting willow chips for heavy oil as a heating fuel could be economical and could help reduce regional GHG emissions.

Key Words
Cost and greenhouse gas (GHG) emission analysis, Growing, harvesting, and utilizing system, Japan, Short rotation forestry (SRF), Willow

1. Introduction

Short rotation forestry (SRF), in which fast-growing tree species such as eucalyptus, poplar, and willow are reforested through the planting of rooted cuttings and repeated harvesting of the sprouting stumps in short-term cycles of several years, has mainly been applied to produce pulp chips. In recent years, however, SRF has attracted attention worldwide as a new source of woody biofuel. Commercial willow plantations have been cultivated as sources of bioenergy in Sweden since the 1980s, and around 16,000 ha of short rotation willow plantations were established domestically from 1986 to 2000 1). Other European countries and North American countries have been testing harvesting operations designed for SRF using agricultural and forestry machines 2) ~ 6). Similarly, in Japan, woody biomass from SRF is defined as an energy...
crop' and is considered to be a resource in the Biomass-Nippon Strategy alongside ‘unused biomass’ such as logging residues\(^{(5)}\).

This paper outlines an experimental project for growing, harvesting, and utilizing willow trees in Japan. This project is currently underway in the boreal forests of Hokkaido prefecture, in northern Japan. In a previous study by the authors of this paper, an experiment on the growing and harvesting of willow trees using SRF methods was conducted\(^{(6)}\). Willows were harvested using a sugarcane harvester in Okinawa prefecture, in southern Japan, during its agricultural off-season. The growing experiment showed the high potential of willow plantations to produce woody biomass of more than 10 dry-\(t/(ha\cdot yr)\). The harvesting experiment (Fig. 1) showed that space for turning the harvester around, the planting of one line per row, a growing cycle of three years, and the presence of an extractor fan in the harvester were necessary for mechanical harvesting. Mechanical harvesting was considered to have little influence on willow regeneration provided that the machine cut reasonably well-grown trees. The system performance for harvesting and collecting willow billets in a hypothetical model field was calculated to be 22.4 m\(^3\)/h, suggesting the feasibility of supplying low-cost wood chips by this method.

In this study, as the next consideration in the project, a system for growing, harvesting, and utilizing willow trees was designed in northern Japan, and the system was evaluated from the viewpoints of cost economy and greenhouse gas (GHG) emission based on a life cycle assessment (LCA) method. In other studies of LCA-based methods, Tahara et al. analyzed forest biomass from SRF in foreign countries as an energy resource for the purpose of trading GHG emissions\(^{(9)}\), while logging residues from domestic conventional forestry were examined by the authors of this paper\(^{(10)}\).

2. Materials and methods
2.1 System framework
The utilization of woody biomass has been promoted in the test area, and wood chip boilers are now being introduced. It is a problem in this area to secure a stable supply of feedstock so that any willows that are cultivated are expected to be utilized as energy. An area of approximately 200 ha in a cluster of idle land, about 20 km from downtown, is a candidate site for cultivation. In this study, therefore, willow was assumed to be grown intensively in 200 ha of idle land in the test area, harvested using a sugarcane harvester, chipped, and utilized as heat energy by burning wood chips directly in a biomass boiler 20 km away from the test field (Fig. 2). In accordance with the previous study, the growing cycle was set to three years; it was assumed that a sugarcane harvester would be newly bought rather than transported from southern Japan during its agricultural off-season, 30 dry-\(t/ha\) of willow billets would be collected when harvesting, and that the test field would be renewed every 20 years. The chipping process was assumed to be carried out at a chip mill 3 km away from the test field. A system for growing, harvesting, and utilizing willow trees was designed in northern Japan, and the system was evaluated from the viewpoints of cost economy and greenhouse gas (GHG) emission based on a life cycle assessment (LCA) method.
away from the boiler.

2.2 Cost calculation

The test field was assumed to be renewed every 20 years so that the plowing, site preparation, planting, weeding, and cut-back operations would be carried out once every 20 years. Therefore, through these operations, the area of 200 ha would be covered in 20 years and the cost per 10 ha was allocated annually and regarded as the initial cost. However, the fertilizing, harvesting, and collecting operations would be conducted every three years, since the growing cycle was set to three years. Thus the area of 200 ha would be covered in three years by these operations, and the cost per 66.7 ha was allocated annually and regarded as the running cost.

With regard to the calculation of the fixed costs of the machinery, civil engineering machines were assumed to be rented for the plowing, site preparation, fertilizing, and weeding operations, and rental charges were assigned to these operations. All the machines to be used in the harvesting and chipping processes, however, were supposed to be bought for the studied system, and so the depreciation costs were considered in these processes, and the variable costs, e.g., labor, fuel and oil costs, were calculated separately.

2.3 GHG emission analysis

From the perspective of agricultural sustainability, an LCA analysis of the whole system is very important. To perform the GHG emission evaluation based on the LCA, the processes ranging from the cultivation of willows as feedstock to the direct combustion of wood chips in a biomass boiler were analyzed. These GHG emissions were compared with those of heavy oil, of which inventory covered the crude oil extraction, fractional distillation, oil refining, and combustion processes.

The energy consumption (light oil) of the machines used in the growing, harvesting, and chipping processes were calculated by the liter (L) and converted to GHG emissions using the GHG emission factor, while the GHG emissions for the hauling operations were estimated by the ton-kilometer method. On the other hand, the GHG emissions related to fixed assets such as buildings and machines were not considered in the evaluation. As for the energy consumption (electricity) in the utilization process, 32.4 kWh per dry-t of wood chips, which was the value determined for a biomass boiler in the test area, was utilized, and the GHG emission was calculated using the GHG emission factor. With respect to the GHG emission of the material input, fertilizer used in the fertilizing process was considered. In addition, CH₄ and N₂O emitted by direct combustion were assessed with consideration of the global warming potential (GWP).

3. Results and discussion

The cost of willow was calculated to be 180.64 US$/dry-t (Table 1; the exchange rate was roughly 100 yen to the U.S. dollar at the time of analysis), which was more than the cost of forest biomass such as logging residues and thinned trees, while willow chips (10.84 US$/GJ) were less expensive than heavy oil (19.18 US$/GJ), which was the market price at the time of analysis in terms of the price per calorific value; the total cost must be reduced for the studied system to be viable: First, the cost of fertilizing accounted for over 10% of the total cost, so lower-cost fertilizers or recycled compost should be introduced; Second, the planting and cut-back processes depended on manual operations so that the sum of the cost of both processes accounted for more than 30% of the total cost, necessitating an examination of the feasibility of mechanizing the planting and cut-back; Third, since the cost of chip hauling accounted for almost 25% of the total cost, the transporting process has to be improved by implementing supply chain management procedures such as constructing a stockyard adjacent to the biomass boiler.

On the other hand, the GHG emission of willow in this study was calculated to be 6.633 kgCO₂eq/GJ (Table 2), less than one-tenth that of heavy oil, i.e., 74.68 kgCO₂eq/GJ. Therefore, it has been suggested that substituting heating fuel containing willow chips for heavy oil could be economical and could help reduce regional GHG emissions.

4. Conclusions

A system for growing, harvesting, and utilizing willow trees aimed at short rotation forestry (SRF) was designed in northern Japan, and the system was evaluated from the viewpoints of cost economy and greenhouse gas (GHG) emission based on a life cycle assessment (LCA) method; the following results were derived from the analysis: The cost of willow was 180.64 US$/dry-t, which was more than the cost of forest biomass such as logging residues and thinned trees, while willow chips were less expensive than heavy oil in terms of their price per calorific value; The GHG emission of willow was 6.633 kgCO₂eq/GJ, less than one-tenth that of heavy oil. Thus the studied system, by substituting heating fuel containing willow chips for heavy oil, was determined to be economical and to help reduce regional GHG emissions.
### Table 1  Breakdown in each process for the cost of willow

| Process     | Subprocess   | Item                  | Original unit | Amount                  | Total (US$/yr) |
|-------------|--------------|-----------------------|---------------|-------------------------|----------------|
| Growing     | Plowing      | Plowing operation     | 171.68 US$/ha | 200 ha/20 yrs           | 1,716.80       |
|             |              | Machine transportation| 2,710.67 US$/time | 1 time/20 yrs                | 135.53         |
|             |              | **Subtotal**          |               |                         | 1,852.33       |
|             | Site preparation | Preparing operation   | 294.39 US$/ha | 200 ha/20 yrs           | 2,943.90       |
|             |              | Machine transportation| 262.36 US$/time | 1 time/20 yrs                | 1312           |
|             |              | **Subtotal**          |               |                         | 2,975.02       |
| Fertilizing |              | Cost of fertilizer    | 431.20 US$/ha  | 200 ha/3 yrs            | 28,746.67      |
|             |              | Fertilizing operation | 159.97 US$/ha  | 200 ha/3 yrs            | 10,664.67      |
|             |              | Machine transportation| 262.36 US$/time | 20 times/20 yrs              | 262.36         |
|             |              | **Subtotal**          |               |                         | 39,673.69      |
| Planting    |              | Planting operation    | 6,535.30 US$/ha^ | 200 ha/20 yrs          | 65,353.00      |
|             |              | Machine transportation| 262.36 US$/time | 1 time/20 yrs             | 1312           |
|             |              | **Subtotal**          |               |                         | 65,366.12      |
| Weeding     |              | Weeding operation     | 294.39 US$/ha  | 200 ha/20 yrs           | 2,943.90       |
|             |              | Machine transportation| 262.36 US$/time | 1 time/20 yrs               | 1312           |
|             |              | **Subtotal**          |               |                         | 2,957.02       |
| Cut-back    |              | Cut-back operation    | 4,542.23 US$/ha | 200 ha/20 yrs          | 45,422.30      |
|             |              | **Subtotal**          |               |                         | 39,673.69      |
| Harvesting  |              | Machine cost          | 393.75 US$/ha  | 200 ha/3 yrs            | 26,250.00      |
|             |              | Harvesting operation  | 197.12 US$/ha  | 200 ha/3 yrs            | 13,141.33      |
|             |              | **Subtotal**          |               |                         | 39,391.33      |
| Collecting  |              | Machine cost          | 976.00 US$/ha  | 200 ha/3 yrs            | 6,506.67       |
|             |              | Collecting operation  | 73.28 US$/ha   | 200 ha/3 yrs            | 4,885.33       |
|             |              | **Subtotal**          |               |                         | 11,392.00      |
| Hauling     |              | Hauling operation     | 301.08 US$/ha  | 200 ha/3 yrs            | 20,072.00      |
|             |              | **Subtotal**          |               |                         | 30,463.33      |
| Chipping    |              | Machine cost          | 2.518 US$/dry-t | 2,000 dry-t/yr         | 5,036.00       |
|             |              | Feeding operation     | 3.545 US$/dry-t | 2,000 dry-t/yr         | 7,090.00       |
|             |              | **Subtotal**          |               |                         | 12,126.00      |
|             |              | Machine cost          | 9.781 US$/dry-t | 2,000 dry-t/yr         | 19,562.00      |
|             |              | Chipping operation    | 9.373 US$/dry-t | 2,000 dry-t/yr         | 18,746.00      |
|             |              | **Subtotal**          |               |                         | 38,308.00      |
| Loading     |              | Machine cost          | 2.290 US$/dry-t | 2,000 dry-t/yr         | 4,580.00       |
|             |              | Loading operation     | 3.725 US$/dry-t | 2,000 dry-t/yr         | 7,450.00       |
|             |              | **Subtotal**          |               |                         | 12,030.00      |
| Hauling     |              | Hauling operation     | 34.87 US$/dry-t | 2,000 dry-t/yr         | 69,740.00      |
|             |              | **Subtotal**          |               |                         | 132,204.00     |
| **Total (per year)** |           |                       |               |                         | 361,287.81     |
| **Total (per dry-t)**    |           |                       |               |                         | 180.64         |

*These were the result values measured and calculated in the project.*
### Table 2 Calculation basis for the GHG emission of willow

#### Energy consumption (light oil)

| Process          | Subprocess     | Item               | Original unit | Amount       | Total (L/yr) |
|------------------|----------------|--------------------|---------------|--------------|--------------|
| Growing          | Plowing        | Ripper-dozer       | 35.8 L/ha²⁸   | 200 ha/20 yrs | 358.0        |
|                  | Crane          |                    | 65.8 L/time²⁵ | 1 time/20 yrs | 3.3          |
|                  | Trailer        |                    | 14.6 L/time²⁵ | 1 time/20 yrs | 0.7          |
|                  |                | Subtotal            |               |              | 362.0        |
| Site preparation | Tractor        | 49.3 L/ha²⁸        | 200 ha/20 yrs | 493.0        |
|                  | Truck          |                    | 10.1 L/time²⁵ | 1 time/20 yrs | 0.5          |
|                  |                | Subtotal            |               |              | 493.5        |
| Fertilizing      | Tractor        | 16.8 L/ha²⁸        | 200 ha/3 yrs  | 1,120        |
|                  | Truck          |                    | 10.1 L/time²⁵ | 20 times/20 yrs | 10.1       |
|                  |                | Subtotal            |               |              | 1,130.1      |
| Planting         | Truck          | 0.9 L/ha²⁸         | 200 ha/20 yrs | 9.0          |
| Weeding          | Tractor        | 49.3 L/ha²⁸        | 200 ha/20 yrs | 493.0        |
|                  | Truck          |                    | 10.1 L/time²⁵ | 1 time/20 yrs | 0.5          |
|                  |                | Subtotal            |               |              | 493.5        |
| Harvesting       | Harvesting     | Sugarcane harvester | 778 L/ha²⁶   | 200 ha/3 yrs  | 5,186.7      |
|                  | Collecting     | Forwarder          | 8.33 L/ha²⁶   | 200 ha/3 yrs  | 555.3        |
|                  |                | Subtotal            |               |              | 5,742.0      |
| Chipping         | Feeding        | Grapple loader     | 108 L/dry-t²⁶ | 2,000 dry-t/yr | 2,160.0     |
|                  | Chipping       | Tub grinder        | 8.15 L/dry-t²⁶ | 2,000 dry-t/yr | 16,300.0    |
|                  | Chipping       | Bucket loader      | 113 L/dry-t²⁶ | 2,000 dry-t/yr | 2,260.0     |
|                  |                | Subtotal            |               |              | 20,720.0     |
|                  |                | Total              |               |              | 29,540.1     |

#### Energy consumption (electricity)

| Process          | Subprocess     | Item               | Original unit | Amount       | Total(kWh/yr) |
|------------------|----------------|--------------------|---------------|--------------|---------------|
| Direct combustion| -              | Biomass boiler     | 324 kWh/dry-t* | 2,000 dry-t/yr | 64,800       |

#### Material input (fertilizer)

| Process          | Subprocess     | Item               | Original unit | Amount       | Total (kg/yr) |
|------------------|----------------|--------------------|---------------|--------------|---------------|
| Growing          | Fertilizing    | Nitrogen           | 80 kg/ha²⁴    | 200 ha/3 yrs  | 5,333         |
|                  |                | Simple fertilizer  | 431.20 US$/ha²⁴ | 200 ha/3 yrs  | 28,746.67 US$/yr |

#### Transportation ton-kilometers (10-ton truck, load factor of 50%)

| Process          | Subprocess     | Quantity           | Transportation distance (km) | Total (t-km/yr) |
|------------------|----------------|--------------------|------------------------------|-----------------|
| Harvesting       | Hauling        | 3,300 wet-t/yr²⁵   | 20 km                        | 66,000          |
| Chipping         | Hauling        | 3,300 wet-t/yr²⁵   | 5 km                         | 9,900           |
|                  |                | Total              |                              | 75,900          |

#### GHG emissions

| Energy consumption | GHG emission factor | Amount   | Total (kgCO₂/yr) |
|--------------------|---------------------|----------|-----------------|
| Light oil          | 2.74 kgCO₂/L²⁸      | (15)     | 80,940          |
| Electric power     | 0.479 kgCO₂/kWh²⁸   | (16)     | 31,039          |
|                    | Total               |          | 112,125         |
| Nitrogen           | 2.263 kgCO₂/kg²⁵    | (17)     | 12,069          |
| Simple fertilizer  | 0.90 kgCO₂/US$/²⁵   | (18)     | 25,872          |
|                    | Total               |          | 37,941          |
| CH₄                | 1.5500 kgCO₂/GJ²⁵   | (20)     | 51,662          |
| N₂O                | 0.1800 kgCO₂/GJ²⁵   | (21)     | 5,999           |
|                    | Total               |          | 57,661          |
|                    | Total (kgCO₂/yr)    |          | 221,092         |

* This was the value determined for a biomass boiler in the test area.
** 3,300 wet-t/yr is equal to 2,000 dry-t/yr since the water content of willow in the test area was measured as 65% on a dry-weight basis. Thus the total amount of calorific value of willow, 33,330 GJ/yr, was calculated from the wet weight, 3,300 wet-t/yr, and the unit calorific value of wet willow, 10.1 GJ/wet-t.
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