Sustaining Smallholders and Rainforests by Eliminating Payment Delay in a Commodity Supply Chain—It Takes a Village

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Millions of poor smallholder farmers produce global commodities, often through illegal deforestation. Multinational commodity buyers have committed to halt illegal deforestation and improve farmers' livelihoods in their supply chains. We propose a profitable way to do so, motivated by field research in Indonesia's palm oil industry. Currently, farmers suffer from delay in payment by processors, and buyers expensively attempt to avoid sourcing from illegally-deforested land by monitoring individual farmers. Instead, we propose that buyers reward all farmers in a village by eliminating payment delay if no production occurs on illegally-deforested land in the village. Using field data, dynamic programming and game theory, we show how eliminating payment delay improves productivity and profitability for farmers, processors and buyers, and how village-level incentives best halt illegal deforestation.

1. Introduction

Hundreds of multinational buyers have made the dual commitments to halt deforestation and improve farmer livelihoods in their supply chains (McCarthy 2016). These commitments are particularly important in Indonesia, where deforestation for palm oil has contributed approximately 10% of global greenhouse gas emissions in the past decade, and millions of smallholder palm oil farmers live in poverty (CAT 2017, EPA 2017, Byerlee et al. 2017).[1] The emissions and social injustice motivate so much NGO pressure that palm oil buyers representing over 60% of the global palm oil market have made such commitments (CRR 2016).

The dual commitments, however, are seemingly at odds, and buyers are failing to meet them (CF 2015, GCP 2016, EII 2016). Having low productivity and little land, smallholder farmers are compelled to improve their livelihoods by illegally burning forest to expand their farms (Higgins et al. 2018, Daemeter 2016b).[2] Buyers are attempting to prevent fruit from illegally-deforested land entering their supply chains by mapping individual farmers (*e.g.*, Wilmar 2017, Musim Mas 2016). This farmer-level approach, however, is expensive and impractical due to the large number

[1] Indonesia produces 53% of globally-traded palm oil (OilWorld 2014) and is the country with the largest area of deforestation in the past decade (Margono et al. 2014). 40-50% of the total area with palm oil plantations in Indonesia is harvested by smallholder farmers, defined as producers with a farm less than 25ha (ICBS 2014, Saragih 2017). The average farm size of a smallholder palm oil farmer in Indonesia is 2 hectares (ha) (Higgins et al. 2018).

[2] This illegal activity occurs in state forests, national parks and other protected areas. Smoke from the fires significantly impacts regional air quality and the health of millions of people (Marlier et al. 2013, ABC 2016, CNBC 2016).

of smallholders. Moreover, it cannot prevent a farmer with a legitimate farm from selling fruit produced illegally on other farms, under the disguise of higher productivity. Hence buyers see two dismal options: stop sourcing from smallholders, or continue sourcing from smallholders and risk brand damage from association with illegal deforestation (*e.g.* Parker 2013 and references therein).

To understand how buyers can meet their dual commitments, we started with field research in Indonesia's palm oil supply chain. We conducted nearly 500 surveys with all participants in the supply chain, from farmers who harvest and sell fruit, to mills that process fruit into crude oil, refineries that process crude oil into refined oil, and manufacturers who use refined oil as an ingredient in basic end-products (see §6 for details). Henceforth, we refer to "buyers" as those who buy oil directly from a mill. We made two key field observations: (1) smallholder farmers suffer from delay in payment by the mill, and (2) the rural landscape, including its forests, can be divided into contiguous areas within which the smallholder farmers could cooperate to prevent illegal deforestation and production. We refer to those as "villages."

The problematic delay in payment occurs because mills are capital-constrained, and pay for fruit when the extracted oil is received and paid for by the buyer, which occurs periodically, for reasons of transport efficiency. Delay is problematic for farmers because they lack access to formal financing and need cash from fruit sales to buy food, pay farm laborers, etc. They therefore care greatly about payment timing; farmers we surveyed discounted a one week delay in payment by 32% on average.

This first field observation prompts us to formulate a dynamic game between heterogeneous farmers and a mill, and analyze how payment delay affects each farmer's welfare and productivity, and the resulting profits for the mill and for the buyer periodically paying the mill for oil. In each period, the mill sets a price for fruit, and each farmer chooses how much fruit to produce and deliver to the mill, how much cash to spend on consumption, and how much cash to borrow or lend in the community. At the end of each period, a buyer pays the mill the commodity market price for the oil extracted during the period, and the mill pays the farmers for the fruits delivered. Synthesizing insights from the disciplines of development economics, operations and finance, we identify a set of assumptions that make the dynamic game analytically tractable (see Related Literature). In the unique equilibrium, the mill sets a "pass-through price:" the fruit price is a fixed fraction of the oil price plus a constant. This provides theoretical backing for pass-through pricing, which is common in practice (see Related Literature). Most importantly, we find that shortening the payment delay increases the equilibrium productivity and consumption of every farmer, and increases the profitability of the mill and (if the buyer's discount rate is not too large) of the buyer.

However, we prove that reducing payment delay also stimulates farmers to engage in deforestation, and farmers with the least land have the greatest propensity to do so. This underscores the challenge faced by a buyer committed to improve the welfare of smallholder farmers and to halt deforestation.

Moreover, this shows that to meet its dual commitments, the buyer should eliminate payment delay *only* as a reward for forest protection, and prompts the question of how to formulate the requirement for forest protection.

We propose village-level requirements, motivated by our second field observation and advances in remote sensing technology. Interviewing smallholder farmers in Indonesia, we learned that they cooperate to prevent fires in their village from spreading. While they might not observe who initiated the fire, they are able to observe whoever is illegally establishing a new palm plantation on the deforested land. Moreover, they would be able to prevent the illegal plantation from developing, allowing the forest to regenerate. In contrast, an outsider would have great difficulty observing and halting the establishment of illegal plantations through deforestation. Therefore, smallholders farming within a village would be able to prevent illegal deforestation and production in their village better than any outsider. Due to recent improvements in remote sensing, a buyer could also easily monitor whether or not deforestation occurs in a particular village (see §7). These observations motivate us to propose the following two requirements: reward all farmers in a village if no deforestation occurs in their village (*'village-level no-deforestation requirement'*) or reward all farmers in a village for preventing any fruit production on illegally-deforested land in their village, thus allowing forests to regenerate (*'village-level regeneration requirement'*). We also consider the approach currently attempted by buyers, to individually reward each farmer who does not engage in deforestation (*'farmer-level no-deforestation requirement'*).

To determine which candidate requirement best prevents deforestation, we analyze a cooperative game in partition function form, where farmers in a village can form coalitions that decide (i) whether to engage in deforestation, and (ii) whether to prevent fruit production on land deforested by other farmers. Our cooperative game has multiple equilibria, so we identify the conditions under which a candidate requirement is *guaranteed* to protect the forest, *i.e.*, no deforestation occurs in any equilibrium. Using this analysis, we prove that the village-level regeneration requirement best protects forests and, in particular, strictly outperforms a farmer-level requirement. The superiority of the village-level regeneration requirement is due to farmers' ability to monitor and influence each other, and the heterogeneity in farmers' welfare gains from elimination of payment delay.

Based on these field observations and analytic results, we propose that buyers reward all farmers in a village by eliminating payment delay *if* no production occurs on any illegally-deforested land in the village. Parameterizing our model with field data, we find that our proposal could substantially improve welfare for farmers, widely prevent deforestation, and prevent deforestation in substantially more villages than the farmer-level approach. Beyond palm oil in Indonesia, our insights of eliminating payment delay and engaging villages apply to other commodities and geographies (see §7).

Related Literature. Environmental science literature documents that production of agricultural commodities is the dominant driver of illegal deforestation in developing countries (*e.g.*, Carlson et al. 2018, Defries et al. 2010, Geist and Lambin 2002). As weak governments struggle to enforce forest protection, buyers of agricultural commodities are increasingly held responsible for such forest protection (GCP 2016). Our work provides guidance for these firms.

We focus on advancing livelihoods of, and forest protection by, independent smallholder farmers. Extensive information about smallholder palm oil farmers in Indonesia is in Daemeter (2016a). Gatto et al. (2017) provide a historical account of smallholder farmers in Indonesia; in their study's province, the share of land in palm production that is cultivated by independent smallholders increased from 5% in 1992 to 74% in 2012. Higgins et al. (2018) provide an excellent exposition of how Indonesia's political environment has spurred rapid expansion by independent smallholder farmers in forests, and document the challenges for government to monitor and enforce environmental laws. They also provide a political-economy argument for the engagement of villages to protect forests. Other work has focused on forest protection by industrial-scale corporate plantations, primarily through a third-party certification scheme developed by the Roundtable for Sustainable Palm Oil (RSPO) (*e.g.*, Carlson et al. 2018 show RSPO's beneficial impact in corporate plantations). However, certifying smallholders with RSPO has proven prohibitively expensive and cumbersome (Saadun et al. 2018, Nicholas 2018). We propose an alternative: motivate smallholder farmers to protect the forest in their village by offering, as a reward, to eliminate payment delay in their supply chain.

In doing so, we extend the literature on responsible supply chain management by considering small (farmer) suppliers in a developing country that can monitor and enforce other suppliers' responsibility. Whereas many papers in this literature model the interaction between one buyer and one supplier (*e.g.*, Kraft et al. 2017, Chen and Lee 2016, Plambeck and Taylor 2016), few share some of our model's main features such as a supply chain with multiple tiers (Huang et al. 2017 and Zhang et al. 2017) or many (farmer) suppliers (Lewis et al. 2017 and Levi et al. 2017). Empirical work documents numerous difficulties in monitoring and enforcing responsibility of farmers (Huang et al. 2017) and factories (Caro et al. 2016, Short et al. 2016, Locke 2013) in developing economies. To the best of our knowledge, our paper is the first to model a multi-tier supply chain with many small (farmer) suppliers in a developing country, and the first to consider engaging suppliers in monitoring and enforcing other suppliers' responsibility.

Literature on joint liability in microlending shows that farmers can monitor and enforce responsible behavior—*i.e.*, loan repayment—in their community (see Banerjee 2013 for a recent review). Under basic joint liability, community members receive individual loans but future loan availability is contingent on repayment by all members. This joint liability—similar in spirit to our village-level requirements—induces community members to use social capital (local information and social punishment) to monitor and enforce loan repayment.

To model farmers' engagement in protecting forests under a village-level requirement, we develop a cooperative game in partition function form in §5. Fang and Cho (2016) develop a cooperative game in partition function form to analyze information sharing by multiple buyers with one common supplier, and provide an up-to-date survey of operations and supply chain management literature that employ cooperative game theory. We refer readers to Ray and Vohra (2015) for a relevant review of cooperative game theory, and Ichiishi (1981) for insights regarding equilibria in cooperative games in partition function form.

To model a farmer's dynamic production decisions, we synthesize insights from operations-finance and development economics. The former literature typically models a firm's dynamic production decisions under limited cash inventories, like our paper, but without game theoretic analysis of supply chain interactions; see Li et al. (2013) and Ning and Sobel (2017) for model formulations most closely related to ours. Like our model, some of this literature uses a quadratic production cost function (*e.g.* Bolton et al. 2013, Tang et al. 2014). Farmers in our model also experience Gaussian shocks in their production costs, which can cause farmers to borrow from friends and family, as reported in the development economics literature (*e.g.* Collins et al. 2009). Development economists have documented how smallholder farmers have limited access to formal banking and, instead, borrow and lend informally within their community (Duflo and Banerjee 2011, Collins et al. 2009), paying interest rates that increase with loan size; we adopt an exponential function to model interest payments by farmers (*e.g.* Ghosh et al. 2000).

Due to the exponential interest function and the quadratic production cost function with Gaussian shocks, a farmer's optimization problem has features of both a Linear-Quadratic Gaussian (LQG) and a Linear-Exponential-Quadratic Gaussian (LEQG) control problem. In both those problems, the optimal decision is linear in the state (*e.g.* Bertsekas 2005); we prove an analogous result—that production is linear in the offered price—in our more general setting.

The linearity of the farmer's production rate in the offered price enables us to characterize the unique subgame perfect equilibrium of the game between heterogeneous farmers and the mill. Whereas Federgruen et al. (2017) recommend using a complex menu of contracts in sourcing from heterogeneous farmers under asymmetric information, we find that the mill optimally sets a single price for all farmers, which does *not* depend on the heterogeneous characteristics of farmers about which each farmer would naturally have private information. In equilibrium, the mill uses a pass-through pricing scheme. That is consistent with empirical evidence documenting that many palm oil mills use pass-through pricing (*e.g.*, in Jelsma et al. 2009) and provides theoretical motivation for academic literature that *assumes* that a processor uses pass-through pricing (*e.g.* Boyabatli 2015).

Finally, by tying payment timing to supplier responsibility, we extend the supply chain finance literature to consider the role of financing in advancing supplier responsibility. Theoretical literature examines how trade credit influences a firm's inventory policy (Haley and Higgins 1973), and ability to share demand risk (Yang and Birge 2017), signal product quality (Babich and Tang 2012, Tunca and Zhu 2017) or reduce moral hazard (Chod 2016). Several papers consider new financing models in supply chains with small suppliers; Tang et al. (2018), Tunca and Zhu (2017) and Chen and Gupta (2014) study buyers issuing loans directly to suppliers ("buyer-direct financing"), whereas Sodhi and Tang (2012) and Tanrisever et al. (2015) study reverse factoring—wherein small suppliers obtain immediate payment for accounts receivable from a bank, and the buyer is responsible for settling that debt with the bank. Reverse factoring is currently impractical in our field sites, but could otherwise be readily combined with our proposal.

2. Model formulation

We model the interaction between a population of F farmers, their local mill, and a buyer. Periodically, the buyer pays the mill the market price for a delivery of oil, and the mill pays the farmers for the fruit processed to make that oil. Let $\tau > 0$ denote the period of time between payments, and $\mathcal{P}_s$ the market price of oil at time $s \geq 0$, assumed to be a Brownian motion with zero drift and volatility ν^2. (We motivate that assumption and other modeling assumptions in §2.1.) This section formulates the dynamic game between the farmers and the mill, parameterized by τ. In subsequent extensions, §4 formulates the buyer's choice of τ, and §5 formulates the buyer's candidate requirements for farmers to protect forests, farmers' deforestation decisions and their associated cooperative game.

We assume that the farmers and the mill know the parameters, assumptions, objectives and decisions described in this section. However, we will prove that in the unique subgame perfect Nash equilibrium, each party only uses information that it would actually know in practice.

Consider a time interval $[0, D]$ divided into payment periods of length τ. We refer to the time interval $\big[(n-1)\tau, n\tau\big)$ as the n-th payment period, and use $N := \frac{D}{\tau}$ to denote the number of periods. For each $n \in \{1, \ldots, N\}$, at the beginning of the n-th payment period, *i.e.* at time $(n-1)\tau$, the mill observes the market price of oil $\mathcal{P}_{(n-1)\tau}$ and sets the per-unit price p_n for any fruit delivered during the period, to be paid at the end of the period, *i.e.* at time $n\tau$. Each farmer $f \in \{1, \ldots, F\}$ starts the n-th payment period with an initial cash position x_n^f, which includes the payment just received for fruit deliveries during the previous period. By assumption $x_1^f = 0$. Having observed the mill's fruit price p_n, each farmer f chooses a rate of expenditure on consumption c_n^f (per unit time) and a production rate $r_n^f \geq 0$ (per unit land per unit time) for the n-th payment period. Farmer f continuously delivers the perishable fruit to the mill at a rate of $r_n^f \ell^f$ per unit time, wherein ℓ^f is farmer f's area of productive land. During the n-th payment period, the farmer thus produces a total amount of fruit $r_n^f \ell^f \tau$, and spends $c_n^f \tau$ on consumption. At the end of the payment period, the mill receives a payment from the buyer, and pays $(r_n^f \ell^f \tau) p_n$ to each farmer f for his fruit deliveries.

Farmer f's cash position at the end of period n is:

$$x_{n+1}^f = x_n^f + \underbrace{(r_n^f \ell^f \tau) p_n}_{\text{revenue from fruit}} - \underbrace{c_n^f \tau}_{\text{consumption}} - \underbrace{\big(r_n^f \mathcal{W}_n^f + (r_n^f)^2 q\big) \ell^f \tau}_{\text{fruit production and delivery cost}} - \underbrace{(e^{-\alpha\tau x_n^f} - 1).}_{\text{interest payments}} \tag{1}$$

Therein, the fruit production and delivery cost accumulated during period n is:

$$\big(r_n^f \mathcal{W}_n^f + (r_n^f)^2 q\big) \ell^f \tau, \tag{2}$$

with q a non-negative constant and $\mathcal{W}_n^f$ a normally distributed random variable with mean k and variance σ^2, realized during period n. The vector of all the farmers' cost shocks $(\mathcal{W}_n^1, \ldots, \mathcal{W}_n^F)$ is independent and identically distributed over periods $n = 1, \ldots, N$. The cost shocks may be correlated across farmers; ρ^{ij} denotes the correlation between $\mathcal{W}_n^i$ and $\mathcal{W}_n^j$ for $i, j \in \{1, \ldots, F\}$ with $i \neq j$.

The interest payments in (1), due at the end of period n, capture that smallholder farmers borrow and lend cash informally within their community. If a farmer spends beyond his available cash ($x_n^f < 0$), he must borrow from community members and, likewise, he can loan excess cash ($x_n^f > 0$) to community members. The exponential function reflects that borrowing more cash increases the marginal interest rate paid, as farmers prioritize the best opportunities for borrowing. Analogously, lending more cash decreases the marginal interest rate received, as farmers prioritize the best opportunities for lending.

Each farmer's objective is to maximize expected discounted consumption:

$$\mathbb{E}\left[\int_0^{(N+1)\tau} e^{-t\beta^f} c_{\lceil t/\tau \rceil}^f dt\right], \tag{3}$$

subject to his cash dynamics in (1) and terminal condition $c_{N+1}^f = \big(x_{N+1}^f - (e^{-\alpha\tau x_{N+1}^f} - 1)\big)/\tau$, corresponding to the consumption of any remaining cash net of interest payments during the terminal period $N+1$. β^f denotes farmer f's discount rate, and is assumed to satisfy $\frac{4}{5}\beta^f \geq \alpha$. Henceforth, for brevity, we refer to a farmer's expected discounted consumption in (3) as the farmer's *welfare*.

The mill receives fruit from farmers at a rate $r_n = \sum_{f=1}^F r_n^f \ell^f$ per unit time, and continuously processes the fruit to extract oil with a deterministic process yield $y \in (0,1)$. At the end of the n-th payment period, *i.e.* at time $n\tau$, the mill delivers a batch of oil of size $(r_n\, y)\tau$ to the buyer, receiving market price $\mathcal{P}_{n\tau}$ per unit oil delivered. We assume that the expected process yield and oil price are large enough to warrant production in the supply chain, *i.e.* $k < \mathcal{P}_s\, y$ for $s \geq 0$.

The mill's objective is to maximize expected discounted profit:

$$\mathbb{E}\left[\sum_{n=1}^N e^{-\kappa n\tau} r_n(p_n)\tau\Big(y\mathcal{P}_{n\tau} - p_n\Big)\right] \tag{4}$$

wherein $\kappa \in (0,1)$ is the mill's discount rate.

2.1. Discussion of Modeling Assumptions

Farmers make decisions about consumption and production at the time they are paid. This assumption, which renders our analysis tractable, is also rooted in practice. Farmers typically cannot adjust their production rate continuously because it is often challenging to deviate from a given harvesting schedule (*e.g.* by hiring new laborers). Similarly, cash-strapped consumers in developing countries often budget a fixed amount of money for consumption over multi-day periods (see, *e.g.* Uppari et al. 2017). The most natural point in time for a farmer to adjust his rate of production or consumption is exactly at the time of a cash inflow (Collins et al. 2009), as in our model.

Production and delivery cost function. A primary explanation for the convexity in a farmer's cost function, represented by the term $q(r_n^f)^2$ in (2), is that a farmer's labor costs are convex increasing in his production rate. Palm fruit grows continuously throughout the year; by harvesting more frequently during a period, which requires more labor, the farmer can pick fruit at its peak ripeness and thereby increase the weight of fruit delivered to the mill during the period. In contrast, with infrequent harvesting, the farmer collects a mixture of fruits that are unripe and overripe, which results in a lower weight of acceptable fruit delivered to the mill. Overripe fruit is rejected by the mill because it contains a high concentration of free fatty acids that would make the oil output ('Crude Palm Oil,' see below) unsalable in the international market. Unripe fruit weighs less, even if the mill accepts it. For these reasons, the production rate has decreasing returns to harvesting frequency, *i.e.* is concave (increasing) in harvesting frequency. On the other hand, labor costs are linear in harvesting frequency. Hence, labor costs are convex increasing in the production rate.

A primary explanation for a farmer's cost shocks, represented by the Gaussian term $\mathcal{W}_n^f r_n^f$ in (2), is that smallholder farmers face shocks in the delivery cost per unit fruit delivered to a mill. Specifically, when unpaved roads turn muddy after rain, a farmer incurs additional costs for fruit transportation due to the need for additional gas and vehicle maintenance, as well as loss of productive time. Figure 2 in the Appendix shows our vehicle stuck on an unpaved road after rain, which stranded our survey team for two days. Figures (3a)-(3b) in the Appendix show receipts from farmers who use the same transport provider; the transport provider passes through the per-unit fruit price of the mill and— when road conditions are poor— charges a farmer for the additional transport cost per-unit fruit, accordingly. The farmer experiences these cost shocks after making production and delivery commitments, possibly forcing him to borrow from friends and family, as reported in the development economics literature.

Additional, empirical motivation for the functional form and distribution of the production and delivery costs in (2) is provided in §6.

The oil price is a Brownian motion with zero drift. This assumption approximates reality. Statistical tests confirm that the price increments for oil extracted from palm fruit (technically referred to as Crude Palm Oil, CPO) are normally distributed with zero mean and are a stationary, finite-variance process (see Figure 1 in the Appendix). While our assumption $k < \mathcal{P}_s y$ would in theory be violated with non-zero probability by a Brownian motion oil price, it is sensible in view of historical price data (this probability is very small, see §6), and makes our analyses tractable.

Negative consumption. Our model allows farmer consumption c_n^f to become negative, which captures the farmer's ability to borrow food from family and community members. As documented in Collins et al. (2009), such situations occur in practice, but farmers dislike such reliance on friends and family, as captured by the farmer's objective in (3) becoming negative when consumption is negative. This assumption makes the analysis tractable.

Exponential function for interest payments. Farmers pay higher interest rates for larger loans (see Related Literature and §6), and we use the exponential function to capture this.

Though our exponential function is primarily motivated by the informal loans that occur in our field sites, it could also represent formal financing for small loans in that (1) approximates compounded interest near zero, *i.e.* $(e^{-\alpha\tau x_n} - 1) \approx (-x_n)[(1+\alpha)^\tau - 1]$ when $x_n \approx 0$.

Many of our results rely on the accepted assumption that no farmer would choose to forgo current consumption solely in order to lend money and use the earned interest for future consumption, *i.e.*, $\alpha \le (e^{\beta^f \tau} - 1)/\tau$ for all f. Only the results in Theorem 2 require the slightly stronger condition $\alpha \le \frac{4}{5}\beta^f$ for all f, which is our stated assumption. Using the field data described in §6, we confirm that these bounds are readily satisfied in practice.

Processors are not capacity constrained. Field research revealed that palm oil mills and refineries in Indonesia all operate with excess capacity. Interviewees reported mill utilization of 50-60% and refinery utilization of 70%, on average (personal communication 2016).

3. Status quo

Theorem 1 characterizes the equilibrium of the dynamic game between the mill and farmers.

THEOREM 1. *In the unique subgame perfect Nash equilibrium, in each period $n = 1, \ldots, N$, the mill sets price:*

$$p_n(\mathcal{P}_{(n-1)\tau}) = \frac{y\,\mathcal{P}_{(n-1)\tau} + k}{2} \tag{5}$$

and farmer f sets production rate and consumption rate:

$$\begin{aligned} r_n^f &= (p_n - k)/\big(2q + \alpha(1 - e^{-\beta^f \tau})\tau^2 \ell^f \sigma^2\big) \\ c_n^f &= \big(x_n^f - (e^{-\alpha\tau x_n^f} - 1) - \big(r_n^f k + (r_n^f)^2 q\big)\tau \ell^f - g_n^f(p_n)\big)/\tau. \end{aligned} \tag{6}$$

A closed form expression for the function $g_n^f(\cdot)$ is in (A.7) in the Appendix.

Remarkably, the equilibrium fruit price p_n does not depend on a farmer's discount rate β^f or land area ℓ^f. To strengthen that key insight, the proof of Theorem 1 allows for the mill to offer a different price p_n^f to each farmer that depends on the farmer-specific parameters (β^f, ℓ^f). Nevertheless, in equilibrium, the mill optimally sets the same fruit price for every farmer, regardless of β^f and ℓ^f. The reason for this independence is that β^f and ℓ^f only have a multiplicative effect on a farmer's optimal production rate and the mill's expected profit. That the equilibrium fruit price does not depend on β^f or ℓ^f is of great practical importance because farmers differ greatly in these two parameters, as we observed in our field research (see §6.1). Moreover, in practice, thousands of smallholder farmers supply a mill, and measuring every farmer's discount rate and land area in order to price accordingly would be difficult and costly for the mill. Hence the simplicity of the single optimal price for all farmers is appealing from a practical implementation perspective.

In equilibrium, the mill uses a "pass through" pricing scheme: in each period n, the mill sets the fruit price p_n equal to a fixed fraction of the market price for oil $\mathcal{P}_{(n-1)\tau}$ plus a constant. Such "pass through" pricing schemes are common in practice (Jelsma et al. 2009). In this setting, the fraction is half the mill's expected yield (y) and the constant is half the mill's expectation of the linear component of a farmer's marginal cost (k).

A farmer's best response has a simple structure: his production rate depends on the outstanding fruit price (p_n) but not his cash position, whereas his consumption depends on both the outstanding fruit price (p_n) and his cash position (x_n). A farmer's best response retains this simple structure in a generalized model with any convex increasing production cost function and any convex decreasing interest payment function, provided that the mill uses some sort of pass-through pricing scheme.

Theorem 2 shows the effect of payment delay on a farmer's productivity and welfare, and other comparative statics. "Productivity" is a farmer's expected production per unit land per unit time.

THEOREM 2. *Farmer f's equilibrium productivity $\mathbb{E}[\int_0^D r^f_{\lceil s/\tau \rceil} ds]/D$ and welfare decrease with τ, α, σ, q, and k. Farmer f's productivity decreases with ℓ^f but his welfare increases with ℓ^f.*

Consistent with the empirical findings in Barrot and Ramana (2017) that reducing payment delay benefits small suppliers, Theorem 2 shows that payment delay (τ) has a negative impact on a farmer's productivity and welfare. The rationale is that payment delay limits the ability of a liquidity-constrained farmer to invest cash in farm productivity. With a longer payment delay τ, the farmer has less cash and also reserves more of that cash to cover any adverse cost shocks during the payment period. Relatedly, as σ increases, meaning that a farmer's production costs become more uncertain, the farmer invests less in farm productivity; Karlan et al. 2014 provide experimental evidence that reducing uncertainty in cash flows increases investments by farmers.

Theorem 2 also confirms that, as one might expect, increasing the cost of borrowing (α) or production costs (k, q) causes the farmer to invest less in farm productivity and reduces his welfare.

The more subtle insight is that a farmer with more land has lower productivity. The rationale is that with limited cash and a larger farm, he invests less on a per acre basis to improve productivity. Despite that lower productivity, a farmer with more land has higher welfare.

Theorem 2 suggests that a buyer committed to improve farmers' welfare should *eliminate payment delay*. To eliminate payment delay is, in our model, to reduce the length of the payment period from the status quo level $\tau = \tau_{sq}$ to $\tau = 1$. In practice, D can be interpreted as the number of Days and $\tau = 1$ is the minimum feasible length for a payment period, corresponding to same-day payment for a farmer for fruit delivered to a mill.

4. Eliminating payment delay creates value for all

Now suppose that the buyer and mill eliminate payment delay (set $\tau = 1$).

The schedule on which the mill delivers oil to the buyer does not change. At each time $n\tau_{sq}$ for $n = 1, \ldots, \frac{D}{\tau_{sq}}$, the mill delivers to the buyer all oil produced since the last delivery at time $(n-1)\tau_{sq}$.

For purposes of implementation, one should interpret this scheme in the following manner. On each day, the buyer pays the mill for the oil the mill produced that day, and the mill pays the farmers for the fruits delivered that day, from which the oil was made. Every τ_{sq} days, the mill delivers the accumulated oil to the buyer.

The buyer operates a refinery and sells refined oil. We use $\mathcal{P}^r_s$ to denote the per-unit market price for refined oil at time s, and assume that $\mathcal{P}^r_s := K\mathcal{P}_s$, $K \geq 1$; Figure 1 in the Appendix and §6.1 provide motivation for those assumptions. Hence the buyer's expected discounted profit is given by:

$$\mathbb{E}\left[\sum_{n=1}^{D/\tau_{sq}} \sum_{m=((n-1)\tau_{sq})/\tau}^{(n\tau_{sq}/\tau)-1} \left(e^{-\delta n\tau_{sq}}\mathcal{P}^r_{n\tau_{sq}} - e^{-\delta(m+1)\tau}\mathcal{P}_{(m+1)\tau}\right) yr_{m\tau}\tau\right].$$

Theorem 3 shows that eliminating payment delay is optimal for the buyer (provided that the buyer's discount rate, denoted by δ, is not too high) and is always optimal for the mill.

THEOREM 3. *There exists a threshold $\overline{\delta} > 0$ such that if $\delta \leq \overline{\delta}$ then eliminating payment delay increases the buyer's expected discounted profit. Eliminating payment delay increases the expected discounted profit of the mill.*

The mechanism is that with earlier payment, farmers become more productive (for reasons explained in the paragraph after Theorem 2), which increases the quantities supplied to the mill and buyer, and hence their revenues. However, the buyer's expected discounted costs increase due to the earlier payment, and this effect is amplified for a larger discount rate δ. In §6, we estimate the buyer's discount rate $\hat{\delta}$ and find that $\hat{\delta} < \overline{\delta}$ readily holds in practice.

Hence we conclude from Theorem 2 and Theorem 3 that eliminating payment delay benefits *all* members of the supply chain: buyer, mill, and farmers.

5. Halting deforestation in the supply chain

This section incorporates farmers' deforestation decisions and provides insights for the buyer on how to halt such deforestation in its supply chain. §5.1 shows that simply eliminating payment delay would stimulate farmers to convert *more* forest into farm land. Therefore, §5.2 considers eliminating payment delay contingent on forest protection. In other words, farmers would earn a reward—elimination of payment delay—if and only if they meet a specified forest-protection requirement. §5.2 evaluates three candidates for the forest-protection requirement and identifies the conditions under which each halts deforestation. The best-performing candidate is a *village-level requirement*, meaning that all the farmers in a village earn the reward if and only the entire village meets the forest-protection requirement.

5.1. Decision to convert forest into farm land

We now allow each farmer to decide how much forest to convert into farm land, before the onset of the dynamic game formulated in §4. At time 0, a farmer f is endowed with farm land $\ell_e^f \geq 0$ and can deforest and develop additional land ℓ_d^f to expand his farm, at a cost $c_d(\ell_d^f)$ assumed to be lower semi-continuous and coercive in its argument. Thereafter, farmer f has productive area $\ell^f = \ell_e^f + \ell_d^f$. Let $J^f(\ell^f, \tau)$ denote farmer f's expected discounted consumption in the unique equilibrium of the dynamic game characterized by Theorem 1, as a function of his productive area ℓ^f and the length of the payment period τ. To maximize his expected discounted consumption ("welfare" for brevity), farmer f chooses the area l_d^f to deforest and develop into farm land according to

$$\max_{\ell_d^f \geq 0} \left[J^f(\ell_e^f + \ell_d^f, \tau) - c_d(\ell_d^f) \right]. \tag{7}$$

Theorem 4 shows how the payment period length (τ) and a farmer's idiosyncratic characteristics (β^f, ℓ_e^f) influence how much land the farmer chooses to deforest and develop into farm land (hereafter abbreviated "deforest").

Theorem 4. *The set of optimal solutions to* (7) *is non-empty and compact, and decreases in* τ, ℓ_e^f, *and* β^f.

The decrease is in the usual induced set order defined in Topkis 1998.

One insight from Theorem 4 is that farmers are heterogeneous in their propensities to engage in deforestation. A farmer with more endowed land (higher l_e^f) is less inclined to engage in deforestation because, having limited cash, he receives decreasing returns from additional land. A farmer who cares relatively less about future consumption (has higher β^f) is less inclined to incur the initial deforestation cost in order to increase his future production and income.

Most importantly, Theorem 4 shows that eliminating payment delay—which makes land more valuable for a farmer—would *stimulate* deforestation. That motivates the next section.

5.2. Forest-protection requirements and associated cooperative games

Suppose that the buyer commits to eliminate payment delay for a farmer if and only if the farmer is compliant with a specified forest-protection requirement. We consider the three candidate requirements in the bullet list below. The first applies to an individual farmer, whereas the other two are defined at the level of a village; $\mathcal{V} \subseteq \{1, \ldots, F\}$ denotes the set of farmers in the focal village.[3]

- *Farmer-level no-deforestation requirement ($\mathbb{F}$):* Farmer f is compliant if and only if he does not engage in deforestation, i.e., $\ell_d^f = 0$.
- *Village-level no-deforestation requirement ($\mathbb{V}$):* All farmers in a village are compliant if and only if no deforestation occurs in the village, i.e., $\ell_d^f = 0$ for all farmers $f \in \mathcal{V}$.
- *Village-level regeneration requirement ($\mathbb{R}$):* All farmers in a village are compliant if and only if no deforestation occurs in the village ($\mathbb{V}$) <u>or</u> forest regenerates on any deforested land in the village. (Farmers can enable the forest to regenerate by preventing fruit production on deforested land.)

We next identify which of these requirements would allow the buyer to best prevent deforestation.

Under the *farmer-level requirement* $\mathbb{F}$, farmer f's optimal amount of land to deforest is the solution to (7) with payment period of length:

$$\tau(\ell_d^f) = \begin{cases} \tau_{sq} & \text{if } \ell_d^f > 0, \\ 1 & \text{if } \ell_d^f = 0. \end{cases} \tag{8}$$

Recall from §4 that to eliminate payment delay is to reduce the length of the payment period from the status quo $\tau = \tau_{sq}$ to $\tau = 1$, corresponding to same-day payment for a fruit delivery, which increases the farmer's welfare. Hence the contingency in (8) incentivizes the farmer to protect the forest (set $\ell_d^f = 0$). An optimal solution exists (as an immediate corollary to Theorem 4) but is not necessarily unique. Henceforth we make the conservative assumption that, in the event that a farmer's optimal amount of land to deforest is not unique, the farmer deforests the maximal optimal amount of land. Let ℓ_d^{f*} denote the maximal optimal solution to (7).

Each *village-level requirement* causes a farmer's welfare and optimal decisions to depend on the decisions of the other farmers in his village. In reality, farmers in a village are able to cooperate and transfer cash or goods for consumption. Therefore, we will analyze each village-level requirement by formulating a cooperative game with transferable utility in partition function form.

[3] In practice, $\mathcal{V}$ is a strict subset of $\{1, \ldots, F\}$ because farmers from many villages supply a mill.

We need the following notation. A *coalition* S is any subset of the set $\mathcal{V}$ of farmers in the village. A *partition* π is any ordered set[4] of coalitions $\{S_i, i=1,\ldots,c\}$ such that $\bigcup_{i=1}^{c} S_i = \mathcal{V}$ and $S_i \cap S_j = \emptyset$ for all $i \neq j$. We denote the size of a coalition S by $|S|$, the number of coalitions in a partition π by $|\pi|$, and the set of all partitions by Π. The significance of a coalition is that farmers within a coalition act cooperatively to maximize their joint welfare, whereas each coalition acts in a noncooperative manner vis a vis the other coalitions of farmers.

We first formulate the game under the *village-level no-deforestation requirement* $\mathbb{V}$. Consider any partition π of the $\mathcal{V}$ farmers in the village into coalitions. In each coalition $S_i \in \pi$, the farmers jointly decide whether to coordinate on forest protection. Formally, each coalition S_i chooses $d_i \in \{0,1\}$, where $d_i = 0$ denotes a decision to protect the forest (set $l_d^f = 0$ for all $f \in S_i$, meaning that no farmer in the coalition engages in deforestation). Otherwise, if $d_i = 1$, each farmer $f \in S_i$ engages in his individually optimal amount of deforestation ℓ_d^{f*} anticipating the length of the payment period in the status quo τ_{sq}. The decisions d_i of all coalitions $S_i \in \pi$ jointly determine the length of the payment period, according to:

$$\tau(\pi, d_1, \ldots, d_{|\pi|}) = \begin{cases} \tau_{sq} & \text{if } \sum_{i=1}^{|\pi|} \sum_{f \in S_i} d_i \ell_d^{f*} > 0, \\ 1 & \text{otherwise.} \end{cases} \tag{9}$$

Each coalition $S_i \in \pi$ would therefore seek to maximize the joint welfare of its farmers, given beliefs about whether or not the other coalitions will protect the forest. A Nash equilibrium associated with partition π is a vector of decisions $(d_1^*, \ldots, d_{|\pi|}^*)$ with

$$d_i^* \in \underset{d_i \in \{0,1\}}{\arg\max} \sum_{f \in S_i} \left[J^f\left(l_e^f + d_i\, l_d^{f*},\, \tau(\pi, d_1^*, .., d_{|\pi|}^*) \right) - c_d(d_i\, l_d^{f*}) \right] \tag{10}$$

wherein the length of the payment period τ is given by (9). For $\pi = \{\mathcal{V}, \emptyset\}$, (10) becomes a regular optimization problem solved by the grand coalition $\mathcal{V}$. Observe that for any partition π having two or more coalitions, $d_i^* = 1$ for all coalitions $S_i \in \pi$ is a Nash equilibrium, but not necessarily the unique Nash equilibrium. This implies that a *partition function*, defined next, exists but is not necessarily unique.

Definition 1 (Partition Function). A *partition function* is a real-valued function $w(S_i, \pi)$ defined on the set of pairs $\{(S_i, \pi) : S_i \in \pi, \pi \in \Pi\}$ with $w(S_i, \pi) = \sum_{f \in S_i} \left[J^f(l_e^f + d_i^*\, l_d^{f*},\, \tau(\pi, d_1^*, .., d_{|\pi|}^*)) - c_d(d_i^*\, l_d^{f*}) \right]$ for some $(d_1^*, \ldots, d_{|\pi|}^*)$ satisfying (10).

In other words, a partition function w evaluated at (S_i, π) yields the welfare of the coalition of farmers S_i in a Nash equilibrium associated with the partition π containing the coalition S_i.

[4] Any ordering is allowed, but must be applied consistently so that the ordering of coalitions in a partition is uniquely defined.

The farmers within a coalition can allocate their joint welfare in any efficient manner. Formally, given a partition π and partition function $w(S_i, \pi)$, each coalition $S_i \in \pi$ can choose any allocation $\{a_f(\pi, w)\}_{f \in S_i}$ for which $\sum_{f \in S_i} a_f(\pi, w) = w(S_i, \pi)$. For an allocation and partition to occur in equilibrium, there must be no *objection* to that allocation and partition.

Definition 2 (Objection). Given a partition function w, partition $\pi = \{S_1, S_2, \ldots, S_{|\pi|}\}$ and allocation a, we say that S_i' has an *objection* to π and a if $w(S_i', \pi') > \sum_{f \in S_i'} a_f(\pi, w)$, where $\pi' = \{S_1 \backslash S_i', S_2 \backslash S_i', \ldots, S_{|\pi|} \backslash S_i', S_i'\}$.

In other words, the objection would be raised by a group of farmers that could obtain strictly higher welfare by forming a different coalition, under partition function w.

We are now prepared to define an *equilibrium* of the cooperative game in partition function form under the village-level no-deforestation requirement.

Definition 3 (Equilibrium). An *equilibrium* is characterized by a partition function w, a partition π, the associated decisions whether to protect the forest $(d_1^*, \ldots, d_{|\pi|}^*)$ and an allocation a, to which no objection exists.

Let us now formulate the game under the *village-level regeneration requirement* $\mathbb{R}$. This is identical to the game under the village-level no-deforestation requirement, except that now a coalition may choose to incur cost $\eta > 0$ to "block" a farmer f who deforested land $l_d^{f*} > 0$ from illegally producing fruit on that land, enabling the forest to regenerate.

Consider any partition π of the farmers in $\mathcal{V}$ into coalitions. As before, each coalition $S_i \in \pi$ of farmers makes a forest-protection decision $d_i \in \{0, 1\}$. Then each coalition of farmers $S_i \in \pi$ observes the set of farmers who have engaged in deforestation $\{f : f \in S_j, S_j \in \pi \text{ and } d_j\, \ell_d^{f*} > 0\}$ and decides whether or not to block such farmers. We represent this blocking decision by a vector $\mathbf{b}_i \in \{1, 0\}^{|\mathcal{V}|}$ with elements $b_{if} = 1$ indicating that coalition S_i blocks farmer $f \in \mathcal{V}$.[5] Forest regenerates on any land deforested by farmer f if and only if $\max_{j \in \{1,..,|\pi|\}} b_{jf} = 1$, indicating that some coalition blocks farmer f. Therefore the forest-protection decisions d_i *and* subsequent blocking decisions b_{if} for all coalitions $S_i \in \pi$ jointly determine the length of the payment period, according to:

$$\tau(\pi, d_1, \ldots, d_{|\pi|}, \mathbf{b}_1, ..., \mathbf{b}_{|\pi|}) = \begin{cases} \tau_{sq} & \text{if } \sum_{i=1}^{|\pi|} \sum_{f \in S_i} d_i \ell_d^{f*} (1 - \max\limits_{j \in \{1,..,|\pi|\}} b_{jf}) > 0, \\ 1 & \text{otherwise.} \end{cases} \tag{11}$$

[5] For ease of exposition, we allow any coalition to block any farmer. In equilibrium, however, a coalition that does not protect the forest will never block farmers, and no farmer who does not engage in deforestation is blocked. This will become apparent in the proof of Theorem 5.

A sequential equilibrium associated with partition π is a set of forest-protection decisions $(d_1^*,\ldots,d_{|\pi|}^*)$ and blocking decisions $(\mathbf{b}_1^*(d_1,\ldots,d_{|\pi|})),\ldots,\mathbf{b}_{|\pi|}^*(d_1,\ldots,d_{|\pi|}))$ such that for all $i\in\{1,\ldots,|\pi|\}$ and $(d_1,\ldots,d_{|\pi|})$:

$$\mathbf{b}_i^*\in\underset{\mathbf{b}_i\in\{0,1\}^{|\mathcal{V}|}}{\arg\max}\sum_{f\in S_i}\left[J^f\left(l_e^f+d_i\,l_d^{f*}(1-\max_{j\in\{1,..,|\pi|\}}b_{jf}^*),\,\tau(\pi,d_1,..,d_{|\pi|},\mathbf{b}_1^*,...,\mathbf{b}_{|\pi|}^*)\right)\right]-\sum_{f\in\mathcal{V}}\eta\,b_{if}\tag{12}$$

$$d_i^*\in\underset{d_i\in\{0,1\}}{\arg\max}\sum_{f\in S_i}\left[J^f\left(l_e^f+d_i\,l_d^{f*}\big(1-\max_{j\in\{1,..,|\pi|\}}b_{jf}^*(d_1^*,...,d_{|\pi|}^*)\big),\,\tau(\pi,d_1^*,..,d_{|\pi|}^*,\mathbf{b}_1^*,...,\mathbf{b}_{|\pi|}^*)\right)-c_d(d_i\,l_d^{f*})\right]\tag{13}$$

with the length of the payment period τ given by (11).

A partition function, objection, and equilibrium for the cooperative game under a village-level regeneration requirement are defined analogously to their counterparts under the village-level no-deforestation requirement, with substitution of sequential equilibrium forest-protection and blocking decisions (12)-(13) for Nash equilibrium forest-protection decisions (10).

Theorem 5 shows that, for preventing deforestation, a village-level regeneration requirement $\mathbb{R}$ outperforms a village-level no-deforestation requirement $\mathbb{V}$, which in turn outperforms a farmer-level requirement $\mathbb{F}$ applied to each farmer in the village.

THEOREM 5. *Under $\mathbb{F}$, no deforestation occurs in the village ($\ell_d^f=0,\ \forall\ f\in\mathcal{V}$) in every equilibrium if and only if:*

$$J^f(\ell_e^f,1)>J^f(\ell_e^f+\ell_d^{f*},\tau_{sq})-c_d(\ell_d^{f*})\ \textit{for every farmer}\ f\in\mathcal{V}.\tag{14}$$

Under $\mathbb{V}$, no deforestation occurs in the village ($\ell_d^f=0,\ \forall\ f\in\mathcal{V}$) in every equilibrium if and only if:

$$\sum_{f\in\mathcal{V}}J^f(\ell_e^f,1)>\sum_{f\in\mathcal{V}}\Big[J^f(\ell_e^f+\ell_d^{f*},\tau_{sq})-c_d(\ell_d^{f*})\Big].\tag{15}$$

Under $\mathbb{R}$, no deforestation occurs in the village ($\ell_d^f=0,\ \forall\ f\in\mathcal{V}$) in every equilibrium if and only if:

$$(15)\ \text{ holds or }\ \sum_{f\in G}\left(J^f(\ell_e^f,1)-J^f(\ell_e^f+\ell_d^{f*},\tau_{sq})\right)>\eta\big|\{\mathcal{V}\backslash G\}\big|,\tag{16}$$

where $G=\big\{f:J^f(\ell_e^f,1)>J^f(\ell_e^f+\ell_d^{f*},\tau_{sq})-c_d(\ell_d^{f*})\big\}$.

The set of model parameters satisfying (14) *is a strict subset of the set of parameters satisfying* (15)*, which is a strict subset of the set of parameters satisfying* (16)*.*

Why is the village-level no-deforestation requirement $\mathbb{V}$ more effective than the farmer-level no-deforestation requirement $\mathbb{F}$? To understand, first consider the gain in welfare for a farmer f from engaging in deforestation rather than having same-day payment,

$$J^f(\ell_e^f+\ell_d^{f*},\tau_{sq})-c_d(\ell_d^{f*})-J^f(\ell_e^f,1).\tag{17}$$

Under $\mathbb{F}$, farmer f engages in deforestation if and only if his gain (17) is positive. Hence, the farmer-level requirement $\mathbb{F}$ protects the forest if and only if every farmer refrains from deforestation, *i.e.*, if and only if the gain (17) is strictly negative for *all* farmers, as stated in condition (14). In contrast, the village-level no-deforestation requirement $\mathbb{V}$ protects the forest if and only if the aggregate welfare for all farmers in the village is greater with same-day payment than with deforestation, *i.e.*, if and only if the *sum* of gains (17) is strictly negative, as stated in (15). In that case, $\mathbb{V}$ motivates the farmers to cooperate to protect the forest and make welfare transfers so that all farmers gain from same-day payment, even if some farmers prefer to deforest (have positive gain (17)). Since each farmer f has a different gain (17) due to his idiosyncratic discount rate β^f and farm size ℓ_e^f, the sum of gains over all farmers is (strictly) negative over a strictly wider parameter region than that for which every gain is (strictly) negative. Hence, $\mathbb{V}$ is more effective than $\mathbb{F}$.

At the village-level, why is the regeneration requirement $\mathbb{R}$ more effective than the no-deforestation requirement $\mathbb{V}$? If farmers with positive gain (17) were to engage in deforestation, the set of farmers that would directly benefit from forest regeneration (the farmers in $G \subseteq \mathcal{V}$, for whom the gain (17) is strictly negative) would block production on the deforested land, assuming η is not too large. Anticipating that production would be blocked on any deforested land, no farmer would choose to incur the cost to deforest and develop land. Hence, when η is not too large, the village-level regeneration requirement $\mathbb{R}$ protects the forest provided at least some farmer(s) benefit from regeneration (G is non-empty), regardless of how much other farmers may gain through deforestation. In the alternative case that η is too large for the threat of blocking to be credible, $\mathbb{R}$ reduces to $\mathbb{V}$. Hence, $\mathbb{R}$ is more effective than $\mathbb{V}$.

All arguments in the proof of Theorem 5 generalize if the buyer offers an additional or different reward to farmers that meet the specified forest-protection requirement. One implication is that if (15) does not hold, the buyer can induce the farmers in the focal village to meet a village-level no-deforestation requirement $\mathbb{V}$ by offering additional rewards with aggregate value greater than $\left[\sum_{f\in\mathcal{V}} J^f\left(l_e^f + l_d^{f*}, \tau_{sq}\right) - c_d(l_d^{f*}) - \sum_{f\in\mathcal{V}} J^f\left(l_e^f, 1\right)\right]$ to those farmers. That would also guarantee that no deforestation would occur under a village-level regeneration requirement $\mathbb{R}$.

Inspection of the conditions in Theorem 5 provides two useful insights (which we use in §6) about when each of the forest-protection requirements is effective. First, increasing the status quo length of a payment period τ_{sq} strictly decreases the right hand side of (14) and of (15), while not affecting the left hand side of (14) and of (15). In short, a longer status quo payment delay makes each of the forest-protection requirements more effective. Each becomes effective for τ_{sq} above a finite threshold. Second, a reduction in the cost η reduces the right hand side of (16). The regeneration requirement $\mathbb{R}$ is therefore effective if η is below a strictly positive threshold. These insights are useful in §6 for making a conservative interpretation of our field data.

Further inspection of (16) provides insight about the areas for which regeneration requirements are effective. To develop that insight, consider two adjacent villages. If (16) holds for one village but not the other, applying a regeneration requirement to the union of the two villages (a farmer in the villages is compliant if and only if both villages meet the regeneration requirement) will halt deforestation if (16) holds with the set of farmers from both villages substituted for $\mathcal{V}$, assuming the farmers in the adjacent villages can cooperate and police each other. More generally, regeneration requirements can halt deforestation for an entire landscape if it can be partitioned into subdivisions such that (16) holds for each subdivision (with the set of farmers in the subdivisions substituted for $\mathcal{V}$) and the farmers within each subdivision are able to cooperate and police each other. Applying a regeneration requirement to each subdivision would then halt deforestation for the entire landscape.

In closing, can the buyer meet its dual commitments by eliminating payment delay for farmers if and only if they comply with a village-level regeneration requirement $\mathbb{R}$? Theorem 2 and 5 show that the answer is "yes" when (16) holds for all villages in the buyer's supply chain. If (16) does not hold for a village, the buyer must either stop sourcing from smallholders in that village, continue sourcing but risk brand damage from illegal deforestation in its supply chain, provide an additional reward for farmers in that village to protect its forest, or divide the landscape in a different manner, in order to apply regeneration requirements to different subdivisions (subject to the conditions highlighted in the previous paragraphs). Fortunately, our empirical analysis in §6 suggests that (16) likely holds for *all* villages surveyed.

6. Field research and analyses

To develop our research questions and model, we first implemented 55 semi-structured, on-site interviews with representative members of Indonesia's palm oil supply chain in March-April 2016. Members included smallholder farmers, mill managers, refinery managers, traders, sustainability managers of large oil buyers, and government representatives (see Table 6.1). Interviews with managers and traders covered operational characteristics, contracting practices, prevailing procurement decision timelines, existing efforts to incentivize and monitor supplier compliance with no-deforestation requirements, and companies' sustainability commitments as well as challenges to address them. Interviews with smallholder farmers covered fruit selling practices, management of their farm(s), familiarity with existing sustainability schemes and challenges to adhere to such schemes, access to credit, and forest protection/conversion decisions.

To calibrate our model, we then collected cross-sectional survey data from a random sample of 420 smallholder farmers in 60 randomly-sampled villages of two target districts (Paser and Paser Penajam Utara) in East Kalimantan, Indonesia, in September-October 2016 (see Figure 6.6 for a geographical overview of villages in our dataset). These two target districts are of particular interest

Supply chain interviewee category	# of interviewees	Interview Location
Smallholder farmers	27	Indonesia: East Kalimantan, Central Sumatra
Corporate plantation managers	5	Indonesia: North & Central Sumatra
Mill managers	7	Indonesia: East Kalimantan, North & Central Sumatra; Malaysia
Refinery managers	3	Malaysia; Singapore
Traders (fruit or oil)	4	Indonesia: East Kalimantan, North & Central Sumatra; Singapore
Government representatives	1	Indonesia
Sustainability managers	8	Indonesia: North & Central Sumatra; Singapore; Malaysia
Total	55	

Table 6.1 On-site interviews in Indonesia's palm oil supply chain, March-April 2016.

because 47% of their households are palm fruit farmers (Indonesia Census 2014), and the districts witnessed an eightfold increase in the rate of illegal deforestation since 2005, with latest estimated illegal deforestation levels of 7,000ha/year on average in 2011-2013 (Daemeter 2016b). Most farmers in our data set (69%) farm less than 5ha in total, whereas 29% farm 5-25ha and 2% farm more than 25ha in total. Some have multiple farms and the number of farms in our data set is 728. Immediately before being planted with palm oil trees, the farms were predominantly forest (43%) or secondary vegetation (43%). In our analyses and results reported below, we treat each farm as a separate observation. For farmers that have multiple farms, treating a farmer's total land area as a single farm does not substantially change the results, as shown in §3.1 of the Appendix.

6.1. Structural estimation of α, q, k, σ, and parameter estimation of $\beta^f, \ell_e^f, \nu, d, \delta, K$

Our model uses an exponential function to model informal interest payments by farmers. To support this assumption empirically, we use data on 171 loans reported by the farmers in our survey. Figure 6.1 below shows the observed interest payments and the estimated interest payments based on an exponential function with parameter $\hat{\alpha} = 2.1 \times 10^{-4}$ USD/day, suggesting that this functional form is a reasonable approximation of reality. The adjusted R-squared is 0.72.

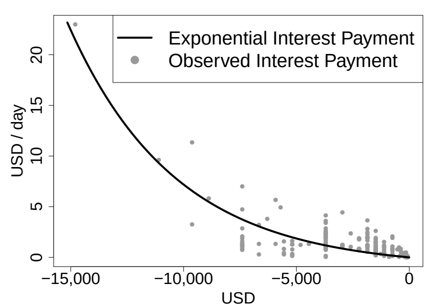

Figure 6.1 Observed interest payments and estimated interest payments based on exponential function.

Our model uses a production cost rate that is quadratic with Gaussian shocks, *i.e.*, $\mathcal{W}_n^f r_n^f + q(r_n^f)^2$ in (2), wherein $\mathcal{W}_n^f$ is normally distributed with mean k and standard deviation σ for each farmer

f in each period n, and q is a non-negative constant. Figure 6.2 plots in grey our observations of the production rate (in kg/ha/day) and resulting production cost rate (in USD/ha/day) at a single point in time for each of the 728 farms in our data set. The apparent heteroskedasticity in the data is consistent with our model's assumption that the variance of the production cost rate increases with the production rate:

$$\mathrm{Var}\left[\mathcal{W}_n^f r_n^f + q(r_n^f)^2\right] = \sigma^2 (r_n^f)^2,$$

and the slight convexity is consistent with having a small positive q in our model.

Under the assumption that production cost shocks are independent across farmers, corresponding to $\rho_{ij} = 0$ for $i, j \in \{1, .., F\}$ with $i \neq j$ in our model, we can estimate the parameters σ, k, and q from the data plotted in grey in Figure 6.2, by regressing the cost rate on the production rate (r):

$$\text{cost rate} = q\,r^2 + k\,r + \varepsilon. \tag{18}$$

We find $\hat{q} = 0.03$ and $\hat{k} = 25.13$ (both significant at $p < 0.001$ using heteroskedasticity-consistent standard errors), and use the modeling structure $\mathrm{Var}(\varepsilon^f) = (\sigma^f)^2 = \sigma^2\,(r^f)^2$ to obtain the estimator $\hat{\sigma} = 7.30$.

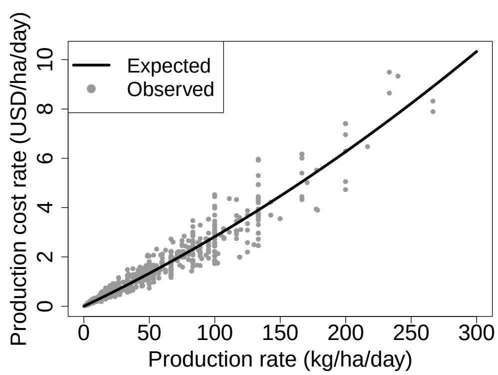

Figure Note: The observed production cost rate is the sum of harvesting costs and transportation costs incurred per hectare per day using cross-sectional data on harvesting wage, transportation costs, and harvesting frequency.

Figure 6.2 Expected and observed cost rate as a function of production rate.

However, we believe that the farms we surveyed experience positively correlated cost shocks, due to their spatial proximity. In our model, the expected sample variance of the cost shocks $\{\mathcal{W}_n^f, f \in \{1, .., F\}\}$ is $\left(1 - \frac{\sum_{i\neq j}\rho^{ij}}{F^2 - F}\right)\sigma^2$, which strictly decreases with the correlation ρ_{ij} for each $i, j \in \{1, \dots, F\}$. Hence insofar as production cost shocks are positively correlated across farms, $\hat{\sigma}$ tends to be an underestimate of the standard deviation σ in a farmer's production cost shock. (In contrast, the estimates $\hat{q}$ and $\hat{k}$ remain unbiased; see, *e.g.*, Greene 2012, Chapter 9.2, page 298.) In the remainder of this section, we will nevertheless employ $\hat{\sigma}$ as our estimate for σ; this is conservative in view of

Proposition 1 below, which shows that by underestimating σ we will underestimate the benefits of eliminating payment delay.

PROPOSITION 1. *The increase in farmer f's equilibrium productivity and welfare from eliminating payment delay increases with σ if and only if $q \geq \overline{q}$.*

We have confirmed that the condition $q \geq \overline{q}$ holds for the vast majority of farms in our dataset (see histograms in Figures 5-7 in the Appendix).

Furthermore, one can verify from the proof of Theorem 5 that increasing every farmer's improvement in welfare from eliminating payment delay expands the parameter region in which no deforestation occurs in equilibrium, so that using $\hat{\sigma}$ in our calculations will also underestimate the benefits in eliminating deforestation.

To estimate each farmer's discount rate β^f, we measured each farmer's time preferences using the Convex Time Budget (CTB) survey instrument from behavioral economics (see, *e.g.*, Andreoni and Sprenger 2012). This instrument relies on placing a respondent's discount rate within a discernible category, which makes our estimates of farmer discount rates categorical (see Table 6.2).

1-week discount rate	>50%	23-50%	15-23%	7-15%	0-7%
% of respondents	50	7	8	19	16
N of respondents	176	25	30	68	55

Table 6.2 Farmer one-week discount rates as estimated by CTB survey instrument.

Each farmer reported the area of productive land ℓ_e^f of his farm(s). Figure 6.3 shows the histogram of ℓ_e^f (measured in hectares).

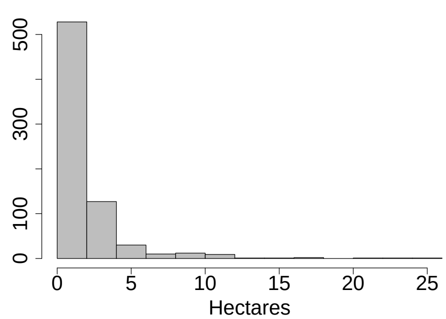

Figure 6.3 Histogram of farmer's endowed land area, ℓ_e^f, measured in hectares (ha).

To estimate the cost of deforesting and developing land into a palm farm, we assume linearity, *i.e.*, $c_d(\ell_d) = d\,\ell_d$, $d > 0$. We estimate d by summing the cost for fire-induced land clearing estimated by Guyon and Simorangkir (2002) and the cost for planting materials, obtained via farmer interviews (40,000 IDR/seedling $\times$ 125 seedlings/ha). Equation (A.29) in the Appendix provides the closed-form expression for a farmer's optimal area to deforest and develop, the unique solution to (7) with linear cost $c_d(\ell_d) = d\,\ell_d$.

To estimate the oil price volatility (ν^2), we used the time series of daily Crude Palm Oil (CPO) reported in Bloomberg (see Figure 1 in the Appendix), and computed the standard deviation of daily differences in CPO prices. Our estimate of ν is $\hat{\nu} = 8.58$ (\$/ton/day).

We also used this Bloomberg data, together with Bloomberg time series data for Refined, Bleached, Deodorized (RBD) prices (see Figure 1 in the Appendix) to estimate K. We regress the RBD price on the CPO price and find $\hat{K} = 1.09$ with an R-squared of 0.999.

We estimate the buyer's discount rate $\hat{\delta}$ by using the Weighted Average Cost of Capital (WACC) of the palm oil refining company Wilmar, which purchases from mills in our field site. Wilmar's WACC at the time of writing is 5.77% per year (Guru Focus 2018).

With this $\hat{K}$ and $\hat{\delta}$, condition $\hat{\delta} < \overline{\delta}$ in Theorem 3 (expressed in closed form in (A.24)-(A.26) in the Appendix) holds for any realistic frequency of the mill delivering a batch to the buyer, *i.e.*, any period between deliveries of $\tau_{sq} \leq 90$ days. The implication is that eliminating payment delay will increase the buyer's expected profit. That increase in the buyer's expected profit is proportional to the increase in farm productivity, which we estimate next.

6.2. Estimation of productivity and welfare

We estimate farm productivity and farmer welfare by substituting the parameter estimates from §6.1 (including the size of each farm and the farmer's idiosyncratic discount rate) into the expressions for equilibrium productivity and welfare (equations (A.12) and (A.14) in the Appendix). We calculate the equilibrium fruit price according to (5), wherein we set the oil price to the empirical mean over all oil prices in the dataset. This is equivalent to calculating the mean productivity over all oil prices in the dataset, due to the linearity of the production rate in oil prices (see (A.12) in the Appendix and (5)). The resulting estimate of productivity at each farm is in kilograms of palm fruit per hectare per day.

Figure 6.4 shows the impact of payment period length on productivity. The left panel shows box-plots of productivity using our entire sample of 728 farms. The figure on the right is obtained in an analogous fashion, except that the sample is split into two sub-samples of "small" and "large" farms, depending on whether a farm's size exceeds the median size. The important new insight from Figure 6.4 is that eliminating payment delay *substantially* increases farm productivity. Consistent with Theorem 2, the productivity at each farm decreases with the size of the farm and with the

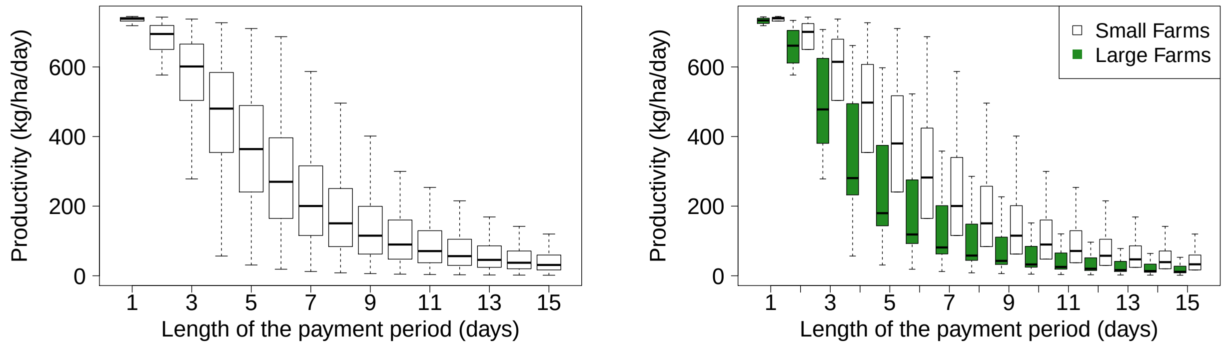

Figure 6.4 **Productivity as a function of the length of the payment period. The left figure shows box-plots for all 728 farms in our sample. The right figure is obtained by splitting the sample into small and large farms (depending on whether the size is smaller or larger than the median size, respectively), and shows separate box-plots for each category.**

payment delay. Most of the variation in production rates across farms is due to variation in the sizes of the farms, whereas the variation in farmer's discount rates has a smaller effect.

To estimate the impact of payment period length on farmer welfare, we set the production horizon D to 9125 days, corresponding to the 25 year productive lifetime of a palm tree (similar results are obtained for shorter horizons). Figure 6.5 shows that eliminating payment delay substantially increases a farmer's welfare, especially when his farm is large. The implication is that a village-level forest-protection requirement would lead farmers who own large farms to transfer welfare to farmers who own small farms.

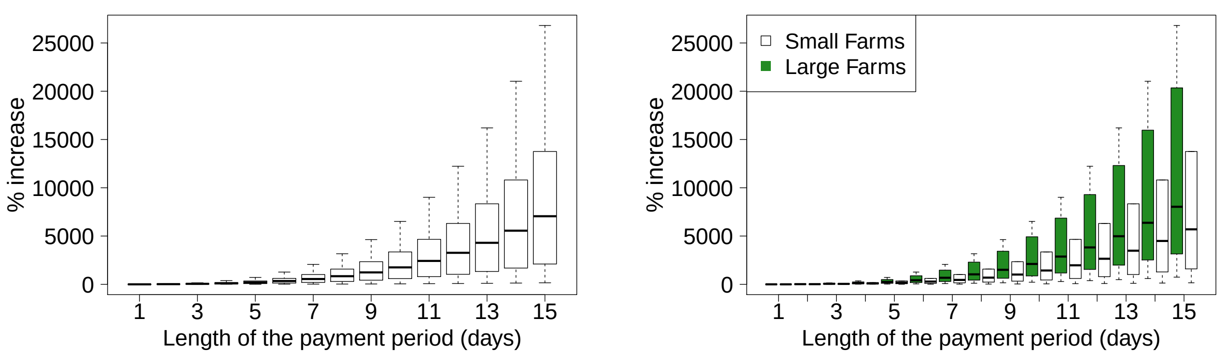

Figure 6.5 **Percentage increase in farmer welfare if the buyer eliminates payment delay, as a function of the status quo payment period length τ_{sq}. The left figure shows box-plots for all 728 farms in our sample. The right figure is obtained by splitting the sample into small and large farms (depending on whether the size is smaller or larger than the median size, respectively), and shows separate box-plots for each category.**

6.3. Estimation of Forest Protection

To understand the effectiveness of our three forest-protection requirements, we evaluate conditions (14)-(16) in section §5.2 at the parameter estimates from §6.1, to determine whether deforestation would occur in equilibrium. We assume that the farms in a village in our dataset are a representative sample of the farms in that village. Because our dataset includes only a relatively small sample for each village (11 farms per village on average), our results below should be interpreted as illustrative, rather than as precise predictions.

Eliminating payment delay without any forest-protection requirement would lead *all* farmers in the dataset to engage in deforestation.

In contrast, if the status quo payment period length were 9 or more days ($\tau_{sq} \geq 9$), eliminating payment delay under a village-level requirement ($\mathbb{V}$ or $\mathbb{R}$) would protect forests in equilibrium in all villages in our dataset. Only if the status quo payment period length were 14 or more days ($\tau_{sq} \geq 14$) would eliminating payment delay under a farmer-level requirement ($\mathbb{F}$) also protect forests in equilibrium in all villages. For the remainder of this section, we make the assumption that the status quo payment period length is 8 days ($\tau_{sq} = 8$). Per our discussion in §5.2, this will result in conservative estimates for the benefits of implementing each of the requirements.

We find that a village-level requirement ($\mathbb{V}$ or $\mathbb{R}$) is substantially more effective than the farmer-level requirement. With no forest-protection requirement, deforestation occurs in equilibrium in all 60 of the villages in our data set. The farmer-level requirement ($\mathbb{F}$) halts deforestation in 24 villages, hashed black in Figure 6.6. The village-level no deforestation requirement ($\mathbb{V}$) halts deforestation in 57 villages, hashed black or orange in Figure 6.6. The remaining 3 villages, hashed blue in Figure 6.6, would be protected by the village-level regeneration requirement ($\mathbb{R}$) as long as the per-farmer blocking cost η does not exceed USD 1.86M. Since this condition is amply satisfied in our setting, the village-level regeneration requirement has the potential to halt deforestation in all 60 villages in the data set.

7. Concluding remarks

This paper proposes eliminating payment delay for farmers that either halt deforestation in their village or, if deforestation occurs, allow the forest to regenerate (meeting a so-called village-level regeneration requirement). By combining dynamic programming and non-cooperative game theory, the paper shows how eliminating payment delay improves productivity and welfare for farmers, and increases profitability for processors and (if the buyer's discount rate is not too high) buyers. Incorporating cooperative game theory, the paper identifies conditions under which a regeneration requirement halts deforestation in a village. Field data suggests that those conditions are satisfied in the villages that we surveyed.

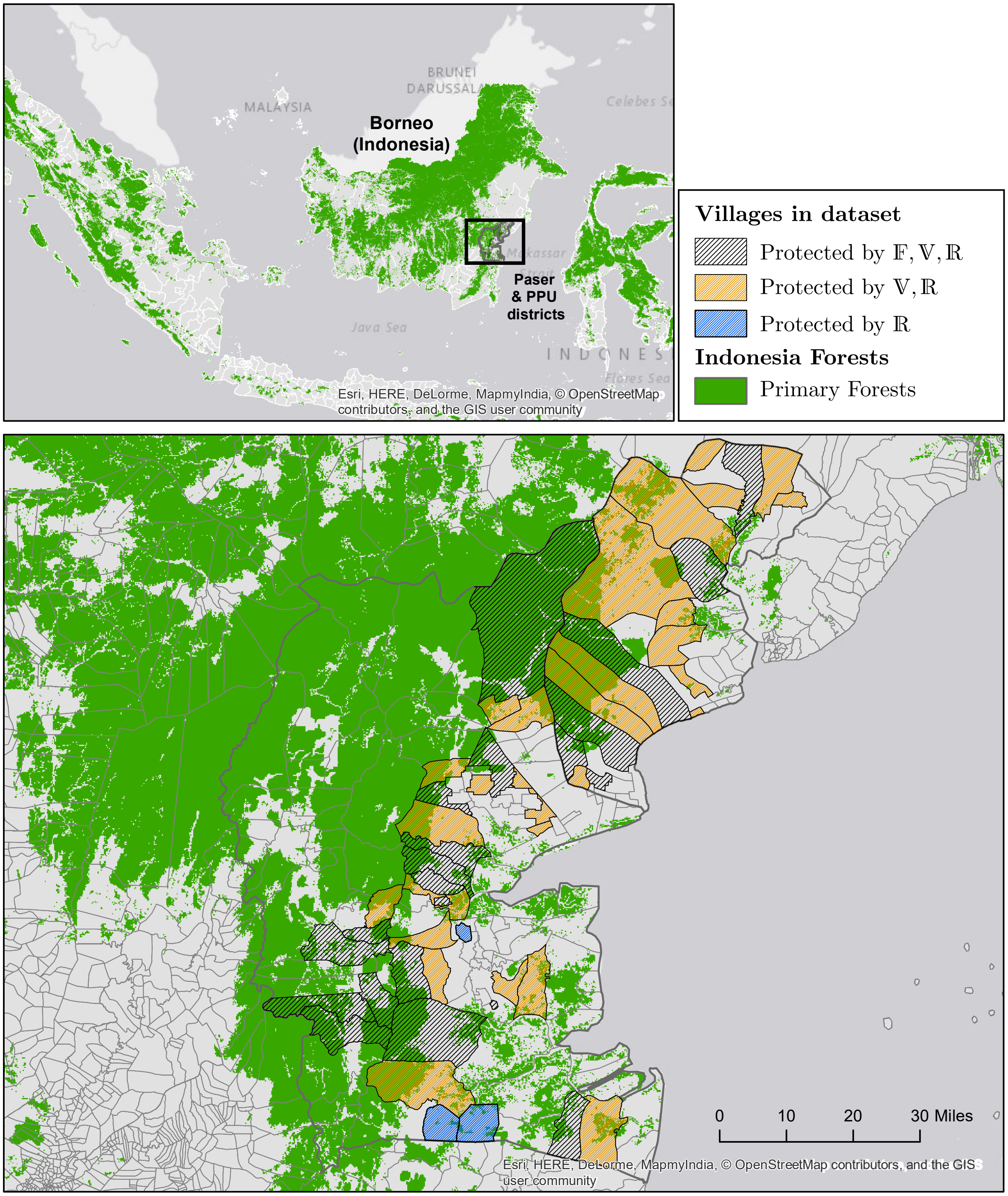

Figure Note: *Primary Forests* includes Primary Intact and Primary Degraded Forests as defined in Greenpeace et al. (2018) and Potapov et al. (2017).

Figure 6.6 **Villages in the dataset predicted to protect forests under the farmer-level requirement $\mathbb{F}$, village-level no-deforestation requirement $\mathbb{V}$ and village-level regeneration requirement $\mathbb{R}$, when eliminating a status quo payment delay $\tau = 8$. Without forest-protection requirement, deforestation occurs in equilibrium in all villages in our dataset when eliminating payment delay. The legend shows which villages are protected under each requirement.**

Though this paper is motivated by our field study of the palm oil supply chain originating in Indonesia, the results are applicable to other commodities and geographies. For example, the coconut, dairy and cassava supply chains in many developing countries also feature *continuous* production by cash-constrained smallholder farmers and *immediate* local processing by cash-constrained local processors, whereas buyers with lower cost of capital purchase *periodically* from the processor and pay upon receiving a shipment. Hence eliminating payment delay would yield the same triple win in those coconut, dairy and cassava supply chains as in the palm oil supply chain. With any alternative reward, our results hold regarding the effectiveness of a regeneration requirement. Although we focused on a village-level regeneration requirement for Indonesia, our results show that to best protect a given landscape from deforestation, regeneration requirements should be applied to the largest possible areas within that landscape wherein farmers are able to cooperate or police each other. Buyers of beef have made commitments to halt deforestation related to beef sourced from the Brazilian Amazon, and could employ regeneration requirements in doing so.

Based on our experience with palm oil buyers in implementing our proposals, four points merit further discussion.

First, monitoring a village for compliance with a regeneration requirement will be relatively cheap and easy, in comparison with buyers' current efforts to monitor individual farmers. Using publicly-available satellite data, *Global Forest Watch* offers a free, weekly alert system for deforestation occuring within any specified contiguous land area (Hansen et al. 2016). A buyer could sign up for a deforestation-alert system for each of the villages from which it is sourcing. Satellite monitoring is improving and may enable a buyer to also monitor whether, in the event of deforestation in a village, the forest is allowed to regenerate. Alternatively, a buyer could partner with NGOs operating on the ground in Indonesia or employ drones to monitor for regeneration in the specific areas where deforestation was observed via satellite. In contrast, no technology currently exists that allows a buyer to identify whether an individual farmer is responsible for deforestation.

Second, to eliminate payment delay for farmers *if and only if* they comply with a village-level regeneration requirement requires innovation in traceability and payment systems. In particular, a buying firm needs traceability to the village-level, *i.e.*, to observe in which village fruit was grown. At present, buyers are attempting to trace fruit to the farm. Tracing fruit to the farm would obviously enable a buyer to trace fruit to the village-level, whereas tracing fruit only to the village-level may be cheaper and easier. A buyer also needs to eliminate payment delay for fruit from compliant villages. A buyer could pay in advance to a mill and engage a local NGO to ensure that the mill indeed uses that capital to pay for fruit upon delivery, rather than with delay. Better yet, blockchain, mobile money, and other new technology may enable a buyer to pay farmers directly for fruit delivered and pay the mill for processing that fruit on the day of delivery and processing. Finally, to incentivize farmers to meet the regeneration requirement, a buyer could decline fruit from noncompliant villages (in which case the fruit would presumably flow to a different buyer, with the status quo delay in payment) or just pay with the status quo delay for fruit from noncompliant villages.

Third, in practice, smallholder farmers often sell to middlemen whose presence, though not represented in our model, reinforces the value of our proposals. In our field sites, financial middlemen offer farmers payment upon delivery of fruit to the mill—at a substantially lower price than offered by the mill. (Farmers' survey responses combined with price data from collaborating mills indicate that those financial middlemen effectively charge a weekly interest rate of 8.5%.) Our proposal of eliminating payment delay would eliminate those middlemen and, for farmers that previously sold to them, substantially increase the fruit price. Our results show that increasing the fruit price increases farmers' productivity, which increases the profitability of the mill and buyer. In our field sites, we also observed that other sorts of middlemen collect a truckload of fruit from multiple farms in a village and transport the fruit to the mill. Both financial middlemen and transportation middlemen create additional links in the supply chain between farmer and buyer, and thereby exacerbate the difficulties for buyers attempting to trace fruit to the farm, monitor farmers, and avoid sourcing from illegally deforested land. This reinforces the value of our proposals to eliminate payment delay and employ a village-level forest protection requirement.

This brings us to the fourth and final point, the risk that irresponsible buyers implement our proposal only partially, *i.e.* eliminate payment delay and reap the profits without imposing forest-protection requirements. That would eliminate the incentive for farmers to meet a regeneration requirement in order to sell to a responsible buyer that eliminates payment delay. Fortunately, international banks—which often facilitate the trade financing required to implement our proposal—have recently formulated policies that prohibit the financing of operations that are illegal or damage high conservation value forests (Greenpeace 2017, Financial Times 2017, 2016). In order to adhere to their policies, such banks would have to withhold financial services that facilitate same-day payments from irresponsible buyers, thereby reducing the risk that irresponsible buyers will eliminate payment delay for farmers unconditionally. The financial sector could thus play a crucial role in halting deforestation and improving farmers' livelihoods.

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