Effects of Partial Harvesting on Napier Grass: Reduced Seasonal Variability in Feedstock Supply and Increased Biomass Yield

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Abstract: The production of cellulosic bioethanol from non-edible plants is receiving increasing attention for its potential to avoid food–fuel competition. However, seasonal variability in feedstock supplies increases the costs of stockpiling and limits commercialization. The cellulosic energy plant Napier grass (Pennisetum purpureum) has conventionally been harvested three times per year (on a 4-month cycle) in Indonesia. To shorten this cycle, we examined an alternative system in which every four rows (rather than the entire crop) were alternately harvested every 2 months (partial harvesting). Results from a 20-month experiment indicated that partial harvesting was effective in shortening the supply cycle from 4 to 2 months. Moreover, partial harvesting significantly increased biomass yield, probably as a result of the border effect. Investigations into available light, atmospheric CO2 concentration, and soil volumetric water content suggested that partial harvesting allowed Napier grass to capture more light for biomass production.

Key words: Biomass production, Edge effect, Energy crop, Feedstock, Lignocellulosic bioethanol.

Bioethanol is regarded as an alternative to fossil fuels and as a potential countermeasure against global warming. However, there is concern that the rapid increase in global bioethanol production may lead to competition with food production (Boddiger, 2007). Thus, cellulosic bioethanol produced from non-edible plants is receiving increasing attention (Hattori and Morita, 2010).

Although attempts are being made worldwide to establish a cellulosic bioethanol industry, most efforts have not progressed beyond the pilot scale (Banerjee et al., 2010; Stephen et al., 2012; Kurian et al., 2013). Various factors limit commercialization of cellulosic bioethanol, including difficulty of amortizing capital costs of facilities (Richard, 2010). The feedstock supply usually concentrates on harvesting seasons. This creates a challenge for year-around operation of ethanol plants and mandates additional investment in storage facilities. Thus, developing methods for reducing seasonal variability of feedstocks is regarded as critically important for cellulosic bioethanol production (Richard, 2010; Kurian et al., 2013).

To address this issue, we examined whether an alternative cultivation system using a technique referred to as partial harvesting can increase the frequency of harvest without disturbing biomass yields. In this study, we tested the partial-harvesting system using the cellulosic energy plant Napier grass (Pennisetum purpureum), in Indonesia (Sekiya et al., 2014). Napier grass is typically harvested three times per year on a 4-month cycle (NEDO, 2012). In contrast, the partial-harvesting method collects every 4 rows alternately every 2 months. The increased frequency of harvest is expected to reduce seasonal variability in the feedstock supply.

In addition, we hypothesized that partial harvesting would enhance biomass yield through the border effect. The border effect refers to improved performance of plants located in outer rows compared to those in interior rows as a result of reduced competition with neighbors for resources such as light, CO2, water, and nutrients (Gomez and De Datta, 1971; Wang et al., 2013). Since its discovery, the border effect has been regarded as a source of overestimation of plant growth in agricultural studies (e.g., McRostie and Hamilton, 1927; Hollowell and Heusinkveld,
In the 1990s, Japanese farmers attempted to take advantage of the border effect to improve rice production by leaving one out of every five to six rows unplanted ("partial non-transplanting") (Kujira et al., 1998). Rice yields were reported to increase despite the reduced number of transplanted rows. This transplanting technique has also been adopted by rice farmers in Indonesia (Siagian, 2014). Partial harvesting is expected to create environmental conditions similar to those generated by partial non-transplanting. Therefore, we also examined the effect of partial harvesting on biomass yield of Napier grass.

**Materials and Methods**

This study was conducted in an experimental field (36 × 76 m) at PT. TOYOTA BIO INDONESIA (TBI) in Lampung, Indonesia (5°3′S, 105°3′E). The study area is characterized by a humid tropical climate with rainfall strongly affected by the tropical monsoon system; the rainy season lasts from October to May and the dry season occurs from June to September (Fig. 1). The temperature is high and stable year round. Soil characteristics in the study area were described in detail by Fauzi et al. (2011); the reddish-grey surface horizon is clayey and very friable; the homogenous, yellowish-red subsurface horizons are also clayey and friable with subangular blocky structure.

Soils were plowed to a depth of 0.15 – 0.20 m with a two-wheeled, 30-hp hand tractor from July 18 to 22, 2011. The field was then divided into three blocks (36 × 24 m each). Each block was separated into two different-sized plots (12 × 24 m and 22 × 24 m), which were randomly positioned in each block. Stem cuttings of Napier grass (0.15 – 0.2 m long and including a few nodes) were planted in each plot on July 27, 2011 (1 × 0.5-m spacing between hills). Chemical fertilizer was applied to each plot at a rate of 30 kg N ha\(^{-1}\), 15 kg P\(_2\)O\(_5\) ha\(^{-1}\), and 15 kg K\(_2\)O ha\(^{-1}\) at 0, 1.5, and 3 months after planting (MAP). Unlike previous years, 2011 was very dry and received no rainfall from July 27 to October 6. Thus, all plots were irrigated weekly from 0 to 2 MAP. Missing hills were replanted one MAP, and weeds were removed manually 3 MAP, and if necessary thereafter.

Plants in the smaller (12 × 24 m) and larger (22 × 24 m) plots were subjected to total and partial harvesting, respectively (Fig. 2). Total harvesting was performed by mowing all plants to 0.15 m above the soil surface every 4 months. In partial harvesting, sets of four consecutive rows were alternately mowed 0.15 m above the soil surface every 4 months (i.e., one harvesting event was conducted every 2 months). The same quantities of chemical fertilizer as described above were applied in each plot 0, 1.5, and 3 months after each harvest. From 8 MAP, each plot was divided into two subplots (12 × 12 m for smaller plots and 11 × 24 m for larger plots), one of which was randomly selected to receive organic fertilizer. Air-dried cattle manure (1.01% N, 1.37% P\(_2\)O\(_5\), and 0.49% K\(_2\)O) obtained from a nearby beef company was applied at rates of 20 t ha\(^{-1}\) at 8 MAP and 10 t ha\(^{-1}\) after every mowing.

During each mowing event, fresh biomass from each plot or subplot, excluding plants along plot borders, was...
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**Results and Discussion**

During the growth period from 0 to 4 MAP, no significant differences in mean biomass yield were detected between total and partial harvesting treatments (12.1 and 10.5 t ha$^{-1}$, respectively) (Fig. 3). This trend continued from 4 to 8 MAP, during which mean biomass yield from total and partial harvesting treatments were 11.1 and 11.7 t ha$^{-1}$, respectively. Thereafter, half of the plants received organic fertilizer in addition to chemical fertilizer. From 8 to 12 MAP, there were no significant effects of fertilizer, harvesting technique, or their interaction on biomass yield; mean yield ranged from 9.4 to 10.1 t ha$^{-1}$. From 12 to 16 MAP, however, a significant ($P = 0.011$) effect of harvesting method was detected, but there were no significant effects of fertilization or of the interaction between fertilization and harvest technique. This indicated that partial harvesting increased biomass yield to 10.2 – 11.8 t ha$^{-1}$ during this period, compared to the yield of 7.2 – 8.6 t ha$^{-1}$ in the total harvesting treatment. The growth-promoting effect of partial harvesting became more pronounced during the next 4 months. While mean biomass yield from total harvesting was 8.7 – 10.1 t ha$^{-1}$, the yield under partial harvesting was 13.7 – 16.5 t ha$^{-1}$ ($P = 0.012$). There were no significant effects of fertilization or of the interaction between fertilization and harvesting technique during this period.

Our findings confirmed that partial harvesting can enable increased harvest frequency without disturbing biomass yield. Due to the seasonal nature of feedstock supplies, stockpiling is considered necessary for production of cellulosic bioethanol. However, because the difficulty of amortizing capital costs limits commercialization of cellulosic bioethanol, added expenses for construction and maintenance of storage facilities should be avoided if possible (Richard, 2010; Kurian et al., 2013). The total harvesting system, used as the control treatment in this study, was developed by TBI with the goal of reducing temporal fluctuations in availability of feedstocks for bioethanol (NEDO, 2012). Their latest study has demonstrated that Napier grass maintains a similar level of biomass yield for approximately 4 years in the total harvesting system (personal communication). Our study demonstrated that partial harvesting can shorten the feedstock supply cycle from 4 to 2 months. Although biomass was harvested from half of the plants every 2 months, a 1-month cycle may be achieved by harvesting one quarter of the plants, or an even shorter, 2-week cycle by harvesting one eighth of the plants. Further studies are now aimed at the development of a practical harvesting system for these crops.

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**Notes:**

- **Chemical fertilizer + Total harvest**
- **Chemical fertilizer + Partial harvest**
- **Organic fertilizer + Total harvest**
- **Organic fertilizer + Partial harvest**

*Fig. 3. Changes in biomass yield of Napier grass (Pennisetum purpureum). All plants were harvested (mowed) every 4 months under the total harvesting regime; alternating sets of 4 rows were harvested every 2 months under the partial harvesting regime (see Fig. 2). Within each growth period (0 – 4, 4 – 8, 8 – 16, and 16 – 20 months after planting [MAP]), the total biomass yield from partial harvesting treatments was compared with that of the total harvesting treatments. Differences in mean biomass values between total and partial harvesting were analyzed by Student’s t-tests for 0 – 4 and 4 – 8 MAP. Two-way analysis of variance (ANOVA) was performed with fertilizer type (F) and harvesting technique (H) as main effects for values obtained at 8 – 12, 12 – 16, and 16 – 20 MAP. Notation: n.s., not significant; *, significant at $P < 0.05$.***

**Methodology:**

- **Material:**
  - A subsample of approximately 8 kg was then extracted, taken to the TBI laboratory, oven-dried at 80 °C for at least 72 h, and weighed. The mass ratio of dry to fresh matter of each subsample was used to calculate dry mass for each plot.
  - A pole (30 mm diameter × 4 m tall) to which two horizontal plates (0.15 × 0.2 m) were attached at 1 and 2 m above the soil surface was installed in each subplot. A color acetate film (35 × 20 mm) (Optleaf Y-1W, Taisei Environment & Landscape Corporation, Tokyo, Japan) was placed on each stainless-steel plate and exposed to solar radiation for 4 days month$^{-1}$. This film was impregnated with azo dyes that faded (decomposed) with exposure to sunlight. The absorbance of each film before ($D_0$) and after exposure ($D$) was determined using a portable D-Meter photometer (Taisei Corp.) based on the fading ratio ($FR$), calculated as follows: $FR = 100 \times (D/D_0)$. $FR$ is thus negatively correlated with photosynthetic photon flux density (PPFD) (Kawamura et al., 2005). Carbon dioxide concentrations were determined from daily measurements (at approximately 0900, 1200, and 1500 hours) beginning 11 MAP at three representative positions in each subplot, 1 and 2 m above the soil surface, using a portable pSense-RH CO$_2$ sensor (SenseAir, Delsbo, Sweden). Soil volumetric water contents (in soil at 0 – 0.12 m depth) were determined weekly beginning 19 MAP at 12 – 18 representative positions in each subplot using a HydroSense time-domain reflectometer (TDR) (Campbell Scientific, Logan, USA).
needed to confirm this prediction.

Partial harvesting also increased biomass yield of Napier grass. Generally, plants adjacent to field borders exhibit better growth than plants in the interior because the former experience less competition with neighbors for resources (the border effect) (Gomez and De Datta, 1971; Wang et al., 2013). Partial harvesting exposed non-harvested plants to environmental conditions similar to those at field borders; thus, more resources may have been available to those plants. We investigated the effect of partial harvesting on available light, CO₂, and soil water below the canopy (Table 1). No significant effects of fertilizer, harvesting technique, or their interaction were detected for any of these parameters, with the exception of a significant effect of harvesting technique on FR from 4 to 8 MAP and from 16 to 20 MAP. From 4 to 8 MAP, FR in the total harvesting treatment was maintained at 86.1%, while partial harvesting was associated with a significant decrease in FR (P = 0.005), to 82.9%. Conversely, from 16 to 20 MAP, while FR was consistent at 85.9 – 86.4% under partial harvesting, total harvesting decreased FR significantly (P = 0.002), to 83.8 – 84.4%. FR is highly negatively correlated with PPFD (Kawamura et al., 2005). Since there was presumably no variation in above-canopy PPFD among the experimental plots, the differences in FR below the canopy could be ascribed solely to light capture by plants. The FR measurements thus indicate that plants in partially harvested treatments intercepted more light than those in totally harvested treatments from 16 MAP, although the opposite effects of harvest treatment on light capture were observed before 8 MAP. Enhanced light capture at the later growth stage suggested that partial harvesting allowed the canopy of Napier grass to exceed that under total harvesting. The growth-promoting effect observed late in the experimental period in the partial harvest treatment was probably a result of gradual modification of the canopy architecture. However, light was the only variable that was continuously measured throughout the experimental

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Table 1. Effects of fertilizer type (chemical or organic) and harvesting technique (total or partial) on fading ratio (FR) of color acetate film, atmospheric CO₂ concentration, and volumetric soil water content measured during five growth periods.

|               | Fertilizer (F) | Harvest (H) | Months after planting (growth periods) |
|---------------|---------------|-------------|---------------------------------------|
|               |               |             | 0 – 4 | 4 – 8 | 8 – 12 | 12 – 16 | 16 – 20 |
| FR (%)        |               |             |       |       |        |         |         |
| Chemical      |               | Total       | 84.3  | 86.1  | 85.8   | 85.8    | 84.4    |
|               |               | Partial     | 83.4  | 82.9  | 85.9   | 86.1    | 85.9    |
| Organic       |               | Total       | 86.1  | 85.4  | 83.8   |        |         |
|               |               | Partial     | 85.8  | 85.5  | 86.4   |        |         |
| t-test        |               |             | n.s.  | **    |        |         |         |
| ANOVA         | F             |             | n.s.  | n.s.  | n.s.   |         |         |
|               | H             |             | n.s.  | n.s.  | **     |         |         |
|               | F × H         |             | n.s.  | n.s.  | n.s.   |         |         |
| CO₂ (ppm)     |               |             |       |       |        |         |         |
| Chemical      |               | Total       | 426   | 397   | 411    |        |         |
|               |               | Partial     | 423   | 396   | 411    |        |         |
| Organic       |               | Total       | 434   | 396   | 412    |        |         |
|               |               | Partial     | 422   | 396   | 411    |        |         |
| ANOVA         | F             |             | n.s.  | n.s.  | n.s.   |         |         |
|               | H             |             | n.s.  | n.s.  | n.s.   |         |         |
|               | F × H         |             | n.s.  | n.s.  | n.s.   |         |         |
| Soil water (m³ m⁻³) |    |             |       |       |        |         |         |
| Chemical      |               | Total       | 35.9  | 34.5  | 34.7   | 35.1    |         |
|               |               | Partial     | 35.9  | 34.5  | 34.7   | 35.1    |         |
| Organic       |               | Total       | 35.9  | 34.5  | 34.7   | 35.1    |         |
|               |               | Partial     | 35.9  | 34.5  | 34.7   | 35.1    |         |
| ANOVA         | F             |             | n.s.  | n.s.  | n.s.   |         |         |
|               | H             |             | n.s.  | n.s.  | n.s.   |         |         |
|               | F × H         |             | n.s.  | n.s.  | n.s.   |         |         |

Values are means for each growth period. Measurements of FR, atmospheric CO₂ concentration, and volumetric soil water content began at 0, 11, and 19 months after planting (MAP), respectively. Differences in mean FR values between total and partial harvesting were analyzed by Student’s t-tests for 0 – 4 and 4 – 8 MAP. Two-way analysis of variance (ANOVA) was performed on each parameter collected 8 – 12, 12 – 16, and 16 – 20 MAP with fertilizer type (F) and harvesting technique (H) as main effects. Notation: n.s., not significant; **, significant at P < 0.01.
period; measurements of CO₂ and soil water content were limited to shorter time intervals. Thus, continuous monitoring of additional environmental variables may help to elucidate the mechanisms responsible for the growth-promoting effect of partial harvesting. For example, from 12 to 16 MAP, while biomass yield decreased under total harvesting (Fig. 3) probably due to rainfall scarcity from 13 to 14 MAP (from August to September, 2012) (Fig. 1), partial harvesting significantly increased biomass yield. The partial harvest treatment might have reduced soil water loss and hence had a positive impact on plant growth under moisture deficient conditions. The continuous monitoring will provide some insights into such hypotheses.

**Conclusion**

Partial harvesting enabled increased frequency of Napier grass harvest (from every 4 to every 2 months) in Indonesia. Increased harvest frequency is expected to greatly reduce seasonal variability in feedstock supply, and thus to reduce the costs of stockpiling. This harvesting technique has the additional benefit of increasing biomass yield of Napier grass, probably as a result of increased light capture. A large-scale trial is needed to determine whether harvest frequency can be further increased without compromising the growth-promoting effect of partial harvesting.

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