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High Biomass Productivity of Short-Rotation Willow Plantation in Boreal Hokkaido Achieved by Mulching and Cutback

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Received: 12 March 2020; Accepted: 27 April 2020; Published: 1 May 2020

Abstract: Weed control, which is commonly achieved by herbicides, is important in successfully establishing short-rotation coppice (SRC) of willow. In this study, we examined agricultural mulch film as a means of effective weed control and the influence of cutback practice (coppicing the first year's shoot growth in the winter following planting) on biomass production in boreal Hokkaido, Japan. One-year-old cuttings from two clones each of *Salix pet-susu* and *S. sachalinensis* were planted in double-rows at a density of 20,000 plants ha^{-1}. All plants were harvested three growing seasons after cutback. Average oven-dried biomass yield was 5.67 t ha^{-1} yr^{-1} with mulching, whereas it was 0.46 t ha^{-1} yr^{-1} in the unmulched control with a weed biomass of 4.13 t ha^{-1} yr^{-1}, indicating that mulching was an effective weed control. However, weeds grew vigorously on the ground between mulch sheets and their dry biomass amounted to 0.87 t ha^{-1} yr^{-1}. Further weeding between the mulch sheets enhanced the willow biomass yield to 10.70 t ha^{-1} yr^{-1} in the treatment with cutback. In contrast, cutback even reduced the willow yield when there were weeds between the mulch sheets. This negative effect of cutback on the willow yield resulted from nutrient competition with weeds; there was similar leaf nitrogen content and dry biomass per unit land area for the weeds and willows combined in the control and mulching treatments. These results suggest that growing SRC willow is feasible in boreal Hokkaido if combined with complete weed control and cutback, and is facilitated by using mulch film.

Keywords: cutback; mulch; *Salix*; short-rotation coppice; weed control; woody biomass

1. Introduction

Woody biomass production is an economically viable and ecologically sound solution to address increasing energy demands; it also has positive effects on reducing global atmospheric CO_2 and, consequently, the greenhouse effect. Willows (*Salix* spp.) are one of the best species for short-rotation coppice (SRC) in temperate climates because they are easily propagated vegetatively, they have a high yield potential in a few years, a broad genetic base, and they can re-sprout from their coppiced stools after harvesting [1]. However, despite their general plasticity, the adoption of willows as a bioenergy production system remains a challenge in respect to high yield [2]. In particular, weed control is of top priority in order to achieve a long-term high yielding SRC willow plantation [3–6]. It is extremely important because weeds have a negative effect on the SRC willows as they compete for light, water, and nutrients, and they consequently reduce the survival rate of cuttings and biomass production [2,7]. Furthermore, the response to weed competition may differ between species and clones, as do growth patterns and competitive abilities, just as soil properties and climate differ between plantations [8]. To date, willow selection and breeding have focused on high biomass production under optimum conditions, and no commercial clone has been found to have high biomass productivity in the presence of competition from weeds [2,7,8]. Therefore, development of environmentally friendly, efficient, and cheap weed control measures might be the best way forward for the establishment of SRC willow plantations.

The application of mulches in agriculture and horticulture has increased dramatically in the last two decades throughout the world. This increase is due to benefits such as suppressed weed growth, soil moisture conservation, reducing certain insect pests, higher crop yield, earlier harvests, improved fruit quality, and more efficient use of soil nutrients [9–15]. The selection of an appropriate mulching material depends on crop type, crop management practices, and climatic conditions. Of the various materials being used as mulches, plastics are most commonly used in agriculture and horticulture. However, to our knowledge, there has been little research on the use of plastic mulch in plantations [16–18], whereas a report demonstrated that plastic mulch is an excellent way of promoting willow productivity by regulating water content in the soil and increasing soil temperature and controlling weeds on the poorly drained soil [17].

Coppicing the first year's shoot growth in the winter following planting, which is hereafter called cutback, is another common practice during the establishment of SRC willow plantations. This is mainly done to promote multiple stem sprouting and to facilitate fertilization and additional weeding during the second growth season [4–6,19,20]. However, recent studies indicate that this practice may reduce biomass productivity [8,20], and is no longer recommended in Sweden [21]. The factors and mechanisms determining the effect of cutback on biomass production are not fully understood. The reduced canopy due to cutback may provide weeds with new establishment opportunities and increase the need for further weed control during the years following establishment. Consequently, willow biomass production would decrease. Therefore, more studies are needed to determine whether cutback affects the ability of willows to compete with weeds, especially at the beginning of the second growing season, since some weed species may start to grow earlier than the willow. The interaction between cutback and weeds in relation to biomass production may be also be linked to resource limitation within plantations [22–24]. In this respect, information on nitrogen acquisition and allocation between willows and weeds would provide an insight into the effect of cutback practice on willow production [23,25,26].

Compared to European and North American countries, SRC willow cultivation is still a developing field in Japan [27–29]. The Feed-in Tariff Policy for renewable energy implemented in 2012 after the Fukushima Daiichi Nuclear Power Plant accident has become a driver, and the demand for wood resources has increased rapidly in recent years. Considering the above factors and their influence on the fast establishment of SRC willow plantations and long-term biomass productivity, we evaluated plastic mulch as a method of weed control. We further tested cutback and its interaction with weed control on the biomass production of *Salix pet-susu* and *S. sachalinensis* in the first harvest cycle, three growing seasons after cutback. There are no commercial willow cultivars in Japan, and these two species were selected because they are widely distributed in Northeastern region of Honshu and Hokkaido [30].

2. Materials and Methods

2.1. Study Site and Experimental Design

This study was carried out in a former grassland located near the Sanru river in Shimokawa town, Hokkaido (44°25′ N, 142°42′ E). The parent material of the soil is quaternary alluvial deposits with rounded or subrounded rock fragments covering the surface [31]. Soil nitrate nitrogen averaged from surface to 40 cm depth was about 4.6 mg per kg soil [31]. During the period 1978–2016, mean annual precipitation was 918.4 mm, mean diurnal mean, maximum, and minimum temperatures were 5.1 °C, 10.3 °C, and −0.5 °C, respectively, obtained at a nearby meteorological station (44°18′ N, 142°38′ E, 143 m a.s.l.; Japanese Bureau of Meteorology). Average days with snow cover depth more than 3 cm at the same station amounted to 150 during the period 1984–2016. Further details about precipitation and temperature during the period 2013–2016 (the first harvest cycle) are presented in Figure S1.

To control weeds, plastic mulch film (150 cm width and 0.021 mm thickness; Sunshat, C.I. TAKIRON Corporation, Tokyo, Japan) was laid using an agricultural machine, following the crushing of surface rock fragments to 20 cm soil depth using a mechanical stone crusher in autumn of 2012 (Figure 1a). We selected this polyethylene mulch because of its excellent strength and weather resistance. In May 2013, one-year-old 20 cm long unrooted cuttings—the length most commonly recommended in most European and northern American countries [3–5,21,32,33]—were planted in a double-row arrangement (Figure 1a). The distances were 1.5 m between the double rows, 0.5 m between rows, and 0.5 m between cuttings within a row, resulting in a density of 20,000 cuttings per hectare. This system is used worldwide in order to facilitate the management of sites using farm machinery [3–5]. Each clone (either P81 and P82 from *S. pet-susu* or S27 and S67 from *S. sachalinensis*) was planted in separate mulched rows next to each other (Figure 1b). In addition, a row without mulch was included as a natural control to confirm the effect of weed competition on biomass productivity. An electric fence was installed around the site to protect the willows from predation by deer and rabbits.

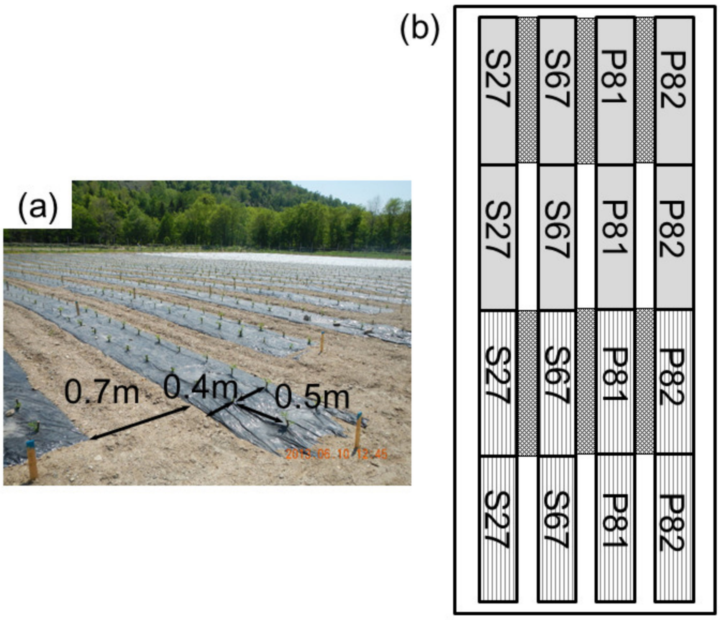

Figure 1. Experimental design: (**a**) double row planting of 20 cm long cuttings through mulch films, (**b**) layout of cutback and weed control treatments of two clones of *Salix sachalinensis* (S27, S67) and *S. pet-susu* (P81, P82) within a block. Vertical lines represent cutback and grey columns represent non-cutback treatments. White areas between the mulched areas represent weed-control treatments and black cross-hatching represent non-weed-control treatments, respectively.

The cutback treatment was conducted over half of the site in order to examine its effect on biomass production of SRC willow. In the winter following planting (the end of 2013), the year's shoots were cut back using pruning shears in order to stimulate development of multiple stems on each plant in the next growing season. Although no weeds grew on soils covered by mulch, weeds grew vigorously on the ground between the mulch sheets in the first growing season. Therefore, half of this site was sprayed with herbicides (Roundup Maxload, Tokyo, Nissan Chemical Corporation) in May 2014 after weeds stated growing. A month later, we confirmed that all weeds had died.

Therefore, four treatments were established in a five-block design (Figure 1b) before the second growing season: with or without cutback and/or weed control. There were 20 cuttings in each treatment within a block.

2.2. Allometric Equations

Twelve sprouted stems from *S. sachalinensis* were cut down to 0.03 m above the ground in August 2015 to enable us to generate allometric equations based on the main-axis cutting method [34]. Immediately after felling, the total height (H) and basal diameter at 0.03 m (D_0) of each stem were measured. D_0 ranged from 13.85 to 41.15 mm, and H ranged from 221 to 445 cm. Each stem was sealed in a plastic bag and stored in an air-conditioned car until taken back to the laboratory. The main stems were divided into 0.50 m lengths. The length and basal diameter (D) of each stem section was measured and organs attached to the main stem were classified into leaves and branches. All samples were then oven-dried at 75 °C for 72 h and weighed. Allometric equations were estimated for biomass of stem, branch, and foliage of each stem in terms of D_0, H, and D (Equations in Supplementary Material).

2.3. Growth Measurements and Harvesting

In November 2016 after leaf senescence, three growing seasons after the cutback treatment, all stems of both *S. sachalinensis* and *S. pet-susu* were harvested. Fresh biomass of aboveground organs including branches and stems from each cutting were weighed immediately. Sub-samples of branches and stems were taken back to the laboratory for biomass production determination, expressed in oven-dried tonnes per hectare per year (t ha^{-1} yr^{-1}). The ratio of dry biomass to fresh biomass was 0.5132, 0.5326, 0.5268, and 0.5474 for P81, P82, S27, and S67, respectively. Neither fertilization nor pesticide were applied during the first harvest cycle.

In order to examine the effect of cutback and weed control on the biomass increment process each year before harvesting, the D_0 and H from each cutting of *S. sachalinensis* were measured in November 2014. All stems were revisited in November 2015 to measure D_0 and H, as well as diameter at the height of the lowest branch (D). The number of sprouted stems from each cutting of *S. sachalinensis* was counted in November 2014.

2.4. Nitrogen Analysis

For nitrogen analysis, mature leaves from the aforementioned twelve sprouted stems used to develop the allometric equations were sampled. On the same occasion, weeds from the ground between mulches in treatments without weed control were harvested in three plots (50 cm × 70 cm) from each treatment.

All samples from leaves of both willow and weed were dried to constant mass at 75 °C and ground to a fine powder in a steel ball mill (MM400; Retsch, Haan, Germany). Total nitrogen concentration of the fine powder derived from each sample was measured after combustion in a CHN Analyzer (Vario Max CN, Elementar, Hanau, Germany).

2.5. Statistical Analyses

The effects of cutback, weeding, and species and their interactions on all dependent variables were analyzed by a two way or three way repeated-measures analysis of variance (ANOVA) using SigmaPlot 13.0 (Systat Software Inc., San Jose, CA, USA). We tested for normality and variance homogeneity at $p < 0.05$, and all variables were log-transformed when needed. The effect of the block on all variables was not significant at $p < 0.05$, and thus, these results are not shown. The Holm–Sidak method procedures were used for pairwise multiple comparison when significant treatment effects were revealed.

3. Results

Mulch had a significant effect on biomass production in the first harvest cycle, three growing seasons after cutback (Table 1). Without mulch, weeds grew fast and its height could reach up to 120 cm in August, which resulted in 69% of unrooted cuttings of willow dying. Therefore, the average biomass production of willows was 0.46 t ha^{-1} yr^{-1}, which was even lower than weed production (4.13 t ha^{-1} yr^{-1}). In contrast, willow biomass production increased to 5.67 t ha^{-1} yr^{-1} when mulches were used to control weeds, although weeds between the rows of willows growing in the ground not covered by mulch produced about 0.87 t ha^{-1} yr^{-1}. Both total plant biomass and leaf nitrogen content had similar values per unit land area in the control and mulched treatment.

Table 1. Annual average biomass production and leaf nitrogen content of both weeds and willow in land under natural conditions (no weed control) or plastic mulch. Values shown are mean ± SE.

Treatment	Plant Type	Biomass (t ha^{-1} yr^{-1})	Leaf Nitrogen (%)	Leaf Nitrogen (kg ha^{-1} yr^{-1})
Natural conditions	Weeds	4.13 ± 0.15	1.36 ± 0.07	56.22 ± 0.16
	Willow	0.46 ± 0.05	na	na
Mulch	Weeds	0.87 ± 0.11	1.84 ± 0.08	15.40 ± 1.27
	Willow	5.67 ± 0.28	2.39 ± 0.10	57.29 ± 0.22

With further weed control on the ground between mulches, willow biomass production increased to 11.43 and 8.84 t ha^{-1} yr^{-1} in the cutback treatment in *S. sachalinensis* and *S. pet-susu*, respectively (Figure 2). Without weed control, in contrast, cutback had no effect on biomass production in *S. pet-susu* and actually reduced yield by about 32% in *S. sachalinensis*. In addition, cutback and weed control had a significant interaction with respect to productivity (Figure 2, Table S1). Since the canopy of the willows closed during the second growing season after cutback, further weed control was not necessary.

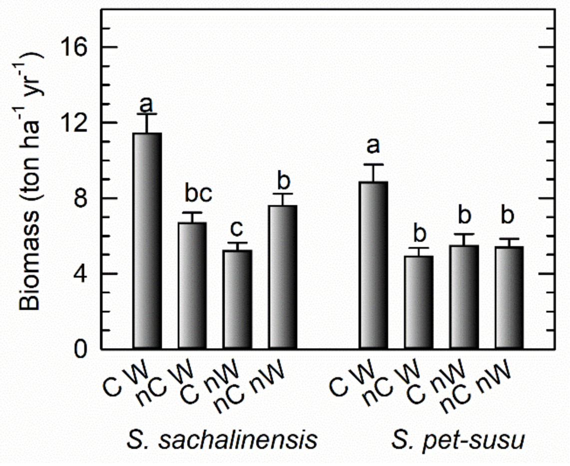

Figure 2. Comparison of dry biomass production in the first harvest cycle after three growing seasons: C and nC represent with and without cutback; W and nW represent with and without weed control, respectively. The significance values of the factorial analysis are shown in Table S1. Different letters indicate significant differences in the corresponding values from the same species at $p < 0.05$. Values shown are mean ± SE from two clones of the same species.

Cutback practice even reduced biomass increase without weed control on the ground between the mulch sheets (Figure 3, Table S2). This negative effect was especially obvious in branches and stems when comparing pairs without weed control in the first growing season (Figure 3b,c). In the second growing season, the negative effect of cutback became insignificant in leaves and branches, but was still significant in stems. Stem biomass increase in the second growing season exhibited a three-fold increase compared to the first growing season in all treatments.

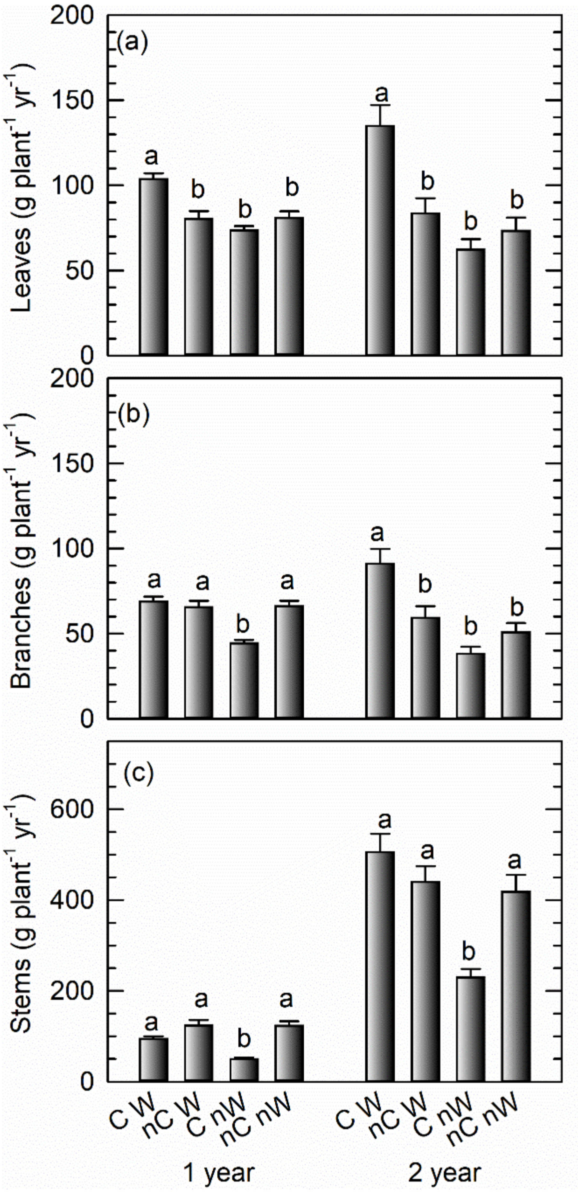

Figure 3. Annual biomass increments of (**a**) leaves, (**b**) branches, and (**c**) stems of *Salix sachalinensis* in the first and second growing seasons after cutback. C and nC represent with and without cutback; W and nW represent with and without weed control, respectively. The significance values of the factorial analysis are shown in Table S2. Different letters indicate significant differences in the corresponding values in a single year at $p < 0.05$. Values shown are mean ± SE from two clones of the same species.

Cutback promoted the formation of multiple stems (Figure 4, Table S1). Interestingly, a significant interaction between cutback and weed control was observed with respect to the number of stems per cutting, indicating that weed control is important for cutback to enhance productivity.

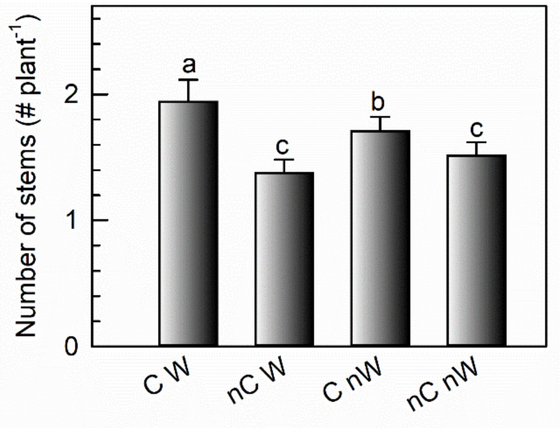

Figure 4. Number of stems sprouting from a single stool, counted after one season of growth since cutback in *Salix sachalinensis*. C and nC represent with and without cutback; W and nW represent with and without weed control, respectively. The significance values of the factorial analysis are shown in Table S1. Different letters indicate significant differences in the corresponding values at $p < 0.05$. Values shown are mean ± SE from two clones of the same species.

4. Discussion

Weed control is commonly achieved by one or two applications of herbicide during land preparation and planting for establishing an SRC willow plantation [3–6]. This study demonstrated that agricultural mulches are also an effective measure to control weeds in the boreal region studied, which has been less studied in forest plantations in comparison with agriculture and horticulture [16–18]. With complete weed suppression combined with cutback, annual average dry biomass production amounted to 10.70 t ha^{-1} yr^{-1} in the first harvest cycle, three growing seasons after cutback. However, cutback had no or even a negative effect on biomass production in the presence of weed competition, as found in previous studies [2,8]. These results suggest that cutback should only be conducted when weeds are absent.

4.1. Weed Control by Agricultural Mulch Film

In spite of mulching, weeds grew vigorously on the ground between mulch sheets. This adversely affected the growth of willows and as a result the biomass production in the first harvest cycle was reduced by 32% in *S. sachalinensis*. These results suggest that weeds on the ground between mulches also need to be controlled before cutback. In previous studies, the extent to which weeds influenced willow growth was reported to depend on both willow species and weed species [8,25]. In the present study, yield difference between *S. sachalinensis* and *S. pet-susu* provides further evidence for this conclusion. In addition, we found that total leaf nitrogen content per unit land area from weeds and willows combined was similar in the unweeded control and the mulched treatment. Thus, total biomass production per unit land area in the control was similar to that in the mulched treatment. These results suggest that competition for nutrients with weeds is the main cause of yield decrease at this site. Weed-related growth reduction may also differ depending on the plantation in terms of different soil nutrient limitation [2,35].

No weeds were observed in the second growing season after cutback because the willow canopy had closed, meaning that weed control conducted once during the establishment stage of a SRC plantation is sufficient. However, the negative effect of cutback on the biomass increment of stems remained as previously reported by Albertsson et al. [8], suggesting that weed control during the establishment year is extremely important in order to obtain a high yield SRC willow plantation [3–6]. Even though weed-related growth reduction decreases over time, the economic returns during the expected life cycle of a plantation will probably be much less if weeds are not controlled [8]. Yields over subsequent harvest cycles should be monitored, however, to validate this statement.

Mulches used in this study remained in good condition after the first harvest. Removal of the plastic is time-consuming (about 16 h/ha) [9]. In the long run, mulches are broken into pieces, some pieces being buried during soil preparation for a new crop and some remaining on the soil surface. The buried pieces are more difficult to decompose since they are less affected by light and high temperatures, creating serious soil problems whose environmental repercussion has not been fully evaluated. Considering that no weeds grow in the second growing season after cutback, biodegradable plastic mulch in organic production may be an environmentally friendly alternative to control weeds that deserves further research [9].

4.2. Cutback

When weeds between mulch sheets were not controlled, cutback had no effect on biomass production in *S. pet-susu* and actually reduced yield by about 32% in the first harvest cycle in *S. sachalinensis.* This negative effect has recently been reported in other willow species [8,20]. Therefore, the commonly recommended practice of cutback during establishment of a willow plantation should only be undertaken when there is sufficient weed control in place. A recent study showed that competition with weeds resulted in reduced willow growth at lower levels of fertilizer application compared to higher levels [7]. In this study, there was little difference in total leaf biomass and leaf nitrogen per land area between the unweeded control and the mulched treatment, indicating the same demand for nitrogen between weeds and willow. This limited nitrogen supply for willows in the presence of weeds resulted in lower leaf and branch increments in the cutback treatment and reduced biomass yield in the first harvest cycle.

S. sachalinensis, which had relatively higher growth reduction in the cutback and no weeding treatment compared to *S. pet-susu*, exhibited higher biomass production under optimum conditions (complete weed control). Similar results were reported previously for 10 commercial breeding clones in southern Sweden [8]. The relatively low biomass production even without weed competition may partly explain the low growth reduction with weed competition. In this respect, commercial breeding has been mainly aimed at the goal of high biomass production, and this is mostly considered under optimum environmental conditions. Willow species with high biomass productivity may have high nutrient demands and, thus, their productivity may decrease when exposed to competition from weeds. Therefore, further studies on physiological traits, such as nutrient and water acquisition and their use efficiency, canopy structure and development, and biomass allocation between aboveground organs and roots of different species and clones, are critical for the effective management of SRC plantations [22,25,36,37]. All these factors can be manipulated through genetic improvement and silvicultural practice [38].

Cutback increased the number of stems produced by each stool in *S. sachalinensis*, in agreement with previous studies [20]. In our previous study, the number of sprouted stems of the same species produced in a nursery in Sapporo was higher than in this study [27]. This difference is probably related to differences in climatic conditions because the mean annual temperature in Sapporo is 2 °C higher than at the current site, indicating that local climatic factors should be taken into account when planning to establish an SRC willow plantation and considering biomass yield and economic return. The number of stems from the experimental willows in this study overlapped the lower end of commercial cultivars in other countries [4–6,17,20,33], indicating the importance of breeding for commercial cultivars to achieve the highest possible yields that are also competitive with weeds [38].

The average oven dry biomass production recorded for the two willows in this study falls within the range of European and North American countries, which is 7.0–18.0 t ha^{-1} yr^{-1} [2,20,21,39–41]. Yields depend on cultivars, site-specific conditions (soil fertility, climate), and type and intensity of management (fertilization, weeding, and protection from blight and insect). For example, fertilized willow SRC plantations had on average 38% higher yield than non-fertilized SRC plantations in Sweden [2]. In addition, it is generally found that yields are higher from the second harvest cycle [19,39,40]. However, nutrient export in harvested biomass over multiple rotations will require soil nutrient amendments to maintain the SRC willow productivity that deserves further research [41,42].

5. Conclusions

This study demonstrated that agricultural mulches are an effective measure for controlling weeds during the establishment of an SRC willow plantation. However, weeds between mulch sheets had negative effects on yield, especially in treatments with cutback, which was resulted from nutrient competition with weeds. Cutback practice should be used only when weeds are completely controlled. With complete weed control, 10.70 t dry biomass per hectare was achieved three years after cutback, indicating the feasibility of successfully establishing an SRC willow plantation in boreal Hokkaido, Japan.

Supplementary Materials: Supplementary Materials can be found online at http://www.mdpi.com/1999-4907/11/5/505/s1.

Author Contributions: Conceptualization, Q.H., H.H., A.U. and H.U.; Methodology, Q.H., H.H., A.U. and H.U.; Formal Analysis, Q.H.; Investigation, Q.H., H.H., A.U., E.I., M.K., Y.M. and H.U.; Writing—Original Draft Preparation, Q.H.; Writing—Review & Editing, Q.H., H.H., A.U., E.I., M.K., Y.M. and H.U.; Project Administration, Q.H., A.U. and H.U.; Funding Acquisition, Q.H. and H.U. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors thank Haruka Yamamoto for the biomass measurements, Yuji Takahashi of Shimokawa town for maintenance the experimental site, and Oji Holdings Co. for offering the willow cuttings. The authors thanks also the editor and the two anonymous reviewers for their valuable comments. This work was supported by an FFPRI Grant.

Conflicts of Interest: The authors declare no conflict of interest.

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