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Abstract

Motivated by the agricultural industries, this paper studies the economic and environmental implications of biomass commercialization; that is, converting organic waste into a saleable product, from the perspective of a processor that uses a commodity input to produce both a commodity output and biomass. We characterize the economic value of biomass commercialization and examine how input and output spot price uncertainties affect this value. Using a model calibration, we find that lower input spot price variability or higher output spot price variability or correlation between the two spot prices increases this value for a typical palm oil mill. To measure the environmental impact we use total expected carbon emissions resulting from profit-maximizing decisions and characterize the change in total expected emissions after commercialization. Our analysis reveals that while higher biomass demand or biomass price always increases the value of biomass commercialization, these changes are not necessarily environmentally beneficial as they may increase the emissions associated with biomass commercialization. We also characterize conditions under which biomass commercialization is environmentally beneficial or harmful; that is, it leads to a reduction or an increase in the total expected emissions, respectively. In comparison with the existing understanding which does not take into account optimization of operational decisions, our analysis highlights two types of misconceptions (and characterizes the specific conditions under which they appear): (i) we would mistakenly think that biomass commercialization is environmentally beneficial when it is not, and (ii) we would mistakenly think that biomass commercialization is environmentally harmful when it is not.

Keywords: Biomass, Agriculture, Commodity, Sustainability, Emissions, Spot Price Uncertainty, Renewable Energy, Palm Oil

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1 Introduction

Global warming and climate change have created an unprecedented interest in reducing greenhouse gas (GHG) emissions, especially in energy production (Kök et al., 2016). Biomass (i.e., organic matter), a renewable energy source, plays a pivotal role in achieving this objective as it can be used as a feedstock in a bioenergy plant replacing fossil fuels to produce energy (e.g., heat, electricity). As highlighted by International Energy Agency (2018), energy produced from biomass has a significant share—50% in 2017—in the global renewable energy consumption. Our focus in this paper is on agricultural residues as biomass source. In several agricultural industries, including the oilseed industry (e.g., palm, coconut) and the sugar industry, processors convert their residues (e.g., kernel shell for the oilseed industry and bagasse for the sugar industry) into a saleable product and sell it to bioenergy plants. Commercializing agricultural residues is gaining momentum due to increasing renewable energy usage standards across the globe. For example, as seen in Table 7 of the U.S. Department of Agriculture report (USDA, 2018), Japan's import of palm kernel shells has increased nearly by ten-fold since 2013, to more than 1.13 million metric tons in 2017. This volume accounts for approximately US$125 million and according to the same report, it is expected to increase further in the near future as a result of Japan's target of providing at least 22% of its energy needs through renewable sources by 2030. Significant import volumes of palm kernel shells are also reported by several other countries, including South Korea and the U.S. (Jakarta Post, 2017). A similar increasing trend is also observed in other agricultural processing industries (see Pearson, 2016). These recent developments give rise to a need for processors to better understand the economic and environmental implications of commercializing their biomass.

On the economic implications, there is a nascent operations management literature that studies the value of converting waste stream into a saleable product albeit in the context of other waste streams such as municipal waste (Ata et al., 2012) and excess fresh produce (Lee and Tongarlak, 2017). The knowledge base developed in these papers is not directly applicable to the context of agricultural residue because agricultural processors feature unique operational characteristics. Consider, for example, the palm oil industry. Palm oil mills produce crude palm oil (a commodity output) and palm kernel shell (biomass) from fresh fruit palm bunches (a commodity input). As both the input and the output are commodities, the processors are exposed to prevailing spot prices in buying and selling these commodities and these prices exhibit considerable variability (Boyabatlı et al., 2017). Moreover, to counteract against spot price variability, palm oil mills may rely on long-term contracts for procurement and sales, as commonly observed in commodity processing industries (Boyabatlı, 2015). These unique operational characteristics play critical roles in the economic implications. In summary, to our knowledge there is no work that studies the economic value of biomass commercialization for the agricultural processor. Therefore, there is also no work that examines the effect of key factors (e.g., spot price uncertainty) on this value. Our first research objective is to fill this void.

On the environmental implications, converting waste into a saleable product is commonly perceived to be environmentally beneficial because it leads to a reduction in GHG emissions owing to lower landfill and replacement of fossil fuel energy source in downstream power plant (Ata et al., 2012). This perception has been one of the key driving forces behind the increasing popularity of biomass commercialization in agricultural processing industries (see, for example, Pearson, 2016). A stream of papers in the industrial ecology literature has refined this perception by highlighting that biomass commercialization requires additional processing (e.g., de-fibring) and transportation activities which may create significant emissions (Iakovou et al., 2010). Although these papers provide a detailed environmental analysis, as also highlighted by Lee (2012), they do not take into account the optimization of operational decisions. Therefore, they fail to incorporate the emissions resulting from the changes in operational decisions (e.g., input procurement and processing volumes, production volumes for each output including biomass) after commercialization. In summary, it is an open question under which conditions biomass commercialization is environmentally beneficial. Moreover, it is also an open question how the environmental footprint of biomass commercialization is affected by biomass market characteristics. Our second research objective is to develop this knowledge base.

To achieve these objectives, we propose an analytical model that captures the most important operational characteristics of an agri-processor in practice. This model is motivated by our interactions with a coconut processor who aims to commercialize its coconut shell. The firm (processor) procures a commodity input and produces a commodity output and biomass in fixed proportions so as to maximize its expected profit in a single selling season. The input is procured from an input spot market. The output can be sold to two channels, an output spot market and a demand that is characterized by a fixed-price fixed-volume sales contract. The output can also be procured from the spot market to satisfy the demand. If commercialized, the biomass is sold to demand that is also characterized by a fixed-price fixed-volume sales contract. To commercialize its biomass, the firm incurs a fixed cost associated with upfront investments in storage, transportation, and processing assets. We model the firm's decisions as a three-stage problem. In the first stage, the firm makes biomass commercialization decision in the face of the input and the output spot price uncertainties. In the second stage, after the input spot price is realized, the firm makes input spot procurement and processing decisions under output spot price uncertainty. If biomass was not commercialized in the first stage, then it goes to landfill after processing in this stage. In the third stage, after the output spot price is realized, the firm makes output selling and spot procurement decisions as well as biomass selling decision if it was commercialized in the first stage.

In achieving our research objectives, we complement our structural analysis with numerical analysis based on realistic instances. To this end, we calibrate our model to represent a typical palm oil mill located in Malaysia (which accounts for 28.1% of world palm oil production in 2018 (USDA, 2019)) selling its biomass to a power plant in Japan to substitute coal in energy production. We use publicly available data from the Malaysian Palm Oil Board, complemented by the data obtained from the extant literature. Our main findings can be summarized as follows.

Economic Implications. Intuitively, the firm optimally commercializes its biomass if the fixed cost is smaller than the difference between the optimal expected profits after and before commercialization which we denote as the value of biomass commercialization. We show that this value can be characterized by the product of biomass demand and an expected biomass margin which captures the effects of input and output spot price uncertainties. We find that the effects of input and output spot price variabilities on the value of biomass commercialization crucially depend on the spot price correlation. In particular, when the correlation is negative, lower input or output spot price variability always increases this value. When the correlation is positive, lower input or output spot price variability increases the value of biomass commercialization only when this variability is sufficiently high; otherwise, higher input or output spot variability increases the value. We also find that higher spot price correlation increases the value of biomass commercialization when this correlation is negative or when this correlation is positive but sufficiently low. Otherwise, lower correlation increases the value of biomass commercialization. Based on our model calibration, we find that lower input spot price variability or higher output spot price variability or correlation increases the value of biomass commercialization for a typical palm oil mill.

Environmental Implications. To measure the environmental impact we use total expected carbon emissions resulting from profit-maximizing decisions and characterize the change in total expected emissions after commercialization. We examine how biomass demand and biomass price impact this emission change. Our analysis reveals that while higher biomass demand or biomass price always increases the value of biomass commercialization (and hence, promotes energy production from biomass), these changes are not necessarily environmentally beneficial as they may increase the emissions associated with biomass commercialization. Using our model calibration, we find that while a higher biomass demand is always environmentally beneficial for a typical palm oil mill, a higher biomass price is environmentally beneficial only when biomass demand is sufficiently low; otherwise, a lower biomass price is environmentally beneficial.

We next examine conditions under which biomass commercialization is environmentally beneficial or harmful; that is, it leads to a reduction or an increase in the total expected emissions, respectively. We identify biomass demand and biomass selling emission intensity (which is given by the unit emission associated with additional processing, transportation, and burning activities less the unit emission saving obtained by burning biomass instead of fossil fuel) as the two main drivers of this assessment. In particular, we establish two biomass selling emission intensity thresholds where (i) biomass commercialization is environmentally beneficial when this emission intensity is lower than the smaller threshold; and (ii) biomass commercialization is environmentally harmful when this emission intensity is higher than the larger threshold. When the biomass emission intensity is between the two thresholds, biomass commercialization is environmentally beneficial only when biomass demand is lower than a demand threshold; otherwise, it is environmentally harmful. Our environmental assessment characterization refines the existing understanding (both in practice and in the industrial ecology literature) that does not take into account optimization of operational decisions after biomass commercialization. In comparison with the existing understanding, our analysis highlights two types of misconceptions (and characterizes the specific conditions under which they appear): (i) we would mistakenly think that biomass commercialization is environmentally beneficial when it is not, and (ii) we would mistakenly think that biomass commercialization is environmentally harmful when it is not.

The remainder of this paper is organized as follows. Section 2 surveys the related literature and discusses our contribution. We examine the economic and environmental impacts of biomass commercialization in Section 3 and Section 4, respectively. Section 5 provides a practical application in the context of the palm oil industry. Section 6 concludes with a discussion of the limitations of our analysis and future research directions.

2 Literature Review

Our paper's main contribution is to the emerging operations management (OM) literature on by-product synergy. The papers in this literature study the economic implications of converting waste stream into a saleable product while considering the operational characteristics of specific processing environments. For example, Ata et al. (2012) study a waste-to-energy (WTE) firm that collects and processes municipal waste to generate electricity. Lee and Tongarlak (2017) focus on a retail grocer setting and examine the value of using unsold fresh produce to make prepared food items. More recently, Ata et al. (2019) examine another type of by-product synergy in the context of agricultural industries: gleaning operations that deal with collecting unharvested crops on the farmlands to be used in food assistance programs. Different from these papers, Sunar and Plambeck (2016) consider the interplay between by-product synergy and costs associated with the GHG emissions. They model the strategic interaction between a seller and a buyer located in different countries. The buyer incurs a cost associated with the GHG emissions of the seller's production activities due to border adjustment. They examine how seller's decision of converting its waste stream into a saleable product has an impact on buyer's operations.

Closest to our work, Lee (2012) studies the economic and environmental implications of converting waste stream into a saleable product in the context of the chemicals and steel manufacturing industries. Motivated by these industries, she focuses on a deterministic model that optimizes production volumes for the main output and the by-product (waste) while considering waste disposal cost, virgin raw material cost and competition in the by-product market. Motivated by our own experience with a coconut processor commercializing its waste stream, we focus on an exogenously given fixed-price fixed-volume sales contract for biomass and do not consider competition in the biomass market. Instead, we consider other important characteristics of agricultural processors (e.g., input and output spot price uncertainties). On the environmental implications, Lee (2012) presents a conceptual framework and makes the critical observation that waste conversion decreases the processing cost which, in turn, increases the production volumes for the outputs (including waste). She conjectures that the increase in total volume could lead to a harmful impact on the environment. Our paper builds on this conjecture and identifies conditions under which biomass commercialization leads to a beneficial or harmful impact on the environment.

Environmental implications of biomass commercialization has also received considerable attention from the industrial ecology literature. We refer the reader to Iakovou et al. (2010) for a comprehensive review. As highlighted by Lee and Tongarlak (2017), the papers in this literature examine the environmental impact without considering the optimization of operations but provide a detailed treatment of GHG emissions related to biomass commercialization. For example, Damen and Faaij (2006) study the emissions associated with using palm kernel shells (PKS) to substitute coal while considering the emissions associated with production, transportation, and consumption of PKS. They neither consider optimization of PKS operations nor take into account uncertainties. Our environmental analysis is motivated by the papers in this literature as it accounts for all emission categories. More importantly, our environmental analysis is based on a more detailed operational framework that not only considers the optimization of processor's decisions but also takes into account the relevant uncertainties. We also provide a model calibration to examine the environmental implications of PKS commercialization for substituting coal.

Our paper is also related to the growing OM literature on commodity processing. As reviewed by Goel and Tanrisever (2017), the papers in this literature capture idiosyncratic features of commodity processors in a variety of industries and examine the economic implications of a broad range of operational features, including processing-yield improving technology (de Zegher et al., 2017), procurement flexibility (Martínez-de Albéniz and Simchi-Levi, 2005), and responsive product pricing (Boyabatlı et al., 2011). Within this literature, our work is closely related to the stream of papers that considers input and output (spot) price uncertainties. In this stream, Plambeck and Taylor (2013) study process improvement investment decision in a clean-tech manufacturing setting; Dong et al. (2014) study the value of operational flexibility in a petroleum refinery; Boyabatlı et al. (2017) study the optimal capacity investment decision of an oilseed processor; and Goel and Tanrisever (2017) examine the optimal sales contract choice of a biofuel processor. Similar to these papers, we capture idiosyncratic features of processors in a particular industry (agriculture). Different from these papers, we focus on biomass commercialization (another operational feature) and study not only the economic implications but also the environmental implications.

This paper also relates to the rapidly growing literature on sustainable operations—see, Drake and Spinler (2013) for a recent review—due to its focus on the environment. Within this literature, our work is more closely related to the stream of papers that examine the environmental implications of operational decisions that are made by profit-maximizing firms without considering their environmental impact (see, for example, Agrawal et al., 2012, Avcı et al., 2014, and Kök et al., 2016). Kök et al. (2016) is closer to our work because of its focus on energy production. They study the economic and environmental implications of using different electricity pricing policies—peak versus flat pricing—from the perspective of a utility firm. They solve for the optimal profit-maximizing operational decisions and investigate the environmental implications by comparing the total expected carbon emissions of an optimally designed utility under each pricing policy. We study the economic and environmental implications of biomass commercialization from the perspective of an agri-processor. We solve for the optimal profit-maximizing operational decisions and investigate the environmental implications by making a comparison between the total expected carbon emissions of an optimally designed processor before and after biomass commercialization.

3 Economic Implications of Biomass Commercialization

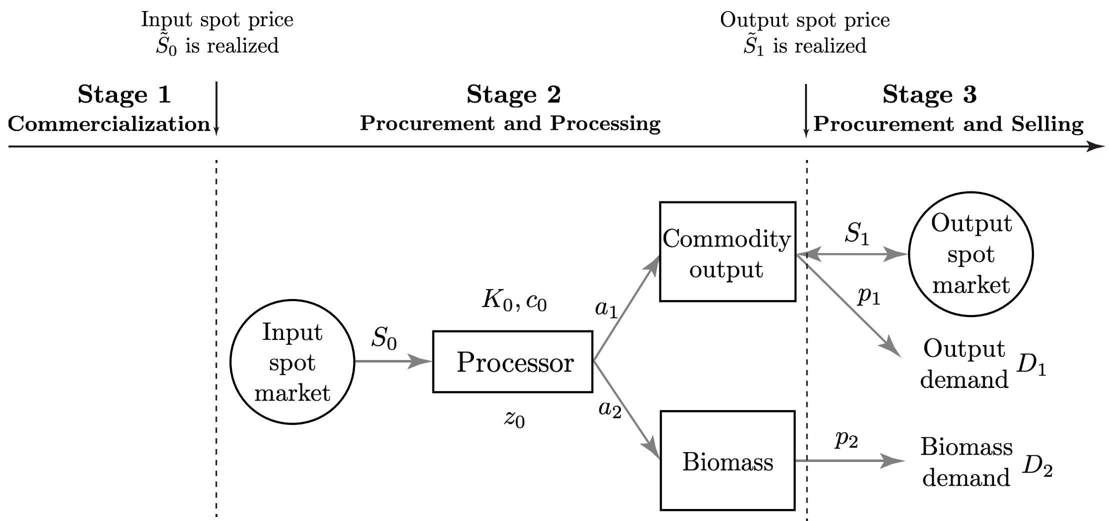
In this section, we examine how a profit-maximizing processor (denoted as "firm" hereafter) should make its biomass commercialization decision. Section 3.1 describes our economic model. Section 3.2 derives the firm's optimal strategy whereas Section 3.3 investigates the effects of input and output spot price uncertainties on the firm's biomass commercialization decision.

3.1 Economic Model Description and Assumptions

The following mathematical representation is used throughout the text: a realization of the random variable $\tilde{y}$ is denoted by y. The expectation operator, probability, and indicator function are denoted by $\mathbb{E}$, $Pr(\cdot)$, and $\chi(\cdot)$, respectively. We use $(u)^+ = \max(u, 0)$. Monotonic relations are used in the weak sense unless otherwise stated. Subscript 0 denotes input-related variables, while subscript 1 and 2 denote the same related to the commodity output and biomass, respectively. The optimal decisions and performance measures evaluated at the optimal solution are denoted by * for the model in the presence of biomass and by ^{bc} (which stands for *b*efore *c*ommercialization) for the model in the absence of biomass. All the proofs are relegated to Section B of the online appendix.

We consider a firm that procures and processes a commodity input to produce and sell a commodity output (denoted as "output" hereafter) and biomass in fixed proportions so as to maximize its expected profit in a single selling season. We model the firm's decisions as a three-stage problem. In stage 1, the firm makes biomass commercialization decision under input and output spot price uncertainties. In stage 2, after the input spot price is realized, the firm makes input spot procurement and processing decisions under output spot price uncertainty. In stage 3, after the output spot price is realized, the firm makes output selling and spot procurement decisions as well as biomass selling decision if it was commercialized in stage 1. Figure 1 illustrates the operational framework considered in the model focusing on the case where biomass is commercialized.

Figure 1: Firm's Operational Framework After Biomass Commercialization



Note. Here, the firm has already decided to commercialize its biomass in stage 1 by incurring a fixed cost F. If biomass is not commercialized, then it goes to landfill after processing in stage 2. In this case, the firm's operational framework can be obtained by removing biomass demand from the illustration.

Let $\tilde{S}_0$ and $\tilde{S}_1$ denote the uncertain input and output spot price, respectively. We assume $(\tilde{S}_0, \tilde{S}_1)$ to follow a bivariate distribution with a positive support, bounded mean (μ_0, μ_1) with covariance matrix $\mathbf{\Sigma}$, where $\mathbf{\Sigma}_{00} = \sigma_0^2$, $\mathbf{\Sigma}_{11} = \sigma_1^2$, $\mathbf{\Sigma}_{01} = \mathbf{\Sigma}_{10} = \rho\sigma_0\sigma_1$, and ρ denotes the correlation coefficient. We use $\mu_{1|0}(S_0)$ to denote the expected output spot price conditional on the realized input spot price (i.e., $\mathbb{E}[\tilde{S}_1|S_0]$). While our characterizations of the optimal decisions in Section 3.2 and our characterization of the environmental assessment of biomass commercialization in Section 4.3 hold for a general bivariate distribution with specified properties, to be able to study the effects of input and output spot price uncertainties we make a further distributional assumption throughout the paper. In particular, we assume $(\tilde{S}_0, \tilde{S}_1)$ to follow a bivariate Normal distribution. In this case, the conditional distribution of output spot price $\tilde{S}_1$ for a given input spot price S_0 is also Normal with mean $\mu_{1|0}(S_0) = \mu_1 + \rho\frac{\sigma_1}{\sigma_0}(S_0 - \mu_0)$ and variance $\sigma_1^2(1-\rho^2)$.

In stage 1, the firm makes its biomass commercialization decision. In practice, biomass commercialization involves significant fixed costs that are associated with upfront investments in preconditioning machines (for removing impurities from the residue and eliminating moisture), storage facility, and transportation assets (for example, conveyor belt or crane for transportation out of the storage facility). Let F denote these fixed costs. Because these upfront investments take significant amount of time we assume that the firm makes its biomass commercialization decision before processing; that is, this decision is made facing input and output spot price uncertainties. In this stage, the firm does not incur the fixed cost F if biomass is not commercialized.

In stage 2, input spot price S_0 is realized. In this stage, facing the output spot price uncertainty, the firm decides its processing volume and sources this volume from the input spot market at the prevailing input spot price. Let z_0 denote the processing volume. We consider a processing capacity $K_0 > 0$ and a unit processing cost $c_0 > 0$. We assume that each unit of processed input yields a_1 and a_2 units of output and biomass, respectively where $a_1 + a_2 \leq 1$. If biomass was not commercialized in stage 1, then it goes to landfill after processing in this stage.

In stage 3, output spot price S_1 is realized and the firm generates revenues using $a_1 z_0$ units of output and $a_2 z_0$ units of biomass produced. We consider two channels for output sale, a spot market and a demand which is characterized by an exogenously given fixed-price fixed-volume sales contract. In particular, we assume that the output is sold at a unit price $p_1 > 0$ to satisfy demand $D_1 > 0$, and any output produced beyond this demand is sold to the spot market at the prevailing spot price S_1. The output can also be procured from the spot market at the prevailing price S_1 to satisfy the demand when the output produced is not sufficient. Throughout the paper, we assume $p_1 = \mu_1$ to indicate the fair pricing of the sales contract for the firm and its buyer. Although we do not model the signing of the sales contract (which is assumed to happen before the firm's biomass commercialization decision), $p_1 = \mu_1$ is arguably the most realistic case when the firm's and the buyer's incentives are considered because the same output can be sourced from the spot market at the prevailing spot price S_1 in this stage. That being said, our economic analysis in this section and our environmental analysis in the next section can easily be generalized to any $p_1 > 0$.

For biomass sale, we consider a demand channel which is characterized by a similar sales contract where the firm can sell up to biomass demand $D_2 > 0$ at a unit biomass price $p_2 > 0$. We note that if the firm incurs an additional cost for selling its biomass (e.g., cost for de-fibring or transportation), then p_2 denotes the effective biomass price after this additional cost is deducted. Moreover, we use D_2 to denote the satisfiable portion of the biomass demand; that is, when the actual biomass demand is larger than $a_2 K_0$ (which is the maximum production volume for biomass), we have $D_2 = a_2 K_0$.

Discussion about the modelling choices: Our parsimonious model is designed to capture the most important operational characteristics of agricultural processors in practice. To this end, following features collectively constitute to the simplest model that represents the processor's business environment in a realistic fashion: (i) existence of input and output spot price uncertainties as both input and output are commodities, (ii) processing of a single input giving rise to an output and biomass in proportions, (iii) a procurement channel for the input (as captured by the input spot market) and a sales channel for the output (as captured by the output spot market), and (iv) a sales channel for the biomass (as captured by the biomass demand). Besides these features, we also consider a contract (as denoted by demand D_1) as another sales channel for the output. In practice, processors often use such sales contracts to counteract against commodity spot price uncertainty (see, for example, Goel and Tanrisever, 2017). Besides its practical relevance, we consider $D_1 > 0$ to showcase its significance for biomass commercialization; specifically, for its environmental assessment. Even when D_1 has no effect on the economic value of biomass commercialization (which is the case in our model as we formally demonstrate in Section 3.2), it has a significant effect on the environmental implications of biomass commercialization (as we formally demonstrate in Section 4). Throughout the paper, we assume $D_1 \leq a_1 K_0$ where $a_1 K_0$ is the maximum production volume for the output. This assumption arguably represents the most realistic case because otherwise, demand is so large that it can never be fully satisfied through processing.

3.2 The Optimal Solution for the Firm's Decisions

In this section, we first describe the optimal solution for the firm's stage 2 and stage 3 decisions considering the case where biomass is commercialized. The optimal decisions when biomass is not commercialized can be obtained as a special case by setting $D_2 = 0$. We then characterize the firm's optimal biomass commercialization decision by making a comparison between the optimal expected profits with and without biomass. We solve the firm's problem using backward induction.

In stage 2, the firm processed z_0 units of input that gave rise to $a_1 z_0$ units of output and $a_2 z_0$ units of biomass. In stage 3, the firm observes the output spot price realization S_1. In this stage, the firm uses $a_1 z_0$ units of available output to satisfy its demand D_1. For the unsatisfied demand over the available output (i.e., $(D_1 - a_1 z_0)^+$), the firm procures from the output spot market to satisfy this demand. The firm optimally sells the available output beyond demand (i.e., $(a_1 z_0 - D_1)^+$) to the spot market. In this stage, the firm also uses $a_2 z_0$ units of available biomass to satisfy its demand D_2. As a result, firm's optimal profit in this stage is given by

$$\min(a_1 z_0, D_1) p_1 + (D_1 - a_1 z_0)^+ (p_1 - S_1) + (a_1 z_0 - D_1)^+ S_1 + \min(a_2 z_0, D_2) p_2. \tag{1}$$

Using $p_1 = \mu_1$ (which holds by our assumption) and the identities $\min(a_1 z_0, D_1) = a_1 z_0 - (a_1 z_0 - D_1)^+$ and $a_1 z_0 = D_1 + (a_1 z_0 - D_1)^+ - (D_1 - a_1 z_0)^+$, the firm's stage 3 optimal profit can be rewritten as $a_1 z_0 S_1 + D_1(\mu_1 - S_1) + \min(a_2 z_0, D_2) p_2$.

In stage 2, the firm observes the input spot price realization S_0. In this stage, constrained by the processing capacity K_0, the firm decides the processing volume $z_0 \geq 0$ (and sources this volume from the input spot market) to maximize the stage 2 expected profit

$$\Pi(z_0; S_0, \tilde{S}_1) = -(S_0 + c_0)z_0 + a_1 z_0 \mu_{1|0}(S_0) + D_1(\mu_1 - \mu_{1|0}(S_0)) + \min(a_2 z_0, D_2)p_2, \tag{2}$$

where $\mu_{1|0}(S_0) = \mathbb{E}[\tilde{S}_1|S_0]$ is the expected output spot price $\tilde{S}_1$ conditional on the realized input spot price S_0 at stage 2. In (2), the first term denotes the input procurement and processing costs whereas the remaining terms denote the expected profit obtained as a result of the firm's optimal stage 3 decisions as discussed above.

Proposition 1 characterizes the optimal processing volume z_0^* that maximizes $\Pi(z_0; S_0, \tilde{S}_1)$.

Proposition 1 *Given input spot price realization S_0, the optimal processing volume z_0^* is characterized by*

$$z_0^* = \begin{cases} 0 & \text{if} \quad a_1\mu_{1|0}(S_0) + a_2 p_2 - c_0 \leq S_0, \\ \frac{D_2}{a_2} & \text{if} \quad a_1\mu_{1|0}(S_0) - c_0 \leq S_0 < a_1\mu_{1|0}(S_0) + a_2 p_2 - c_0, \\ K_0 & \text{if} \quad S_0 < a_1\mu_{1|0}(S_0) - c_0. \end{cases} \tag{3}$$

The optimal processing volume is determined by comparing the relevant unit processing margin with the input procurement cost S_0 at this stage. The unit processing margin takes two forms based on the availability of unsatisfied biomass demand. In particular, $a_1\mu_{1|0}(S_0) + a_2 p_2 - c_0$ and $a_1\mu_{1|0}(S_0) - c_0$ are unit processing margins when there is unsatisfied biomass demand and no unsatisfied biomass demand, respectively. When $a_1\mu_{1|0}(S_0) - c_0 \leq S_0 < a_1\mu_{1|0}(S_0) + a_2 p_2 - c_0$, it is profitable to process only when there is unsatisfied biomass demand, and thus, $z_0^* = \frac{D_2}{a_2}$. When $a_1\mu_{1|0}(S_0) + a_2 p_2 - c_0 \leq S_0$, it is not profitable to process even in the presence of unsatisfied biomass demand, and thus, the firm optimally does not process. When $S_0 < a_1\mu_{1|0}(S_0) - c_0$, it is profitable to process even in the absence of unsatisfied biomass demand, and thus, the firm optimally processes up to processing capacity K_0.

In stage 1, facing input and output spot price uncertainties, the firm decides whether to commercialize its biomass (while incurring a fixed cost F if biomass is commercialized) so as to maximize its expected profit. By substituting z_0^* from Proposition 1 in the stage 2 profit $\Pi(z_0; S_0, \tilde{S}_1)$ as given in (2) and using the identity $\mathbb{E}[\mu_{1|0}(\tilde{S}_0)] = \mu_1$, the firm's optimal expected profit after commercialization without considering the fixed cost F can be written as

$$V^* = \mathbb{E}\left[\left(a_1\mu_{1|0}(\tilde{S}_0) + a_2p_2 - c_0 - \tilde{S}_0\right)^+\right]\frac{D_2}{a_2} + \mathbb{E}\left[\left(a_1\mu_{1|0}(\tilde{S}_0) - c_0 - \tilde{S}_0\right)^+\right]\left(K_0 - \frac{D_2}{a_2}\right). \tag{4}$$

In (4), the two terms are characterized by the product of a specific input volume and its relevant unit expected processing margin (which incorporates the conditions under which processing is profitable as characterized by Proposition 1). The expected processing margin of first D_2/a_2 units of input involves the biomass revenue a_2p_2 whereas the same for the remaining $K_0 - D_2/a_2$ units does not. When biomass is not commercialized, the firm's optimal processing decision z_0^{bc} at stage 2 and the optimal expected profit V^{bc} at stage 1 can be obtained from our characterizations in (3) and (4), respectively by setting $D_2 = 0$.

In summary, when the firm decides to commercialize its biomass, the firm's optimal expected profit at stage 1 is $V^* - F$; otherwise, it is V^{bc}. Therefore, the firm optimally commercializes its biomass only if the fixed cost is smaller than the change in the optimal expected profit due to commercialization, i.e., $F < V^* - V^{bc}$. We define $\Delta V = V^* - V^{bc}$ and denote it as the value of biomass commercialization. Proposition 2 characterizes ΔV.

Proposition 2 *The value of biomass commercialization is given by $\Delta V = \Lambda D_2$ where*

$$\Lambda = \frac{1}{a_2}\mathbb{E}\left[\left(a_2p_2 - \left(\tilde{S}_0 + c_0 - a_1\mu_{1|0}(\tilde{S}_0)\right)^+\right)^+\right]. \tag{5}$$

The value of biomass commercialization is characterized by the product of biomass demand D_2 and Λ which can be interpreted as the expected biomass margin at stage 1. This expected margin is characterized based on three different forms of biomass margin at stage 2 resulting from three different processing scenarios. In particular, when processing is profitable even in the absence of biomass at stage 2 (i.e., $a_1\mu_{1|0}(S_0) - S_0 - c_0 > 0$), the waste stream is already available, and hence, the biomass margin is p_2. When processing is not profitable even in the presence of biomass at stage 2 (i.e., $a_2p_2 + a_1\mu_{1|0}(S_0) - S_0 - c_0 \leq 0$), there is no processing and the biomass margin is 0. Otherwise (i.e., $a_1\mu_{1|0}(S_0) - S_0 - c_0 \leq 0 < a_2p_2 + a_1\mu_{1|0}(S_0) - S_0 - c_0$), biomass commercialization makes the processing profitable and the biomass margin is $p_2 - \frac{S_0 + c_0 - a_1\mu_{1|0}(S_0)}{a_2}$. Combining the biomass margins from these three scenarios at stage 2 leads to the expected biomass margin Λ expression in (5).

3.3 Effects of Input and Output Spot Price Uncertainties

In this section, we investigate the effects of input and output spot price uncertainties on the firm's biomass commercialization decision. To this end, we conduct sensitivity analyses to study the effects of spot price correlation (ρ) and input and output spot price variabilities (σ_0 and σ_1, respectively) on the value of biomass commercialization ΔV. When the change in any of these parameters increase ΔV, we conclude that this change incents the firm to commercialize its biomass. Throughout this section, to eliminate unrealistic cases, we assume $a_1\mu_1 - \mu_0 - c_0 > 0$; that is, the firm has a profitable business on expectation before commercialization decision is made at stage 1. This is a reasonable assumption for the palm oil industry as we empirically demonstrate in Section 5.

As follows from Proposition 2, input and output spot price uncertainties impact ΔV through the expected biomass margin Λ given in (5). Using $\mu_{1|0}(S_0) = \mu_1 + \rho\frac{\sigma_1}{\sigma_0}(S_0 - \mu_0)$ for bivariate Normal $(\tilde{S}_0, \tilde{S}_1)$, we obtain

$$\Lambda = \frac{1}{a_2}\mathbb{E}[(a_2 p_2 - (\tilde{X})^+)^+] \text{ where } \tilde{X} = (1 - a_1\rho\frac{\sigma_1}{\sigma_0})\tilde{S}_0 + c_0 - a_1(\mu_1 - \rho\frac{\sigma_1}{\sigma_0}\mu_0).$$

Here, $(\tilde{X})^+$ can be interpreted as the marginal production cost of biomass. It follows that $\tilde{X}$ is Normally distributed with mean $\mu_X = c_0 + \mu_0 - a_1\mu_1$ and standard deviation $\sigma_X = |\sigma_0 - a_1\rho\sigma_1|$ where $|\cdot|$ denotes the absolute value. Because $\mu_X < 0$ by our assumption, it can be proven that the effects of ρ, σ_0, and σ_1 on ΔV can be explained based on the opposite of how the expected marginal production cost $\mathbb{E}[(\tilde{X})^+]$ changes in these parameters. It is well-known that this expectation increases in σ_X because while high X realizations are beneficial, low X realizations are inconsequential due to considering only positive values. *In summary, the impacts of ρ, σ_0, and σ_1 on ΔV can be explained based on the opposite of how $\sigma_X = |\sigma_0 - a_1\rho\sigma_1|$ changes in these parameters.*

The impacts of σ_0 and σ_1 critically depend on the spot price correlation ρ because this correlation measures the effect of the input spot price $\tilde{S}_0$ that is realized at stage 2 on the output spot price $\tilde{S}_1$ that is realized at stage 3. In the special case of $\rho = 0$ (i.e., when $\tilde{S}_0$ and $\tilde{S}_1$ are independent), there is no such effect. In this case, because $\mu_{1|0}(S_0) = \mu_1$ for all S_0 realizations we have $\tilde{X} = \tilde{S}_0 + c_0 - a_1\mu_1$ and $\sigma_X = \sigma_0$. Therefore, ΔV is only impacted by σ_0 as illustrated next.

Proposition 3 *Assume $\rho = 0$. We obtain $\frac{\partial \Delta V}{\partial \sigma_0} < 0$ and $\frac{\partial \Delta V}{\partial \sigma_1} = 0$.*

Because $\sigma_X = \sigma_0$, as σ_0 increases, σ_X also increases, and thus, ΔV decreases.

When $\rho \neq 0$, input spot price realization at stage 2 has an effect on the output spot price uncertainty. We first examine the case where input and output spot prices are negatively correlated.

Proposition 4 *Assume $\rho < 0$. We obtain (i) $\frac{\partial \Delta V}{\partial \rho} > 0$; (ii) $\frac{\partial \Delta V}{\partial \sigma_0} < 0$; (iii) $\frac{\partial \Delta V}{\partial \sigma_1} < 0$.*

When $\rho < 0$, we have $\sigma_0 - a_1\rho\sigma_1 > 0$ for any σ_0 and σ_1, and thus, $\sigma_X = \sigma_0 - a_1\rho\sigma_1$. Therefore, higher ρ or lower σ_0 or lower σ_1 decreases σ_X, and thus, increases ΔV.

When the input and output spot prices are positively correlated, the impacts of ρ, σ_0, and σ_1 on ΔV are more nuanced as illustrated next.

Proposition 5 *Assume $\rho > 0$. When $\frac{a_1\sigma_1\rho}{\sigma_0} = 1$, ΔV is independent of ρ, σ_0, and σ_1. Otherwise, (i.e., $\frac{a_1\sigma_1\rho}{\sigma_0} \neq 1$), we obtain*

(i) $\frac{\partial \Delta V}{\partial \rho} > 0$ if $\rho < \min\left(\frac{\sigma_0}{a_1\sigma_1}, 1\right)$ and $\frac{\partial \Delta V}{\partial \rho} < 0$ if $\rho > \min\left(\frac{\sigma_0}{a_1\sigma_1}, 1\right)$;

(ii) $\frac{\partial \Delta V}{\partial \sigma_0} > 0$ if $\sigma_0 < a_1\sigma_1\rho$ and $\frac{\partial \Delta V}{\partial \sigma_0} < 0$ if $\sigma_0 > a_1\sigma_1\rho$;

(iii) $\frac{\partial \Delta V}{\partial \sigma_1} > 0$ if $\sigma_1 < \frac{\sigma_0}{a_1\rho}$ and $\frac{\partial \Delta V}{\partial \sigma_1} < 0$ if $\sigma_1 > \frac{\sigma_0}{a_1\rho}$.

When ρ, σ_0, and σ_1 are such that $\frac{a_1\sigma_1\rho}{\sigma_0} = 1$, we have $\sigma_X = 0$; that is, the marginal production cost $(\tilde{X})^+$ does not have any uncertainty. In this case, because $\mu_X = c_0 + \mu_0 - a_1\mu_1 < 0$ by assumption, $(X)^+ = 0$ and the value of biomass commercialization attains its maximum; that is, $\Delta V = p_2 D_2$. When ρ, σ_0, and σ_1 are such that $\frac{a_1\sigma_1\rho}{\sigma_0} \neq 1$, we have $\sigma_X > 0$. In this case, the impacts of ρ, σ_0, and σ_1 on ΔV are non-monotonic because their impacts on $\sigma_X = |\sigma_0 - a_1\rho\sigma_1|$ are non-monotonic. In particular, when $\frac{a_1\sigma_1\rho}{\sigma_0} < 1$, we have $\sigma_X = \sigma_0 - a_1\rho\sigma_1$ and lower ρ or higher σ_0 or lower σ_1 increases σ_X, and thus, decreases ΔV. When $\frac{a_1\sigma_1\rho}{\sigma_0} > 1$, we have $\sigma_X = a_1\rho\sigma_1 - \sigma_0$ and higher ρ or lower σ_0 or higher σ_1 increases σ_X, and thus, decreases ΔV. Combining these two cases establish the sensitivity results associated with ρ, σ_0, and σ_1 presented in Proposition 5.

Our results in this section have important practical implications for processors in agricultural industries. In these industries, input and output are commodities and their spot prices are highly uncertain owing to a variety of uncontrollable factors including weather conditions, macroeconomic conditions, and government policies. It is important for a processor to understand how input and output spot price uncertainties impact its investment decisions including its biomass commercialization decision. Based on our analysis, we provide the following managerial insights that showcase under what conditions changes in input and output spot price uncertainties increase the value of biomass commercialization, and thus, incent the firm to commercialize its biomass:

(1) The impacts of input and output spot price variabilities on biomass commercialization decision crucially depend on the spot price correlation. In particular, when this correlation is

negative, lower input or output spot price variability always incents the firm to commercialize its biomass. When this correlation is positive, lower input or output spot price variability incents the firm to commercialize its biomass only when this variability is sufficiently high; otherwise, higher input or output spot variability incents the firm to commercialize its biomass. Our model calibration in Section 5 demonstrates that input and output spot prices are positively correlated for a typical palm processor in Malaysia. Moreover, we also find $\frac{a_1\sigma_1\rho}{\sigma_0} < 1$ in our model calibration. Therefore, lower input spot price variability and higher output spot price variability incent a typical palm processor to commercialize its biomass.

(2) Higher spot price correlation incents the firm to commercialize its biomass when this correlation is negative or when this correlation is positive but sufficiently low. Otherwise, lower correlation incents the firm to commercialize its biomass. Our model calibration in Section 5 suggests that higher spot price correlation incents a typical palm processor to commercialize its biomass.

4 Environmental Implications of Biomass Commercialization

In this section, we examine the impact of firm's biomass commercialization decision on the environment. Throughout this section, we assume $\frac{a_1\sigma_1\rho}{\sigma_0} \neq 1$ so that the value of biomass commercialization ΔV is not independent of input and output spot price uncertainties. We also assume that this value is larger than the fixed cost F such that the firm optimally commercializes its biomass. Section 4.1 describes our environmental model and demonstrates how we capture the environmental footprint of biomass commercialization. Section 4.2 examines how biomass market characteristics (biomass demand and biomass price) impact this environmental footprint. Section 4.3 characterizes the conditions under which biomass commercialization is environmentally beneficial or harmful.

4.1 Environmental Model Description

In line with the industry practice and the academic literature (see, for example, Kök et al., 2016), we use carbon emissions (hereafter, "emissions") to measure the environmental impact and calculate the total expected emissions resulting from profit-maximizing decisions before and after biomass commercialization. As customary in the literature, we assume a linear emission structure and define a unit emission intensity parameter for firm's relevant activities. All emission intensity parameters are in units of kg CO_2/mt; that is, kilogram of carbon dioxide per metric ton (equal to 1,000 kg).

Let $e_0^p > 0$ denote the *processing emission intensity* which accounts for the emissions associated with (i) energy consumption during processing, (ii) sourcing of each input delivered to the firm, and (iii) other by-products (for example, emissions related to disposal of palm oil mill effluent). For (ii), we consider emissions from production (growing) of the input and its transportation to the firm. For biomass, paralleling the environmental impact discussed in practice (Ata et al., 2012), we define two emission parameters. For unsold biomass, we define $e_2^l > 0$ as the *landfill emission intensity* which captures the emissions associated with release of methane gas as a result of anaerobic decomposition. For biomass that is sold, we define e_2^s as the *biomass selling emission intensity* which accounts for the emissions associated with additional processing (e.g., de-fibring), transportation to the bioenergy plant, and usage—that is, emissions associated with burning of biomass less the emission savings obtained by substituting fossil fuel for energy production. Although this intensity parameter is unrestricted in sign, it takes positive values in realistic cases as empirically verified in Section 5. For the output, we also define two emission parameters. For the output sold, $e_1^s > 0$ denotes the *output selling emission intensity* which captures emissions associated with transportation to the buyer (e.g., refinery) and usage (e.g., refining). We assume that this emission intensity is the same for output sold to the spot market and output used to satisfy demand. This is a reasonable assumption when both outputs are sold to nearby buyers. For the output purchased from the spot market to satisfy demand, $e_1^b > 0$ denotes the *output buying emission intensity* which captures the emissions associated with production (which include all emissions incurred during the production of this output in another firm) and transportation to the firm.

We now characterize the emissions associated with the firm's optimal decisions using backward induction considering the case where biomass is commercialized. In stage 3, as follows from (1), the firm generates the following total emissions at the optimal solution:

$$e_1^s \min(a_1 z_0^*, D_1) + e_1^s (a_1 z_0^* - D_1)^+ + (e_1^b + e_1^s)(D_1 - a_1 z_0^*)^+ + e_2^s \min(a_2 z_0, D_2) + e_2^l (a_2 z_0^* - D_2)^+. \quad (6)$$

In (6), the first two terms represent the emissions from output sales—to demand and spot market, respectively—whereas the third term denotes the emissions associated with output spot procurement that is used for satisfying demand. The last two terms denote the emissions related to biomass, from satisfying the biomass demand and waste disposal through landfill, respectively.

In stage 2, the firm chooses the optimal processing volume z_0^*. In stage 1, when the firm commercializes its biomass, the total expected emissions are given by

$$M^* = e_0^p \, \mathbb{E}[\tilde{z}_0^*] + e_1^s \, \mathbb{E}[a_1 \tilde{z}_0^*] + (e_1^b + e_1^s) \, \mathbb{E}[(D_1 - a_1 \tilde{z}_0^*)^+] + e_2^s \, \mathbb{E}[\min(a_2 \tilde{z}_0^*, D_2)] + e_2^l \, \mathbb{E}[(a_2 \tilde{z}_0^* - D_2)^+]. \quad (7)$$

In (7), the first term represents the expected emissions associated with input processing whereas the remaining terms are obtained by taking the expectation of the emissions at stage 3 as given in

(6) while using $a_1 z_0^* = \min(a_1 z_0^*, D_1) + (a_1 z_0^* - D_1)^+$. The optimal processing volume is uncertain at stage 1 because it depends on the input spot price realization S_0 at stage 2.

In stage 1, when biomass is not commercialized, the total expected emissions are given by

$$M^{bc} = e_0^p \, \mathbb{E}[\tilde{z}_0^{bc}] + e_1^s \, \mathbb{E}[a_1 \tilde{z}_0^{bc}] + (e_1^b + e_1^s) \, \mathbb{E}[(D_1 - a_1 \tilde{z}_0^{bc})^+] + e_2^l \, \mathbb{E}[a_2 \tilde{z}_0^{bc}], \tag{8}$$

where all biomass is disposed through landfill at stage 2. Here, the optimal processing volume z_0^{bc} at stage 2 can be obtained from Proposition 1 by substituting $D_2 = 0$. In particular, the firm optimally processes up to full capacity (i.e., $z_0^{bc} = K_0$) when it is profitable to process (i.e., $a_1 \mu_{1|0}(S_0) - S_0 - c_0 > 0$) at stage 2; otherwise, the firm optimally does not process (i.e., $z_0^{bc} = 0$).

To characterize the environmental footprint of biomass commercialization, we define $\Delta M = M^* - M^{bc}$ as the change in total expected emissions after commercialization. Using M^* in (7) and M^{bc} in (8), we obtain

$$\begin{aligned} \Delta M = & \left(e_2^s - e_2^l\right) D_2 \, Pr\left(\tilde{S}_0 < a_1 \mu_{1|0}(\tilde{S}_0) - c_0\right) \\ & + \left[(e_0^p + a_1 e_1^s + a_2 e_2^s) \frac{D_2}{a_2} - \left(e_1^b + e_1^s\right) \left[D_1 - \left(D_1 - a_1 \frac{D_2}{a_2}\right)^+ \right] \right] \\ & \times Pr\left(a_1 \mu_{1|0}(\tilde{S}_0) - c_0 \le \tilde{S}_0 < a_1 \mu_{1|0}(\tilde{S}_0) + a_2 p_2 - c_0\right). \end{aligned} \tag{9}$$

To delineate the intuition behind (9), let us consider the optimal processing decisions with and without biomass (i.e., z_0^* and z_0^{bc}, respectively) at stage 2. When $S_0 < a_1 \mu_{1|0}(S_0) - c_0$, the firm optimally processes K_0 units of input with or without biomass. In this case, biomass commercialization induces the firm to convert D_2 units of landfill to biomass sales. Therefore, for each unit, the firm avoids the landfill emission e_2^l while incurring the biomass selling emission e_2^s. When $S_0 > a_1 \mu_{1|0}(S_0) + a_2 p_2 - c_0$, the firm optimally does not process with or without biomass, and thus, there is no change in emissions in this case. Otherwise (i.e., $a_1 \mu_{1|0}(S_0) - c_0 \le S_0 < a_1 \mu_{1|0}(S_0) + a_2 p_2 - c_0$), biomass commercialization makes the processing profitable. In particular, while the firm optimally does not process without biomass, it optimally processes D_2/a_2 units of input after commercialization. In this case, the firm incurs the processing emission e_0^p per unit for these inputs after commercialization. Moreover, because the firm optimally sells $a_1 D_2/a_2$ units of output (to either demand or spot market) and D_2 units of biomass, it also incurs output selling emission e_1^s and biomass selling emission e_2^s per unit of output and biomass, respectively. Because the firm optimally does not process without biomass, the output demand is satisfied by spot procurement, and thus, the firm incurs the output buying emissions $(e_1^b + e_1^s)D_1$. By commercializing its biomass and producing a_1D_2/a_2 units of output, the firm uses less spot procurement (if any) to satisfy the output demand and incurs the output buying emissions $(e_1^b + e_1^s)(D_1 - a_1D_2/a_2)^+$. Therefore, biomass commercialization reduces the output buying emissions where the magnitude of reduction is given by $(e_1^b + e_1^s)(D_1 - (D_1 - a_1D_2/a_2)^+)$.

4.2 Effects of Biomass Market Characteristics

In this section, we examine how changes in biomass demand D_2 and biomass price p_2 impact the environmental footprint of biomass commercialization. As follows from Proposition 2, an increase in D_2 or p_2 is always economically beneficial; that is, these changes increase the value of commercialization ΔV. Are these changes also environmentally beneficial? To answer this question, we conduct sensitivity analyses to study the effects of D_2 and p_2 on the change in expected emissions due to commercialization (ΔM). We say that a higher D_2 or p_2 is environmentally beneficial when it leads to a decrease in ΔM whereas this change is environmentally harmful when it leads to an increase in ΔM. As we will discuss at the end of this section, our analyses are useful for understanding the environmental consequences of some commonly adopted government policies in practice that have been devised to promote energy production from biomass.

We first investigate the effect of biomass demand D_2 on ΔM. To this end, we define ΔM in (9) as a function of D_2 and examine how ΔM changes in D_2. We obtain

$$\begin{aligned}\frac{\partial \Delta M}{\partial D_2} = &\left(e_2^s - e_2^l\right) Pr\left(\tilde{S}_0 < a_1\mu_{1|0}(\tilde{S}_0) - c_0\right) \\ &+ \frac{1}{a_2}\left[(e_0^p + a_2e_2^s + a_1e_1^s) - \left(a_1e_1^b + a_1e_1^s\right)\chi\left(\frac{D_2}{a_2} \le \frac{D_1}{a_1}\right)\right] \\ &\times Pr\left(a_1\mu_{1|0}(\tilde{S}_0) - c_0 \le \tilde{S}_0 < a_1\mu_{1|0}(\tilde{S}_0) + a_2p_2 - c_0\right).\end{aligned} \tag{10}$$

The intuition behind (10) directly follows from the explanations associated with (9). It is easy to establish that ΔM is piecewise linear in D_2 with its slope increasing at the breakpoint $D_2 = a_2D_1/a_1$. For $D_2 \le a_2D_1/a_1$, the reduction in the output buying emissions when biomass commercialization makes processing profitable—the last term in the second line of (9)—is given by $-(e_1^b + e_1^s)a_1D_2/a_2$ where the magnitude of this term (i.e., its absolute value) increases in D_2. For $D_2 > a_2D_1/a_1$, this term is given by $-(e_1^b + e_1^s)D_1$ which is independent of D_2. The sign of $\frac{\partial \Delta M}{\partial D_2}$ can be determined using the slopes of two linear components. Proposition 6 establishes this based on the biomass selling emission intensity e_2^s and the biomass demand D_2.

Proposition 6 *Let*

$$\underline{e}_2^s = \frac{a_2 e_2^l Pr\left(\tilde{S}_0 < a_1\mu_{1|0}(\tilde{S}_0) - c_0\right) - (e_0^p + a_1 e_1^s)\, Pr\left(a_1\mu_{1|0}(\tilde{S}_0) - c_0 \le \tilde{S}_0 < a_1\mu_{1|0}(\tilde{S}_0) + a_2 p_2 - c_0\right)}{a_2 Pr\left(\tilde{S}_0 < a_1\mu_{1|0}(\tilde{S}_0) + a_2 p_2 - c_0\right)},$$

$$\overline{e}_2^s = \frac{a_2 e_2^l Pr\left(\tilde{S}_0 < a_1\mu_{1|0}(\tilde{S}_0) - c_0\right) - (e_0^p - a_1 e_1^b) Pr\left(a_1\mu_{1|0}(\tilde{S}_0) - c_0 \le \tilde{S}_0 < a_1\mu_{1|0}(\tilde{S}_0) + a_2 p_2 - c_0\right)}{a_2 Pr\left(\tilde{S}_0 < a_1\mu_{1|0}(\tilde{S}_0) + a_2 p_2 - c_0\right)},$$

where $\underline{e}_2^s < \overline{e}_2^s$*. We have*

(i) *if* $e_2^s \le \underline{e}_2^s$*, then* $\frac{\partial \Delta M}{\partial D_2} < 0$*;*

(ii) *if* $e_2^s \ge \overline{e}_2^s$*, then* $\frac{\partial \Delta M}{\partial D_2} \ge 0$*;*

(iii) *otherwise,* $\frac{\partial \Delta M}{\partial D_2} < 0$ *for* $D_2 < a_2 D_1/a_1$ *and* $\frac{\partial \Delta M}{\partial D_2} > 0$ *for* $D_2 \ge a_2 D_1/a_1$*.*

Proposition 6 demonstrates that an increase in biomass demand is not always environmentally beneficial and the environmental impact crucially depends on two biomass selling emission intensity thresholds $\underline{e}_2^s < \overline{e}_2^s$ as well as a biomass demand threshold $a_2 D_1/a_1$. When the biomass emission intensity is sufficiently high (i.e., $e_2^s \ge \overline{e}_2^s$), an increase in D_2 is always environmentally harmful. Here, the threshold $\overline{e}_2^s$ is characterized based on $\frac{\partial \Delta M}{\partial D_2} = 0$ for $D_2 \le a_2 D_1/a_1$ in (10). On the other hand, when the biomass emission intensity is sufficiently low (i.e., $e_2^s \le \underline{e}_2^s$), an increase in D_2 is always environmentally beneficial. Here, the threshold $\underline{e}_2^s$ is characterized based on $\frac{\partial \Delta M}{\partial D_2} = 0$ for $D_2 > a_2 D_1/a_1$ in (10). When the biomass emission intensity is moderate (i.e., $\underline{e}_2^s < e_2^s < \overline{e}_2^s$), an increase in D_2 is environmentally beneficial only when the biomass demand is sufficiently low (i.e., $D_2 < a_2 D_1/a_1$); otherwise, it is environmentally harmful.

We next examine the impact of biomass price p_2 on ΔM. As can be observed from (9), higher p_2 affects ΔM by increasing the probability of the event that processing becomes profitable only after biomass commercialization (the last term in (9)). Therefore, the sign of impact of p_2 on ΔM is determined by the sign of $(e_0^p + a_1 e_1^s + a_2 e_2^s)\, D_2/a_2 - \left(e_1^b + e_1^s\right)\left[D_1 - (D_1 - a_1 D_2/a_2)^+\right]$. Because this term is piecewise linear in D_2 with its slope increasing at the breakpoint $D_2 = a_2 D_1/a_1$, its sign can be determined using the slopes of two linear components. This pattern is structurally similar to the case of how D_2 affects ΔM, and thus, the effect of p_2 on ΔM can proven to be structurally similar to Proposition 6.

Proposition 7 *We have*

(i) *if* $e_2^s \le -\frac{1}{a_2}(e_0^p + a_1 e_1^s)$*, then* $\frac{\partial \Delta M}{\partial p_2} < 0$*;*

(ii) *if* $e_2^s \ge \frac{1}{a_2}(a_1 e_1^b - e_0^p)$*, then* $\frac{\partial \Delta M}{\partial p_2} \ge 0$*;*

(iii) otherwise, there exists a unique $\hat{D}_2(e_2^s) > a_2 D_1/a_1$ *such that* $\frac{\partial \Delta M}{\partial p_2} \leq 0$ *for* $D_2 \leq \hat{D}_2(e_2^s)$*, and* $\frac{\partial \Delta M}{\partial p_2} > 0$ *for* $D_2 > \hat{D}_2(e_2^s)$*.*

Paralleling the impact of biomass demand, Proposition 7 demonstrates that an increase in biomass price is also not always environmentally beneficial. Moreover, the environmental impact is also characterized based on two biomass selling emission intensity thresholds and a biomass demand threshold. In particular, when the biomass selling intensity is sufficiently high (i.e., $e_2^s \geq \frac{1}{a_2}(a_1 e_1^b - e_0^p)$), an increase in p_2 is always environmentally harmful. When the biomass selling intensity is sufficiently low (i.e., $e_2^s \leq -\frac{1}{a_2}(e_0^p + a_1 e_1^s)$), an increase in p_2 is always environmentally beneficial. When the biomass selling intensity is moderate (i.e., e_2^s is between two thresholds), an increase in p_2 is environmentally beneficial only when D_2 is lower than a threshold $\hat{D}_2(e_2^s)$; otherwise, it is environmentally harmful. We relegate the explicit characterization of the biomass demand threshold $\hat{D}_2(e_2^s)$ to the proof of Proposition 7.

The general insights from our analysis are that while higher biomass demand or biomass price always increases the value of biomass commercialization, these changes are not necessarily environmentally beneficial as they may increase the emissions associated with biomass commercialization. In particular, a higher biomass demand or biomass price is environmentally beneficial only when the biomass selling emission intensity is sufficiently low or when it is moderate and the biomass demand is low; otherwise, both changes are environmentally harmful. These results are useful for policymakers to understand the environmental consequences of some commonly adopted policies in practice that have been devised to promote energy production from biomass. An example is a feed-in-tariff policy that provides a guaranteed, above-market price for energy produced from renewable sources. In recent years governments have adopted this policy to promote investment in renewable energy production (Babich et al., 2019) including energy produced from biomass (PennEnergy, 2013). Adoption of this policy increases the biomass demand. Another example is a government grant that provides subsidies for processing (e.g., de-fibring) cost associated with converting waste into a saleable by-product (see, for example, Ashton et al. (2014) for a processing cost subsidy grant in the woody biomass industry). Adoption of this grant increases the biomass price (recall from Section 3.1 that in our model biomass price denotes the effective price after additional cost for selling biomass is deducted). Our results demonstrate that adoption of a feed-in-tariff policy or a cost subsidy grant does promote energy production from biomass as it incents the processor to convert its waste to a saleable by-product; however, it does not necessarily reduce the emissions associated with this conversion. If policymakers also target to reduce these emissions, then our results suggest that this can be achieved by taking actions to decrease the biomass selling emission intensity. One such action is to require pelletizing of the biomass before shipment so that for the same weight of biomass transported, a larger amount of fossil fuel is substituted in energy production due to higher calorific value of the pelletized biomass.

4.3 Environmental Assessment of Biomass Commercialization

In the previous section, we examined how biomass market characteristics impact the environmental footprint of biomass commercialization as captured by ΔM. In this section, using this environmental footprint, we characterize the conditions under which biomass commercialization is environmentally beneficial or harmful. We say that biomass commercialization is environmentally beneficial when it leads to a reduction in expected emissions (i.e., $\Delta M < 0$) and it is environmentally harmful when it leads to an increase in expected emissions (i.e., $\Delta M > 0$).

It follows from our characterization of ΔM in (9) that its sign cannot be easily determined because (i) there are positive and negative terms associated with increase and decrease in emissions due to commercialization, respectively; and (ii) biomass selling emission intensity e_2^s is unrestricted in sign by definition. To characterize the conditions under which $\Delta M > 0$ and $\Delta M < 0$, we first make the intuitive observation that when there is no biomass demand, the firm does not convert landfill to biomass sale and thus, biomass commercialization does not have any impact on the environment; that is, $\Delta M = 0$ for $D_2 = 0$. We next use our results associated with how D_2 affects ΔM in (9) as characterized by Proposition 6 to determine the sign of ΔM for $D_2 > 0$. Paralleling these results, Proposition 8 illustrates the conditions under which $\Delta M < 0$ and $\Delta M > 0$ based on the biomass selling emission intensity e_2^s and biomass demand D_2.

Proposition 8 *Let $\underline{e}_2^s$ and $\overline{e}_2^s$ as defined in Proposition 6. We have*

(i) if $e_2^s \leq \underline{e}_2^s$, then $\Delta M < 0$;

(ii) if $e_2^s \geq \overline{e}_2^s$, then $\Delta M \geq 0$ with equality holding when $e_2^s = \overline{e}_2^s$;

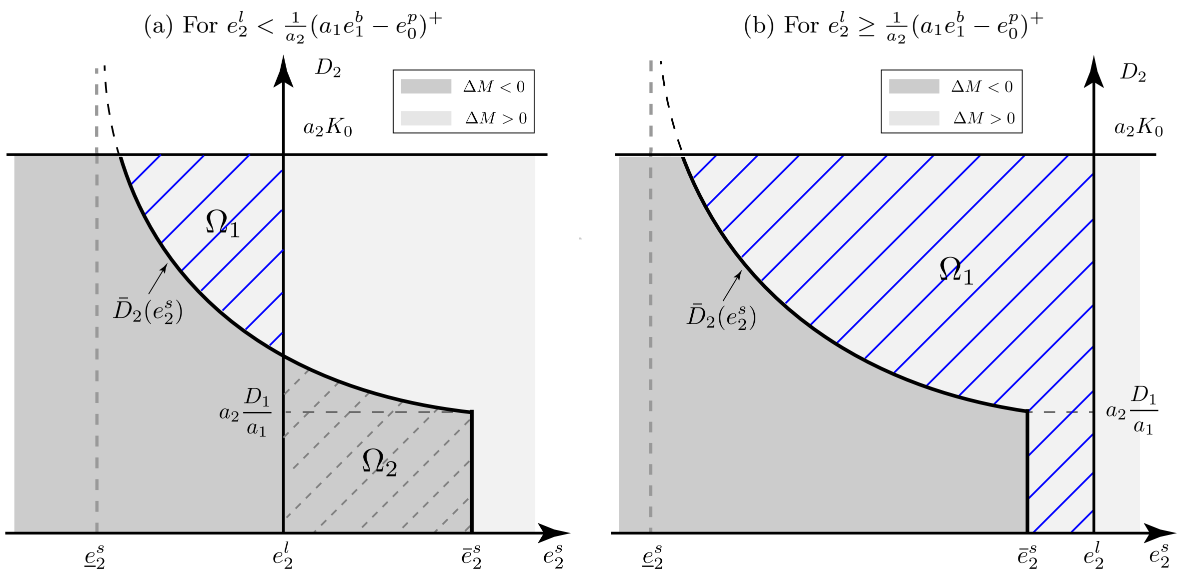
(iii) otherwise, there exists a unique biomass demand threshold $\bar{D}_2(e_2^s) > a_2 D_1/a_1$ such that $\Delta M \leq 0$ for $D_2 \leq \bar{D}_2(e_2^s)$ with equality holding when $D_2 = \bar{D}_2(e_2^s)$, and $\Delta M > 0$ for $D_2 > \bar{D}_2(e_2^s)$. We have $\bar{D}_2(e_2^s)$ decreasing in e_2^s.

When the biomass selling emission intensity e_2^s is sufficiently low (i.e., $e_2^s \leq \underline{e}_2^s$), biomass commercialization is environmentally beneficial regardless of biomass demand. In this case, as follows from Proposition 6, an increase in biomass demand decreases ΔM. Because $\Delta M = 0$ for $D_2 = 0$, we have $\Delta M < 0$ for $D_2 > 0$. When e_2^s is sufficiently high (i.e., $e_2^s \geq \overline{e}_2^s$), biomass commercialization is environmentally harmful regardless of biomass demand. In this case, as follows from Proposition 6, an increase in biomass demand always (weakly) increases ΔM. Because $\Delta M = 0$ for $D_2 = 0$, we have $\Delta M \geq 0$ for $D_2 > 0$. When e_2^s is moderate (i.e., $\underline{e}_2^s < e_2^s < \overline{e}_2^s$), the environmental assessment of biomass commercialization crucially depends on the biomass demand. In particular, biomass commercialization is environmentally beneficial only when biomass demand is lower than a threshold $\bar{D}_2(e_2^s)$; otherwise, it is environmentally harmful. In this case, as follows from Proposition 6, an increase in biomass demand decreases ΔM for $D_2 < a_2 D_1/a_1$ and increases ΔM otherwise. Therefore, the threshold $\bar{D}_2(e_2^s)$ is larger than $a_2 D_1/a_1$.

Our characterization in Proposition 8 has important implications as it refines the existing understanding (both in practice and in the industrial ecology literature) associated with the environmental assessment of biomass commercialization. As discussed in the Introduction, the existing understanding is based on an assessment that does not take into account the optimization of operational decisions and thus, it does not incorporate the emissions resulting from the changes in these decisions after commercialization. In particular, the environmental assessment is made based on a comparison between increase in emissions due to additional processing and transportation activities as well as burning of biomass in downstream power plant and decrease in emissions due to lower landfill and replacement of fossil fuel energy source in downstream power plant. In the context of our model, this is equivalent to making a comparison between biomass selling emission intensity e_2^s and landfill emission intensity e_2^l. In other words, there is a single e_2^s threshold (which is e_2^l) that determines whether biomass commercialization is environmentally beneficial or harmful. Our results reveal that when the optimization of operational decisions are considered, the environmental assessment becomes more nuanced as it depends on two biomass intensity thresholds and a biomass demand threshold. The intuition behind the differences between two assessments can easily be observed from our ΔM characterization in (9). When the firm processes the same amount of input and hence, produces the same amount of output and biomass before and after commercialization (which corresponds to the processing scenario depicted in the first line in (9)), the sign of ΔM in this scenario is also given by a comparison between e_2^s and e_2^l. However, when the commercialization induces the firm to process more input and produce more output and biomass (which corresponds to the processing scenario depicted in the last two lines in (9)), the sign of ΔM in this scenario is not given by a comparison between e_2^s and e_2^l.

We next investigate how the environmental assessment characterized by Proposition 8 contrasts with the assessment based on the existing understanding; that is, are there cases in which these two assessments reach opposite conclusions? To answer this question, we compare $\underline{e}_2^s$ and $\overline{e}_2^s$ thresholds with e_2^l. It follows from the characterizations given in Proposition 6 that (i) $\underline{e}_2^s < e_2^l$ and (ii) $\overline{e}_2^s > e_2^l$ if $e_2^l < \frac{1}{a_2}(a_1 e_1^b - e_0^p)^+$, $\overline{e}_2^s \le e_2^l$ otherwise. Using these results, Figure 2 illustrates the environmental assessment characterization for a given low (panel a) and high (panel b) e_2^l which is set to be the origin of the horizontal axis representing e_2^s.

Figure 2: When Does Biomass Commercialization Lead to a Reduction or an Increase in Total Expected Emissions (i.e., $\Delta M < 0$ or $\Delta M > 0$, respectively)?



Note. Effects of biomass selling emission intensity e_2^s and biomass demand D_2 for a given landfill emission intensity e_2^l. It can be proven that $\lim_{e_2^s \to \overline{e}_2^{s-}} \bar{D}_2(e_2^s) = a_2 D_1 / a_1$, $\lim_{e_2^s \to \underline{e}_2^{s+}} \bar{D}_2(e_2^s) = \infty$, and $\bar{D}_2(e_2^s)$ convexly decreases in e_2^s.

In comparison with the existing understanding, Figure 2 highlights two types of misconceptions where the environmental assessment conclusion is in the opposite direction (and illustrates specific conditions under which they appear). In the first type of misconception (Ω_1 region) because $e_2^s < e_2^l$, *based on the existing understanding we would mistakenly think that biomass commercialization is environmentally beneficial when it is not.* In this case, the increase in emissions due to processing more input and producing more output and biomass after commercialization ($(e_0^p + a_1 e_1^s + a_2 e_2^s) \frac{D_2}{a_2}$ term in (9)) is sufficiently high so that $\Delta M > 0$. In the second type of misconception (Ω_2 region) because $e_2^s > e_2^l$, *based on the existing understanding we would mistakenly think that biomass commercialization is environmentally harmful when it is not.* In this case, the decrease in emissions due to using less spot procurement to satisfy output demand after commercialization ($\left(e_1^b + e_1^s\right)\left[D_1 - (D_1 - a_1 D_2/a_2)^+\right]$ term in (9)) is sufficiently high so that $\Delta M < 0$. These two misconceptions underline the importance of considering the optimization of operational decisions in the environmental assessment of biomass commercialization.

5 Numerical Analysis: Application to the Palm Oil Industry

We now discuss an application of our model in the context of a palm oil mill processing fresh fruit palm bunches (FFB), a commodity input, to produce crude palm oil (CPO), a commodity output, while generating palm kernel shell (PKS) as organic waste. We calibrate our model parameters to represent a palm oil mill (hereafter, denoted as "typical palm oil mill") in Malaysia selling its PKS to a power plant in Japan where PKS is used for substituting coal in energy production. We relegate the description of data and calibration used for our numerical experiments to Section A of the online appendix.

Table 1 summarizes the calibrated parameter values representing the baseline scenario in our numerical experiments. In a palm oil mill, processing of FFB yields not only CPO and PKS but also palm kernel (another by-product) that has economic value. Because our model only considers commodity output (CPO) and biomass (PKS) for brevity, the unit sale revenue from this by-product is normalized into the processing cost c_0. Hence, c_0 takes a negative value in our baseline scenario. Because we consider a palm oil mill that commercializes its PKS, there is no need for a calibrated value of fixed cost of commercialization F. Moreover, there is no calibrated value for biomass demand D_2 because our results can be presented without using a specific value of D_2.

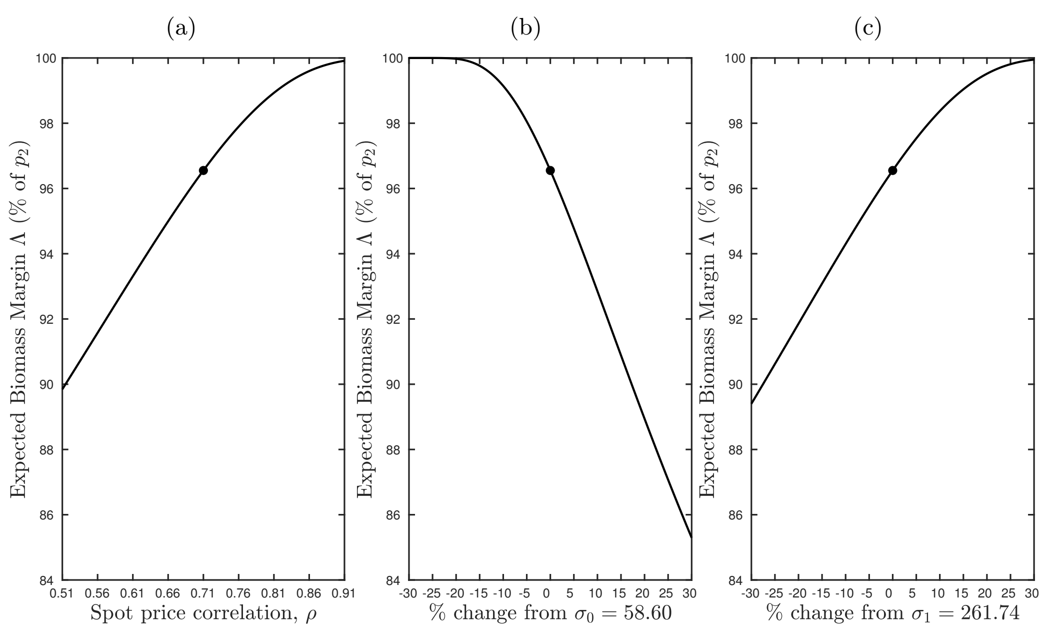
Table 1: Description of the Baseline Scenario Used in Our Numerical Experiments

Notation	Description	Value
μ_0, μ_1	Means of FFB and CPO spot prices	498.77, 2468.50 RM
σ_0, σ_1	Standard deviations of FFB and CPO spot prices	58.60, 261.74 RM
ρ	Correlation between FFB and CPO spot prices	0.71
c_0	Unit processing cost (normalized by other by-product revenues)	-39.47 RM/mt
K_0	Processing capacity	56688.06 mt
a_1, a_2	Production yields of CPO and PKS	19.77%, 5.65%
D_1	CPO demand	3922.53 mt
p_1, p_2	CPO and PKS prices for demand sales	2468.50, 476.40 RM/mt
e_0^p	FFB processing emission intensity	314.09 kg CO_2/mt
e_2^l	PKS landfill emission intensity	1470.00 kg CO_2/mt
e_2^s	PKS selling emission intensity	151.34 kg CO_2/mt
e_1^s	CPO selling emission intensity	217.74 kg CO_2/mt
e_1^b	CPO buying emission intensity	2012.73 kg CO_2/mt

Note. FFB (fresh fruit bunches) is the commodity input, CPO (crude palm oil) is the commodity output, and PKS (palm kernel shell) is the biomass. FFB and CPO spot prices are bivariate Normally distributed. All emission intensity parameters are in units of kg CO_2/mt; that is, kilogram of carbon dioxide per metric ton (equal to 1,000 kg). "RM" denotes Malaysian ringgit (currency). We keep two decimals for the calibrated parameter values.

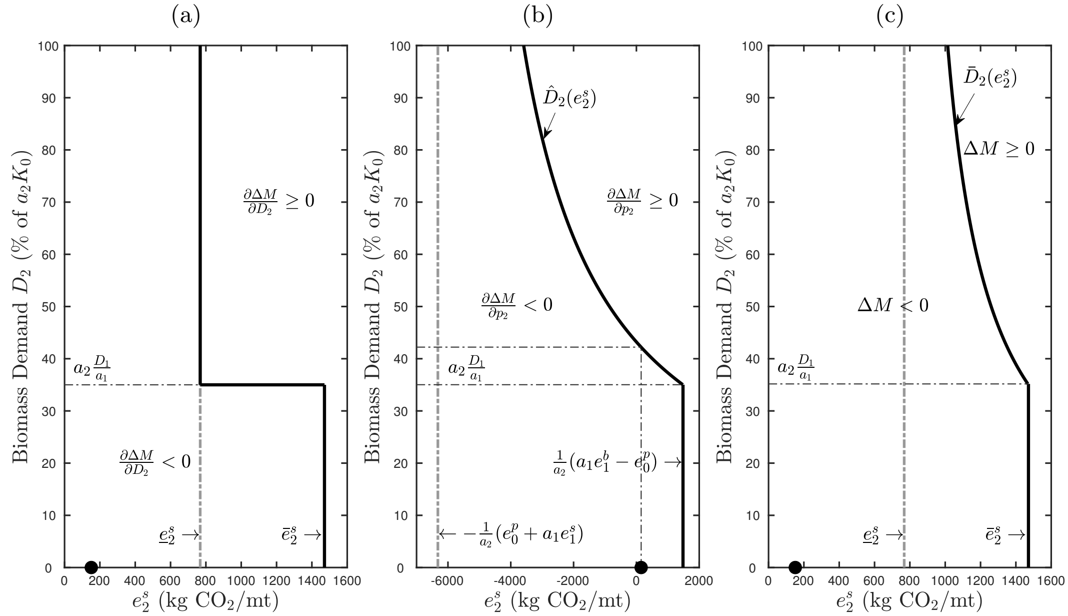
We first examine the effects of FFB and CPO spot price variabilities (σ_0 and σ_1, respectively) and spot price correlation (ρ) on the value of PKS commercialization ΔV. Because $\Delta V = \Lambda D_2$ as characterized by Proposition 2, the influence of these parameters is through their impacts on the expected PKS margin Λ. Our analytical results in Section 3.3 fully characterize these effects for the entire range of these parameters. In our data-calibrated baseline scenario, it can be observed from Table 1 that FFB and CPO spot prices are positively correlated (i.e., $\rho > 0$) and the calibrated parameters satisfy $\frac{a_1 \sigma_1 \rho}{\sigma_0} < 1$. Therefore, the sensitivity results presented in Proposition 5 are relevant for a typical palm oil mill. Figure 3 plots the effects of changing ρ (panel a), σ_0 (panel b), and σ_1 (panel c) on Λ—which is presented as the percentage of the PKS price p_2—in our baseline scenario. While the analytical results presented in Proposition 5 illustrate non-monotone effects of these parameters, as follows from Figure 3, in realistic instances that represent the palm oil industry we only observe monotone effects of these parameters. In particular, we observe that lower FFB spot price variability σ_0, higher CPO spot price variability σ_1, and higher spot price correlation ρ increase the value of PKS commercialization for a typical palm oil mill.

Figure 3: Effects of Spot Price Correlation ρ (Panel a), FFB Spot Price Variability σ_0 (Panel b), and CPO Spot Price Variability σ_1 (Panel c) on the Expected PKS Margin Λ as a Percentage of the Expected PKS Price p_2 in the Baseline Scenario



Note. In panel a, $\rho \in [0.51, 0.91]$ is evenly-spaced around the baseline value $\rho = 0.71$ with a step size of 0.001. In panel b and panel c, σ_0 and σ_1 are within 30% of the baseline values 58.60 and 261.74, respectively with 0.5% increments. In all three panels, baseline scenario is indicated by • aligned horizontally with the baseline value.

Figure 4: The Impacts of PKS Demand D_2 (Panel a) and PKS Price p_2 (Panel b) on The Change in Expected Emissions Due to Commercialization (ΔM), and The Environmental Assessment of PKS Commercialization (Panel c)



Note. In each panel, $\bullet$ represents the calibrated biomass selling emission intensity e_2^s. Biomass demand D_2 is presented as a percentage of a_2K_0, processing capacity required to satisfy biomass demand, which is no greater than 100% because of our assumption of $D_2 \leq a_2K_0$.

We next investigate (i) how changes in biomass demand and biomass price impact the environmental footprint of PKS commercialization and (ii) whether PKS commercialization is environmentally beneficial or harmful for a typical palm oil mill. To illustrate the effect of biomass demand, panel a of Figure 4 plots the biomass selling emission intensity thresholds $\underline{e}_2^s$, $\bar{e}_2^s$ and the biomass demand threshold a_2D_1/a_1 (as characterized by Proposition 6) in our baseline scenario. To illustrate the effect of biomass price, panel b plots the biomass selling emission intensity thresholds $-\frac{1}{a_2}(e_0^p + a_1e_1^s)$, $\frac{1}{a_2}(a_1e_1^b - e_0^p)$ and the biomass demand threshold $\hat{D}_2(e_2^s)$ (as characterized by Proposition 7) in our baseline scenario. To illustrate the environmental assessment of PKS commercialization, panel c plots the biomass selling emission intensity thresholds $\underline{e}_2^s$, $\bar{e}_2^s$ and the biomass demand threshold $\bar{D}_2(e_2^s)$ (as characterized by Proposition 8) in our baseline scenario. We make the following two important observations (written in italic below) based on Figure 4:

(1) *While a higher PKS demand is always environmentally beneficial for a typical palm oil mill, a higher PKS price is environmentally beneficial only when PKS demand is sufficiently low; otherwise, it is environmentally harmful.* For the impact of PKS demand D_2, as can be observed from panel a, the biomass selling emission intensity e_2^s is less than the threshold $\underline{e}_2^s$ in our baseline scenario. Therefore, a higher PKS demand D_2 decreases ΔM (the change in expected emissions

due to commercialization). For the impact of PKS price p_2, as can be observed from panel b, e_2^s is between the two thresholds $-\frac{1}{a_2}(e_0^p + a_1 e_1^s)$ and $\frac{1}{a_2}(a_1 e_1^b - e_0^p)$ in our baseline scenario. Therefore, the impact of p_2 on ΔM depends on D_2. In particular, an increase in p_2 decreases ΔM only when D_2 is smaller than a level that is associated with approximately 42% processing capacity utilization; otherwise, it increases ΔM. Our result may prove to be important for policy makers in the context of palm industry as it showcases an advantage of a policy that increases PKS demand (e.g., feed-in-tariff) over a policy that increases PKS price (e.g., subsidy for PKS processing): the former reduces the emissions associated with PKS commercialization whereas the latter may not.

(2) *PKS commercialization is environmentally beneficial for a typical palm oil mill.* As can be observed from panel c, the biomass selling emission intensity e_2^s is less than the threshold $\underline{e}_2^s$ in our baseline scenario. Therefore, we have $\Delta M < 0$. While this result is encouraging for PKS-to-energy industry, it comes with a caveat. In our numerical calibration, we assume that PKS is used for substituting coal in power plant for energy production. In the near future we expect the power plants to use PKS for substituting a cleaner energy source (e.g., liquified natural gas, hydrogen) than coal given the current trend that suggests the discontinuation of coal-fired energy production by 2030 (Dempsey, 2019). When a cleaner energy source is substituted by PKS, the calibrated biomass selling emission intensity e_2^s (represented by $\bullet$) in panel c of Figure 4 increases and it may fall into a region where PKS commercialization is not environmentally beneficial for a typical palm oil mill. To this end, the on-going industry-wide efforts for reducing the carbon emissions in shipping (Milne, 2018) also have an indirect, and potentially a crucial positive environmental impact on the PKS-to-energy industry. This is because reduction in emissions associated with shipping of PKS from Malaysia to Japan decreases the biomass selling emission intensity e_2^s.

To assess the sensitivity of our results to the emission parameters, we extend our numerical instances around the baseline scenario. In particular, we consider emission parameters e_0^p, e_2^l, e_2^s, e_1^s, and e_1^b that are $\{-10\%, 0\%, 10\%\}$ of their calibrated values presented in Table 1. Altogether, we evaluate 243 numerical instances. We verify that the same two observations written in italic are relevant for all numerical instances considered.

6 Conclusion

This paper studies the economic and environmental implications of biomass commercialization; that is, converting organic waste into a saleable product, from the perspective of an agricultural processing firm. We characterize the economic value of biomass commercialization and provide insights on how the spot price uncertainty shapes this value. We also characterize the environmental footprint of biomass commercialization; that is, the change in expected total carbon emissions, and provide insights on how biomass market characteristics affect this environmental footprint. We provide guidance on when biomass commercialization is environmentally beneficial or harmful. Based on our results, we put forward important practical implications that are of relevance to both agricultural processors and policy makers.

To examine the robustness of our results, we conduct additional analyses to provide three extensions of our model; the details of these analyses are relegated to Section C of the online appendix. First, in Section C.1, we extend our model to consider uncertain biomass demand which follows a two-point discrete distribution and show that our structural results continue to hold in this setting. Second, we extend our model to consider uncertain biomass price which includes a variable component that is indexed on the output spot price in Section C.2. Although the effects of input and output spot price uncertainties on the value of biomass commercialization can only be partially characterized analytically, our numerical experiments reveal that our main insights do not change. We also verify that our main insights associated with the environmental implications of biomass commercialization do not change either. In this extension, we also investigate how increasing the biomass price's dependence on the output spot price without changing the expected biomass price affects the value and the environmental footprint of biomass commercialization. Using our model calibration, we find that higher dependence on the output spot price decreases the value of biomass commercialization and increases the prevalence of conditions under which biomass commercialization is environmentally harmful for a typical palm oil mill. Finally, in Section C.3, we relax our assumption on the commodity output demand $D_1 \in (0, a_1K_0]$ (where a_1K_0 is the maximum production volume for the commodity output) and consider the two extreme cases of $D_1 > a_1K_0$ and $D_1 = 0$. Because the value of biomass commercialization is independent of D_1, our results associated with the economic implications are not affected. However, our results associated with environmental implications are affected because, as depicted in (9), biomass commercialization reduces the commodity output buying emissions where the magnitude of reduction is given by $(e_1^b + e_1^s)(D_1 - (D_1 - a_1D_2/a_2)^+)$. When $D_1 = 0$, there is no such reduction. When $D_1 > a_1K_0$, the magnitude of this reduction is given by $(a_1e_1^b + a_1e_1^s)D_2/a_2$ and it is independent of D_1. For the $D_1 = 0$ case, in our characterizations associated with the impact of biomass demand (Proposition 6) and biomass price (Proposition 7) on the change in expected emissions after commercialization as well as the environmental assessment of biomass commercialization (Proposition 8), only the smaller biomass selling emission intensity threshold is relevant. For the $D_1 > a_1K_0$ case, in the same characterizations, only the larger biomass selling emission intensity threshold is relevant.

In our data-calibrated computational study throughout Section 5, we provided a practical application in the palm oil industry. Because our model is applicable to a wide range of industries in which processing residue has economic value, future research can be conducted by using our paper's methodology to calibrate the model based on these industries to provide other practical applications. In the context of biomass-to-energy conversion, these industries include other agricultural processing industries (e.g., coconut and sugarcane) and forestry processing industries (e.g., wood processing, pulp and paper production). Outside of the context of biomass-to-energy conversion, these industries include biofuel industry (where corn is processed to produce ethanol while generating glycerin as residue which has economic value in chemical industry) and steel industry (where iron ore is processed to produce steel while generating slag as residue which has economic value in construction industry).

Relaxing the assumptions made about the environmental assessment of biomass commercialization gives rise to a number of interesting areas for future research. First, paralleling the current industry practice, we (implicitly) assume that biomass commercialization decision is made without considering its environmental impact. One potential approach to factor in the environmental impact is to use the ratio of emission change to profit change (without considering the fixed cost) $\Delta M/\Delta V$ where biomass is commercialized only when $\Delta M/\Delta V < T$. Here, $T \geq 0$ denotes the processor's internal target level which can be chosen by benchmarking to the carbon offset price (price paid in dollars to reduce the one kg of CO_2 emissions somewhere else). A lower T would imply a more stringent environmental impact consideration (for example, when $T = 0$, biomass is commercialized only if it reduces the expected emissions). Another approach to factor in the environmental impact for the biomass commercialization decision is to consider a unit cost associated with carbon emission and directly incorporate this emission cost into the firm's profit-maximization problem. This should prove to be an interesting avenue for future research. Second, we investigate the environmental implications of biomass commercialization from the perspective of a single processor. It would be interesting to examine the environmental implications of biomass commercialization in an industry equilibrium that involves multiple processors. One potential approach is to consider the strategic interaction among multiple processors with different operational (e.g., processing cost, capacity) characteristics in satisfying the overall industry biomass demand using an equilibrium model and examine how biomass commercialization decision of these processors affect the total expected emissions in the industry.

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