Area Conditions and Positive Incentives: Engaging Local Communities to Protect Forests

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Commodity buyers increasingly pledge to adopt zero-deforestation sourcing and to improve the livelihoods of the smallholder farmers who supply them. They typically offer conditional positive incentives that reward either (i) individual farmers who do not clear forest on their own plots or (ii) entire communities if no one clears forest in an area. However, such individual or area no-deforestation schemes have delivered mixed success and have been problematic in areas where deforestation is fire-induced. This paper proposes and examines a novel scheme that rewards an entire community conditional on *area no use*, i.e., if no one *derives economic benefit* from clearing forest in the area. To compare this with more traditional schemes, we develop a game-theoretic model of heterogeneous farmers who can form limited coalitions, clear forest, and block other farmers–at a cost–from using cleared plots to generate economic benefit. We formalize a novel "Pessimistic Recursive Core" solution concept that enables us to analyze our game with partial cooperation and multiple non-cooperative equilibria. We then use this to characterize the cases when each conditional incentive scheme (i) prevents deforestation and (ii) meets an equity requirement of compensating farmers for their opportunity costs. We find that the choice of best scheme critically depends on local conditions. When smallholder farmers have full ability to cooperate–meaning they can form arbitrary coalitions–an area no-deforestation condition is cheapest and most robust, and also achieves the equity requirement. With limited cooperation, area no-use is best at preventing deforestation at low blocking costs, but does not meet the equity principle. Otherwise, individual schemes are best at both preventing deforestation and meeting the equity requirement, but these require "perfect incentives" that ensure that each smallholder individually prefers the incentive to clearing forest. Increased ability to cooperate can either raise or lower the effectiveness of the area no-use condition. Calibrated to 58 villages of palm fruit smallholder farmers we surveyed in East Kalimantan, Indonesia, our framework indicates that village-specific price premiums tied to the area no-use condition prevent deforestation in most cases and are also resilient to external encroachment.

1. Introduction

Under mounting pressure from consumers and regulators, prominent commodity buyers such as Unilever, Cargill, and Nestlé have made dual commitments to prevent deforestation in areas where their inputs originate while also raising the incomes of the smallholder farmers who supply them. This is most consequential in the tropics, where clearing forests for agricultural expansion contributes roughly 15% of annual global CO_2 emissions and harms biodiversity, soils, watersheds, and public health. Because smallholders clear forest to expand their farms as a pathway out of poverty, the dual commitments are tightly coupled. Regulatory pressure is also mounting: the European Union's Regulation on Deforestation-Free Products (EUDR) requires firms selling deforestation-linked products on the EU market to demonstrate that inputs were not produced on land deforested after 2020 (EU 2023), and the forthcoming Corporate Sustainability Due Diligence Directive (CSDDD) requires firms to ensure fair prices and living incomes for their smallholder suppliers (EU 2024).

A common strategy for buyers to meet the dual commitments is to implement an *individual conditional incentive*, whereby each farmer whose land plots remain deforestation free is rewarded with a positive incentive such as a price premium, subsidized inputs or equipment, loans, or a cash payment for conservation. Unilever's palm-oil program in Indonesia illustrates the approach: with NGO partners, the company has mapped 47,000 farms and monitors them daily for deforestation via a live dashboard that integrates satellite and radar feeds; farmers whose plots remain deforestation-free are eligible for RSPO certification and to receive an RSPO price premium for fruit produced on those plots. (§EC.1 surveys related approaches for other commodity buyers.)

In practice, such schemes that require verifying every farmer's plots face several obstacles. Enrollment presumes that smallholders have clear land titles, which is rare in frontier regions with ambiguous or overlapping property rights. Plot-level mapping–usually done using GPS technology, but through manual processes–remains costly and imprecise due to the large number of smallholders. Most critically, *leakage* can erode the buyer's "zero deforestation" claims: a farmer could clear an *unmapped* forest plot–or source from a neighbor who does so–and then sell the additional output under the guise of improved productivity on mapped plots.

An alternative that addresses these challenges is an *area* (or landscape) scheme: all smallholders within a defined area earn a reward only if no forest is cleared anywhere in the area. The area can be defined at multiple scales, from the boundary of a single village or a mill's supply-shed to an entire administrative jurisdiction. For example, under Malaysia's state-wide Sabah Jurisdictional Approach, Unilever, Nestlé, and other buyers offer RSPO price premiums to all smallholders conditional on zero new clearing across the entire landscape (see §EC.1 for other examples).

Evidence from prior implementations and from our fieldwork in Indonesia and Thailand suggests that such *collective* incentives are promising, but entail important risks. Because conditions are set at the area level, monitoring can rely on aggregate forest-cover change rather than plot-by-plot verification, which reduces leakage and strengthens buyers' zero-deforestation claims. However, success depends on cooperation and collective action within the community. A tightly-knit farming community often cooperates and coordinates on important decisions, but when social ties are weak, a single farmer who expects to be undercompensated may clear forest and thereby void payments for all. The risk is amplified when outsiders can clear forest within the same area or when deforestation occurs via fires that spread quickly. Such events are common in tropical frontiers with weak property rights and limited enforcement, where "accidental" dry-season fires ignited in (often protected) forest rapidly convert land to productive use. In West Kalimantan, a village-level cash-incentive trial collapsed after a handful of such fires (Falcon et al. 2022), underscoring the importance of collective-action risk and the presence of actors with limited benefits from the incentive. A further concern is elite capture: powerful local actors may appropriate a large share of payments, leaving poorer households undercompensated and exacerbating local inequality.

Motivated by practitioner calls for clearer design guidance (Pacheco et al. 2021), this paper proposes a novel area condition and develops an analytical framework to compare *individual*- and *area*-conditional incentives, providing guidance on which scheme better halts deforestation and raises rural incomes depending on local conditions. Although aimed primarily at commodity buyers, the framework also applies to government agencies, watershed funds, conservation NGOs, or carbon-offset developers that seek to reward communities for protecting forests and other natural resources. To serve this broader audience, the framework accommodates multiple positive incentives and centers attention on the key design choices and levers that drive outcomes.

Our first contribution is to propose and analyze a novel forest protection condition inspired by recent industry practice: the *area no-use* condition, which rewards an entire community if *no one derives economic benefit* from clearing forest within the area. Compared with the more common *area no-deforestation* condition, the *area no-use* condition is more flexible: compliance is achieved either by preventing any forest clearing or–if clearing occurs–by ensuring that no timber is extracted and no production takes place on the affected land. This distinction matters because stopping every act of clearing, especially those involving fire, may be infeasible, whereas preventing use of deforested plots can be more tractable. Depending on local conditions, communities can deter use by reporting culprits to authorities, applying peer pressure (e.g., public censure or ostracism), or enforcing material sanctions such as cutting down seedlings in new plantations (Villadiego 2017) or confiscating produce. Our *area no-use* condition is motivated by recovery-plan policies adopted by several commodity buyers: firms such as Wilmar and Unilever allow suspended suppliers that cleared forest to regain market access after they cease productive use of the cleared land and undertake verified actions to restore the forest (Wilmar International Limited 2023, Unilever 2022). The *area no-use* condition scales this recovery-plan logic to the entire area and redirects a local community's enforcement actions to the more tractable task of blocking economic activity on deforested plots.

To compare (incentives under) the novel *area no-use* condition with the more common *individual* or *area no-deforestation* conditions, we develop a general analytical framework. We consider a given forested area inhabited by several smallholder *locals*. An interested party (commodity buyer, NGO, or agency) offers each local a positive incentive conditional on a specified forest-protection condition. Locals are heterogeneous in the value they derive from the positive incentive or by clearing forest in the area, and some locals may strictly prefer clearing. Locals are organized into extended *families*; members of the same family can form coalitions wherein they *cooperate* by coordinating decisions and sharing benefits and costs, but no cooperation is possible across families. The interaction unfolds in two steps. First, locals form coalitions within their families. Second, the coalitions of locals engage in a two-stage, non-cooperative game wherein (i) they decide whether to engage in deforestation (at a cost) and, (ii) after observing all deforestation decisions, they decide whether to block individuals from generating income from cleared land (at a cost). The model thus captures several key primitives: the locals community's ability to cooperate (through the structure of families), the locals' gains from the incentive and from clearing forest, and the costs of blocking use of cleared land.

We analyze several formulations of the problem. Reflecting the buyer's dual mandate, we focus on incentives that prevent deforestation and bring gains to every local. But we define two feasibility criteria depending on the level of the gains: an incentive that merely *prevents deforestation* would only guarantee that no local is worse off then before (so any *positive* incentive would work), whereas an incentive that *prevents deforestation* and *achieves compensation* would guarantee that each local's gain meets or exceeds what he could have gained by engaging in deforestation. The latter is a strong ethical desideratum advocated in the PES literature, which also ensures a fair/living income to each local and strengthens the scheme's resilience. To ensure robustness in our predictions, we define an incentive as feasible if it meets the chosen criterion in *every* possible outcome of the locals' interaction. We then characterize the full set of feasible conditional incentives, separately for each criterion, and identify the choice that is *most robust* (feasible for the inclusion-wise largest set of problem parameters) and the choice that is *most cost-effective* (minimizing the incentive cost).

To analyze these problems, we make our main methodological contribution: a new solution concept–the Pessimistic Recursive Core for games in partition correspondence form–which allows characterizing the outcomes of the process through which locals form coalitions. This generalizes a concept due to Kóczy (2007) to settings with multiple non-cooperative equilibria and restricted cooperation. The premise of the Recursive Core is that locals who form a coalition anticipate that locals outside that coalition will act to maximize their own payoff by engaging in a smaller, "residual cooperative game." The Recursive Core is obtained by solving recursively over residual games, and contains those outcomes at which no set of locals would obtain higher payoff by forming different coalitions. If the core of a residual game has multiple elements or the non-cooperative game among coalitions has multiple equilibria, we assume that locals forming a coalition have *pessimistic* beliefs and evaluate their payoffs according to the worst-case possible outcome. Pessimism gives rise to the largest possible core and makes our predictions on the incentive's feasibility robust/conservative.

Our analysis shows that no single conditional incentive is universally optimal; the optimal choice depends on the local community's ability to cooperate, on the magnitude of the cost of blocking economic use of deforested land, and on whether achieving compensation is required.

When locals have full ability to cooperate–meaning a single family exists, so arbitrary coalitions are possible–the *area no-deforestation* condition with an incentive that guarantees enough aggregate value to the community (so that the community prefers the incentive to clearing forest) would deliver simultaneously the most robust and least costly scheme. That scheme would readily achieve compensation, as locals would coordinate on forest protection and redistribute the incentive gains so that every local would gain at least what she would have gained by clearing forest.

With limited cooperation, if blocking costs are small and achieving compensation is not required, the *area no-use condition*–with appropriate incentive values–would deliver the most robust and cost-effective scheme. This can deter deforestation even when the local community in aggregate prefers clearing forest to the incentive, provided at least one family values the incentive more than clearing and some members of that family value it enough to afford blocking the use of deforested land by all other locals. The caveat with this scheme is distributional equity: locals with high opportunity costs for land–typically the poorest locals, with least land–may remain under-compensated. In fact, the most cost-effective scheme would channel the entire incentive gains to those locals with the *lowest* opportunity costs, thereby widening local inequalities and inviting elite capture.

In all other remaining cases with limited cooperation–specifically, when blocking costs are prohibitively large or achieving compensation is required–the *individual condition* is the most robust and cost-effective choice. This would, however, require a *perfect* incentive: each local's gains with the incentive should exceed his opportunity cost from clearing forest, a requirement that is often difficult to meet in practice. But when such generous incentive gains are possible, the individual condition outperforms both area conditions, which are hampered by coordination challenges.

With the area no-use condition, we find that the relationship between local cooperation and incentive effectiveness is non-monotone and subtle. Specifically, deforestation is the only possible outcome when either (i) locals have full ability to cooperate and collectively prefer clearing forest or (ii) there is limited cooperation but every family prefers clearing forest. In both circumstances, a more fragmented family structure–meaning a *reduced* ability to cooperate–could isolate a family willing and able to enforce the no-use condition, which could prevent deforestation. In contrast, if at least one family prefers the incentive, then a configuration with *increased* ability to cooperate would always *increase* the incentive's effectiveness.

In an extension, we find that hybrid schemes that allow partitioning the area into smaller areas and tailoring conditions to (locals within) subareas yield no benefit if locals in the larger area have full ability to cooperate, but may lower costs under limited cooperation.

We then calibrate our framework with data we collected in 58 villages in East Kalimantan, Indonesia, an area with strong socio-economic ties within villages and ongoing pressure from oil-palm expansion. We develop a structured model for a household's decision-making and use survey data to estimate the key parameters of our base model. To stress-test the effectiveness of conditional incentives and make conservative predictions, we use an estimation procedure based on robust data-envelopment-analysis to deliberately *overestimate* the profits from clearing forest. As incentive, we consider a price premium paid per ton of palm fresh-fruit bunches. We apply village-specific area conditions, with the area corresponding to the perimeter of each village. We find that a single price premium that would stop clearing in all villages would have to reach USD 470–800 per ton under area conditions or USD 4863 per ton under individual conditions–far above the current RSPO premium. In contrast, *village-specific* price premiums of just a few hundred dollars conditioned on area no-use can prevent deforestation in most villages and are also effective at deterring outsiders from clearing forest.

The results allow formulating several concrete recommendations to help commodity buyers (and governmental agencies, NGOs, or carbon offset providers) achieve the dual mission of preventing deforestation and benefiting smallholder farmers; §5 discusses these, together with certain limitations of the study and important directions for future work.

1.1. Literature Review

Our study is broadly related to a growing literature in OM on agricultural value chains, surveyed in Sodhi and Tang (2014), Swaminathan and Deshpande (2021), Sunar and Swaminathan (2022), Dong (2021). Closest to our study are the sub-streams focused on preventing deforestation, helping farmers, and managing agricultural cooperatives.

On preventing deforestation, Orsdemir et al. (2019) show how a firm avoids buying illegal wood by instead buying a mill and its log inputs, and selling wood to competitors. Agrawal et al. (2022) analyze contract terms for offset credits, including for avoided deforestation.

A growing body of OM research studies interventions to improve farmers' welfare. Some studies have focused on government tools, such as price supports and risk-coverage schemes (Alizamir et al. 2019), taxes or subsidies (Akkaya et al. 2021, Tang et al. 2023), guaranteed-price programs (Chintapalli and Tang 2021), financial access (Pay et al. 2022, Calmon et al. 2024), and the dissemination of market-price information (Chen and Hall 2007). Other studies have considered interventions by private parties: NGOs that enable farmers to share information Liao et al. 2019, Xiao et al. 2020 or get certified (Agrawal and Zhang 2024); commodity buyers that redesign sourcing contracts de Zegher et al. 2019, Hu et al. 2019, run novel auction schemes (Levi et al. 2024), pay premiums or subsidize inputs (Chintapalli and Tang 2021, Calmon et al. 2024), or allow consumers to tip farmers (Alizamir et al. 2022). All of these studies model farmers as *non-cooperative* agents and offer incentives *unconditionally*; the research challenge is to find settings where such incentives do not backfire–e.g., by inducing oversupply, worsening equity, or spurring environmental harm. The positive incentive in our model could, in principle, correspond to any of these interventions. Different from these studies, we model *conditions* tied to the incentive that prevent negative spillover effects on the environment (deforestation) or on distributive justice, and we study how farmers' ability to cooperate influences the effectiveness of interventions.

Our work is also related to OM literature that discusses how farmers can improve their welfare by cooperating, typically through agricultural cooperatives. An et al. (2015) show how farmers can increase their profits when jointly choosing their production quantities, and Li et al. (2024) show how cooperation can improve farmers' joint decisions of how much land to allocate to distinct crops. Qian and Olsen (2020, 2022) model how farmers coordinate their quality, quantity, and financial decisions through a cooperative and provide an excellent survey of the literature on farmers' cooperatives. Boyabatli et al. (2021) chapters 3 and 12 consider cooperation in sharing water and knowledge. Different from these papers, we model an explicit lever (the families) that controls the farmers' ability to cooperate and we allow for arbitrary constrained coalitions to form, leveraging cooperative game theory concepts to examine how this influences outcomes.

Cooperative game theory, surveyed by Nagarajan and Sošić (2008), has longstanding importance in the OM literature, but has not been applied in agricultural OM. Recent advances involve the use of *farsighted* solution concepts in which players are strategic in forming a coalition, anticipating how other players would respond; see Tian et al. (2019) and papers surveyed therein. Most cooperative games in OM literature have characteristic function form: a coalition's payoff depends only on that coalition. The only OM paper that we are aware of analyzing a cooperative game in partition function form is Fang and Cho (2020), wherein manufacturers partition into coalitions to audit suppliers, and coalitions' payoffs are determined by the *unique* non-cooperative equilibrium in the coalitions' auditing efforts. We contribute the concept of a cooperative game in partition *correspondence* form and its Recursive Core, which allows analyzing cooperation in settings with *multiple* non-cooperative equilibria. Because many OM models–including those related to agriculture (e.g., Mu et al. 2016, de Zegher et al. 2019, Pay et al. 2022, Alizamir et al. 2022)– exhibit such multiplicity, we hope that our novel solution concept will prove useful and will encourage broader use of cooperative game theory to study how (partial) cooperation can improve outcomes in competitive environments.

Our work is also related to the ample literature on Payments for Ecosystem Services (PES), surveyed in Wunder (2008), Engel et al. (2008), Wunder et al. (2008). PES schemes reward landholders for conservation, usually through monetary (or sometimes in-kind) transfers contingent on verifiable actions. Classic PES contracts target individual landowners, but practical experience has exposed several shortcomings. First, such contracts-which require participants to have clear land titles–are rarely effective in areas where land tenure is ambiguous, which are often also those areas where deforestation is most acute (Wunder 2008, Börner et al. 2010). Second, payment targeting is often inefficient: too large for some recipients, who would have conserved anyway (which lowers the scheme's additionality), but insufficient for other participants, who still find clearing more profitable (Engel et al. 2008, Jack and Jayachandran 2019). Third, conservation in one location can simply induce forest clearing nearby, a phenomenon known as leakage (Alix-Garcia et al. 2012, Delacote et al. 2016).

Fourth, enrolling and monitoring thousands of smallholders drives up transaction costs (Wunder et al. 2018). Finally, allocating payments in proportion to the forest area conserved often skews benefits toward wealthier landholders, exacerbating local inequities; this issue has been acknowledged amply in the PES literature and many have advocated for payments that compensate participants for their opportunity costs (Pascual et al. 2010, Wunder et al. 2018, Haas et al. 2019).

Collective or community-based PES (C-PES) schemes tackle several weaknesses of plot-level contracts by rewarding an entire community for conservation on communally or publicly held land. Evidence from diverse settings shows that C-PES schemes have important advantages (Brownson et al. 2019, Kaiser et al. 2023). They are effective in settings where communities–but not individuals–have ownership or operating rights to land. Because the entire village (or jurisdiction) enrolls as a single unit, C-PES curbs leakage and infra-marginal payments, reduces transaction costs, and enables the conservation of large, contiguous blocks of forest (which is essential for watershed or biodiversity conservation efforts). C-PES is also well suited when the reward itself is collective, as with investments in schools, roads, shared equipment, or the granting of communal land-use rights (Kerr et al. 2014, Suyanto et al. 2008, Pender et al. 2007, Knox et al. 2011).

However, despite their promise, C-PES schemes face three recurring pitfalls. First, collective action: communities must not only steward the resource but also govern the allocation and enforcement of conditional payments–a task that succeeds when local institutions are strong but invites disagreement, conflict, and ultimately non-compliance when they are weak or contested (Hayes et al. 2019, Brownson et al. 2019). Second, elite capture: local power brokers can appropriate a disproportionate share of the funds, leaving poorer households undercompensated, which exacerbates local income inequalities and erodes the scheme's legitimacy (Hayes et al. 2019, Sommerville et al. 2010). Third, external pressure: migrants or other outsiders may clear forest within the community's reach, negating any conservation gains (Darmawan et al. 2016, Ruf et al. 2015, Carr 2009).

PES schemes inform several elements of our model–most notably the choice between individual and area conditions and the requirement to achieve compensation by rewarding each local enough to offset his opportunity costs (see §2.1). Our contribution to the PES literature is a systematic analytical framework for quantifying the effectiveness of conditional incentives as a function of important characteristics, including the local community's ability to cooperate, the values with the incentive and with deforestation, and the costs of blocking economic use. Earlier PES theory makes simplistic assumptions about the local cooperation, e.g., assuming that a single coalition can exist (Zavalloni et al. 2019, Bareille et al. 2021) or ignoring cooperation altogether; our partition-correspondence approach captures multiple, endogenously formed coalitions. Our novel area no-use condition, which is primarily inspired by new policies adopted by commodity buyers, also bears some resemblance to specific PES implementations, which ban all agricultural activity in biodiversity easements; one such example is the Simanjiro Conservation Easement in Tanzania, where villagers receive fixed payments for abstaining entirely from farming a designated zone (Nelson et al. 2010). Our main contribution is in comparing the effectiveness of such no-use conditions with more traditional area no-deforestation conditions in the context of forest protection.

Our results align with and formalize several empirical findings in the PES literature. We find that area-based incentives succeed in communities with strong social ties and trust, in which case all participants are also compensated for their opportunity costs; this echoes evidence on C-PES schemes. We find that when cooperation is limited and budgets are tight, directing payments to those farmers with the lowest opportunity costs minimizes implementation costs–consistent with the targeting advice in Wunder et al. (2018)–but also risks deepening local inequities, as documented in Hayes et al. (2019), Sommerville et al. (2010). That C-PES schemes can lead to empty cores or be less effective than individual incentives is also consistent with the collective action problems documented in the PES literature (Hayes et al. 2019, Brownson et al. 2019). Finally, our finding that the most cost-effective way to combine forest protection with full compensation may involve generous, individually tailored contracts parallels the celebrated Vittel programme in France (Perrot-Maître 2006, Wunder et al. 2018), which involved in-depth negotiations with individual landowners to understand their opportunity costs and designing generous payments to offset these.

Lastly, our work is also related to the literature in economics dealing with cooperative games with externalities. Our work proposes games in partition *correspondence* form and generalizes the recursive core originally proposed by Kóczy (2007), to deal with *multiple* equilibria and to allow for *partial cooperation* among the players in the game.

Notation. For a set S, $\mathbb{R}^S$ denotes the set of vectors with real components indexed by the elements of S, and $\{0,1\}^S$ denotes the set of vectors with binary components indexed by the elements of S. For a vector x with components indexed by some set N and for a subset $S \subseteq N$, we define the notation $x_S := \sum_{i \in S} x_i$. We use x_{-i} to denote the vector obtained by removing component i from x, and $[x_i, x_{-i}]$ to denote the vector where component i of x is replaced with value x_i. (This notation also applies to matrices, interpreted on rows: for $M \in \mathbb{R}^{m \times n}$, $[m_i, M_{-i}]$ represents the matrix obtained from M by replacing its i-th row with the row vector m_i.) A *partition* π of a set N is a set of mutually exclusive subsets whose union includes all the elements of N, i.e., $\bigcup_{S \in \pi} S = N$ and $S \cap H = \emptyset$ for all $S, H \in \pi$ with $S \neq H$. The set of all partitions of a set N is denoted by Π_N. For $R \subseteq N$ and partitions $\pi \in \Pi_R$ and $\sigma \in \Pi_N$, we say π is "finer than" σ and write $\pi \prec \sigma$ if for every $S \in \pi$, there exists $S' \in \sigma$ such that $S \subseteq S'$.

2. Model Formulation

Consider the problem of preventing deforestation in an area by offering a positive incentive to "locals" who meet a specified forest protection condition. (By "locals," we refer to all parties that could profit by engaging in deforestation in the area.) In response to the conditional incentive, some locals may form coalitions. Next, locals decide whether or not to engage in deforestation in the area. Lastly, locals observe any locals engaging in deforestation and decide whether or not to block them from using the deforested land (or its timber) to generate income. We describe this formally below.

Coalitions. Locals can form limited coalitions that allow them to cooperate. With $\mathcal{L}$ denoting the set of all locals, a *coalition* $S \in \mathcal{L}$ is a set of locals who *cooperate*, i.e., make decisions to maximize their aggregate net income and make transfers among themselves to implement any agreed-upon allocation of that aggregate net income. Coalition formation is constrained: $\mathcal{L}$ has an exogenous partition $\pi^{\mathcal{F}} \in \Pi_{\mathcal{L}}$ and every coalition S must satisfy $S \subseteq F$ for some $F \in \pi^{\mathcal{F}}$. We refer to any $F \in \pi^{\mathcal{F}}$ as a "family." Coalition formation thus results in a partition $\pi \in \Pi_{\mathcal{L}}$ of locals that is finer than $\pi^{\mathcal{F}}$, $\pi \prec \pi^{\mathcal{F}}$. As an extreme case, the partition could contain coalitions consisting of a single local, $\pi = \{\{\ell\} : \ell \in \mathcal{L}\}$. As the opposite extreme case, the partition could be $\pi = \pi^{\mathcal{F}}$.

Deforestation Decisions. The locals within each coalition $S \in \pi$ jointly decide whether each local $\ell \in S$ should *engage in deforestation*, i.e., whether ℓ should clear an individually-optimal amount of forest to *potentially* generate income (an action denoted by $d_\ell = 1$, with cost c_ℓ) or leave the forest intact (denoted by $d_\ell = 0$). We use $d_S := (d_\ell)_{\ell \in S}$ to denote the decisions of coalition S and $d := (d_\ell)_{\ell \in \mathcal{L}}$ to denote whether any local $\ell \in \mathcal{L}$ engages in deforestation.

Blocking Decisions. Having observed all the deforestation decisions d, the locals in each coalition jointly decide whether to "block" each local $\ell \in \mathcal{L}$, i.e., prevent him from using the land he deforested to generate income. Blocking one local incurs cost $\eta \geq 0$. We represent the blocking decisions for all locals i in coalition S as a matrix $B_S(d) \in \{0,1\}^{S \times \mathcal{L}}$ and the blocking decisions for all locals $i \in \mathcal{L}$ as the matrix $B(d) \in \{0,1\}^{\mathcal{L} \times \mathcal{L}}$. ($B$ and B_S depend on d because blocking is done after observing deforestation decisions; when no confusion can arise, we omit the dependency on d.) For either matrix, the i-th row denotes the blocking done by local i and the ℓ-th column denotes whether local ℓ is blocked. Thus, $B_{i\ell} = 1$ if and only if i blocks ℓ, and $\max_{i \in \mathcal{L}} B_{i\ell} = 1$ indicates that ℓ is blocked from using deforested land. Coalition $S \in \pi$ thus incurs a total blocking cost of $\eta \cdot \sum_{i \in S, \ell \in \mathcal{L}} B_{i\ell}$, shared among the locals in the coalition.

Locals' Incomes. The income function $J_\ell : \{0,1\} \times \{\text{yes}, \text{no}\} \to \mathbb{R}$ for local ℓ corresponds to the income that local ℓ can generate subsequently, following any deforestation and blocking. J_ℓ depends only on whether local ℓ uses deforested land to generate income (1 or 0) and on whether ℓ receives the incentive (yes or no). For local ℓ to use deforested land, he must engage in deforestation ($d_\ell = 1$) and cannot be blocked from using deforested land ($\max_{i \in \mathcal{L}} B_{i\ell} = 0$). Locals receive the incentive if and only if their deforestation and blocking decisions comply with the specified forest protection condition; this is determined by $\mathbb{C}(d, B) \in \{\text{yes}, \text{no}\}^{\mathcal{L}}$, where $\mathbb{C}_\ell(d, B)$ indicates whether the deforestation and blocking decisions d, B are such that local ℓ should receive the incentive. (The forest protection condition $\mathbb{C}$ is formalized subsequently.) Local ℓ's income therefore takes the form:

$$J_\ell\Big(d_\ell \cdot \big(1 - \max_{i\in\mathcal{L}} B_{i\ell}\big), \mathbb{C}_\ell(d, B)\Big). \tag{1}$$

The incentive is positive, i.e., increases the income for every local $\ell \in \mathcal{L}$. We use

$$\phi_\ell := J_\ell(0, \text{yes}) - J_\ell(0, \text{no}) \geq 0 \tag{2}$$

to denote the value of the incentive for a local who doesn't engage in deforestation, and ϕ to denote the vector of all such values for all locals $\ell \in \mathcal{L}$.

Absent any incentive, each local $\ell \in \mathcal{L}$ would strictly prefer to incur the deforestation cost c_ℓ to engage in his individually-optimal amount of deforestation; we use

$$\delta_\ell := \big(J_\ell(1, \text{no}) - c_\ell\big) - J_\ell(0, \text{no}) > 0 \tag{3}$$

to denote the value from engaging in deforestation for local ℓ.

For any coalition S, we say that S *prefers the incentive* if $\phi_S := \sum_{\ell\in S} \phi_\ell > \delta_S := \sum_{\ell\in S} \delta_\ell$, whereas that coalition *prefers deforestation* if $\phi_S < \delta_S$. We denote by $\mathcal{G}$ the set of all locals who prefer the incentive individually, $\mathcal{G} := \{\ell \in \mathcal{L} : \phi_\ell > \delta_\ell\}$. The interesting case is that the incentive is *imperfect*, in that at least one local prefers deforestation:

$$\emptyset \neq \mathcal{G} \subset \mathcal{L}. \tag{4}$$

The base analysis in §3 adopts this assumption, but §4 then relaxes it.

Decision Timeline and Overall Game Formulation. Given an incentive ϕ and forest protection condition $\mathbb{C}$, the locals first organize themselves into a partition $\pi \prec \pi^{\mathcal{F}}$ of coalitions. Subsequently, the coalitions $S \in \pi$ engage in a two-stage, non-cooperative game–which we refer to concisely as *the non-cooperative game*–wherein the locals in each coalition $S \in \pi$ choose their deforestation decisions d_S followed by their blocking decisions $B_S(d)$ to maximize their aggregate *net* income, i.e., their income net of any deforestation and blocking costs:

$$\sum_{\ell\in S}\left[J_\ell\Big(d_\ell \cdot \big(1 - \max_{i\in\mathcal{L}} B_{i\ell}\big), \mathbb{C}_\ell(d, B)\Big) - c_\ell \cdot d_\ell - \eta \cdot \sum_{i\in\mathcal{L}} B_{\ell i}\right]. \tag{5}$$

To predict how locals form coalitions and the net income a_ℓ that is allocated to each local ℓ within each coalition, we formalize a cooperative game with transferable utility and externalities–which we refer to as *the cooperative game*–and use a recursive core solution concept.

An equilibrium in our overall game will be a partition π and allocation of net income $(a_\ell)_{\ell\in\mathcal{L}}$ belonging to the recursive core for the cooperative game, and a subgame perfect equilibrium for the non-cooperative game corresponding to partition π.

Candidates for the Forest Protection Condition $\mathbb{C}$. We consider three conditions:

1. *Individual condition,* $\mathbb{I}$. Local ℓ receives the incentive if and only if he does not individually engage in deforestation: $\mathbb{I}_\ell(d,B) = \text{yes} \;\Leftrightarrow\; d_\ell = 0$.
2. *Area No-Deforestation Condition,* $\bar{\mathbb{D}}$. Each local $\ell \in \mathcal{L}$ receives the incentive if and only if no local engages in deforestation: $\bar{\mathbb{D}}_\ell(d,B) = \text{yes} \;\Leftrightarrow\; d_i = 0, \forall i \in \mathcal{L}$.
3. *Area No-use Condition* $\bar{\mathbb{U}}$. Each local $\ell \in \mathcal{L}$ receives the incentive if and only if no local uses land that he deforested to generate income: $\bar{\mathbb{U}}_\ell(d,B) = \text{yes} \;\Leftrightarrow\; d_i \cdot \left(1 - \max_{g\in\mathcal{L}} B_{gi}\right) = 0, \forall i \in \mathcal{L}$.

With the Individual Condition, whether a local receives the incentive depends only on his individual deforestation decision, and blocking is therefore irrelevant.

With either area condition, compliance for any local is determined by the decisions of all (coalitions of) locals. The Area No-Deforestation Condition $\bar{\mathbb{D}}$ requires that no locals engage in deforestation. The Area No-Use Condition $\bar{\mathbb{U}}$ is weaker and is satisfied if $\bar{\mathbb{D}}$ is satisfied or if every local that engaged in deforestation is blocked from using the land that he deforested to generate income.

Problem Formulation. We formalize two feasibility requirements for the conditional incentive.

- We say that the conditional incentive *prevents deforestation* if in every equilibrium, no local engages in deforestation in the area, $d_\ell = 0$ for all $\ell \in \mathcal{L}$.
- We say that a conditional incentive *prevents deforestation with compensation* if it *prevents deforestation* and in every equilibrium, the net income a_ℓ allocated to each local exceeds his net income with deforestation, $a_\ell \geq J_\ell(1,\text{no}) - c_\ell$ for all $\ell \in \mathcal{L}$. To emphasize that a conditional incentive that *prevents deforestation* meets this stronger constraint, we say it *achieves compensation.*

Either requirement is consistent with the dual commitments–in that it prevents deforestation in the area and it benefits every local–but the difference lies in the benefits. Because the incentive is positive, by (2), *preventing deforestation* weakly benefits each local ℓ because his net income with the incentive is at least his "status quo" net income without the incentive and without deforestation, $J_\ell(0,\text{no})$. The stronger constraint of *preventing deforestation with compensation* ensures that each local is reimbursed for his opportunity cost of forgoing forest clearance, which strictly increases his net income relative to the status quo, by (3). To emphasize that a conditional incentive that *prevents deforestation* also meets this stronger fairness constraint, we say that it *achieves compensation.*

In §3, we characterize the set of problem parameters (values with the incentive ϕ and with deforestation δ, and blocking cost η) that make each condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$ feasible, considering each requirement–preventing deforestation and preventing deforestation with compensation–separately. §4.1 then compares the conditions and characterizes the most robust choice, i.e., the choice of condition $\mathbb{C}$ and associated incentive values ϕ that are feasible in the inclusion-wise largest set of problem parameters. Lastly, §4.2 allows adjusting the incentive values ϕ freely and characterizes the feasible incentive[1] ϕ and condition $\mathbb{C}$ that minimize the total cost of providing the incentive, $\sum_{\ell\in\mathcal{L}} \phi_\ell$.

[1] Because each local's status-quo income $J_\ell(0,\text{no})$ is exogenously fixed, a choice of incentive only influences $\{\phi_\ell\}_{\ell\in\mathcal{L}}$.

2.1. Discussion of Modeling Assumptions

Deforestation and Blocking Decisions. We focus on the decision of *whether* to engage in deforestation, which is consistent with the goal of preventing any deforestation. Importantly, however, for each local $\ell \in \mathcal{L}$, the key parameters c_ℓ, $J_\ell(1,\text{no})$, and $\delta_\ell = J_\ell(1,\text{no}) - c_\ell - J_\ell(0,\text{no})$ account for the *optimal amount* of land to deforest and *optimal decisions* regarding land use that maximize ℓ's net income. Our model and results are general because we impose no assumptions on the underlying decision-making that leads to the key parameters. In §EC.5, we demonstrate how to estimate the key parameters through a field study of a specific area and detailed structural model of the underlying optimal decisions for locals; the reader may find it helpful to briefly refer to that section to better understand the key parameters. Similarly, we do not explicitly model any punitive measures on a local ℓ who generates income by engaging in deforestation, but those could be represented by decreasing $J_\ell(1,\text{no})$ and the value from engaging in deforestation, δ_ℓ.

In areas with clear and strong property rights, blocking a local from generating income by deforesting his own land may be impossible, which would correspond to setting $\eta = +\infty$ in our model.

In our field sites in Indonesia and Thailand, and in many other deforestation-prone areas with weak property rights, locals use fires to clear forests, then establish agriculture on the cleared land (Tyukavina et al. 2018, van Wees et al. 2021, Falcon et al. 2022). In Indonesia, such fires are illegal, yet fire remains a preferred means of engaging in deforestation due to the difficulty of catching a culprit in the act of lighting a fire, as needed to prevent its spread and hold him accountable. To light a fire requires little cost or effort, and fire spreads rapidly in forest. Hence, the parameter c_ℓ would primarily represent the cost to establish agriculture on the cleared land, which in Indonesia involves planting palm seedlings. To block a local from generating income from agriculture on deforested land, other locals would take the easiest, least-costly approach in their specific context. If establishing agriculture on the deforested land is illegal, locals could report a culprit to the authorities. Alternatively, locals could apply peer pressure (public shaming, ostracism) or material forms of social sanction such as cutting down the seedlings for a new plantation (as documented in Indonesia by Villadiego 2017) or confiscating produce. The blocking cost η therefore should be thought of as the minimum cost to block a local from generating income from deforested land.

Our model is also applicable in an area where heavy equipment (rather than fire) would be used to clear forest, with or without harvest of the timber. In this case, d_ℓ represents the decision of whether or not to bring heavy equipment to the area and use it to clear an optimal amount of forest, and c_ℓ represents the cost of doing so. Furthermore, J_ℓ would represent the optimal net income for local ℓ from timber sales and/or economic use of the land, if he isn't blocked. Other locals could prevent local ℓ from extracting timber for sale, e.g., by reporting him to authorities, damaging his equipment, blocking the road, or protecting the trees themselves (Linkie et al. 2014, Donald 2021, Evans 2013, Burton 2004), and could prevent him from producing on cleared land by means discussed above.

Lastly, our model is valid in an area where locals can block any *attempt* at deforestation before any deforestation actually occurs. Specifically, suppose locals in such an area are offered an incentive conditional on no deforestation. One may reinterpret d_ℓ as the decision whether to *attempt* to engage in deforestation, c_ℓ the cost of doing so (e.g., the cost of bringing in heavy equipment), and $B_S(d)$ and η as the decisions of whether to block attempted deforestation and cost of doing so, respectively. The locals receive the incentive if and only if every local who attempts deforestation is blocked: $d_i \cdot \left(1 - \max_{g\in\mathcal{L}} B_{gi}\right) = 0, \forall i \in \mathcal{L}$. This is structurally equivalent to our base model with the area no-use condition–only parameter values differ–so our analysis of the area no-use condition remains relevant. In general, the area no-use condition potentially has a parametric advantage for preventing deforestation because locals could comply by blocking an attempt at deforestation or blocking economic use, depending on whichever costs less (i.e., has lower η).

Drawing on the Indonesia and Thailand motivation, our model assumes that blocking use is cheaper than blocking attempts at deforestation. Suppressing a fire is challenging, as (Falcon et al. 2022) also documented: it requires round-the-clock monitoring to detect outbreaks and an immediate and resource-intensive response. In Indonesia, extinguishing a peat-soil blaze demands pumps, protective gear, trained crews, and large volumes of water (Kopansky 2018). The labor and equipment involved make stopping a single ignition far more costly than, say, cutting down illicit seedlings days or weeks later to prevent economic use of the cleared plot.

Our base model assumption that the cost of blocking is a constant η per local blocked is reasonable in the examples described above, and facilitates the derivation and exposition of our main results. §EC.4.2 of the Appendix extends our results to the case where this cost depends on the family that engages in the blocking, i.e., the cost is η_F for all $\ell \in F$ and all $F \in \pi^{\mathcal{F}}$. Our results extend to an even more general case where the cost depends on the local who is blocking and the local who is being blocked ($\eta_{\ell i}$ for $\ell, i \in \mathcal{L}$) at the expense of more complex notation and analysis. If instead the cost of blocking were to depend on the amount of forest converted to agricultural land, locals' strategic interactions (in how *much* land to deforest and develop so as to deter blocking, how to form coalitions that deter blocking, etc.) would become analytically intractable.

Cooperation and Families. In some rural communities, locals coordinate on key decisions for the management of agriculture and natural resources, and share in the costs and benefits. Such cooperation can arise within an extended family or ethnic group (Rosenzweig 1988, Angelucci et al. 2018) or among farmers in an agricultural cooperative or members of a savings and loan association (Geertz 1962, Ksoll et al. 2016), and is fostered by a traditional culture of mutual assistance in many rural settings (e.g., *gotong royong* and *subak* in Indonesia, *bayanihan* in the Philippines, *harambee* and *iddir* in East Africa, and *tequio* and *minga* in Latin America). Our own experience in Indonesia and Thailand showed that residents of the same village and members of well-run agricultural cooperatives have many mechanisms for cooperation and for sharing money, labor, food or other goods. We refer to a set of locals who can coordinate decisions and transfer utility among themselves in our model as a “family.” A “family” might correspond, in reality, to an extended family of relatives, an ethnic community, a smaller village, or a business group (cooperative, savings and loan association) whose members do not cooperate with non-members.

Imperfect Incentive. Summarizing the incentive’s effect through $J_\ell(0, \text{yes})$ and ϕ_ℓ – without requiring specific functional forms – makes our model applicable in many settings. For instance, the incentive could be a price premium or an input subsidy offered to smallholder farmers producing a certain commodity (as in our analysis in §EC.5). The incentive could be an investment in assets shared by the local community (schools, roads, equipment) or granting the community land tenure and land-use rights (Kerr et al. 2014, Suyanto et al. 2008). The incentive could also be a carbon offset payment, determined by the prevailing market price per tonne of avoided CO2 emissions and the estimated tonnage of CO2 emissions avoided by preventing deforestation in the area (Börner et al. 2013).

Our base analysis with a fixed incentive in §3 considers the common circumstance that the incentive is *imperfect*, i.e., at least one farmer prefers engaging in deforestation to the incentive, per (4). This mirrors reality: the value of a practical incentive (like the ones in the prior paragraph) can rarely be tailored to each local, data challenges make it hard to precisely estimate a local’s value from the incentive or his opportunity costs, and budget constraints limit payments and outreach efforts.

Area No-use Condition. The main rationale for considering the area no-use condition $\bar{\mathbb{U}}$ lies in its ability to address fire-induced deforestation. Recall from our discussion of blocking that locals could, in principle, comply with $\bar{\mathbb{U}}$ by blocking an attempt at deforestation or blocking income-generation, depending on whichever costs less (i.e., has lower η). In keeping with our motivating examples in Indonesia, the rest of the paper focuses on a setting where the latter alternative is cheaper, but the no-use condition $\bar{\mathbb{U}}$ remains relevant in many other practical settings.

Feasibility. We focus on conditional incentives that prevent deforestation, but also consider separately the stronger constraint of preventing deforestation with compensation. This reflects the widespread view in the PES literature that participants should be compensated for their opportunity costs (Pascual et al. 2010, Wunder 2008, Luttrell et al. 2013). The EUDR has been criticized for harming local smallholder farmers because it requires commodity buyers to prevent deforestation but it does *not* require compensation (Zhunusova et al. 2022). Insofar as a local’s net income with deforestation is sufficient for a decent living standard, an incentive that achieves compensation can arguably be deemed sufficient for compliance with the EU’s CSDDD fair price/living income requirements. Beyond its equity benefits, compensation also strengthens the scheme’s resilience by further reducing each local’s incentive to clear forest. Thus, commodity buyers with a strong focus on social justice (such as the Dutch chocolate manufacturer Tony's Chocolonely, which makes fair prices a core part of its mission), governmental agencies, or NGOs may consider this more restrictive feasibility criterion.

Problem Formulation. Characterizing the most robust conditional incentives–i.e., that are feasible in the largest set of problem instances, as in §4.1–is important due to practical challenges in estimating key model parameters. Characterizing the lowest-cost conditional incentive (as in §4.2) gives a benchmark for cost-efficiency, albeit an optimistic one because incentive values can be freely adjusted.

3. Feasibility Analysis

This section analyzes when a specific conditional incentive–given by incentive values ϕ and condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$–is feasible. We focus on *imperfect* positive incentives ϕ, meaning that at least one local prefers deforestation, per (4) and we also assume that each local has a strict preference between the incentive and deforestation: $\phi_\ell \neq \delta_\ell$ for every $\ell \in \mathcal{L}$. (We relax both assumptions in §4.) §3.1 analyzes the non-cooperative game for a given partition π of locals into coalitions, characterizing the possible equilibria. §3.2 then formalizes the cooperative game whereby locals form coalitions within their families, formalizes our novel solution concept (the Pessimistic Recursive Core), and characterizes when a conditional incentive is feasible.

3.1. Analysis of the Non-Cooperative Game (of Deforestation and Blocking)

Consider a fixed partition $\pi \in \Pi_{\mathcal{L}}$ and the non-cooperative game among the coalitions $S \in \pi$. A subgame-perfect equilibrium of that game is a set of deforestation decisions d^* and blocking policies $B^*(d)$ that satisfy, for each $S \in \pi$:

$$B^*_S(d) \in \underset{B_S \in \{0,1\}^{S \times \mathcal{L}}}{\arg\max} \sum_{\ell \in S} \left[J_\ell\Big(d_\ell \cdot \big(1 - \max_{i \in \mathcal{L}} B^*_{i\ell}(d)\big), \mathbb{C}_\ell\big(d, [B_S, B^*_{-S}(d)]\big)\Big) - \eta \cdot \sum_{i \in \mathcal{L}} B_{\ell i} \right] \tag{6}$$

$$d^*_S \in \underset{d_S \in \{0,1\}^S}{\arg\max} \sum_{\ell \in S} \left[J_\ell\Big(d_\ell \cdot \big(1 - \max_{i \in \mathcal{L}} B^*_{i\ell}([d_S, d^*_{-S}])\big), \mathbb{C}_\ell\big([d_S, d^*_{-S}], B^*([d_S, d^*_{-S}])\big)\Big) - c_\ell \cdot d_\ell - \eta \cdot \sum_{i \in \mathcal{L}} B^*_{Si} \right]. \tag{7}$$

In the second stage, each coalition S chooses its blocking policy $B_S(d)$ to maximize its net income (5), given the deforestation decisions d and the blocking decisions of all other coalitions $B^*_{-S}(d)$; in the first stage, each coalition S chooses its deforestation decisions d_S to maximize its net income given the deforestation decisions of all other coalitions d^*_{-S} and the equilibrium blocking policy $B^*(d)$.

We use $\mathcal{Q}(\pi, \mathbb{C})$ to denote the set of all subgame-perfect equilibria $(d^*, B^*(d))$ that satisfy (6)-(7) for partition $\pi \in \Pi_{\mathcal{L}}$ and forest protection condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$.

We first analyze the individual condition $\mathbb{I}$. Because $\mathbb{I}_\ell(d, B)$ solely depends on local ℓ's deforestation decision d_ℓ, it is easy to see that regardless of the partition π, each individual ℓ would make his optimal deforestation decision and no blocking would occur in equilibrium. Formally, $d^*_\ell = 1$ if and only if $\phi_\ell < \delta_\ell$, and $B^*(d) = 0$. With an imperfect incentive, the individual condition $\mathbb{I}$ would therefore not prevent deforestation and would be *infeasible*.

Our next result concerns the area conditions $\bar{\mathbb{D}}, \bar{\mathbb{U}}$ and establishes that in equilibrium, no blocking occurs and either no local engages in deforestation or all locals engage in deforestation.

LEMMA 1. *For every partition $\pi \in \Pi_{\mathcal{L}}$ and condition $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$, $\mathcal{Q}(\pi, \mathbb{C})$ is non-empty and any subgame-perfect equilibrium in $\mathcal{Q}(\pi, \mathbb{C})$ has $B^*(d^*) = 0$ and either $d^* = 0$ or $d^* = 1$.*

Only the two extreme types of equilibrium exist because each coalition is more inclined to engage in deforestation when other coalitions do so. With $\bar{\mathbb{D}}$, deforestation by any coalition prevents all the others from earning the incentive, so their best response is to engage in deforestation, too. With $\bar{\mathbb{U}}$, deforestation by more individuals raises the total cost that a coalition would have to incur to block them and earn the incentive, which favors the coalition also engaging in deforestation.

In every subgame-perfect equilibria, no blocking would occur. With $\bar{\mathbb{D}}$, blocking would not influence the condition and because blocking is costly, it would not occur. With $\bar{\mathbb{U}}$, in any equilibrium where the threat of being blocked is credible, a coalition that prefers to engage in deforestation would anticipate this and not do so because deforestation is costly, leading to no blocking.

When discussing the subgame perfect equilibria in the noncooperative game, we henceforth use the term *deforestation equilibrium* to refer to an equilibrium with $d^* = 1$, *no-deforestation equilibrium* to refer to an equilibrium with $d^* = 0$, and *equilibrium indicator* to refer to d^*.

The next result identifies when each type of equilibrium exists. $T(\pi, \mathbb{C})$ represents the types of equilibria in $\mathcal{Q}(\pi, \mathbb{C})$: $T(\pi, \mathbb{C}) = \{0\}$ means only no-deforestation equilibria exist, $T(\pi, \mathbb{C}) = \{1\}$ means only deforestation equilibria exist, and $T(\pi, \mathbb{C}) = \{0, 1\}$ means both types exist.

LEMMA 2. *Consider a partition $\pi \in \Pi_{\mathcal{L}}$. With the area no-deforestation condition $\bar{\mathbb{D}}$,*

$$T(\pi, \bar{\mathbb{D}}) = \begin{cases} \{0\} & \text{if } \pi = \{\mathcal{L}\} \text{ and } \phi_{\mathcal{L}} > \delta_{\mathcal{L}} \\ \{1\} & \text{if } \phi_S < \delta_S \text{ for some coalition } S \text{ in } \pi \\ \{0, 1\} & \text{otherwise.} \end{cases}$$

With the area no-use condition $\bar{\mathbb{U}}$, there exist thresholds (on the cost of blocking) $\eta_1(\pi), \eta_2(\pi)$ so that $\eta_1(\pi) \leq \eta_2(\pi)$ and

$$T(\pi, \bar{\mathbb{U}}) = \begin{cases} \{0\} & \text{if } \eta < \eta_1(\pi) \\ \{1\} & \text{if } \eta > \eta_2(\pi) \\ \{0, 1\} & \text{otherwise.} \end{cases}$$

With $\bar{\mathbb{D}}$, deforestation equilibria exist unless the locals form the grand coalition ($\pi = \{\mathcal{L}\}$) and collectively prefer the incentive ($\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$). Only deforestation equilibria exist when a coalition prefers deforestation ($\phi_S < \delta_S$) because with $\bar{\mathbb{D}}$, there is no credible threat of blocking to deter this coalition (i.e., $B^*(d) = \mathbf{0}$) and deforestation would be the best response from all other parties in that case.

With $\bar{\mathbb{U}}$, a credible threat of blocking can sustain no-deforestation equilibria. Consider the expressions of the thresholds $\eta_1(\pi), \eta_2(\pi)$ in the statement:

$$\eta_1(\pi) := \sup\{\eta : \exists S \in \pi \text{ with } (\phi_S - \delta_S) > \eta\,(|\mathcal{L} \setminus S|)\} \tag{8a}$$

$$\eta_2(\pi) := \inf\left\{\eta : \sum_{S\in\pi:\phi_S>\delta_S} \left\lfloor \frac{(\phi_S-\delta_S)}{\eta} \right\rfloor < \max_{H\in\pi:\phi_H<\delta_H} |H| \right\}. \tag{8b}$$

When $\eta < \eta_1(\pi)$, some coalition of locals $S \in \pi$ could profitably block all other locals $\mathcal{L}\setminus S$ from using deforested land because coalition S's net benefit from the incentive $(\phi_S - \delta_S)$ is larger than the cost of blocking all other locals $(\eta|\mathcal{L}\setminus S|)$. Given the credible threat of blocking, no local would engage in deforestation. When $\eta > \eta_2(\pi)$, some coalition $H \in \pi$ that prefers deforestation $(\phi_H < \delta_H)$ will engage in deforestation, knowing that coalitions that prefer the incentive ($S \in \pi$ with $\phi_S > \delta_S$) would not block use of that deforested land. This is because the term $\sum_{S\in\pi:\phi_S>\delta_S} \lfloor(\phi_S-\delta_S)/\eta\rfloor$ is the maximum number of locals that coalitions preferring the incentive could block; the floor operator $\lfloor\cdot\rfloor$ is used because utility transfer occurs only within coalitions, not across coalitions. When $\eta \in [\eta_1(\pi), \eta_2(\pi)]$, deforestation and no-deforestation equilibria exist because no single coalition could profitably block all other locals, whereas two or more coalitions jointly could.

The thresholds $\eta_1(\pi)$ and $\eta_2(\pi)$ depend on the partition π. If locals are in the grand coalition $(\pi = \{\mathcal{L}\})$ and prefer the incentive $(\phi_{\mathcal{L}} > \delta_{\mathcal{L}})$, then $\eta_1(\pi) = \eta_2(\pi) = +\infty$ and only no-deforestation equilibria exist, irrespective of the blocking cost. Similarly, with any partition of locals into coalitions that all prefer the incentive ($\phi_S > \delta_S$ for all $S \in \pi$), $\eta_2(\pi) = +\infty$, so no-deforestation equilibria exist irrespective of the blocking cost. With any partition of locals into coalitions that all prefer deforestation $(\phi_S < \delta_S, \forall S \in \pi)$, $\eta_1(\pi) = \eta_2(\pi) = -\infty$ and only deforestation equilibria exist, irrespective of the blocking cost. Except in the aforementioned cases, $\eta_1(\pi)$ and $\eta_2(\pi)$ are strictly positive and finite, so the types of equilibria depend on the blocking cost. The threshold $\eta_1(\pi)$ is decreasing as the partition π becomes finer, meaning that smaller coalitions are less able to create the blocking threats needed to support cases without deforestation equilibria. ($\eta_2(\pi)$ is not necessarily monotonic in π.)

3.2. Analysis of the Cooperative Game (of Coalition Formation)

To formalize the cooperative game through which locals organize themselves into coalitions under a given condition $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$, we must first assign a value to each coalition $S \in \pi$ in every feasible partition $\pi \prec \pi^{\mathcal{F}}$. To that end, consider any subgame-perfect equilibrium $(d^*, B^*(d)) \in \mathcal{Q}(\pi, \mathbb{C})$ in the noncooperative-game corresponding to $\mathbb{C}$ and π. By Lemma 1 and Lemma 2, this is either a no-deforestation or a deforestation equilibrium, as indicated by $d^* \in T(\pi, \mathbb{C}) \subseteq \{0,1\}$, and no blocking occurs, $B^*(d^*) = 0$. Therefore, the net income for each coalition in this equilibrium can be written as:

$$w(S,\pi;d^*) = \begin{cases} \sum_{\ell\in S} J_\ell(0,\text{yes}) & \text{if } d^* = 0 \\ \sum_{\ell\in S}\left[J_\ell(1,\text{no}) - c_\ell\right] & \text{if } d^* = 1 \end{cases}, \forall S \in \pi. \tag{9}$$

Because the partition π only affects the value of w through the deforestation indicator d^*, we can write the value above even more concisely as $w(S;d^*)$, with the understanding that $d^* \in T(\pi, \mathbb{C})$.

This motivates the following definitions needed for formalizing the TU-game.

Definition 1 (Partition Function and Partition Correspondence). The *partition function* associated with $\pi \in \Pi_{\mathcal{L}}$, $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$, and a subgame-perfect equilibrium with indicator $d^* \in T(\pi, \mathbb{C})$ is the function $w(S, \pi; d^*)$ defined in (9). The *partition correspondence* $V(\pi; \mathbb{C})$ associated with $\pi \in \Pi_{\mathcal{L}}$ and $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$ is the set of all partition functions corresponding to subgame-perfect equilibria in the non-cooperative game for π and $\mathbb{C}$, i.e., $V(\pi; \mathbb{C}) = \{w(S, \pi; d^*) : d^* \in T(\pi, \mathbb{C})\}$.

We now formalize a *TU cooperative game in partition correspondence form.* Offered the incentive to meet condition $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$, the locals $\ell \in \mathcal{L}$ form coalitions and may transfer utility within each coalition. The locals know that with partition $\pi \prec \pi^{\mathcal{F}}$, the net income for each coalition $S \in \pi$ would be $w(S, d^*)$ for some $d^* \in T(\pi, \mathbb{C})$. An *outcome* of this game is a triple: a partition $\pi \prec \pi^{\mathcal{F}}$, an equilibrium indicator $d^* \in T(\pi)$, and an allocation of net income to each local $\{a_\ell\}_{\ell \in \mathcal{L}}$ satisfying $\sum_{\ell \in S} a_\ell = w(S, d^*)$ for every $S \in \pi$.

To predict which outcomes could occur, we extend the *Pessimistic Recursive Core* solution concept due to Kóczy (2007) to games in partition correspondence form and with limited cooperation. The premise of the Recursive Core is that locals who form a coalition anticipate that locals left out of that coalition will act so as to maximize their own net income, engaging in a smaller, "residual TU cooperative game." Through recursion over residual games, one solves for the Recursive Core: the set of outcomes at which no set of locals would expect to achieve higher net income by forming different coalitions. If the core outcome of a residual game or the partition functions $w(\cdot)$ are not unique, we assume locals who form a coalition have *pessimistic* beliefs about how the other locals will act. The next definitions formalize this.

Definition 2 (Residual TU Cooperative Game). Consider a subset of locals $R \subseteq \mathcal{L}$ and a fixed partition $\pi_{\mathcal{L}\setminus R} \in \Pi_{\mathcal{L}\setminus R}$ (with $\pi_{\mathcal{L}\setminus R} \prec \pi^{\mathcal{F}}$) of the other locals. In response to $\pi_{\mathcal{L}\setminus R}$, the locals in R face a *residual TU cooperative game* in partition correspondence form: the sub-partition $\pi_R \in \Pi_R$ with $\pi_R \prec \sigma$ formed by the locals in R together with the sub-partition of the other locals $\pi_{\mathcal{L}\setminus R}$ and the associated equilibrium indicator $d^* \in T(\pi_R \cup \pi_{\mathcal{L}\setminus R})$ determine the net income $w(S, \pi_R \cup \pi_{\mathcal{L}\setminus R}; d^*)$ for the locals in each coalition $S \in \pi_R$. An *outcome for the residual game* is a partition $\pi_R \in \Pi_R$ with $\pi_R \prec \sigma$, an equilibrium indicator $d^* \in T(\pi_R \cup \pi_{\mathcal{L}\setminus R})$, and an allocation $\{a_\ell\}_{\ell \in R}$ satisfying $\sum_{\ell \in S} a_\ell = w(S, \pi_R \cup \pi_{\mathcal{L}\setminus R}; d^*)$ for every $S \in \pi_R$.

Definition 3 (Pessimistic Recursive Core). Suppose that for an integer $k \in [1, |\mathcal{L}| - 1]$, the core $C(R; \pi_{\mathcal{L}\setminus R})$ is defined for every residual game in which a set of locals $R \subset \mathcal{L}$ with $|R| \in [1, k]$ respond to a partition of the other locals $\pi_{\mathcal{L}\setminus R} \in \Pi_{\mathcal{L}\setminus R}$ (with $\pi_{\mathcal{L}\setminus R} \prec \sigma$). For $k = 1$, the residual game has a single local $R = \{\ell\}$ and the core $C(\{\ell\}; \pi_{\mathcal{L}\setminus\{\ell\}})$ is the set of triples of partition, equilibrium indicator, and allocations of the form $(\{\{\ell\}\}, d^*, a_\ell)$ with $a_\ell = w(\{\ell\}, \{\{\ell\}\}; d^*)$ and $d^* \in T(\{\{\ell\}\} \cup \pi_{\mathcal{L}\setminus\{\ell\}})$. For a residual game with $|R| = k + 1$, the core $C(R; \pi_{\mathcal{L}\setminus R})$ is the set of *un-dominated* outcomes, where an outcome with allocation $\{a_\ell\}_{\ell\in R}$ and partition π_R is *dominated* if there exists a coalition $H \subseteq R$ forming partition $\pi_H \in \Pi_H$ so that

$$w\big(S, \hat{\pi}_{R\setminus H} \cup \pi_H \cup \pi_{\mathcal{L}\setminus R}; \hat{d}\big) > \textstyle\sum_{\ell\in S} a_\ell \tag{10}$$

for **every** coalition $S \in \pi_H$, **every** sub-partition $\hat{\pi}_{R\setminus H} \in \Pi_{R\setminus H}$ with $\hat{\pi}_{R\setminus H} \prec \sigma$, and **every** equilibrium indicator $\hat{d}$ and real values $\{\hat{a}_\ell\}_{\ell\in R\setminus H}$ satisfying:

$$\begin{cases} \big(\hat{\pi}_{R\setminus H}, \hat{d}, \{\hat{a}_\ell\}_{\ell\in R\setminus H}\big) \in C(R\setminus H; \pi_H \cup \pi_{\mathcal{L}\setminus R}) & \text{if } H \subset R \text{ and } C(R\setminus H; \pi_H \cup \pi_{\mathcal{L}\setminus R}) \neq \emptyset \\ \hat{d} \in T(\hat{\pi}_{R\setminus H} \cup \pi_H \cup \pi_{\mathcal{L}\setminus R}) & \text{otherwise.} \end{cases} \tag{11}$$

The pessimistic Recursive Core of the TU cooperative game among all locals is then given by $C(\mathcal{L};\emptyset)$.

Notice how the definition of dominated outcome represents *pessimism*: locals forming coalitions anticipate their *worst-case* net income when the residual locals act to maximize their own net income. For coalition H to deviate, it should form some new partition π_H in which every coalition $S \in \pi_H$ has strictly greater net income than in the starting outcome (per 10) under *every* plausible configuration that could emerge in the residual game played by the remaining locals in $R\setminus H$, i.e., any core outcome if the core of the residual game is non-empty, or any possible equilibrium outcome otherwise (per 11).

The alternative to pessimism is optimism: locals that form a coalition anticipate their *best-case* net income when residual locals act to maximize their own net income. §EC.4.1 formulates the optimistic Recursive Core and, in Proposition 5, shows that this is a subset of the pessimistic Recursive Core. Our performance criteria require that *only* outcomes with the desired performance are in the Recursive Core. Therefore, we conservatively assume pessimism: if the performance criteria are met with pessimistic locals, they would also be met with optimistic locals.

For brevity, we subsequently use "core" to refer to the pessimistic Recursive Core. To identify the possible outcomes in the core, we introduce the following definition.

Definition 4. A *Deforestation Outcome* is an outcome with a deforestation equilibrium $d^* = 1$. A *No-Deforestation Outcome* is an outcome with a no-deforestation equilibrium $d^* = 0$ that allocates $a_\ell \geq \min\big(J_\ell(0,\text{yes}),\, J_\ell(1,\text{no}) - c_\ell\big)$ to every local $\ell \in \mathcal{L}$; it is a

$$\textit{Compensation Outcome} \qquad \text{if } a_\ell \geq J_\ell(1,\text{no}) - c_\ell, \text{ for all } \ell \in \mathcal{L}\setminus\mathcal{G}, \tag{12a}$$

$$\textit{Blocking-Threat Outcome} \qquad \text{if } a_\ell < J_\ell(1,\text{no}) - c_\ell, \text{ for some } \ell \in \mathcal{L}\setminus\mathcal{G}. \tag{12b}$$

Our subsequent results will show that *only* the outcomes in Definition 4 can exist in the core.

A condition prevents deforestation when the core only contains No-Deforestation Outcomes. In any such outcome, every local is allocated at least his status quo income $J_\ell(0,\text{no})$ (without deforestation and without the incentive). This arises because the incentive is positive–by (2)–and because every local would benefit by engaging in deforestation–by (3)–which collectively imply that local ℓ's allocation a_ℓ in any No-Deforestation Outcome exceeds the status quo net income $J_\ell(0,\text{no})$.

A condition achieves compensation when the core only contains Compensation Outcomes: every local is allocated at least the net income he would have earned with deforestation, $J_\ell(1,\text{no}) - c_\ell$, thereby covering his opportunity cost. In contrast, a Blocking-Threat Outcome prevents deforestation through credible blocking threats, so some locals who prefer deforestation are allocated less than their potential net income with deforestation.

Theorems 1 and 2 characterize the recursive cores under conditions $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$. These theorems distinguish cases depending on the exogenous partition $\pi^{\mathcal{F}}$ of locals into families. When $\pi^{\mathcal{F}}$ contains a single family with all locals $\pi^{\mathcal{F}} = \{\mathcal{L}\}$, so that any coalition of locals is possible and π can be any partition, we say that locals have *full ability* to cooperate. Otherwise, we say that locals have *partial ability* to cooperate. (A special instance with partial ability to cooperate is when each family contains a single local, $\pi^{\mathcal{F}} = \{\{\ell\} : \ell \in \mathcal{L}\}$, so that locals are completely unable to cooperate.)

Theorem 1. *With $\bar{\mathbb{D}}$: If $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ and $\pi^{\mathcal{F}} = \{\mathcal{L}\}$, the core is the set of all Compensation Outcomes. If $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$ and $\phi_F > \delta_F$ for all $F \in \pi^{\mathcal{F}}$, the core is the set of all Deforestation Outcomes and all Compensation Outcomes. Otherwise, the core is the set of all Deforestation Outcomes.*

Theorem 1 shows that the area no-deforestation condition $\bar{\mathbb{D}}$ prevents deforestation – and achieves compensation – when locals have full ability to cooperate ($\pi^{\mathcal{F}} = \{\mathcal{L}\}$) and collectively prefer the incentive ($\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$). This arises through utility transfers: to induce a no-deforestation equilibrium, the locals who prefer the incentive must transfer utility to the locals within their coalition who prefer deforestation (i.e., $S \cap \mathcal{G}$ transfer utility to $S \setminus \mathcal{G}$ in every coalition $S \in \pi$) so every local is fully compensated for his missed deforestation opportunity and thus motivated to set $d_\ell = 0$. This compensation mechanism is effective only when the locals have full ability to cooperate and collectively prefer the incentive, because this allows for any possible coalition to be formed wherein any locals who prefer deforestation could be compensated. Otherwise, the core contains Deforestation Outcomes. Notably, this can happen even if every family prefers the incentive ($\phi_F > \delta_F$, for all $F \in \pi^{\mathcal{F}}$) if there are more than two families, because the coalitions formed within these families may fail to coordinate among themselves to prevent a deforestation equilibrium in the non-cooperative game among coalitions. If the incentive is so weak that at least one family prefers deforestation ($\phi_F < \delta_F$ for some $F \in \pi^{\mathcal{F}}$), then *only* Deforestation Outcomes are in the core.

Theorem 2 characterizes the core under the area no-use condition $\bar{\mathbb{U}}$. While reading the statements, consider glancing at Figure 3.1, which illustrates how the core outcomes vary with the magnitude of the blocking cost η and with the locals' ability to cooperate.

Theorem 2. *If $\pi^{\mathcal{F}} = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, the core under condition $\bar{\mathbb{U}}$ can only contain No-Deforestation Outcomes and there exist thresholds $\eta_1^{\text{TU}} \leq \underline{\eta}_2^{\text{TU}} = \overline{\eta}_2^{\text{TU}} \leq \eta_3^{\text{TU}}$ such that:*

- *If $\eta < \eta_1^{\text{TU}}$, the core is nonempty and contains only Blocking-Threat Outcomes;*

- *If* $\eta_1^{\text{TU}} < \eta < \underline{\eta}_2^{\text{TU}}$*, if the core is nonempty, it contains only Blocking-Threat Outcomes;*
- *If* $\underline{\eta}_2^{\text{TU}} = \overline{\eta}_2^{\text{TU}} < \eta < \eta_3^{\text{TU}}$*, the core is non-empty, contains Compensation Outcomes, and may contain Blocking-Threat Outcomes;*
- *If* $\eta_3^{\text{TU}} < \eta$*, the core is non-empty and contains only Compensation Outcomes.*

If $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$ *and there exists* $F \in \pi^{\mathcal{F}}$ *with* $\phi_F > \delta_F$*, then there exist* η_1^{TU} *and* $\underline{\eta}_2^{\text{TU}} \leq \overline{\eta}_2^{\text{TU}} \leq \eta_3^{\text{TU}}$ *such that*

- *If* $\eta < \min\{\eta_1^{\text{TU}}, \underline{\eta}_2^{\text{TU}}\}$*, the core is non-empty and contains only Blocking-Threat Outcomes;*
- *If* $\min\{\eta_1^{\text{TU}}, \underline{\eta}_2^{\text{TU}}\} < \eta < \underline{\eta}_2^{\text{TU}}$*, if the core is nonempty, it contains only Blocking-Threat Outcomes;*
- *If* $\underline{\eta}_2^{\text{TU}} < \eta < \min\{\max\{\eta_1^{\text{TU}}, \underline{\eta}_2^{\text{TU}}\}, \overline{\eta}_2^{\text{TU}}\}$*, the core is non-empty and contains only Deforestation Outcomes and Blocking-Threat Outcomes;*
- *If* $\min\{\max\{\eta_1^{\text{TU}}, \underline{\eta}_2^{\text{TU}}\}, \overline{\eta}_2^{\text{TU}}\} < \eta < \overline{\eta}_2^{\text{TU}}$*, if the core is non-empty, it contains Deforestation Outcomes and may contain Blocking-Threat Outcomes;*
- *If* $\overline{\eta}_2^{\text{TU}} < \eta < \max\{\eta_1^{\text{TU}}, \overline{\eta}_2^{\text{TU}}\}$*, the core is non-empty and contains Deforestation Outcomes, Blocking-Threat Outcomes, and may contain Compensation Outcomes;*
- *If* $\max\{\eta_1^{\text{TU}}, \overline{\eta}_2^{\text{TU}}\} < \eta < \eta_3^{\text{TU}}$*, the core is non-empty and contains Deforestation Outcomes and may contain Compensation Outcomes and Blocking-Threat Outcomes;*
- *If* $\eta_3^{\text{TU}} < \eta$*, the core is non-empty, contains Deforestation Outcomes and may contain Compensation Outcomes;*

If $\phi_F < \delta_F$ *for every* $F \in \pi^{\mathcal{F}}$*, the core contains only Deforestation Outcomes and may be empty.*

Theorem 2 shows that, for low enough blocking cost, the area No-Use condition $\bar{\mathbb{U}}$ can prevent deforestation if and only if at least one family prefers the incentive ($\phi_F > \delta_F$ for some $F \in \pi^{\mathcal{F}}$). To understand the underlying intuition, focus on that case and consider the threshold expressions:

$$\eta_1^{\text{TU}} := \min_{F,S:F\in\pi^{\mathcal{F}},S\subseteq F,\phi_S<\delta_S} \max\left\{\eta : \sum_{H\in\pi^{\mathcal{F}}:\phi_{H\setminus S}>\delta_{H\setminus S}} \left\lfloor \frac{\phi_{H\setminus S}-\delta_{H\setminus S}}{\eta} \right\rfloor > |S| \right\},$$

$$\underline{\eta}_2^{\text{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}},S\subseteq F,\phi_F>\delta_F,S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}, \quad \overline{\eta}_2^{\text{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}},S\subseteq F,S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|},$$

$$\eta_3^{\text{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}},S\subseteq F,\phi_S>\delta_S} (\phi_S-\delta_S).$$

Each threshold is defined by an intuitive deviation in the TU cooperative game. When blocking costs are below the threshold η_1^{TU}, no coalition S that prefers to engage in deforestation ($\phi_S < \delta_S$) would deviate from a Blocking-Threat Outcome to engage in deforestation because the remaining locals could block them. The two middle thresholds $\underline{\eta}_2^{\text{TU}}$ and $\overline{\eta}_2^{\text{TU}}$ bear a similar interpretation: for blocking costs below $\overline{\eta}_2^{\text{TU}}$, there is at least one coalition S that prefers the incentive ($\phi_S > \delta_S$) and can block every other local in $\mathcal{L}\setminus S$; for blocking costs below $\underline{\eta}_2^{\text{TU}} \leq \overline{\eta}_2^{\text{TU}}$, this coalition S belongs to a family that itself prefers the incentive, i.e., $S \subseteq F$ with $F \in \pi^{\mathcal{F}}$, $\phi_F > \delta_F$. In view of this, when

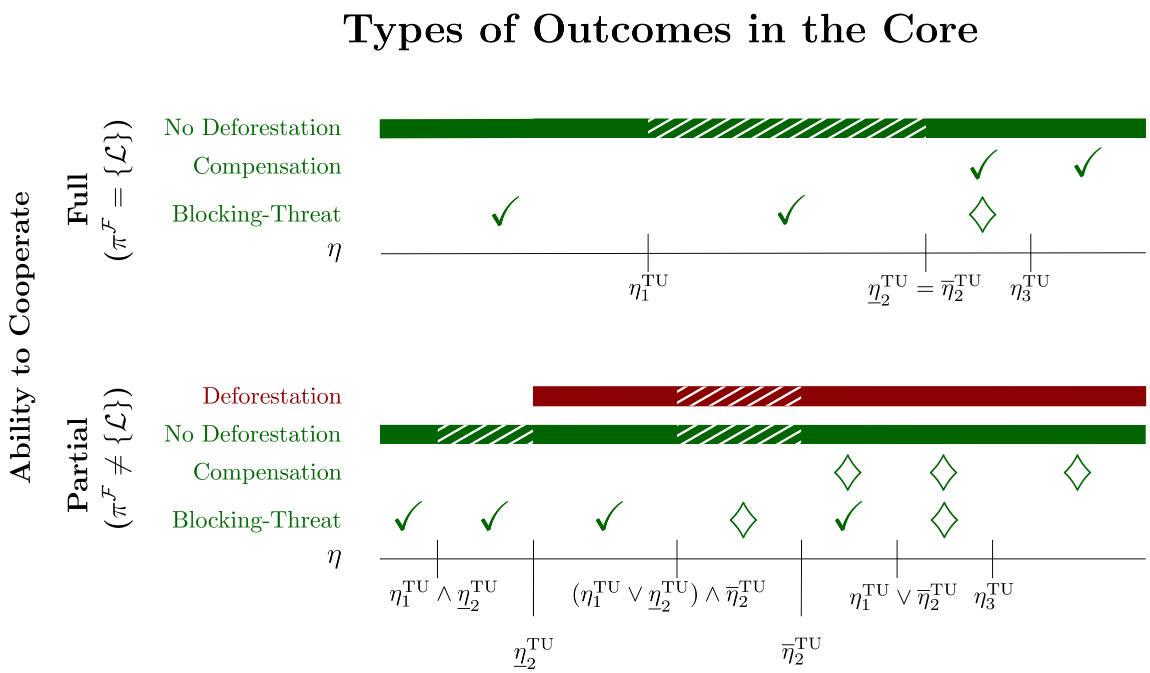

Figure 3.1 Core outcomes under the no-use condition $\bar{\mathbb{U}}$ as a function of the blocking cost η, when at least one family $F \in \pi^{\mathcal{F}}$ prefers the incentive ($\phi_F > \delta_F$). A solid bar indicates that the core is non-empty and a slashed bar indicates that the core may be empty. For a specific type of No-Deforestation Outcome (Compensation or Blocking-Threat), a "✓" indicates that it is in the core when the core is nonempty, whereas a "$\diamondsuit$" indicates that it *may* be in the core. We denote $\min\{a, b\}$ with $a \wedge b$ and $\max\{a, b\}$ with $a \vee b$.

blocking costs are below $\underline{\eta}_2^{\text{TU}}$, any outcome with deforestation would be dominated by coalition S deviating, which would strictly increase its net income and create a credible threat of blocking all other locals $\mathcal{L} \setminus S$. On the other hand, between $\underline{\eta}_2^{\text{TU}}$ and $\overline{\eta}_2^{\text{TU}}$, any coalition S that could deviate from a Deforestation Outcome and create a threat to block all other locals would belong to a family $F \in \pi^{\mathcal{F}}$ that prefers to deforest ($\phi_F < \delta_F$), so the other members of that family $F \setminus S$ could compensate the coalition S enough to incentivize it to engage in deforestation and avoid the deviation. Lastly, when blocking costs exceed η_3^{TU}, no coalition could profitably block even one local, so the No-Use condition $\bar{\mathbb{U}}$ becomes equivalent to the No-Deforestation condition $\bar{\mathbb{D}}$. Notably, when comparing the case with full ability to cooperate $\pi^{\mathcal{F}} = \{\mathcal{L}\}$ with the case with partial ability to cooperate $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$, the latter results in a more complex landscape of sub-cases because $\underline{\eta}_2^{\text{TU}}$ can be strictly smaller than $\overline{\eta}_2^{\text{TU}}$ and η_1^{TU} can take any value below η_3^{TU} (whereas $\underline{\eta}_2^{\text{TU}} \leq \overline{\eta}_2^{\text{TU}} \leq \eta_3^{\text{TU}}$ always holds).

With full ability to cooperate ($\pi^{\mathcal{F}} = \{\mathcal{L}\}$), every Deforestation Outcome is dominated because the grand coalition can always protect the forest, claim the incentive, and earn more than under deforestation ($\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$). The core then depends on the blocking cost η. When η is below the threshold $\underline{\eta}_2^{\text{TU}} = \overline{\eta}_2^{\text{TU}}$, some sub-coalition S can profitably block all other locals $\mathcal{L} \setminus S$, so only Blocking-Threat Outcomes survive. Once η rises above $\overline{\eta}_2^{\text{TU}}$ but remains below η_3^{TU}, such blocking is not universally profitable, so all Compensation Outcomes appear in the core, though some Blocking-Threat Outcomes may continue to exist. If η exceeds η_3^{TU}, blocking is never profitable; the core then coincides with that under the No-Deforestation condition $\bar{\mathbb{D}}$ and consists solely of Compensation Outcomes.

Assume next that locals only have partial ability to cooperate, $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$. For sufficiently low blocking costs, $\eta < \underline{\eta}_2^{\mathrm{TU}}$, the picture mirrors the case with full ability to cooperate, so the core only contains Blocking-Threat Outcomes. The difference appears once η surpasses $\underline{\eta}_2^{\mathrm{TU}}$. Because no coalition S can afford to block every other local $\mathcal{L} \setminus S$, every non-empty core must now include Deforestation Outcomes. When η lies in the range $(\underline{\eta}_2^{\mathrm{TU}}, \overline{\eta}_2^{\mathrm{TU}})$, the locals inside some family F that strictly prefers clearing the forest ($\phi_F < \delta_F$) can transfer utility to all other family members who prefer the incentive to induce them to engage in deforestation. These transfers cease to be profitable only when the cost exceeds $\overline{\eta}_2^{\mathrm{TU}}$, at which point no coalition can deviate from a Deforestation Outcome to block all other locals. Even in this setting, the core may contain No-Deforestation Outcomes–Blocking-Threat allocations at lower blocking cost values and Compensation Outcomes at higher blocking cost–for precisely the same reasons as in the case with full ability to cooperate.

Under the no-use condition $\bar{\mathbb{U}}$, coordination may fail, leaving the core empty. This can occur when at least one family F prefers the incentive and the blocking cost falls in the intermediate range $\eta \in (\eta_1^{\mathrm{TU}}, \overline{\eta}_2^{\mathrm{TU}})$. In that interval, any Deforestation Outcome is dominated by a No-Deforestation Outcome in which a sub-coalition $S \subseteq F$ blocks use of the cleared land; yet that outcome is itself dominated by another Deforestation Outcome in which locals $B \subseteq F \setminus S$ who prefer deforestation transfer enough utility to S to form a larger coalition $B \cup S$ that favors deforestation ($\phi_{B\cup S} < \delta_{B\cup S}$) and that cannot be blocked by the remaining locals. On the positive side, the core may also be empty when every family prefers deforestation ($\phi_F < \delta_F$ for all $F \in \pi^{\mathcal{F}}$), in which case $\bar{\mathbb{U}}$ prevents the community from settling Deforestation Outcomes.

Lastly, we note that reducing the locals' ability to cooperate has ambiguous effects under the no-use condition $\bar{\mathbb{U}}$. When the community prefers deforestation ($\delta_{\mathcal{L}} > \phi_{\mathcal{L}}$), full cooperation guarantees deforestation, yet limited cooperation can still avert it if at least one family prefers the incentive and blocking costs are low. Conversely, if no family initially values the incentive, $\bar{\mathbb{U}}$ is ineffective; but refining the partition into families–thereby further limiting cooperation–may isolate a family that does value the incentive, enlarging the set of cases in which deforestation is prevented. By contrast, once at least one family already prefers the incentive, any additional fragmentation lowers the critical cost thresholds $\underline{\eta}_2^{\mathrm{TU}}$, $\overline{\eta}_2^{\mathrm{TU}}$, and η_3^{TU}, reducing the parameter region where $\bar{\mathbb{U}}$ can succeed.

The following corollary to Theorems 1 and 2 summarizes the performance of the area conditions.

Corollary 1. *When locals have full ability to cooperate, $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$ prevent deforestation if and only if locals collectively prefer the incentive ($\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$); in this case, both $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$ prevent deforestation, $\bar{\mathbb{D}}$ achieves compensation, and $\bar{\mathbb{U}}$ achieves compensation if $\eta > \phi_{\mathcal{G}} - \delta_{\mathcal{G}}$. When locals have partial ability to cooperate, $\bar{\mathbb{D}}$ cannot prevent deforestation, and $\bar{\mathbb{U}}$ prevents deforestation if and only if at least one family prefers the incentive and $\eta < \underline{\eta}_2^{\mathrm{TU}}$.*

Corollary 1 shows that locals' ability to fully cooperate is critical for the performance of area conditions. When locals only have partial ability to cooperate, neither $\bar{\mathbb{U}}$ nor $\bar{\mathbb{D}}$ can achieve compensation and $\bar{\mathbb{U}}$ cannot prevent deforestation at high blocking costs $\eta > \underline{\eta}_2^{\mathrm{TU}}$, even when every family prefers the incentive ($\phi_F > \delta_F$ for all $F \in \pi^{\mathcal{F}}$). Overall, $\bar{\mathbb{U}}$ is superior to $\bar{\mathbb{D}}$ for preventing deforestation, but $\bar{\mathbb{D}}$ is superior to $\bar{\mathbb{U}}$ for preventing deforestation with compensation.

4. Selecting an Incentive and a Forest Protection Condition

This section provides guidance on selecting an incentive and a forest protection condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$. We relax assumption (4), allowing for "perfect" incentives with

$$\phi_\ell \geq \delta_\ell \text{ for every } \ell \in \mathcal{L}. \tag{13}$$

§4.1 characterizes the most robust conditional incentive and §4.2 characterizes the most cost-effective incentive. (§EC.3.1 provides formal statements for all the results in these sections, in Propositions 1-4, and proves these leveraging the results of §3.) Lastly, §4.3 examines an extension to more complex, hybrid forest protection conditions.

4.1. Most Robust Conditional Incentive

Recall that for robustness, we seek the condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$ and incentive payments ϕ that prevent deforestation (respectively, achieve compensation) in the inclusion-wise largest set of problem instances. Figure 4.2 presents the optimal choice of condition and corresponding feasible set of incentives ϕ, which depend on whether or not the locals can fully cooperate, and whether or not compensation is required. We will explain each of the four quadrants, in turn.

One can use Figure 4.2 to check whether a specific incentive (e.g, a price premium) will be sufficient to prevent deforestation and achieve compensation, respectively.

Ability to Cooperate	**Prevent Deforestation**	**Prevent Deforestation with Compensation**
Full ($\pi^{\mathcal{F}} = \{\mathcal{L}\}$)	Area No-Deforestation $\bar{\mathbb{D}}$ or Area No-Use $\bar{\mathbb{U}}$ with $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$	Area No-Deforestation $\bar{\mathbb{D}}$ with $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$
Partial ($\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$)	Area No-Use $\bar{\mathbb{U}}$ with $\phi_F > \delta_F$ for some $F \in \pi^{\mathcal{F}}$, $\phi_S > \delta_S + \eta \cdot (\lvert\mathcal{L}\rvert - \lvert S\rvert)$ for some $S \subseteq F$ or Individual $\mathbb{I}$ with $\phi_\ell > \delta_\ell$ for all $\ell \in \mathcal{L}$	Individual $\mathbb{I}$ with $\phi_\ell > \delta_\ell$ for all $\ell \in \mathcal{L}$

Figure 4.2 Recommended forest protection condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$ and corresponding feasible set of incentives for the robust objective. Each inequality has a distinct color to highlight similarities and differences between the feasible sets of incentives.

4.1.1. When locals have full ability to cooperate, to **prevent deforestation** one should use either area no-deforestation condition $\bar{\mathbb{D}}$ or area no-use condition $\bar{\mathbb{U}}$, and an incentive with

$$\phi_{\mathcal{L}} > \delta_{\mathcal{L}}. \tag{14}$$

The individual condition $\mathbb{I}$ requires a perfect incentive (satisfying (13)) to prevent deforestation. Requirement (13) is stronger than (14), so $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$ are best.

Area conditions $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$ have another, practical advantage over individual condition $\mathbb{I}$: to verify that a candidate incentive satisfies (14) requires assessing only whether the value of the incentive exceeds the value of deforestation for the entire community of locals as a whole, which is easier to do in practice rather than verifying this for each local individually, as required by (13).

To **prevent deforestation with compensation**, $\bar{\mathbb{D}}$ is the unique best condition. An incentive with (14) conditional on $\bar{\mathbb{D}}$ will prevent deforestation with compensation. The locals' ability to fully cooperate enables $\bar{\mathbb{D}}$ to prevent deforestation *and* promote distributive justice, as $\bar{\mathbb{D}}$ incentivizes locals to transfer utility so that every local is compensated for not engaging in deforestation. The feasible set of incentives is strictly smaller with $\bar{\mathbb{U}}$ than $\bar{\mathbb{D}}$, and is strictly smaller with $\mathbb{I}$ than $\bar{\mathbb{U}}$. An incentive conditional on $\bar{\mathbb{U}}$ prevents deforestation with compensation if and only if (14) and (13) hold or (14) and $\phi_{\mathcal{G}} < \eta + \delta_{\mathcal{G}}$ hold. An incentive conditional on $\mathbb{I}$ prevents deforestation with compensation if and only if (13) holds.

4.1.2. When locals have partial ability to cooperate, to **prevent deforestation**, one should either use Individual condition $\mathbb{I}$ with a perfect incentive (13), or area no-use condition $\bar{\mathbb{U}}$ and an incentive with

$$\phi_F > \delta_F \text{ for some } F \in \pi^{\mathcal{F}} \tag{15a}$$

$$\phi_S > \delta_S + \eta \cdot (|\mathcal{L}| - |S|) \text{ for some } S \subseteq F. \tag{15b}$$

The meaning of (15a)-(15b) is that at least one family $F \in \pi^{\mathcal{F}}$ prefers the incentive, and some of its members $S \subseteq F$ benefit enough to be willing to block all the other locals $\mathcal{L} \setminus S$. Neither the set of perfect incentives defined by (13) nor the set of incentives defined by (15a)-(15b) is included in the other, so neither $\bar{\mathbb{U}}$ nor $\mathbb{I}$ is universally dominant. Whereas a candidate perfect incentive (13) conditional on $\mathbb{I}$ prevents deforestation, that same incentive conditional on $\bar{\mathbb{U}}$ fails to prevent deforestation if the blocking cost is sufficiently large. Due to the lack of coordination among the multiple families in the area, a Deforestation Outcome always exists under the area no-deforestation condition $\bar{\mathbb{D}}$ and also, when the blocking cost is sufficiently large, under the area no-use condition $\bar{\mathbb{U}}$. This highlights a limitation in using area conditions: When locals in the area have limited ability to cooperate and the blocking cost is too high, a perfect incentive and individual condition $\mathbb{I}$ (which resolves the coordination problem) is required to prevent deforestation.

In practice, $\bar{\mathbb{U}}$ may have other advantages over $\mathbb{I}$. With $\bar{\mathbb{U}}$, one only needs to provide an appropriate incentive to a single family, by assessing the value of the incentive vs. deforestation for the locals in that family and the blocking costs. To direct a perfect incentive and verify compliance with $\mathbb{I}$ for every local is onerous, particularly in an area with many locals.

To **prevent deforestation with compensation**, $\mathbb{I}$ is the unique best condition. With a perfect incentive (13), $\mathbb{I}$ prevents deforestation by compensating each local for the missed deforestation opportunity. Due to locals' limited ability to cooperate, $\bar{\mathbb{D}}$ fails and, to prevent deforestation with compensation, $\bar{\mathbb{U}}$ requires a perfect incentive (13) that also satisfies (15b) for some family F. The meaning of (15b) is that the incentive for the locals $S \subseteq F$ is sufficient to motivate them to block all the other locals $\mathcal{L} \setminus S$.

4.2. Most Cost-Effective Conditional Incentive

Figure 4.3 characterizes forest protection conditions and incentives that minimize the cost $\sum_{\ell \in \mathcal{L}} \phi_\ell$ to prevent deforestation and achieve compensation, respectively.

Ability to Cooperate	Prevent Deforestation	Prevent Deforestation with Compensation
Full ($\pi^{\mathcal{F}} = \{\mathcal{L}\}$)	Area No-Deforestation $\bar{\mathbb{D}}$ or Area No-Use $\bar{\mathbb{U}}$ with $\phi_{\mathcal{L}} \downarrow \delta_{\mathcal{L}}$	Area No-Deforestation $\bar{\mathbb{D}}$ with $\phi_{\mathcal{L}} \downarrow \delta_{\mathcal{L}}$
Partial ($\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$)	Area No-Use $\bar{\mathbb{U}}$ with $\phi_F > \delta_F$ for some $F \in \pi^{\mathcal{F}}$, $\phi_S > \delta_S + \eta \cdot (\lvert\mathcal{L}\rvert - \lvert S\rvert)$ for some $S \subseteq F$ $\phi_{\mathcal{L}} \downarrow \min_{F \in \pi^{\mathcal{F}}} \max\left[\delta_F, \min_{S \subseteq F, S \neq \emptyset} \left(\delta_S + \eta(\lvert\mathcal{L}\rvert - \lvert S\rvert)\right)\right]$ or Individual $\mathbb{I}$ with $\phi_\ell \downarrow \delta_\ell$ for all $\ell \in \mathcal{L}$	Individual $\mathbb{I}$ with $\phi_\ell \downarrow \delta_\ell$ for all $\ell \in \mathcal{L}$

Figure 4.3 Recommended forest protection condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$ and set of incentives for the cost minimization objective. Down arrow ($\downarrow$) indicates that the minimum cost is achieved in the limit from above.

4.2.1. When locals have full ability to cooperate,

to **prevent deforestation**, both area no-deforestation condition $\bar{\mathbb{D}}$ and area no-use condition $\bar{\mathbb{U}}$ are optimal, in combination with any incentive with aggregate value to all locals $\phi_{\mathcal{L}}$ slightly above their value from deforestation $\delta_{\mathcal{L}}$.

To **prevent deforestation with compensation** one should again use area no-deforestation condition $\bar{\mathbb{D}}$ and any incentive with $\phi_{\mathcal{L}}$ slightly above $\delta_{\mathcal{L}}$.

Individual condition $\mathbb{I}$ could potentially also prevent deforestation with compensation at minimal cost, if (13) could be made to hold at near equality for every local $\ell \in \mathcal{L}$. However, that would require more information and increased monitoring and verification costs (for $\mathbb{I}$) compared with $\bar{\mathbb{D}}$.

4.2.2. When locals have partial ability to cooperate,

the minimum total payment to **prevent deforestation** is slightly above:

$$\min\left(\min_{F \in \pi^{\mathcal{F}}} \max\left(\delta_F, \min_{S \subseteq F, S \neq \emptyset} \left(\delta_S + \eta \cdot (\lvert\mathcal{L}\rvert - \lvert S\rvert) \right) \right), \ \delta_{\mathcal{L}} \right). \tag{16}$$

When the minimum is achieved in the first term (at intermediate blocking cost values η), this corresponds to using the area no-use condition $\bar{\mathbb{U}}$ and a payment of $\phi_S = \delta_S + \eta \cdot (\lvert\mathcal{L}\rvert - \lvert S\rvert)$ to the locals in $S \subseteq F$, with an arbitrary split of any remaining payment $\left(\delta_{F \setminus S} - \eta \cdot (\lvert\mathcal{L}\rvert - \lvert S\rvert)\right)^+$ among locals in $F \in \pi^{\mathcal{F}}$. The set S includes all locals in F with values from deforestation strictly less than the blocking cost (when such locals exist), or a local with the lowest value from engaging in deforestation otherwise, i.e., $S := \{\ell \in F : \delta_\ell < \eta\} \cup \{i\}$ for some $i \in \arg\min_{\ell \in F} \delta_\ell$. This favors locals with low opportunity costs (i.e., low value from engaging in deforestation) and thus performs poorly from a distributional justice perspective. In this case, locals having a *reduced* ability to cooperate – because the partition $\pi^{\mathcal{F}}$ into families is finer – could actually *decrease* the total cost of preventing deforestation. This arises at low blocking costs: if F is the optimal family and $S \subseteq F$ is the optimum coalition in (16), and $\eta < \delta_{F \setminus S}/(|\mathcal{L}| - |S|)$ and $\delta_F < \delta_{\mathcal{L}}$ hold, the minimum payment would be δ_F, which can decrease with a finer partition $\pi^{\mathcal{F}}$. In all other cases, however, reduced ability to cooperate always *increases* the minimum cost of preventing deforestation.

When the minimum in (16) is achieved in the second term ($\delta_{\mathcal{L}}$), this corresponds to using Individual Condition $\mathbb{I}$ with a perfect incentive (13).

To **prevent deforestation with compensation** at minimal cost requires the Individual condition $\mathbb{I}$ and for (13) to hold at near equality for every local $\ell \in \mathcal{L}$.

4.3. Cost Minimization with Hybrid Conditions.

Whereas our base model only allowed applying a single condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$ to all locals $\ell \in \mathcal{L}$, we now relax this by considering two possible hybrid schemes. The first involves individual incentives for each local $\ell \in \mathcal{L}$, but based on any condition $\mathbb{C}_\ell \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$; in other words, with $\bar{\mathbb{D}}$ or $\bar{\mathbb{U}}$, local ℓ would be compliant if no deforestation happens in the entire area. The second hybrid scheme allows partitioning the area into subareas and applying distinct conditions for all locals in each subarea; formally, the second scheme allows the following types of subarea conditions:

1. *Subarea No-Deforestation Condition*, $\bar{\mathbb{D}}^H$. Each local $\ell \in H \subseteq \mathcal{L}$ receives the incentive if and only if no local in H engages in deforestation: $\bar{\mathbb{D}}^H_\ell(d, B) = \text{yes} \Leftrightarrow d_i = 0, \forall i \in H$.
2. *Subarea No-Use Condition*, $\bar{\mathbb{U}}^H$. Each local $\ell \in H \subseteq \mathcal{L}$ receives the incentive if and only if no local in H generates income on deforested land: $\bar{\mathbb{U}}^H_\ell(d, B) = \text{yes} \Leftrightarrow d_i(1 - \max_{g \in \mathcal{L}} B_{gi}) = 0, \forall i \in H$.

Proposition 3 in §EC.3.2 proves that any combination of the two hybrid conditions *cannot* reduce the minimum cost to prevent deforestation if locals have full ability to cooperate. In this case, the hybrid incentives achieve the same minimum cost as a uniform no-deforestation condition $\bar{\mathbb{D}}$ on the entire area, with $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, as recommended in §4.2. The latter conditional incentive is simpler and easier to implement, so it should be chosen in this case.

In contrast, Proposition 4 in §EC.3.2 proves that hybrid schemes *can* reduce the costs of an optimal incentive if locals have partial ability to cooperate. The minimum cost to prevent deforestation can be reduced by applying a subarea no-deforestation condition $\bar{\mathbb{D}}^H$ (or equivalently, a subarea no-use condition $\bar{\mathbb{U}}^H$) for a family H satisfying $\delta_H < \eta|H|$ and a subarea no-use condition $\bar{\mathbb{U}}^{\mathcal{L} \setminus H}$ for all other locals. Intuitively, this reduces costs because it is cheaper to compensate family H to forego deforestation rather than block all its members. This could be implemented in practice if the subarea in which family H could engage in deforestation does not overlap with the subarea in which the other locals $\mathcal{L} \setminus H$ could engage in deforestation.

Hybrid incentives would be particularly appealing at a landscape or jurisdictional scale, where the territory includes multiple, geographically separate communities with limited ability to cooperate. Then, assigning a distinct condition (and possibly a tailored incentive) to each sub-area would likely be both defensible to the stakeholders and more effective than a single area-wide rule. Designing such a scheme optimally would, however, require a spatially explicit model that captures spatial blocking costs or important ecological linkages–details that lie beyond the scope of our present analysis.

5. Conclusions, Recommendations, and Future Research Directions

Commodity buyers should consider area-based conditions in their efforts to eliminate deforestation and raise smallholder incomes. Area conditions can succeed even when the underlying incentive is imperfect. In practice, limits on budgets, policy levers, or information readily make incentives imperfect. A uniform price premium, for instance, can leave some smallholders–especially those with limited land–preferring to clear additional forest, as our Indonesian case study in §EC.5 shows. Conditioning that same premium on collective compliance across the area alters that calculus: if a tightly-knit community collectively prefers the incentive to clearing forest or a group in the community is sufficiently motivated to block economic use of cleared forest, the prospect of losing the incentive can deter deforestation and possibly even compensate smallholders for their opportunity costs.

Area conditions also offer other practical advantages over individual conditions. With area conditions, one only needs to provide an appropriate incentive to a group of locals, which only requires estimating the cumulative value of the incentive vs. deforestation for that group (and estimating the cost of blocking use of cleared forest, for $\bar{\mathbb{U}}$). Verifying compliance with an area condition also does not require mapping out the individual plots of each smallholder, which reduces implementation costs in areas with unclear land tenure or thousands of smallholders. Lastly, area conditions with a larger, contiguous area could significantly reduce leakage and help with biodiversity conservation.

However, our results also show that area-based conditions are *not* universally optimal; the best form of conditional incentive hinges on local context and on the buyer's strategic priorities. The recommendations that follow therefore differentiate among buyer types and landscape characteristics.

Consider a small buyer of specialty coffee or cocoa that sources exclusively from a compact geographic region. Instead of mapping every supplier's plot, the buyer could designate a broader area–encompassing all forest patches that anyone in the community therein, supplier or not, might be tempted to convert into farmland–and consider a forest protection condition on that entire area. The choice of condition depends on the strength of the community's socio-economic ties and on the cost of blocking economic use of cleared land (which in turn is shaped by factors such as local property law, enforcement capacity, the availability of tools or equipment, the area's size, or the means through which forest is cleared–see §2.1).

When the community (including suppliers and non-suppliers) is tightly knit–for example, residents of the same village or members of a cooperative that jointly manages resources and shares costs and benefits–the buyer can attach the incentive to the area no-deforestation condition, $\bar{\mathbb{D}}$. The incentive need only be large enough to make the community better off *in aggregate* than they would have been with deforestation. Importantly, the buyer need not worry that the incentive might disproportionately benefit some suppliers and insufficiently motivate other locals to protect forests. In fact, this scheme would guarantee that every local is compensated for his opportunity cost of engaging in deforestation, as those who prefer the incentive would transfer utility to those who prefer deforestation to motivate them to protect the forest. Insofar as the poorest locals have the largest opportunity costs from clearing forest (as in §EC.5), the scheme would also promote distributive justice.

When socio-economic ties within the community are loose, a buyer can still employ an area-based condition, but only if the priority is to prevent deforestation and the cost of blocking economic use is sufficiently low. Then, the buyer can apply an area no-use condition $\bar{\mathbb{U}}$, under which the reward is forfeited if anyone extracts timber or cultivates the land after clearance. The key is to identify an extended family–perhaps a tight-knit cluster of suppliers and their relatives–whose members have strong ties to one another but weak ties to the rest of the village; that family should value the incentive more than clearing forest, and a group of members within that family should value the incentive enough to credibly block all other locals' attempts to profit from deforested land. If those requirements are met, $\bar{\mathbb{U}}$ can prevent deforestation, even when some residents still favor clearing and even in the more extreme case that the entire community in aggregate prefers clearing. Two caveats follow. First, because deterrence would rely on blocking threats rather than financial compensation, some locals (including certain suppliers) may not be fully compensated for their opportunity costs. Second, buyers implementing the most cost-effective scheme of this nature should be aware that this would allocate all incentive benefits on those locals with lowest opportunity costs, which would exacerbate existing inequalities and enable local elites to grow even wealthier.

In all remaining cases with weak socio-economic ties–such as when the buyer insists on compensating smallholders for their opportunity costs, or when the cost of blocking economic use of cleared land is high–the buyer must rely on individual conditions. That would require a *perfect* incentive: each local's benefit must exceed his private gain from clearing, so that no one has a reason to deforest. If the buyer can only compensate its direct suppliers while other local landholders (with weak ties to the suppliers) continue to prefer clearing forest, deforestation outside the supplier group will persist, and the buyer's claim of a zero-deforestation supply chain will be weak. The upside is that, given perfect incentives, the individual approach is more robust than both area-based conditions, which face coordination challenges even when payments are generous (but local ties are weak).

The same principles can also guide a large buyer sourcing from many scattered regions. Applying a single, uniform condition across an area covering all regions is possible–one can treat each region as one or more independent "families" and suitably adjust the (inter-regional) costs for blocking economic use–but would rarely be economical. A better strategy is to partition the landscape into subareas and tailor the conditions (and possibly the incentives) to each subarea. In this case, our results could guide optimal choices within each subarea, as in the Indonesian case study of §EC.5.

All the recommendations above were based on the conservative premise that a scheme should meet the buyer's dual commitments under *every* likely outcome of the local interaction. With additional effort, a buyer could help a local community *coordinate* on a specific desirable outcome from several possibilities.[2] Doing so would enlarge the set of feasible conditional incentives, and the more specific results that we derived in §3 could provide guidance for selecting a robust or cost-effective scheme.

Our results also point towards additional measures that buyers could take–possibly in collaboration with partners–to increase the effectiveness of any conditional incentive schemes they offer.

Area conditional incentives work best when coupled with initiatives that build community capacity–above all, by encouraging cooperation among all residents. In partnership with government agencies, commodity buyers could help communities of smallholders secure (communal) land titles or establish agricultural cooperatives where none exist. Buyers could also subsidize membership fees that let farmers join cooperatives, organize community training sessions, or invest in assets managed collectively–tractors, irrigation, storage, or local processing plants. In so doing, however, buyers should make sure that the community values the incentive more than the gains from clearing; otherwise, greater coordination could backfire and make a conditional incentive scheme fail!

Area-based incentives also become more practical as the cost of monitoring and verification falls. High-resolution remote-sensing platforms–now widely available from both public and commercial sources, and based on either satellite or radar technology (see §EC.2)–can detect small-scale clearing quickly and cheaply and enable buyers to verify compliance with a no-deforestation policy. Moreover, efforts to train local communities to use such tools, as Slough et al. (2021) did for 39 community forest areas in the Peruvian Amazon, would also lower monitoring costs and enable locals to rapidly detect and respond to deforestation activity.

To complement the area no-use condition $\bar{\mathbb{U}}$, buyers could also work towards reducing the cost of blocking by supporting locals with technology, equipment, and training to detect and halt an attempt at clearing forest (if possible) or the economic use of deforested land. Quick response and proper equipment may facilitate putting out a small fire nearby, stopping trucks with illegally harvested timber before they leave the area, or destroying a new plantation on illegally cleared land. Buyers

[2] In technical terms, choose a specific outcome from the recursive core.

could also deploy technology that makes it easy for any local to report perpetrators, as CP Foods did with a mobile app in efforts to combat crop-burning in Thailand (Kaohoon International 2024).

Although our messages have been framed for commodity buyers, they also speak directly to development agencies, NGOs, and governments committed to curbing deforestation and lifting rural incomes. Moreover, our results suggest that EU regulators responsible for the EUDR implementation could explicitly recognize area-based conditions, which lower monitoring costs and (critically) yield more credible zero-deforestation claims.

Several limitations in our work deserve acknowledgment and consideration in future research. A priority for future research is to consider the problem of partitioning a larger landscape into areas and choosing conditional incentives for each area. Our results in § 4.3 and § EC.4.4 indicate that applying different conditions to different subareas can lower the costs of preventing deforestation or–when that is impossible–reducing the extent of deforestation. But analyzing such schemes rigorously will require important *spatial* extensions of the model: capturing the configuration of plots, adjusting blocking costs for distance, modeling a bonus value for conserving contiguous forest (crucial for biodiversity and watershed services), and considering how multiple conditions overlapping on the same subarea would change the strategic interaction among the locals. The problem of jointly optimizing the delineation of sub-areas and the conditional incentives applied in each is a rich and challenging spatial-optimization problem, which we view as an important direction for future research. Second, future work could consider a dynamic model that endogenizes contract length, allows payments and opportunity costs to evolve with time, and admits periodic renegotiation. Lastly, future work could relax some of the strong rationality assumptions in our framework. Our model assumes fully rational, forward-looking farmers who can anticipate the futility of engaging in deforestation when no economic benefit can be extracted subsequently and who can anticipate all the outcomes in complex games in partition function form. Considering how limited foresight, misperceived enforcement risks, or social norms could affect behavior would test the robustness of our conclusions.

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E-companion to Area Conditions and Positive Incentives: Engaging Locals to Protect Forests

EC.1. Survey of Programs Implemented by Commodity Buyers

- **Unilever** *(Indonesia & Malaysia, palm oil).* Unilever engages tens of thousands of Indonesian smallholders through its three new smallholder hubs in Aceh, North Sumatra, and Riau. In collaboration with NGOs partners, the company first creates GPS polygon maps for every farmer (47 000 mapped so far) and deforestation is checked with Unilever's dashboard, which combines satellite and radar alerts to flag any tree-cover loss in near-real time (Unilever 2025). Mapped farmers receive agronomy training (26 000 trained) and help to gain RSPO Independent Smallholder (ISH) certification (17 500 certified). Unilever then purchases the farmers' ISH credits, which amounts to paying a premium for every palm fruit produced on certified plots (148 000 such credits were bought in 2024). If an alert confirms that forest on a mapped plot has been newly cleared, the farmer's credit income is suspended while the case is investigated (Unilever 2022). Unilever suspends suppliers linked to deforestation, but is open to allowing them to rejoin if they are able to show they have improved their practices in line with best industry standards, which includes providing a recovery plan for any recent deforestation or new development on peat that occurred in their supply chain. (Unilever 2022)
- **Charoen Pokphand (CP) Foods** *(Thailand, feed corn).* CP Foods has implemented a corn traceability system that combines Blockchain technology, GPS mapping and monitoring, and a mobile app to ensure that maize used in their feed production is sourced from areas free of forest encroachment and stubble burning across Myanmar, Laos, and Vietnam (WBCSD 2020). Once verified, growers receive a comprehensive incentive bundle: free soil-fertility testing, hands-on GAP training that helps them cut fertiliser use and plough crop residues back instead of burning, on-farm drone-spraying demos and other precision-agriculture tools supplied via CP's True Digital arm, shared modern machinery, and pop-up buying stations that reduce transportation costs and pay transparent, pre-announced prices (WBCSD 2020).
- **Wilmar** *(Indonesia & Malaysia, palm oil).* Wilmar's smallholder scheme in Sabah links a package of cash and agronomic support to compliance with RSPO sustainability standards. Independent growers who join the Wild Asia Group Certification Scheme (WAGS) must keep their plots free of illegal forest clearance and follow RSPO good-practice criteria; in return they receive two rewards: a premium on every tonne of fresh-fruit bunches delivered to Wilmar mills and a second RSPO premium when downstream buyers purchase the certified palm oil. Certified members also gain continuous field advice, wholesale-price fertiliser with supervised application, and priority access to a replanting finance facility that Wilmar is designing with banks and NGOs to offer low-interest loans even to farmers lacking formal land titles. (Wilmar International 2025).

- **Tony's Chocolonely** *(Ghana & Ivory Coast, cocoa).* Tony's pays cocoa farmers a Living Income Reference Price (LIRP) via farmer cooperatives and monitors individual farm plots in collaboration with Satelligence. The company also offers assistance through training in agroforestry methods and best practices (Tony's Chocolonely 2023).
- **Mondelez International** *(Ivory Coast & Ghana, cocoa).* Cocoa Life pilots *payment-for-environmental-services* contracts: staged cash rewards for planting and nurturing shade trees and avoiding further forest clearance. Payments stop if the farm expands into forest (International 2021).
- **Cargill "Triple S"** *(Brazil, soy).* Cargill offers export premiums and priority contracts only to soy growers verified (via satellite and audit) as having zero post-2008 native-vegetation conversion; non-compliant farms lose the channel (Cargill 2021).
- **Starbucks** *(Global origins, coffee).* C.A.F.E. Practices pays quality & sustainability premiums to farms/coops scoring high on its rubric; a zero tolerance rule bars any farm that cleared forest after 2004, and failure in audit removes the premium (Starbucks 2024).
- **Mars Inc** *(Ivory Coast & Ghana, cocoa).* Mars pays farm-gate premiums ($50–$120 per ton) solely for cocoa traced to farms verified deforestation-free via GPS and satellite; expansion into forest voids the premium (Ionova 2018, Askew 2022).
- **Hershey's** *(Ivory Coast, cocoa).* Hershey boosts cocoa-farmer livelihoods by helping smallholders expand Village Savings & Loan Associations for affordable credit, and funding community schools (Hershey 2023).

Area-Based Conditions

- **Nestlé & Earthworm Foundation – Cavally Forest project** *(Ivory Coast, cocoa).* Nestlé funds community livelihood projects and forest-restoration wages for villages around the Cavally Reserve, conditional on the prevention of new encroachment; collective compliance is verified via patrols and satellite alerts (Foundation 2023).
- **Unilever, Wilmar, PepsiCo, Nestlé** *(Malaysia and Indonesia, palm oil).* Unilever backs jurisdiction-wide, "produce-and-protect" deals that reward whole districts or states once they can prove zero-deforestation palm oil. In Sabah, Malaysian Borneo, the company co-funds local government and NGO partners to secure state-wide RSPO jurisdictional certification; when the entire state is verified, every compliant mill and smallholder will gain premium access to Unilever's supply chain and the RSPO credit market. (Other buyers, such as Nestlé, also participate in the initiative.) In Aceh Tamiang (Sumatra, Indonesia), Unilever, IDH, and PepsiCo finance a three-year Production-Protection-Inclusion compact that ties district-level investment and priority sourcing to collective targets, including no new forest loss in the Leuser ecosystem. Similar landscape programs exist in other areas, including Riau and Central Kalimantan. (Unilever 2022a)

EC.2. Examples of Monitoring Platforms

We document publicly available and commercial platforms that monitor forest cover and detect deforestation, categorizing these based on **Geographic focus** (global or specific region), and **Spatial Resolution**. The list is not exhaustive.

Platform (Provider)	Region	Resolution	Citation
Global Forest Watch (WRI)	Global	30m (Landsat), 10m (Sentinel-2)	World Resources Institute (2023)
UMD GLAD Alerts (UMD)	Pantropical/Amazon	30m (Landsat), 10m (Sentinel-2)	University of Maryland (2023)
Hansen/UMD Global Forest Change (NASA/UMD)	Global	30m (Landsat)	Hansen et al. (2013)
FAO SEPAL	Global	Varies (10–30m)	FAO (2023)
Collect Earth Online (FAO, NASA)	Global	High-res (Google, Bing, Sentinel)	FAO and NASA (2023)
JJ-FAST (JAXA/JICA)	Tropical countries	25m (L-band SAR)	JICA and JAXA (2023)
PRODES (INPE)	Brazilian Amazon	20-30m (Landsat)	INPE (2023b)
DETER (INPE)	Brazilian Amazon	64m (CBERS-4), 56m (IRS)	INPE (2023a)
Geobosques (MINAM)	Peru	30m (Landsat), 10m (Sentinel-2)	MINAM Peru (2023)
WRI Forest Atlases	Africa (DRC, etc.)	10–30m (via GFW)	WRI (2023)
Planet Forest Monitoring (Planet Labs)	Global	3–5m (Dove satellites)	Planet Labs (2023)
Starling (Airbus, Earthworm)	Global tropics	10m (Sentinel-2), 1.5–5m (Airbus SPOT)	Airbus and Earthworm Foundation (2023)
Satelligence	Global/custom	10m (Sentinel), 3–5m (optional)	Satelligence (2023)
EOS Forest Monitoring	Global	10–30m (Sentinel, Landsat)	EOS Data Analytics (2023)
LiveEO Deforestation	Global	3–10m (multi-source)	LiveEO (2023)
TruTrace + EUDR tools	Global	Varies (10m–30m)	TruTrace (2023)

Table EC.1: Forest Monitoring Tools

EC.3. Proofs of results in §3

Before proving Lemmas 1 and 2, we state and prove Lemma EC.1, where we show that in equilibria every local in a coalition will jointly make deforestation decisions, and Lemma EC.2, where we show that $\mathcal{Q}(\pi, \mathbb{C})$ is not empty, for $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$.

Lemma EC.1. *For the cooperative game with transferable utility, consider a partition $\pi \in \Pi_{\mathcal{L}}$, with $\pi \prec \pi^{\mathcal{F}}$. Any subgame-perfect equilibria $(d^*, B^*(d)) \in \mathcal{Q}(\pi, \mathbb{C})$ satisfies that $d^*_S = 0$ (i.e., $d^*_\ell = 0$, for every $\ell \in S$) or $d^*_S = 1$ (i.e., $d^*_\ell = 1$, for every $\ell \in S$), for every coalition $S \in \pi$, and any forest protection condition $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$. Note that this result does not require condition 4.*

Proof of Lemma EC.1. Assume by contradiction that there is an equilibrium $(d^*, B^*(d)) \in \mathcal{Q}(\pi, \mathbb{C})$ such that for a coalition $S \in \pi$ there are $d^*_g = 0$, $d^*_\ell = 1$, for some $\ell, g \in S$.

Under $\bar{\mathbb{D}}$, we note first that, because $\bar{\mathbb{D}}_\ell(d, B)$ does not depend on B, but blocking is costly (as expressed in (6) by the blocking cost η), then in equilibria, $B^* = 0$. But then, $\bar{\mathbb{D}}_g(d, B) = \text{no}$, and because g would gain from deforestation ($\delta_g > 0$ by (3)), then (7) can be improved by setting $d^*_g = 1$, which contradicts $(d^*, B^*(d))$ being an equilibrium.

Under $\bar{\mathbb{U}}$, if $\max_{i \in \mathcal{L}} B^*_{i\ell}(d^*) = 1$, then local ℓ is being blocked. But then, because deforestation is costly, (7) can be increased by c_ℓ by setting $d^*_\ell = 0$. If, on the other hand, $\max_{i \in \mathcal{L}} B^*_{i\ell}(d^*) = 0$, then, by the definition of the No-Use Condition, $\bar{\mathbb{U}}_g(d^*, B^*(d^*)) = \text{no}$, and, as before, the coalition S could increase its net income in (7) by setting $d_g^* = 1$. Therefore, in any equilibrium, all locals in a coalition coordinate their deforestation decisions ($d_S^* = 0$ or $d_S^* = 1$). □

For the following proofs, we will use Lemma EC.1 and consider only equilibria where $d_S^* = 1$ or $d_S^* = 0$, for any coalition $S \in \pi$, with $\pi \prec \pi^{\mathcal{F}}$.

Lemma EC.2. *For the cooperative game with transferable utility, consider a partition $\pi \in \Pi_{\mathcal{L}}$, with $\pi \prec \pi^{\mathcal{F}}$. Under the area no-deforestation condition $\bar{\mathbb{D}}$, if $\pi = \{\mathcal{L}\}$, and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, then $\mathcal{Q}(\pi, \bar{\mathbb{D}})$ contains a no-deforestation equilibrium ($d^* = 0$); otherwise, $\mathcal{Q}(\pi, \bar{\mathbb{D}})$ contains a deforestation equilibrium ($d^* = 1$). Under the area no-use condition $\bar{\mathbb{U}}$, if*

$$\eta < \eta_1(\pi) = \sup\{\eta : \exists S \in \pi \text{ with } (\phi_S - \delta_S) > \eta\, |\mathcal{L} \setminus S|\},$$

the set of equilibria, $\mathcal{Q}(\pi, \bar{\mathbb{U}})$ contains a no-deforestation equilibrium ($d^* = 0$); otherwise, $\mathcal{Q}(\pi, \bar{\mathbb{U}})$ contains a deforestation equilibrium ($d^* = 1$). Note that this result does not require condition 4.

Proof of Lemma EC.2. Under $\bar{\mathbb{D}}$, we will consider three cases. First, if $\pi = \{\mathcal{L}\}$, and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, then there are only two options, either $d_{\mathcal{L}}^* = 1$, or $d_{\mathcal{L}}^* = 0$ (by Lemma EC.1). Because $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, the optimal decision in (7) is $d_{\mathcal{L}}^* = 0$, resulting in a no-deforestation equilibrium. Second, if $\pi = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} \le \delta_{\mathcal{L}}$, the solution to the maximization in (7) must include $d_{\mathcal{L}}^* = 1$, and $\mathcal{Q}(\pi, \bar{\mathbb{D}})$ includes a deforestation equilibria. Finally, if $\pi \neq \{\mathcal{L}\}$, then there are at least two coalitions S_1, and S_2, in π. Hence, if we consider a deforestation equilibrium, with $d_{S_1}^* = 1$, and $d_{S_2}^* = 1$, we can see that $\bar{\mathbb{D}}(\pi, d^*, B^*) = \text{no}$, and no unilateral deviation of any $S \in \pi$ can change this, which implies that, absent any reward, each coalition will engage in deforestation and therefore, $\mathcal{Q}(\pi, \bar{\mathbb{D}})$ contains a deforestation equilibrium.

Under $\bar{\mathbb{U}}$, if $\eta < \eta_1(\pi)$, then there exists $S \in \pi$ such that $\phi_S - \delta_S > \eta|\mathcal{L} \setminus S| \ge 0$. Thus, a no-deforestation equilibrium (d^*, B^*) must be in $\mathcal{Q}(\pi, \bar{\mathbb{U}})$ because in such an equilibrium, if any coalition S' unilaterally deviates and sets $d_{S'} = 1$, then coalition S would block all individuals who deviated in the second stage.

On the other hand, if $\eta \ge \eta_1(\pi)$, no coalition S exists so that $(\phi_S - \delta_S) > \eta|\mathcal{L} \setminus S|$. We consider two (sub)cases, the first with $|\pi| = 1$ and the second with $|\pi| \ge 2$.

First, if $\pi = \{\mathcal{L}\}$, then $\eta \ge \eta_1(\pi)$ implies that $\phi_{\mathcal{L}} \le \delta_{\mathcal{L}}$ or equivalently

$$\sum_{\ell \in \mathcal{L}} J_\ell(0, \text{yes}) \le \sum_{\ell \in \mathcal{L}} J_\ell(1, \text{no}) - c_\ell.$$

Therefore, $B_{\mathcal{L}i}^* = 0$ is an optimal solution in (6) for each $i \in \mathcal{L}$, conditional on $d_{\mathcal{L}}^* = 1$, which in turn implies that these deforestation decisions are optimal in (7), which proves that this deforestation equilibrium is in $\mathcal{Q}(\{\mathcal{L}\}, \bar{\mathbb{U}})$.

Assume now that $\eta \geq \eta_1(\pi)$ and $|\pi| \geq 2$. Let S_1, and S_2 be two coalitions in π. Consider a deforestation equilibrium, where $d^*_S = 1$ and $B^*_{Si} = 0$, for every $S \in \pi$, $i \in \mathcal{L}$. In this case, $\kappa^{\bar{\mathbb{U}}}(\pi, d^*, B^*) =$ no, and there is no profitable deviation of any one coalition that can change this: for instance, coalition S_1 would not change its second stage blocking decision because $\eta \geq \eta_1(\pi)$ implies that it would not be strictly profitable to block all other locals in $\mathcal{L} \setminus S_1$, and the compliance indicator would not change even if $d_{S_1} = 0$ because there are at least two coalitions, and $d^*_{S_2} = 1$. Therefore, this deforestation equilibrium must be in $\mathcal{Q}(\pi, \bar{\mathbb{U}})$. □

Proof of Lemma 1. By Lemma EC.2, we know that $\mathcal{Q}(\pi, \mathbb{C}) \neq \emptyset$ for $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$ and any partition $\pi \in \Pi_{\mathcal{L}}$. By Lemma EC.1, we know that every coalition $S \in \pi$ would either jointly decide to deforest $d^*_S = 1$ or not to deforest $d^*_S = 0$. Hence, we must only prove that any equilibrium in $\mathcal{Q}(\pi, \mathbb{C})$ is either a deforestation equilibrium (with $d^*_S = 1$ for all $S \in \pi$) or a no-deforestation equilibrium (with $d^*_S = 0$ for all $S \in \pi$).

If $|\pi| = 1$, then the result is immediate by the definition of the game, as the single coalition in π can only choose $d^*_{\mathcal{L}} = 1$ or $d^*_{\mathcal{L}} = 0$, corresponding to a deforestation equilibrium and no-deforestation equilibrium respectively. Thus, we consider below only the case with $|\pi| \geq 2$.

We first show the result for the area no-deforestation condition $\bar{\mathbb{D}}$. Assume by contradiction that there exists an equilibrium such that $d^*_{S_1} = 1$ and $d^*_{S_2} = 0$, for $S_1 \neq S_2$, and both $S_1, S_2 \in \pi$. By definition, $\bar{\mathbb{D}}_\ell(\pi, d^*, B^*) =$ no for every $\ell \in \mathcal{L}$, as there is at least one coalition that engages in deforestation (and blocking decisions do not matter with $\bar{\mathbb{D}}$). But without rewards, it is always optimal to engage in deforestation by (3), so it is a profitable deviation for S_2 to set $d^*_{S_2} = 1$. Therefore, no equilibrium can exist in $\mathcal{Q}(\pi)$ with $d^*_{S_1} = 1$ and $d^*_{S_2} = 0$.

We now show the result for the area no-use condition $\bar{\mathbb{U}}$. Assume by contradiction that there exists an equilibrium such that $d^*_{S_1} = 0$ and $d^*_{S_2} = 1$, for $S_1 \neq S_2$, and both $S_1, S_2 \in \pi$. Consider then the second stage blocking decisions; there are two possible scenarios, either all locals in S_2 that engage in deforestation are blocked in the second stage (i.e., $\max_{i \in \mathcal{L}} B_{i\ell} = 1$, for every $\ell \in S_2$), or at least one local in S_2 is not blocked (i.e., $\max_{i \in \mathcal{L}} B_{i\ell} = 0$, for some $\ell \in S_2$). In the former case, coalition S_2 has a profitable deviation by changing $d^*_{S_2} = 0$ and not incurring the deforestation costs $\sum_{\ell \in S_2} c_\ell$. In the latter case, $\bar{\mathbb{U}}_h(\pi, d^*, B^*) =$ no, for every $h \in S_1$, as at least one local from S_2 is engaging in deforestation and not being blocked by any other local. Hence, S_1 has a profitable deviation by either changing $B_{hf} = 1$ for some $h \in S_1$, and block the unblocked local $\ell \in S_2$ (depending on the magnitude of the blocking cost η) or setting $d^*_{S_1} = 1$. In all cases, there is a profitable deviation, and therefore every equilibrium must either be a deforestation equilibrium or a no-deforestation equilibrium. Note we do not use condition 4 to prove these results, and therefore they hold even if $\mathcal{L} = \mathcal{G}$. □

Proof of Lemma 2. We begin by showing the results under the area no-deforestation condition $\bar{\mathbb{D}}$. We have shown in Lemma 1 that $T(\pi)$ can take only values $\{0\}$, $\{1\}$, or $\{0, 1\}$, so we only need to prove that a) $T(\pi) = \{0\}$ if and only if $\pi = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, and b) $T(\pi) = \{1\}$ if and only if $\phi_S < \delta_S$ for some $S \in \pi$.

Lemma EC.2 implies that $T(\pi) = \{0\}$ (i.e., *only* no-deforestation equilibria) can occur only if $\pi = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$. Conversely, if $\pi = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ then $d^*_{\mathcal{L}} = 0$ is the unique solution to (7) by definition of $\phi_{\mathcal{L}}$ and $\delta_{\mathcal{L}}$, which implies that $T(\pi) = \{0\}$.

If $\phi_S < \delta_S$ for some $S \in \pi$, then $d^*_S = 1$ for *any* equilibrium in $\mathcal{Q}(\pi, \bar{\mathbb{D}})$, as this is the only solution to (7). But then, Lemma 1 implies $T(\pi) = \{1\}$. Conversely, if $\phi_S \geq \delta_S$ for all $S \in \pi$, then any no-deforestation equilibrium will be in $\mathcal{Q}(\pi, \bar{\mathbb{D}})$, because when $\kappa^{\bar{\mathbb{D}}}(\pi, d^*) = \text{yes}$, then $d^*_S = 0$ is the only solution to (7), which implies that no coalition would want to deviate from a no-deforestation equilibrium if they all prefer not to deforest. Therefore, $T(\pi) = \{1\}$ if and only if $\phi_S < \delta_S$ for some $S \in \pi$.

Under the area no-use condition $\bar{\mathbb{U}}$, we showed in Lemma EC.2 that if $\eta < \eta_1(\pi) = \sup\{\eta : \exists S \in \pi \text{ with } (\phi_S - \delta_S) > \eta\,|\mathcal{L} \setminus S|\}$, then $0 \in T(\pi)$; and if $\eta \geq \eta_1(\pi)$, then $1 \in T(\pi)$. Because

$$\eta_1(\pi) \leq \eta_2(\pi) := \inf\left\{\eta : \sum_{S \in \pi : \phi_S > \delta_S} \left\lfloor \frac{(\phi_S - \delta_S)}{\eta} \right\rfloor < \max_{H \in \pi : \phi_H < \delta_H} |H| \right\},$$

we need only to show that $\eta < \eta_1(\pi)$ implies $1 \notin T(\pi)$ and that $\eta > \eta_2(\pi)$ implies $0 \notin T(\pi)$.

To see that $\eta < \eta_1(\pi)$ implies $1 \notin T(\pi)$, assume by contradiction that $1 \in T(\pi)$. If $\eta < \eta_1(\pi)$, there exists a coalition $S \in \pi$, such that $(\phi_S - \delta_S) > \eta|\mathcal{L} \setminus S|$. Thus, given any deforestation equilibrium, S will have a profitable deviation of setting $d_S = 0$, and $\sum_{j \in S} B_{ji} = 1$, for every $i \in \mathcal{L} \setminus S$, blocking all locals outside of S that deforest. This implies that there cannot be a deforestation equilibrium in $\mathcal{Q}(\pi, \bar{\mathbb{U}})$.

To see that $\eta > \eta_2(\pi)$ implies $0 \notin T(\pi)$, assume by contradiction that $0 \in T(\pi)$. As η is finite, it follows from the definition of $\eta_2(\pi)$ that there exists some coalition $H \in \pi$ with $\phi_H < \delta_H$. Consider $H \in \arg\max_{S' \in \pi : \phi_{S'} < \delta_{S'}} |S|$. In any no-deforestation equilibrium, H could deviate by setting $d_H = 1$ and because $\eta > \eta_2(\pi)$, the locals in H cannot be blocked by the coalitions $S \in \pi$ with $\phi_S \geq \delta_S$. It follows that there cannot be a no-deforestation equilibrium in $\mathcal{Q}(\pi, \bar{\mathbb{U}})$ if $\eta > \eta_2(\pi)$. Note we do not use condition 4 to prove these results, and therefore they hold even if $\mathcal{L} = \mathcal{G}$. □

To prove our subsequent results, we define the following set:

$$A(R; \pi_{\mathcal{L}\setminus R}) = \begin{cases} \displaystyle\bigcup_{\left(\pi_R, (d^*, B^*), \{a_\ell\}_{\ell \in R}\right) \in C(R; \pi_{\mathcal{L}\setminus R})} T(\pi_R \cup \pi_{\mathcal{L}\setminus R}) & \text{if } C(R; \pi_{\mathcal{L}\setminus R}) \neq \emptyset \\ \displaystyle\bigcup_{\pi_R \in \Pi_R, \pi_R \prec \pi^{\mathcal{F}}} T(\pi_R \cup \pi_{\mathcal{L}\setminus R}) & \text{otherwise.} \end{cases} \tag{EC.1}$$

To understand the construction, consider the definition of the core and specifically (EC.1). The set in (EC.1) contains all the deforestation decisions $d^* \in \{0, 1\}$ that could be encountered in the residual game played by locals in R when all the other locals form a partition $\pi_{\mathcal{L}\setminus R}$, specifically, all the Deforestation Outcomes encountered in core outcomes of that residual game if the core is non-empty, or all Deforestation Outcomes arising in equilibria of any non-cooperative games between locals in R (and the other locals organized as $\pi_{\mathcal{L}\setminus R}$) if that core is empty. The notation $\underline{A}(\cdot)$ highlights that this set contains all the plausible Assumptions that a deviating coalition $S \in \pi_{\mathcal{L}\setminus R}$ should make regarding outcomes in the residual game played by R. Because the deforestation decisions $d^* \in \{0,1\}$ suffices for purposes of calculating the welfare of any coalition S, per (9), the set $A(R;\pi_{\mathcal{L}\setminus R})$ provides a very concise summary of the information needed when determining whether a deviation is profitable or not (and whether an outcome is dominated).

Proof of Theorem 1. First consider the case where $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ and $\pi^{\mathcal{F}} = \{\mathcal{L}\}$. Under the area no-deforestation condition $\bar{\mathbb{D}}$, no outcome that violates (12a) could be in the core because it would have at least one local ℓ with $a_\ell < J_\ell(1,\text{no}) - c_\ell$ for whom the outcome is dominated by local ℓ who forms the singleton coalition $\{\ell\}$. In the case $\phi_\ell < \delta_\ell$, Lemma 2 implies that for every partition $\pi_{\mathcal{L}\setminus f}$ of the residual locals $\mathcal{L}\setminus f$, $T(\{\{\ell\}\} \cup \pi_{\mathcal{L}\setminus f}) = \{1\}$ which yields strictly greater welfare $J_\ell(1,\text{no}) - c_\ell > a_\ell$ for the local ℓ. In the case that $\phi_\ell \geq \delta_\ell$ by forming the singleton coalition $\{\ell\}$, local ℓ will gain strictly greater welfare regardless of whether or not deforestation occurs because

$$J_\ell(0,\text{yes}) \geq J_\ell(1,\text{no}) - c_\ell > a_\ell.$$

If $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ and $\pi^{\mathcal{F}} = \{\mathcal{L}\}$ no outcome with deforestation $d^* = 1$ could be in the core because it would be dominated by locals $\ell \in \mathcal{L}$ who form the grand coalition $\{\mathcal{L}\}$ and maximize their aggregate welfare without deforestation $d^* = 0$, as $\{0\} = T(\{\mathcal{L}\})$ by Lemma 2. This implies that when $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ and $\pi^{\mathcal{F}} = \{\mathcal{L}\}$, the core may only contain Compensation Outcomes.

Now, we show that for any partition into families $\pi^{\mathcal{F}}$, if $\phi_F > \delta_F$, for all $F \in \pi^{\mathcal{F}}$, then the core must contain all Compensation Outcomes. Notice that this implies that if $\pi^{\mathcal{F}} = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, the core must be exactly all Compensation Outcomes. To see that the core contains all Compensation Outcomes, we show that any outcome with partition $\pi \prec \pi^{\mathcal{F}}$, $d^* = 0$, and allocations $a_\ell > J_\ell(1,\text{no}) - c_\ell$, for all $\ell \in \mathcal{L}$, such that $0 \in T(\pi)$, must be in the core (note that at least once such Outcome exists because by Lemma 2, $1 \in T(\pi^{\mathcal{F}})$). For this, we show that no coalition $S \subseteq \mathcal{L}$ would deviate from such an outcome. If $\pi^{\mathcal{F}} = \{\mathcal{L}\}$, the whole set $S = \mathcal{L}$ would not deviate, as $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ implies that $\sum_{\ell\in\mathcal{L}} a_\ell = w(\mathcal{L},0) > w(\mathcal{L},1)$. Moreover, for any partition of $\mathcal{L}$ into families, $\pi^{\mathcal{F}}$, no subset $S \subset \mathcal{L}$ would deviate and form partition $\pi_S \in \Pi_S$, with $\pi_S \prec \pi^{\mathcal{F}}$, as Lemma 2 implies that $1 \in T(\pi_S \cup \pi_{\mathcal{L}\setminus S})$, for any partition $\pi_{\mathcal{L}\setminus S}$, which in turn implies that $1 \in A(\mathcal{L}\setminus S;\pi_S)$. But then under pessimism, any (sub)coalition $S_i \in \pi_S$ would not prefer to deforest:

$$\sum_{\ell\in S_i} a_\ell \geq \sum_{\ell\in S_i} (J_\ell(1,\text{no}) - c_\ell) = w(S_i,1).$$

This proves that there would be no deviation from the Compensation Outcome we considered, and therefore, the core contains all Compensation Outcomes.

We have proven that if $\pi^{\mathcal{F}} = \{\mathcal{L}\}$, and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, then the core is exactly the set of Compensation Outcomes, while if $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$ and $\phi_F > \delta_F$, for each $F \in \pi^{\mathcal{F}}$, then the core contains all Compensation Outcomes. We will next show that in this latter case, the core contains as well all Deforestation Outcomes. For this, notice that for any $\pi' \in \Pi_{\mathcal{L}}$, with $\pi' \prec \pi^{\mathcal{F}}$, Lemma 2 implies $1 \in T(\pi')$. Therefore, the core contains the set of outcomes $(\pi, d^*, \{a_\ell\}_{\ell\in\mathcal{L}})$ with $d^* = 1$, any feasible partition $\pi \in \Pi_{\mathcal{L}}$, with $\pi \prec \pi^{\mathcal{F}}$, and allocation $a_\ell = J_\ell(1,\text{no}) - c_\ell$, for all $\ell \in \mathcal{L}$. No coalition S could deviate and form partition $\pi_S \in \Pi_S$, with $\pi_S \prec \pi^{\mathcal{F}}$, because $1 \in T(\pi_S \cup \pi_{\mathcal{L}\setminus S})$, for any $\pi_{\mathcal{L}\setminus S} \in \pi_{\mathcal{L}\setminus S}$, with $\pi_{\mathcal{L}\setminus S} \prec \pi^{\mathcal{F}}$, and $\sum_{\ell\in S_i} a_\ell = w(S_i;1) \geq \min_{d^*\in A(\mathcal{L}\setminus S;\pi_S)} w(S_i;d^*)$, for any $S_i \in \pi_S$. No (sub)coalition S_i would deviate because there is always a Deforestation Outcome in the residual game. Hence, if $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$ and $\phi_F > \delta_F$, for each $F \in \pi^{\mathcal{F}}$, the core contains all Deforestation Outcomes.

Finally, we consider the case of $\pi^{\mathcal{F}} = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} < \delta_{\mathcal{L}}$ or $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$, but $\phi_F < \delta_F$, for some $F \in \pi^{\mathcal{F}}$ and show that in both these cases, the core contains all Deforestation Outcomes. In both cases, for any partition $\pi \in \Pi_{\mathcal{L}}$, with $\pi \prec \pi^{\mathcal{F}}$, there must be a coalition $S \in \pi$ such that $\phi_S < \delta_S$, which, by Lemma 2 implies that $T(\pi) = \{1\}$. Therefore, the core contains the set of outcomes $(\pi, d^*, \{a_\ell\}_{\ell\in\mathcal{L}})$ with $d^* = 1$, any feasible partition $\pi \in \Pi_{\mathcal{L}}$, with $\pi \prec \pi^{\mathcal{F}}$, and allocation $a_\ell = J_\ell(1,\text{no}) - c_\ell$, for all $\ell \in \mathcal{L}$. Any outcome with a different allocation must have $a_\ell < J_\ell(1,\text{no}) - c_\ell$ for at least one local ℓ and would be dominated by the local forming the singleton coalition $\{\ell\}$, by which local ℓ would have guaranteed the welfare of $J_\ell(1,\text{no}) - c_\ell$. We conclude that the core is exactly the set of Deforestation Outcomes. □

We now prove Theorem 2. For this, we divided the proof into a series of lemmas stated and proven below the Theorem.

Proof of Theorem 2. We prove each statement in the theorem by combining the above-mentioned lemmas.

(a) If $\eta \leq \min\{\eta_1^{\text{TU}}, \underline{\eta}_2^{\text{TU}}\}$, and $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$, Lemma EC.5 implies that there are only No-Deforestation Outcomes in the core. Additionally, Lemma EC.12 implies that the core contains all Blocking-Threat Outcomes.

(b) If $\min\{\eta_1^{\text{TU}}, \underline{\eta}_2^{\text{TU}}\} < \eta < \underline{\eta}_2^{\text{TU}}$ and $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$, as in the previous case, Lemma EC.5 implies that there are only No-Deforestation Outcomes in the core. Lemma EC.19, on the other hand, implies that there can only be Blocking-Threat Outcomes in the core, while Lemma EC.13 and Lemma EC.20 combined show that the core may be empty or it may contain Blocking-Threat Outcomes.

(c) If $\underline{\eta}_2^{\text{TU}} < \eta < \min\{\max\{\eta_1^{\text{TU}}, \underline{\eta}_2^{\text{TU}}\}, \overline{\eta}_2^{\text{TU}}\}$, and $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$, then $\eta \in (\underline{\eta}_2^{\text{TU}}, \eta_1^{\text{TU}})$, which, by Lemma EC.12 implies that the core contains all Blocking-Threat Outcomes. Moreover, because $\underline{\eta}_2^{\mathrm{TU}} < \overline{\eta}_2^{\mathrm{TU}}$, then $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$ and there exists $H \in \pi^{\mathcal{F}}$ such that $\phi_H < \delta_H$, hence, by Lemma EC.7, the core must contain Deforestation Outcomes.

(d) If $\min\{\max\{\eta_1^{\mathrm{TU}}, \underline{\eta}_2^{\mathrm{TU}}\}, \overline{\eta}_2^{\mathrm{TU}}\} < \eta < \overline{\eta}_2^{\mathrm{TU}}$, and $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$, then $\eta \in (\eta_1^{\mathrm{TU}}, \overline{\eta}_2^{\mathrm{TU}})$, and $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$ and there exists $H \in \pi^{\mathcal{F}}$ such that $\phi_H < \delta_H$. This implies that by Lemma EC.15 and Lemma EC.21, the core may contain Blocking-Threat Outcomes or may be empty. Moreover, by Lemma EC.9, and $\underline{\eta}_2^{\mathrm{TU}} < \eta$, if the core contains No-Deforestation Outcomes, then it must contain Deforestation Outcomes. Finally, by Lemma EC.17, the core cannot contain Compensation Outcomes.

(e) If $\overline{\eta}_2^{\mathrm{TU}} < \eta < \max\{\eta_1^{\mathrm{TU}}, \overline{\eta}_2^{\mathrm{TU}}\}$, and $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$, then $\eta \in (\overline{\eta}_2^{\mathrm{TU}}, \eta_1^{\mathrm{TU}})$, and $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$. Lemma EC.12 implies that the core contains all Blocking-Threat Outcomes. While Lemma EC.7 implies the core contains all Deforestation Outcomes. Finally, if $\phi_F > \delta_F$, for every $F \in \pi^{\mathcal{F}}$, then Lemma EC.16 implies that all Compensation Outcomes are in the core.

(f) If $\max\{\eta_1^{\mathrm{TU}}, \overline{\eta}_2^{\mathrm{TU}}\} < \eta < \eta_3^{\mathrm{TU}}$, and $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$, by Lemma EC.14, the core may contain Blocking Threat Outcomes. If $\phi_F > \delta_F$, for every $F \in \pi^{\mathcal{F}}$, then Lemma EC.16 implies that all Compensation Outcomes are in the core, and if $\phi_F < \delta_F$, for some $F \in \pi^{\mathcal{F}}$, Lemma EC.17 implies no Compensation Outcome is in the core. If $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$, then $\eta > \overline{\eta}_2^{\mathrm{TU}}$ and Lemma EC.7 imply the core contains all Deforestation Outcomes, while if $\pi^{\mathcal{F}} = \{\mathcal{L}\}$, then Lemma EC.4 implies the core contains only No-Deforestation Outcomes.

(g) If $\eta_3^{\mathrm{TU}} < \eta$, and $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$, then Lemma EC.18 implies that any No-Deforestation Outcome in the Core must be a Compensation Outcome. If $\phi_F > \delta_F$, for every $F \in \pi^{\mathcal{F}}$, then Lemma EC.16 implies that all Compensation Outcomes are in the core, and if $\phi_F < \delta_F$, for some $F \in \pi^{\mathcal{F}}$, Lemma EC.17 implies no Compensation Outcome is in the core (and therefore the core can contain only Deforestation Outcomes). Finally, if $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$, then $\eta > \overline{\eta}_2^{\mathrm{TU}}$ and Lemma EC.7 imply the core contains all Deforestation Outcomes, while if $\pi^{\mathcal{F}} = \{\mathcal{L}\}$, then Lemma EC.4 implies the core contains only No-Deforestation Outcomes.

If $\phi_F < \delta_F$, for every $F \in \pi^{\mathcal{F}}$, then the core either contains Deforestation Outcomes or is empty.

To see this, notice that Lemma EC.6 implies that if any No-Deforestation Outcome is in the core, then there must be a No-Deforestation Outcome with partition $\pi^{\mathcal{F}}$. But, $\phi_F < \delta_F$ for every $F \in \pi^{\mathcal{F}}$ implies that $\eta > \eta_2(\pi^{\mathcal{F}})$, for any $\eta > 0$, where $\eta_2(\cdot)$ is defined in (8b), which, by Lemma 2 implies that $T(\pi^{\mathcal{F}}) = \{1\}$. Which implies that any Outcome in the Core would have to be a Deforestation Outcome. Finally, Lemma EC.22 implies that the core may be empty when $\phi_F < \delta_F$, for every $F \in \pi^{\mathcal{F}}$, which completes the proof of the theorem. □

LEMMA EC.3. *Consider the cooperative game with transferable utility defined in §3.2. Every outcome in the core with allocation $\{a_\ell\}_{\ell \in \mathcal{L}}$ must satisfy:*

$$a_g \geq J_g(1, no) - c_g \text{ for all } g \in \mathcal{G} \tag{EC.2a}$$

$$a_\ell \geq J_\ell(0, yes) \text{ for all } \ell \in \mathcal{L} \setminus \mathcal{G}. \tag{EC.2b}$$

Proof of Lemma EC.3. We show the following generalization of both requirements (EC.2a) and (EC.2b):

$$a_\ell \geq \min\{J_\ell(0,\text{yes}), J_\ell(1,\text{no}) - c_\ell\} \text{ for all } \ell \in \mathcal{L},$$

for every outcome in the core with allocation $\{a_\ell\}_{\ell\in\mathcal{L}}$.

Assume by contradiction that there is an outcome in the core with a local $\ell \in \mathcal{L}$, that receives allocation $a_\ell < \min\{J_\ell(0,\text{yes}), J_\ell(1,\text{no}) - c_\ell\}$. Then, local ℓ can deviate and form a coalition $\{\ell\}$. And, by our assumption, $a_\ell < w(\{\ell\}, d^*)$, for every $d^* \in \{0,1\}$, so the outcome is dominated and cannot be in the core. □

Lemma EC.4. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ *and locals have full ability to cooperate (*$\pi^{\mathcal{F}} = \{\mathcal{L}\}$*), then the core contains only No-Deforestation Outcomes.*

Proof of Lemma EC.4. Assume by contradiction that the core contains a Deforestation Outcome ($d^* = 1$). But then, the trivial deviation of $\mathcal{L}$ forming the grand coalition dominates this outcome:

$$\sum_{\ell\in\mathcal{L}} a_\ell = \sum_{\ell\in\mathcal{L}} J(1,N) < w(\mathcal{L},0) = \sum_{\ell\in\mathcal{L}} J(0,Y). \tag{EC.3}$$

Where the inequality is due to $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$. Finally, because $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, $\eta_1(\{\mathcal{L}\}) = \infty$, and by Lemma 2, $T(\{\mathcal{L}\}) = \{0\}$, for any η, proving that the deviation is profitable for all equilibria. And therefore, the core cannot contain Deforestation Outcomes. □

Lemma EC.5. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F > \delta_F$*, for some* $F \in \pi^{\mathcal{F}}$*, and* $\eta < \underline{\eta}_2^{\text{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}},S\subseteq F,\phi_F>\delta_F,S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$*, the core contains only No-Deforestation Outcomes. Note that this result does not require condition 4.*

Proof of Lemma EC.5. We show that every Deforestation Outcome ($d^* = 1$) is dominated. The assumption on the value of η implies that there exists a coalition $S \subseteq F$ such that

$$(\phi_S - \delta_S) > \eta|\mathcal{L} \setminus S| \geq 0. \tag{EC.4}$$

Moreover, because including in S the locals in $\mathcal{G} \setminus S$ only expands $(\phi_S - \delta_S)$ and reduces $|\mathcal{L} \setminus S|$ in (EC.4), we consider a S that also satisfies $\mathcal{G} \cap F \subseteq S$.

Consider then any Deforestation Outcome ($d^* = 1$). We show that the coalition S satisfying (EC.4) and $\mathcal{G} \cap F \subseteq S$ could profitably deviate towards a No-Deforestation Outcome. Because $\phi_F > \delta_F$ and $d^* = 1$, we have:

$$\sum_{\ell\in S} a_\ell + \sum_{\ell\in F\setminus S} a_\ell = \sum_{\ell\in F}\big(J_\ell(1,\text{no}) - c_\ell\big) < \sum_{\ell\in F} J_\ell(0,\text{yes}) = \sum_{\ell\in S} J_\ell(0,\text{yes}) + \sum_{\ell\in F\setminus S} J_\ell(0,\text{yes}).$$

But note that $\mathcal{G} \cap F \subseteq S$ and Lemma EC.3 imply that $\sum_{\ell \in F \setminus S} a_\ell \geq \sum_{\ell \in F \setminus S} J_\ell(0, \text{yes})$. Therefore, $\sum_{\ell \in S} a_\ell < \sum_{\ell \in S} J_\ell(0, \text{yes})$. But then, consider any partition $\pi_{\mathcal{L} \setminus S} \in \Pi_{\mathcal{L} \setminus S}$, with $\pi_{\mathcal{L} \setminus S} \prec \pi^{\mathcal{F}}$. Condition (EC.4) implies that $\eta < \eta_1(\pi_{\mathcal{L} \setminus S} \cup \{S\})$, which by Lemma 2 (which does not require condition 4) implies that $\{0\} = T(\pi_{\mathcal{L} \setminus S} \cup \{S\})$. Because this holds for every partition of the remaining locals $\mathcal{L} \setminus S$, then $\{0\} = A(\mathcal{L} \setminus S; \{S\})$, as defined in (EC.1). Finally, this implies that $\sum_{\ell \in S} a_\ell < w(S; d^*)$ for every $d^* \in A(\mathcal{L} \setminus S; \{S\})$, proving that the Deforestation Outcome is dominated by coalition S deviating and guaranteeing higher welfare with a No-Deforestation Outcome. □

LEMMA EC.6. *If the core $C(\mathcal{L}; \emptyset)$ contains an Outcome with allocations $\{a_\ell\}_{\ell \in \mathcal{L}}$, and deforestation decisions d, then it must contain all Outcomes with the same allocation and deforestation decision d (in particular, the Outcome with partition $\pi^{\mathcal{F}}$).*

Proof of Lemma EC.6. Notice that we need only prove that if the core contains an Outcome with a given allocation, it must contain any other Outcomes with the same allocation and deforestation decisions d for every feasible partition.

To see this, assume that we have an outcome with partition $\pi \prec \pi^{\mathcal{F}}$, $d^* = d$, and allocation $\{a_\ell\}_{\ell \in \mathcal{L}}$. Consider then any partition $\sigma_{\mathcal{L}} \prec \pi^{\mathcal{F}}$ that satisfies:

$$\sum_{\ell \in S} a_\ell = w(S, d), \text{ for every } S \in \sigma_{\mathcal{L}}. \tag{EC.5}$$

We show that the outcome with partition $\sigma_{\mathcal{L}}$, $d^* = d$ and allocation $\{a_\ell\}_{\ell \in \mathcal{L}}$ is in the core. To see this, assume by contradiction that a coalition $S \subseteq \mathcal{L}$ could deviate and form partition $\hat{\pi}_S \in \Pi_S$, $\hat{\pi}_S \prec \pi^{\mathcal{F}}$. This means that for each $S_i \in \hat{\pi}_S$,

$$\sum_{\ell \in S_i} a_\ell < w(S_i, d'), \text{ for every } d' \in A(\mathcal{L} \setminus S; \hat{\pi}_S).$$

But then, this same coalition S with partition $\hat{\pi}_S$ constitutes a deviation from the original outcome with partition π, which contradicts the premise that the outcome is in the core. □

LEMMA EC.7. *Consider the area no-use condition $\bar{\mathbb{U}}$ in the cooperative game with transferable utility defined in §3.2. If $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$, locals have partial ability to cooperate ($\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$), and $\eta > \overline{\eta}_2^{\text{TU}} := \max_{F,S: F \in \pi^{\mathcal{F}}, S \subseteq F, S \neq \mathcal{L}} \frac{(\phi_S - \delta_S)}{|\mathcal{L} \setminus S|}$, the core contains all Deforestation Outcomes. Note that this result does not require condition 4.*

Proof of Lemma EC.7. Consider any Deforestation Outcome, with $a_\ell = J_\ell(1, \text{no}) - c_\ell$, for all $\ell \in \mathcal{L}$, and $d^* = 1$. We will show that this outcome must be in the core. Assume by contradiction that a coalition $H \subseteq \mathcal{L}$ can profitably deviate and form partition $\pi_H \prec \pi^{\mathcal{F}}$.

Because $H \subseteq F \in \sigma$ and $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$, we must have $H \subset \mathcal{L}$. Then, Lemma EC.8 (which does not require condition 4) implies that $1 \in A(\mathcal{L} \setminus H, \pi_H)$. So any (sub)coalition $S \in \pi_H$ must satisfy

$$\sum_{\ell \in S} a_\ell < \min_{d^* \in A(\mathcal{L} \setminus H, \pi_H)} w(S; d^*) \leq w(S; 1) := \sum_{\ell \in S} \big(J_\ell(1, \text{no}) - c_\ell\big)$$

where the strict inequality comes from π_H being a profitable deviation and the second inequality follows from $1 \in A(\mathcal{L} \setminus H, \pi_H)$. This provides the contradiction and completes the proof. □

Lemma EC.8. *Consider the area no-use condition $\bar{\mathbb{U}}$ in the cooperative game with transferable utility defined in §3.2. If $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$ and $\eta > \overline{\eta}_2^{\text{TU}} := \max_{S \subseteq F, F \in \pi^{\mathcal{F}}, S \neq \mathcal{L}} \frac{(\phi_S - \delta_S)}{|\mathcal{L} \setminus S|}$, then for every residual game with $|R| \leq |\mathcal{L}| - 1$ and any partition $\pi_{\mathcal{L} \setminus R} \prec \pi^{\mathcal{F}}$ of the remaining locals, we have $1 \in A(R; \pi_{\mathcal{L} \setminus R})$. Note that this result does not require condition 4.*

Proof of Lemma EC.8. We proceed by induction on the size of the residual set $|R| = k$. We first prove the base case $k = 1$: that the core for a residual game with one local $R = \{h\}$ for $h \in \mathcal{L}$ and any partition $\pi_{\mathcal{L} \setminus \{h\}} \in \Pi_{\mathcal{L} \setminus \{h\}}$, with $\pi_{\mathcal{L} \setminus \{h\}} \prec \pi^{\mathcal{F}}$, of the other locals contains a Deforestation Outcome.

We claim that in this case, our standing assumption on η implies that $\eta > \eta_1(\{\{h\}, \pi_{\mathcal{L} \setminus \{h\}}\})$, for any partition $\pi_{\mathcal{L} \setminus \{h\}} \prec \pi^{\mathcal{F}}$. This follows directly from the definition of $\eta_1(\cdot)$ in (8a), because we have:

$$\forall \pi \prec \pi^{\mathcal{F}}, \pi \neq \{\mathcal{L}\}, \quad \eta > \max_{F, S: F \in \pi^{\mathcal{F}}, S \subseteq F, S \neq \mathcal{L}} \frac{(\phi_S - \delta_S)}{|\mathcal{L} \setminus S|} \geq \sup\Big\{\eta : \exists S \in \pi : (\phi_S - \delta_S) > \eta |\mathcal{L} \setminus S|\Big\} := \eta_1(\pi). \tag{EC.6}$$

Therefore, according to Lemma 2 (which does not require condition 4), $1 \in T(\{\{h\}, \pi_{\mathcal{L} \setminus \{h\}}\})$, so the core of the residual game $C(\{h\}; \pi_{\mathcal{L} \setminus \{h\}})$ contains the Deforestation Outcome $(\pi_h = \{\{h\}\}, d^* = 1, a_h = J_h(1, \text{no}) - c_h)$.

Having just established our claim for $k = 1$, assume by induction that for an integer $k \in [1, |\mathcal{L}| - 2]$, every residual game with $|R| \leq k$ locals has

$$1 \in A(R; \pi_{\mathcal{L} \setminus R}). \tag{EC.7}$$

We prove the inductive assumption for a residual game with $|R| = k + 1$. Our assumption $k \leq |\mathcal{L}| - 2$ implies that $\mathcal{L} \setminus R$ is non-empty, so by (EC.6) we have again that $\eta \geq \eta_1(\{\pi_R, \pi_{\mathcal{L} \setminus R}\})$ for any partitions π_R and $\pi_{\mathcal{L} \setminus R}$, with $\pi_R \cup \pi_{\mathcal{L} \setminus R} \prec \pi^{\mathcal{F}}$, and therefore according to Lemma 2, $1 \in T(\{\pi_R, \pi_{\mathcal{L} \setminus R}\})$. Hence,

$$\pi_R = \{R \cap F : F \in \pi^{\mathcal{F}}\}, \; d^* = 1, \; a_\ell = J_\ell(1, \text{no}) - c_\ell, \forall \ell \in R \tag{EC.8}$$

is an outcome of the residual game. That outcome is un-dominated under pessimism because for any coalition $S \subset R$, partition $\pi_S \in \Pi_S$, with $\pi_S \prec \pi^{\mathcal{F}}$ and (sub)coalition $S_i \in \pi_S$,

$$\min_{d^* \in A(R \setminus S; \pi_S \cup \pi_{\mathcal{L} \setminus R})} w(S_i; d^*) \leq w(S_i; 1) = \sum_{\ell \in S_i} J_\ell(1, \text{no}) - c_\ell = \sum_{\ell \in S_i} a_\ell \tag{EC.9}$$

wherein the inequality follows from the inductive assumption (because the residual set $R\setminus S$ has size at most $k-1$), the first equality from (9), and the second equality from (EC.8). Hence the outcome (EC.8) is in the core for the residual game, which completes our inductive proof. $\square$

LEMMA EC.9. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F > \delta_F$ *for some* $F\in\pi^{\mathcal{F}}$*, and* $\underline{\eta}_2^{\mathrm{TU}} < \eta$*, where* $\underline{\eta}_2^{\mathrm{TU}} := \max_{F,S: F\in\pi^{\mathcal{F}}, S\subseteq F, \phi_F>\delta_F, S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$*, then either the core contains Deforestation Outcomes or it is empty. Note that this result does not require condition 4.*

Proof of Lemma EC.9. We will prove by induction that if $0\in A(R;\pi_{\mathcal{L}\setminus R})$, then $1\in A(R;\pi_{\mathcal{L}\setminus R})$, for every residual set $R\subseteq\mathcal{L}$, and partition of the remaining locals $\pi_{\mathcal{L}\setminus R}$ satisfying:

$$\text{for every } S\in\pi_{\mathcal{L}\setminus R}, S\subseteq F, \text{ with } F\in\pi^{\mathcal{F}}, \phi_F>\delta_F. \tag{EC.10}$$

The result then follows, taking $R=\mathcal{L}$.

We proceed by induction in $|R|$. If $|R|=1$, (EC.10) implies that either $R=F$, for some $F\in\pi^{\mathcal{F}}$, with $\phi_R\le\delta_R$, or $R\subseteq F$, for $F\in\pi^{\mathcal{F}}$, with $\phi_F>\delta_F$. Hence, $\eta_1(\{R\}\cup\pi_{\mathcal{L}\setminus R}) = \max\{\frac{\phi_R-\delta_R}{|\mathcal{L}|-1}, \max_{H\in\pi_{\mathcal{L}\setminus R}} \frac{\phi_H-\delta_H}{|\mathcal{L}\setminus H|}\} \le \underline{\eta}_2^{\mathrm{TU}} < \eta$. But then, by Lemma 2, $T(\{R\}\cup\pi_{\mathcal{L}\setminus R}) \neq \{0\}$. And, because $A(R;\pi_{\mathcal{L}\setminus R})$ can only take values $\emptyset, \{0\}, \{1\}$, or $\{0,1\}$, if $0\in A(R;\pi_{\mathcal{L}\setminus R})$, then, $1\in A(R;\pi_{\mathcal{L}\setminus R})$.

Consider then any $R\subseteq\mathcal{L}$, with $|R|>1$, we will show that if the results holds for any R', with $|R'|<|R|$, then it holds for R. In particular, if $0\in A(R;\pi_{\mathcal{L}\setminus R})$, consider a No-Deforestation Outcome $(\pi'_R, d'=0, \{a'_\ell\}_{\ell\in R}) \in A(R;\pi_{\mathcal{L}\setminus R})$, we will show that the following Deforestation Outcome must also be in $A(R;\pi_{\mathcal{L}\setminus R})$:

$$\pi_R = \{F\cap R\}_{F\in\pi^{\mathcal{F}}} \tag{EC.11a}$$

$$d=1 \tag{EC.11b}$$

$$a_\ell \ge a'_\ell \text{ for every } \ell\in F\cap R, F\in\pi^{\mathcal{F}} \text{ such that } \phi_F\le\delta_F \tag{EC.11c}$$

$$a_\ell = J_\ell(1,\text{no}) - c_\ell \text{ for every } \ell\in F\cap R, F\in\pi^{\mathcal{F}} \text{ such that } \phi_F>\delta_F \tag{EC.11d}$$

Allocation $(\pi_R, d, \{a_\ell\}_{\ell\in R})$ is feasible because (EC.10) implies that for every $F\in\pi^{\mathcal{F}}$, such that $\phi_F\le\delta_F$, $F\subseteq R$ and therefore $\sum_{\ell\in F} a_\ell = w(F;1) \ge w(F;0) = \sum_{\ell\in F} a'_\ell$. Moreover, (EC.10) implies that every coalition $S\in\pi_R\cup\pi_{\mathcal{L}\setminus R}$ with $\phi_S>\delta_S$, must be a subset $S\subseteq F'$, for some F' with $\phi_{F'}>\delta_{F'}$. But then, $\eta_1(\pi_R\cup\pi_{\mathcal{L}\setminus R}) = \max_{S\in\pi_R\cup\pi_{\mathcal{L}\setminus R}} \frac{\phi_S-\delta_S}{|\mathcal{L}\setminus S|} \le \underline{\eta}_2^{\mathrm{TU}} < \eta$, which implies by Lemma 2 that $1\in T(\pi_R\cup\pi_{\mathcal{L}\setminus R})$. We need only to see then that there is no profitable deviation. Assume by contradiction that there exists a coalition H, forming partition $\pi_H \prec \pi^{\mathcal{F}}$, that can profitably deviate from (EC.11a)-(EC.11d).

If $H\subseteq F$, with $\phi_F\le\delta_F$, then H is as well a deviation from $(\pi'_R, d'=0, \{a'_\ell\}_{\ell\in R})$, which contradicts $(\pi'_R, d'=0, \{a'_\ell\}_{\ell\in R}) \in A(R;\pi_{\mathcal{L}\setminus R}$. This is easy to see, as for every $H_i\in\pi_H$, $\sum_{\ell\in H_i} a'_\ell \le \sum_{\ell\in H_i} a'_\ell < \min_{d^*\in A(R\setminus H;\pi_H\cup\pi_{\mathcal{L}\setminus H})} w(H_i, d^*)$.

If $H \subseteq F$, with $\phi_F > \delta_F$, then, $\pi_H \cup \pi_{\mathcal{L}\setminus R}$ satisfies (EC.10), and therefore, by our inductive assumption, either $1 \in A(R\setminus H; \pi_H \cup \pi_{\mathcal{L}\setminus R})$, or $\emptyset = A(R\setminus H; \pi_H \cup \pi_{\mathcal{L}\setminus R})$. If $1 \in A(R\setminus H; \pi_H \cup \pi_{\mathcal{L}\setminus R})$, then for any $H_i \in \pi_H$, (EC.11d) implies that $\sum_{\ell \in H_i} a_\ell = \sum_{\ell \in H_i} J_\ell(1, \text{no}) - c_\ell \geq \min_{d^* \in A(R\setminus H; \pi_H \cup \pi_{\mathcal{L}\setminus H})} w(H_i, d^*)$, which contradicts H being a deviation. If $\emptyset = A(R \setminus H; \pi_H \cup \pi_{\mathcal{L}\setminus R})$, then because $\eta > \underline{\eta}_2^{\text{TU}} \geq \eta_1(\{R \setminus H \cup F\}_{F\in\pi^{\mathcal{F}}} \cup \pi_H \cup \pi_{\mathcal{L}\setminus R})$, then by Lemma 2, $1 \in T(\{R \setminus H \cup F\}_{F\in\pi^{\mathcal{F}}} \cup \pi_H \cup \pi_{\mathcal{L}\setminus R})$, but then, by the definition of a recursive core in (11), $\sum_{\ell \in H_i} a_\ell = \sum_{\ell \in H_i} J_\ell(1, \text{no}) - c_\ell > w(H_i; 1) = sum_{\ell \in H_i} J_\ell(1, \text{no}) - c_\ell$, for every $H_i \in \pi_H$. This shows that there can be no deviation H, and concludes the proof. □

Lemma EC.10. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F > \delta_F$ *for some* $F \in \pi^{\mathcal{F}}$, $\underline{\eta}_2^{\text{TU}} < \eta_1^{\text{TU}}$, *and* $\eta \in (\underline{\eta}_2^{\text{TU}}, \eta_1^{\text{TU}})$, *where* $\eta_1^{\text{TU}} := \min_{S\subseteq F, F\in\pi^{\mathcal{F}}:\phi_S<\delta_S} \sup\left\{\eta : \sum_{H\in\pi^{\mathcal{F}}:\phi_{H\setminus S}>\delta_{H\setminus S}} \left\lfloor \frac{\phi_{H\setminus S}-\delta_{H\setminus S}}{\eta}\right\rfloor > |S|\right\}$ *and* $\underline{\eta}_2^{\text{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}}, S\subseteq F, \phi_F>\delta_F, S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$, *then the core contains Deforestation Outcomes.*

Proof of Lemma EC.10. By Lemma EC.12, $\eta < \eta_1^{\text{TU}}$ implies that $0 \in A(\mathcal{L}; \emptyset)$, but then, by Lemma EC.9 and $\underline{\eta}_2^{\text{TU}} < \eta$, we must have that $1 \in A(\mathcal{L}; \emptyset)$, which proves the result. □

Lemma EC.11. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F > \delta_F$ *for some* $F \in \pi^{\mathcal{F}}$ *and*

$$\eta < \eta_1^{\text{TU}} = \min_{S\subseteq F, F\in\pi^{\mathcal{F}}:\phi_S<\delta_S} \sup\left\{\eta : \sum_{H\in\pi^{\mathcal{F}}:\phi_{H\setminus S}>\delta_{H\setminus S}} \left\lfloor \frac{\phi_{H\setminus S}-\delta_{H\setminus S}}{\eta}\right\rfloor > |S|\right\} \tag{EC.12}$$

then for any residual set of locals $R \subseteq \mathcal{L}$, $R \neq \emptyset$, *and any feasible partition of the other locals* $\pi_{\mathcal{L}\setminus R} \in \Pi_{\mathcal{L}\setminus R}$, *with* $\pi_{\mathcal{L}\setminus R} \prec \pi^{\mathcal{F}}$, *that satisfies*

$$\phi_S < \delta_S \text{ for every } S \in \pi_{\mathcal{L}\setminus R}, \tag{EC.13}$$

the residual core $C(R; \pi_{\mathcal{L}\setminus R})$ *contains the following Blocking-Threat Outcomes:*

$$\pi_R = \{\{\mathcal{G} \cap R \cap F\}_{F\in\pi^{\mathcal{F}}}, \{\ell\}_{\ell\in R\setminus\mathcal{G}}\} \tag{EC.14a}$$

$$d^* = 0 \tag{EC.14b}$$

$$a_\ell = J_\ell(0, yes) \text{ for all } \ell \in R. \tag{EC.14c}$$

Proof of Lemma EC.11. We prove the result by induction on the number of residual locals, $|R|$. To verify the inductive assumption for $|R| = 1$, consider a residual game with one local $R = \{h\}$ and a partition of the other locals $\pi_{\mathcal{L}\setminus R}$ that satisfies (EC.13). This implies that $\sum_{S\in\pi_{\mathcal{L}\setminus R}} \phi_S < \sum_{S\in\pi_{\mathcal{L}\setminus R}} \delta_S$. Because $\phi_F > \delta_F$, for some $F \in \pi^{\mathcal{F}}$, this implies that $h \in \mathcal{G}$, and therefore $\eta < \eta_1^{\text{TU}}$ implies:

$$\eta < (\phi_R - \delta_R) \cdot \left[\max_{S\in\pi_{\mathcal{L}\setminus R}:\phi_S<\delta_S} |S|\right]^{-1} := \eta_2(\{R\} \cup \pi_{\mathcal{L}\setminus R}).$$

Therefore, by Lemma 2, $0 \in T(\{h\} \cup \pi_{\mathcal{L}\setminus\{h\}})$, which implies that the core contains the outcome $\big(\{h\}, 0, a_h = J_h(0,\text{yes})\big)$, which is (EC.14a)-(EC.14c) for this residual game with $R = \{h\}$.

To complete the inductive proof, assume that the claim holds for any residual game with $|R| \le k$ for some integer $k \in [1, |\mathcal{L}| - 1]$, and consider a residual game with $|R| = k+1$ residual locals and a partition of the other locals $\pi_{\mathcal{L}\setminus R} \prec \sigma$ for which (EC.13) holds. We first claim that (EC.12) and (EC.13) imply that $R \cap \mathcal{G}$ is non-empty and

$$\begin{aligned}\eta &< \sup\left\{\eta : \sum_{F\in\pi^{\mathcal{F}}} \left\lfloor \frac{(\phi_{R\cap\mathcal{G}\cap F} - \delta_{R\cap\mathcal{G}\cap F})}{\eta} \right\rfloor > \max_{S\in\pi_{\mathcal{L}\setminus R}\cup\{\{\ell\}:\ell\in R\setminus\mathcal{G}\}:\phi_S<\delta_S} |S| \right\} \\ &= \eta_2(\{\{R\cap\mathcal{G}\cap F\}_{F\in\pi^{\mathcal{F}}}, \{\ell\}_{\ell\in R\setminus\mathcal{G}}\} \cup \pi_{\mathcal{L}\setminus R}).\end{aligned}$$

The first inequality is implied by (EC.12) with a specific choice $S = \underset{H\in\pi_{\mathcal{L}\setminus R}\cup\{\{\ell\}_{\ell\in R\setminus\mathcal{G}}\}:\phi_H<\delta_H}{\arg\max} |H|$ and because $\sum_{H\in\pi^{\mathcal{F}}:\phi_{H\setminus S}>\delta_{H\setminus S}} \left\lfloor \frac{(\phi_{H\setminus S}-\delta_{H\setminus S})}{\eta} \right\rfloor \le \sum_{F\in\pi^{\mathcal{F}}} \left\lfloor \frac{(\phi_{R\cap\mathcal{G}\cap F}-\delta_{R\cap\mathcal{G}\cap F})}{\eta} \right\rfloor$, for all $\eta > 0$. Because both sums are decreasing in η, we have

$$\sup\left\{\eta : \sum_{H\in\pi^{\mathcal{F}}:\phi_{H\setminus S}>\delta_{H\setminus S}} \left\lfloor \frac{\phi_{H\setminus S} - \delta_{H\setminus S}}{\eta} \right\rfloor > |S| \right\} \le \sup\left\{\eta : \sum_{F\in\pi^{\mathcal{F}}} \left\lfloor \frac{(\phi_{R\cap\mathcal{G}\cap F} - \delta_{R\cap\mathcal{G}\cap F})}{\eta} \right\rfloor > |S| \right\}.$$

The equality follows from the definition of $\eta_2(\cdot)$ in (8b). Lemma 2 then implies that $0 \in T(\{\{R\cap\mathcal{G}\cap F\}_{F\in\pi^{\mathcal{F}}}, \{\ell\}_{\ell\in R\setminus\mathcal{G}}\} \cup \pi_{\mathcal{L}\setminus R})$, so the outcome (EC.14a)-(EC.14c) is valid.

To see that this outcome is undominated, consider a coalition of locals $S \subseteq R$ that forms a partition $\pi_S \in \Pi_S$, with $\pi_S \prec \pi^{\mathcal{F}}$. We distinguish two mutually exclusive and exhaustive cases. In Case 1, there exists a (sub)coalition $S_i \in \pi_S$ such that $(\phi_{S_i} - \delta_{S_i}) \ge 0$. For this (sub)coalition, (9) implies that

$$w(S_i; d^*) \le \sum_{\ell\in S_i} J_\ell(0,\text{yes}) = \sum_{\ell\in S_i} a_\ell, \text{ for all } d^* \in \{0,1\}.$$

Therefore, our initial outcome with allocation (EC.14c) cannot be dominated by coalition $S \subseteq R$ forming partition $\pi_S \in \Pi_S$ that satisfies $(\phi_{S_i} - \delta_{S_i}) \ge 0$ for some $S_i \in \pi_S$. In Case 2, there is no (sub)coalition $S_i \in \pi_S$ with $(\phi_{S_i} - \delta_{S_i}) \ge 0$, which with (EC.13) implies that:

$$\phi_{S_i} < \delta_{S_i}, \text{ for every coalition } S_i \in \pi_{\mathcal{L}\setminus R} \cup \pi_S. \tag{EC.15}$$

Therefore, $\phi_F > \delta_F$ for some $F \in \pi^{\mathcal{F}}$ and (EC.15) imply $\phi_{R\setminus S} > \delta_{R\setminus S}$. Also, $S \ne \emptyset$ and $|R| = k+1$ imply that $|R \setminus S| \le k$, so our inductive assumption applies to the residual game played by locals $R \setminus S$ when the other locals form a partition $\pi_{\mathcal{L}\setminus R} \cup \pi_S \prec \pi^{\mathcal{F}}$. This implies that $0 \in A(R\setminus S; \pi_{\mathcal{L}\setminus R} \cup \pi_S)$ and thus:

$$\min_{d^*\in A(R\setminus S;\pi_{\mathcal{L}\setminus R}\cup\pi_S)} w(S_i; d^*) \le w(S_i; 0) = \sum_{\ell\in S_i} J_\ell(0,\text{yes}) = \sum_{\ell\in S_i} a_\ell, \text{ for every (sub)coalition } S_i \in \pi_S.$$

Therefore, an outcome with allocation (EC.14c) is not dominated by coalition $S \subseteq R$ forming partition $\pi_S \in \Pi_S$ under pessimism in Case 2, which completes the inductive proof. □

Lemma EC.12. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F > \delta_F$ *for some* $F \in \pi^{\mathcal{F}}$ *and*

$$\eta < \eta_1^{\mathrm{TU}} = \min_{S \subseteq F, F \in \pi^{\mathcal{F}} : \phi_S < \delta_S} \sup \left\{ \eta : \sum_{H \in \pi^{\mathcal{F}} : \phi_{H \setminus S} > \delta_{H \setminus S}} \left\lfloor \frac{\phi_{H \setminus S} - \delta_{H \setminus S}}{\eta} \right\rfloor > |S| \right\} \tag{EC.16}$$

then the core contains every Blocking-Threat Outcome.

Proof of Lemma EC.12. Consider the special case of Lemma EC.11 for the residual game with $R = \mathcal{L}$. We established that if $\eta < \eta_1^{\mathrm{TU}}$ holds, then the core contains the outcome with $\pi = \left\{ \{\mathcal{G} \cap F\}_{F \in \pi^{\mathcal{F}}}, \{\ell\}_{\ell \in \mathcal{L} \setminus \mathcal{G}} \right\}$, $d^* = 0$ and $a_\ell = J_\ell(0, \mathrm{yes})$ for $\ell \in \mathcal{L}$. Moreover, by Lemma EC.6, because the core contains one Blocking-Threat Outcome, every Blocking-Threat Outcome must be in the core, which concludes the proof. □

Lemma EC.13. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F > \delta_F$ *for some* $F \in \pi^{\mathcal{F}}$ *and* $\eta \in (\eta_1^{\mathrm{TU}}, \underline{\eta}_2^{\mathrm{TU}})$, *where* $\eta_1^{\mathrm{TU}} := \min_{S \subseteq F, F \in \pi^{\mathcal{F}} : \phi_S < \delta_S} \sup \left\{ \eta : \sum_{H \in \pi^{\mathcal{F}} : \phi_{H \setminus S} > \delta_{H \setminus S}} \left\lfloor \frac{\phi_{H \setminus S} - \delta_{H \setminus S}}{\eta} \right\rfloor > |S| \right\}$ *and* $\underline{\eta}_2^{\mathrm{TU}} := \max_{F,S : F \in \pi^{\mathcal{F}}, S \subseteq F, \phi_F > \delta_F, S \neq \mathcal{L}} \frac{(\phi_S - \delta_S)}{|\mathcal{L} \setminus S|}$, *then the core may contain Blocking-Threat Outcomes.*

Proof of Lemma EC.13. To prove the Lemma, we consider first the following instance with full ability to cooperate, $\pi^{\mathcal{F}} = \{\mathcal{L}\}$ and $\mathcal{L} = \{\ell, g, h\}$ satisfying:

$$\phi_g - \delta_g > \phi_\ell - \delta_\ell > 0, \quad \phi_h < \delta_h, \quad \phi_{\{\ell,h\}} < \delta_{\{\ell,h\}}, \quad (\phi_g - \delta_g) = -2(\phi_h - \delta_h), \quad \phi_{\mathcal{L}} > \delta_{\mathcal{L}}, \tag{EC.17}$$

and $\eta_1^{\mathrm{TU}} = \frac{\phi_g - \delta_g}{2} < \eta < \underline{\eta}_2^{\mathrm{TU}} = \phi_{\{g,\ell\}} - \delta_{\{g,\ell\}}$. We show that the core contains the Blocking-Threat Outcome with $d^* = 0$, partition $\pi = \{\{g, \ell\}, \{h\}\}$, and allocations

$$a_\ell = J_\ell(0, \mathrm{yes}) + (\delta_h - \phi_h), \quad a_g = J_g(0, \mathrm{yes}) - (\delta_h - \phi_h), \quad a_h = J_h(0, \mathrm{yes}). \tag{EC.18}$$

First, note that this is a valid No-Deforestation Outcome outcome according to Definition 4; the only condition that is potentially less obvious is that $a_g \geq \min(J_g(0, \mathrm{yes}), J_g(1, \mathrm{no}) - c_g)$, which holds because $a_g = J_g(0, \mathrm{yes}) - (\delta_h - \phi_h) = J_g(1, \mathrm{no}) - c_g + (\delta_h - \phi_h) > J_g(1, \mathrm{no}) - c_g$, where the inequality follows because $(\phi_g - \delta_g) = -2(\phi_h - \delta_h)$ and $\phi_h < \delta_h$ by (EC.17). Moreover, this is a Blocking-Threat Outcome because h is allocated $J_h(0, \mathrm{yes}) < J_h(1, \mathrm{no}) - c_h$.

To prove that this is in the core, we consider all possible deviations.

Local g would not deviate and form partition $\{g\}$ because $\eta > \frac{\phi_g - \delta_g}{2}$ and $\phi_{\{\ell,h\}} < \delta_{\{\ell,h\}}$ imply that $\{\ell, h\}$ could deforest and not be blocked. Formally, because $\eta_2(\{\{g\}, \{\ell, h\}\}) = \frac{\phi_g - \delta_g}{2}$ and $\eta > \frac{\phi_g - \delta_g}{2}$, Lemma 2 implies that $T(\{\{g\}, \{\ell, h\}\}) = \{1\}$, which in turn implies that $1 \in A(\{\ell, h\}; \{\{g\}\})$. Therefore, because $a_g = J_g(1, \mathrm{no}) - c_g = w(\{g\}; 1)$, g would not deviate under pessimism.

Local ℓ would not deviate and form partition $\{\ell\}$ because

$$a_\ell > J_\ell(0,\text{yes}) > J_\ell(1,\text{no}) - c_\ell \geq \min_{d^*\in\{0,1\}} w(\{\ell\};d^*),$$

where the first inequality is due to $\phi_h < \delta_h$ and the second due to $\phi_\ell > \delta_\ell$.

Local h would not deviate as a singleton $\{h\}$ because $\eta < (\phi_\ell - \delta_\ell) + (\phi_g - \delta_g)$ implies $\eta < \eta_2(\{\{\ell,g\},\{h\}\})$, so Lemma 2 implies $0 \in T(\{\{\ell,g\},\{h\}\}) \subseteq A(\{\ell,g\};\{\{h\}\}$ and thus $a_h \geq \min_{d^*\in\{0,1\}} w(\{h\};d^*)$.

Locals g and ℓ would also not deviate from forming coalition $\{g,\ell\}$ because that coalition is already formed in the current outcome and is receiving $a_\ell + a_g = w(\{\ell,g\};0)$, which is the maximum joint allocation possible because $\phi_{\{\ell,g\}} > \delta_{\{\ell,g\}}$.

Locals g and h would not deviate and form coalition $\{g,h\}$. To see this, notice that $\eta_1(\{\{\ell\},\{g,h\}\}) = max(\frac{\phi_\ell-\delta_\ell}{2}, \phi_{\{g,h\}} - \delta_{\{g,h\}}) = \frac{\phi_g-\delta_g}{2}$, which holds because by (EC.17) implies $\phi_{\{g,h\}} - \delta_{\{g,h\}} = \frac{\phi_g-\delta_g}{2}$, and $\phi_g - \delta_g > \phi_\ell - \delta_\ell$. But then, $\eta > \eta_1(\{\{\ell\},\{g,h\}\})$ and by Lemma 2, $1 \in A(\{\ell\};\{\{g,h\}\})$. And, because $\phi_g - \delta_g = -2(\phi_h - \delta_h)$, then $a_g + a_h = w(\{g,h\};1)$, and thus they would not deviate under pessimism.

Locals ℓ and h would not deviate because,

$$a_\ell + a_h = J_\ell(0,\text{yes}) + (\delta_h - \phi_h) + J_h(0,\text{yes}) = J_\ell(0,\text{yes}) + J_h(1,\text{no}) - c_h > J_\ell(0,\text{yes}) + J_h(0,\text{yes}),$$

where the inequality follows because $\phi_h < \delta_h$; moreover, $\phi_\ell > \delta_\ell$ implies that

$$a_\ell + a_h > J_\ell(1,\text{no}) - c_\ell + J_h(1,\text{no}) - c_h.$$

This proves that $a_\ell + a_g > w(\{\ell,g\};d^*)$, for every $d^* \in \{0,1\}$, so $\{\ell,h\}$ would not deviate together.

Finally, the grand coalition $\{\ell,g,h\}$ would not deviate because $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ implies $a_\ell + a_g + a_h = w(\mathcal{L};0)$ already takes the largest possible value.

We have shown that this instance contains a Blocking-Threat Outcome in the core.

To show that this instance can be extended to a case with partial ability to cooperate, we consider the groups of locals with two families $\mathcal{L} = \{\ell,g,h,e\}$, with $\pi^{\mathcal{F}} = \{\{\ell,g,h\},\{e\}\}$, satisfying (EC.17), $\phi_e < \delta_e$, and $\frac{(\phi_g-\delta_g)}{2} < (\phi_g = \delta_g) + (\phi_\ell - \delta_\ell) + (\phi_h - \delta_h)$. Following the same analysis as above, we can show that the outcome with no-deforestation ($d^* = 0$), locals forming the coalition $\pi = \{\{\ell,g\},\{h\},\{e\}\}$, and allocations following (EC.18) and $a_e = J_e(0,\text{yes})$ is in the core. This is because $\eta < (\phi_\ell - \delta_\ell) + (\phi_g - \delta_g)$ implies that the coalition $\{\ell,g\}$ can block either h or e, which leads to $\eta < \eta_2(\{\{\ell,g\},\{h\},\{e\}\})$. Therefore, the same example works to show that the core may contain Blocking-Threat outcomes. □

Lemma EC.14. *Consider the area no-use condition $\bar{\mathbb{U}}$ in the cooperative game with transferable utility defined in §3.2. If $\phi_H > \delta_H$ for some $H \in \pi^{\mathcal{F}}$ and $\eta \in \left(\overline{\eta}_2^{\mathrm{TU}}, \eta_3^{\mathrm{TU}}\right)$, where $\overline{\eta}_2^{\mathrm{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}},F\neq\mathcal{L},S\subseteq F} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$ and $\eta_3^{\mathrm{TU}} := \max_{F\in\pi^{\mathcal{F}}}(\phi_{F\cap\mathcal{G}} - \delta_{F\cap\mathcal{G}})\big)$, the core may contain Blocking-Threat Outcomes.*

Proof of Lemma EC.14. Consider first an example with $\mathcal{L} = \{\ell, g, h\}$ and full ability to cooperate $(\pi^{\mathcal{F}} = \{\mathcal{L}\})$ so that:

$$\phi_g > \delta_g,\ \phi_\ell < \delta_\ell,\ \phi_h < \delta_h,\ \phi_{\mathcal{L}} > \delta_{\mathcal{L}}. \tag{EC.19}$$

We show that the core $C(\mathcal{L};\emptyset)$ contains outcomes with $\pi_{\mathcal{L}} = \{\{\mathcal{L}\}\}$, $d^* = 0$, and $\{a_i\}_{i\in\mathcal{L}}$ satisfying:

$$a_h = J_h(1,\mathrm{no}) - c_h + \epsilon \tag{EC.20a}$$

$$a_g = J_g(0,\mathrm{yes}) - (a_\ell - J_\ell(0,\mathrm{yes})) - (a_h - J_h(0,\mathrm{yes})) \geq J_g(1,\mathrm{no}) - c_g + \epsilon \tag{EC.20b}$$

$$a_\ell = J_\ell(1,\mathrm{no}) - c_\ell - \epsilon \tag{EC.20c}$$

$$a_\ell \geq J_\ell(0,\mathrm{yes}). \tag{EC.20d}$$

for some $\epsilon > 0$. Note first that an outcome satisfying (EC.20a)-(EC.20d) is feasible due to (EC.19). We prove that it belongs to the core by checking that it is not dominated, i.e., no subset $S \subseteq \mathcal{L}$ could profitably deviate.

The conditions in the Lemma imply that η satisfies:

$$\overline{\eta}_2^{\mathrm{TU}} = \frac{\phi_g - \delta_g}{2} < \eta < \eta_3^{\mathrm{TU}} = (\phi_{\mathcal{G}} - \delta_{\mathcal{G}}) = (\phi_g - \delta_g). \tag{EC.21}$$

The locals in $\{h,\ell\}$ would not deviate together, because

$$a_h + a_\ell = J_h(1,\mathrm{no}) - c_h + J_\ell(1,\mathrm{no}) - c_\ell \geq w(\{h,f\},d^*), \forall d^* \in \{0,1\},$$

where the inequality follows because $\ell, h \in \mathcal{L}\setminus\mathcal{G}$.

Neither h nor ℓ could profitably deviate as singletons. Local h would not deviate due to (EC.20a), which implies that $a_\ell > w(\{\{h\},\pi_{\mathcal{L}\setminus\{h\}}\};d^*), \forall \pi_{\mathcal{L}\setminus\{h\}} \in \Pi_{\mathcal{L}\setminus\{h\}}, \forall d^* \in \{0,1\}$. To verify this for ℓ, we show that there is a No-Deforestation Outcome in $C(\{h,g\};\{\{\ell\}\})$, which by (EC.20d) implies that ℓ would not deviate under pessimism. To that end, we claim that the residual outcome $\pi_{\{h,g\}} = \{\{h\},\{g\}\}$, $d^* = 0$, and $a_i = J_i(0,\mathrm{yes})$, for $i \in \mathcal{L}$ is an outcome of the residual game played by $\{g,h\}$ when ℓ deviates. $\eta < (\phi_{\mathcal{G}} - \delta_{\mathcal{G}})$ implies that $\eta < \eta_2\big(\{\{h\},\{g\},\{\ell\}\}\big)$, and therefore Lemma 2 implies that $0 \in T(\{\{h\},\{g\},\{\ell\}\})$. Thus $0 \in A(\{h,g\};\{\{\ell\}\})$, so neither g nor h could profitably deviate from the residual outcome under pessimism, which in turn proves that ℓ would not deviate under pessimism from the outcome (EC.20a)-(EC.20d).

Lastly, to see that local g would not unilaterally deviate or form a coalition with ℓ or h to deviate, consider any $S \subset \mathcal{L}$ with $g \in S$. Because $\eta > \max_{S \subset \mathcal{L}} \frac{(\phi_S - \delta_S)}{|\mathcal{L} \setminus S|}$ implies that $\eta > \eta_1(\{\mathcal{L} \setminus S, S\})$ in this case, Lemma 2 implies that $1 \in A(\mathcal{L} \setminus S; \{S\})$. But then, because any such S satisfies

$$\sum_{i \in S} a_i \geq \sum_{i \in S} \big(J_i(1, \text{no}) - c_i\big)$$

from (EC.20a)-(EC.20c), the coalition S would not strictly benefit from deviating under pessimism.

To conclude the proof, consider the instance with partial ability to cooperate as above but with one additional local, $\mathcal{L} = \{\ell, g, f, e\}$, $\pi^{\mathcal{F}} = \{\{\ell, g, f\}, \{e\}\}$, and $\phi_e < \delta_e$. We claim that the outcome with partition $\pi = \{\{\ell, g, f\}, \{e\}\}$ and allocations satisfying (EC.20a)-(EC.20c), and $a_e = J_e * (0, Y)$ is in the core $C(\mathcal{L}; \emptyset)$ provided that $\overline{\eta}_2^{\text{TU}} < \eta < \eta_2^{\text{TU}} = (\phi_g - \delta_g)$. The requirement $\eta < (\phi_g - \delta_g)$ implies $\eta < \eta_2(\{\{h\}, \{g\}, \{\ell\}, \{e\}\})$, which, as shown above, implies that e would not deviate, as $0 \in A(\{\ell, g, h\}; \{\{e\}\})$. The rest of the proof proceeds exactly as above to show that this Blocking-Threat Outcome is in the core. □

LEMMA EC.15. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F > \delta_F$ *for some* $F \in \pi^{\mathcal{F}}$, $\underline{\eta}_2^{\text{TU}} < \eta_1^{\text{TU}} < \overline{\eta}_2^{\text{TU}}$, *and* $\eta \in (\eta_1^{\text{TU}}, \overline{\eta}_2^{\text{TU}})$, *where* $\eta_1^{\text{TU}} := \min_{S \subseteq F, F \in \pi^{\mathcal{F}} : \phi_S < \delta_S} \sup \left\{ \eta : \sum_{H \in \pi^{\mathcal{F}} : \phi_{H \setminus S} > \delta_{H \setminus S}} \left\lfloor \frac{\phi_{H \setminus S} - \delta_{H \setminus S}}{\eta} \right\rfloor > |S| \right\}$, $\underline{\eta}_2^{\text{TU}} := \max_{F, S : F \in \pi^{\mathcal{F}}, S \subseteq F, \phi_F > \delta_F, S \neq \mathcal{L}} \frac{(\phi_S - \delta_S)}{|\mathcal{L} \setminus S|}$, *and* $\overline{\eta}_2^{\text{TU}} := \max_{F, S : F \in \pi^{\mathcal{F}}, S \subseteq F, S \neq \mathcal{L}} \frac{(\phi_S - \delta_S)}{|\mathcal{L} \setminus S|}$, *then the core may contain Blocking-Threat Outcomes.*

Proof of Lemma EC.15. We will show that, for every $\epsilon > 0$, the following instance always contains a Blocking-Threat Outcome in the core. Consider $\mathcal{L} = \{\ell, h, g_1, e_1, e_2, e_3, g_2\}$, $\pi^{\mathcal{F}} = \{\{\ell, h\}, \{g_1, e_1, e_2, e_3\}, \{g_2\}\}$, such that

$$\phi_{g_1} = \phi_{g_2} > \delta_{g_1} = \delta_{g_2}, \quad \phi_{e_i} - \delta_{e_i} = -\epsilon/3, \text{ for every } i \in \{1, 2, 3\},$$
$$\phi_{g_1} - \delta_{g_1} = (\phi_h - \delta_h)/6, \quad \phi_{\{\ell, h\}} < \delta_{\{\ell, h\}}, \quad \phi_{\{g_1, e_1, e_2, e_3\}} > \delta_{\{g_1, e_1, e_2, e_3\}}.$$

Note first that $\underline{\eta}_2^{\text{TU}} = (\phi_{g_1} - \delta_{g_1} - \epsilon)/3$, $\overline{\eta}_2^{\text{TU}} = (\phi_h - \delta_h)/6 = \phi_{g_1} - \delta_{g_1}$, $\eta_1^{\text{TU}} = (\phi_{g_1} - \delta_{g_1})/2$ (obtained by taking $S = \{e_1, e_2, e_3\}$), and $\underline{\eta}_2^{\text{TU}} < \eta_1^{\text{TU}} < \overline{\eta}_2^{\text{TU}}$. We will show then that for any $\eta \in ((\phi_{g_1} - \delta_{g_1})/2, \phi_{g_1} - \delta_{g_1} - \epsilon] = (\eta_1^{\text{TU}}, \overline{\eta}_2^{\text{TU}} - \epsilon]$, this core contains the following Blocking Threat Outcome:

$$\pi = \{\{\ell\}, \{h\}, \{g_1, e_1, e_2, e_3\}, \{g_2\}\}, d = 0,$$
$$a_{e_i} = J_{e_i}(1, \text{no}) - c_{e_i}, \text{ for every } i \in \{1, 2, 3\},$$
$$a_{g_1} = J_{g_1}(0, \text{yes}) - \sum_{i=1}^{3} (J_{e_i}(1, \text{no}) - c_{e_i} - J_{e_i}(0, \text{yes}) > J_{g_1}(1, \text{no}) - c_{g_1}.$$

To see this, we will show that there can be no coalition S that would deviate.

First, we show that S cannot be formed by only one local. Neither h, nor g_2 would deviate and form coalitions $S=\{h\}$, or $S=\{g_2\}$, because $a_h = w(\{h\},0) > w(\{h\},1)$ and $a_{g_2} = w(\{g_2\},0) > w(\{g_2\},1)$. Similarly, no e_i would deviate by themselves, because $a_{e_i} = w(\{e_i\},1) > w(\{e_i\},0)$, for every $i\in\{1,2,3\}$. Local ℓ would not deviate and form coalition $S=\{\ell\}$, because $\eta<(\phi_{g_1}-\delta_{g_1}-\epsilon)<(\phi_h-\delta_h)/6<\eta_1(\{\{\ell\},\{h\},\}\cup\pi'_{\mathcal{L}\setminus\{\ell,h\}})$, for every partition $\pi'_{\mathcal{L}\setminus\{\ell,h\}}\prec\pi^{\mathcal{F}}$. But then, by Lemma 2, $0\in A(\mathcal{L}\setminus\{\ell\};\{\{\ell\}\})$, and because $a_\ell = w(\{\ell\},0)$, under pessimism, ℓ would not deviate. To see that g_1 would not deviate and form coalition $S=\{g_1\}$, notice that $1\in A(\mathcal{L}\setminus;\{\{g_1\}\})$. This is because $\eta>\eta_1^{\mathrm{TU}}$ implies that the following residual Deforestation Outcome is in the residual core $(\pi'_{\mathcal{L}\setminus\{g_1\}}=\{\{\ell,h\},\{e_1,e_2,e_3\},\{g_2\}\}, d=1, a'_h=J_h(0,\text{yes}))\in C(\mathcal{L}\setminus\{g_1\};\{\{g_1\}\}$. The only potential deviations from this residual outcome would be $\{g_2\}$ or $\{h\}$, but $a'_h=w(\{h\};0)>w(\{h\};1)$, and $\eta>\eta_1^{\mathrm{TU}}=\eta_2(\{g_1\}\cup\pi_{\mathcal{L}\setminus\{g_1\}})$ implies that g_2 would not deviate because they would not be able to block $\{e_1,e_2,e_3\}$. But then, $1\in A(\mathcal{L}\setminus;\{\{g_1\}\})$, and because $a_{g_1}>w(\{g_1\};1)$, $S=\{g_1\}$ would not deviate.

Now we show that S cannot be formed by two locals. Locals ℓ and h would not deviate and form $S=\{\ell,h\}$, $\pi_S=S$, because $\eta\le\overline{\eta}_2^{\mathrm{TU}}-\epsilon=\phi_{g_1}-\delta_{g_1}-\epsilon=\eta_2(\{\{\ell,h\},\{g_1,e_1,e_2,e_3\},\{g_2\}\})$ implies that $0\in A(\mathcal{L}\setminus\{\ell,h\})$. To see this, notice that the following residual No Deforestation Outcome is in the residual core, $(\pi'_{\mathcal{L}\setminus\{\ell,h\}}=\{g_1,e_1,e_2,e_3\},\{g_2\},a'_{e_i}=a_{e_i},a'_{g_1}=a_{g_1},d=0)\in C(\mathcal{L}\setminus\{\ell,h\};\{\{\ell,h\}\})$. No deviation from this residual core is possible because g_1 would not deviate (for the same argument as above) and all other locals prefer their allocation to any other, and $\eta<\eta_2(\{\{\ell,h\},\{g_1,e_1,e_2,e_3\},\{g_2\}\})$ implies by Lemma 2 that $0\in T(\{\{\ell,h\},\{g_1,e_1,e_2,e_3\},\{g_2\}\})$. The case where $S=\{\ell,h\}$ and $\pi_S=\{\{\ell\},\{h\}\}$ is covered by the same arguments that prevent $\{h\}$ and $\{\ell\}$ from deviating.

Locals g_1 and e_1, would not deviate and form $S=\{g_1,e_1\}$, $\pi_S=\{S\}$, because $\eta>\eta_1^{\mathrm{TU}}\ge\eta_1(\{\{g_1,e_1\},\{\ell,h\},\{e_2,e_3\},\{g_2\}\})$ implies that $1\in A(\mathcal{L}\setminus\{g_1,e_1\};\{\{g_1,e_1\}\})$, and $a_{g_1}+a_{e_1}>w(\{g_1,e_1\};1)$. To see that $1\in A(\mathcal{L}\setminus\{g_1,e_1\};\{\{g_1,e_1\}\})$, notice that the following residual Deforestation Outcome is in the residual core, $(\pi'_{\mathcal{L}\setminus\{g_1,e_1\}}=\{\{g_1,e_1\},\{\ell,h\},\{e_2,e_3\},\{g_2\}\},a'_h=J_h(0,\text{yes}),d=1)\in C(\mathcal{L}\setminus\{g_1,e_2\};\{\{g_1,e_1\}\})$. As above, g_2 cannot deviate from this residual outcome because $\eta>(\phi_{g_2}-\phi_{g_2})/2$ implies that g_2 and $\{g_1,e_1\}$ would not be able to block the coalitions of two locals $\{e_2,e_3\}$ or $\{\ell,h\}$. Neither e_2, e_3, nor h would deviate because they already have their maximum possible allocation allocated. Local ℓ would not deviate because $a'_\ell>w(\{\ell\};0)$, and it is easy to see that because $\eta<(\phi_h-\delta_h)/6$, then would ℓ deviate from this residual outcome, h could block all other locals and enforce a No-Deforestation residual Outcome. Therefore, because Lemma 2 implies $1\in T(\pi'_{\mathcal{L}\setminus\{g_1,e_1\}}\cup\{\{g_1,e_1\}\})$, we have that $1\in A(\mathcal{L}\setminus\{g_1,e_1\};\{\{g_1,e_1\}\})$. By symmetry of the e_is, g_1 and e_i would not deviate and form partition $\pi_S=\{S\}$ for every $i\in\{1,2,3\}$. Moreover, partitions $\pi_S=\{\{g_1\},\{e_i\}\}$ are prevented by the same arguments used above for $S=\{e_i\}$.

A similar argument can be used to show that $S=\{g_1,e_1,e_2\}$ would not deviate, because $\eta > \eta_1^{\text{TU}} \geq \eta_1(\{\{g_1,e_1,e_2\},\{\ell,h\},\{e_3\},\{g_2\}\})$ implies $1 \in A(\mathcal{L} \setminus \{g_1,e_1,e_2\};\{\{g_1,e_1,e_2\}\})$. So, $S=\{g_1,e_1,e_2\}$ would not deviate, and by symmetry, no $S=\{g_1,e_i,e_j\}$ with $i \neq j \in \{1,2,3\}$, would deviate.

Any $S \subseteq \{e_1,e_2,e_3\}$ would not deviate because $a_S = w(S;1) > w(S;0)$, and $S=\{g_1,e_1,e_2,e_3\}$ would not deviate and form partition $\pi_S=\{S\}$, because $a_S = w(S;0) > w(S;1)$. Notice that any other partition π_S for $S=\{g_1,e_1,e_2,e_3\}$ would imply an $S_i \in \pi_S$ covered in a previous case.

Therefore, there is no coalition S that would deviate, and the Blocking-Threat Outcome is in the core. Because this holds for any $\epsilon > 0$, we have shown that for any $\eta_1^{\text{TU}} < \eta < \overline{\eta}_2^{\text{TU}}$, the result holds. □

Lemma EC.16. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F > \delta_F$*, for every* $F \in \pi^{\mathcal{F}}$*,* $\eta > \overline{\eta}_2^{\text{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}},S\subset F,S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$*, then the core contains the set of Compensation Outcomes.*

Proof of Lemma EC.16. Consider a Compensation Outcome with partition $\pi=\pi^{\mathcal{F}}$ and allocation

$$a_\ell \geq J_\ell(1,\text{no}) - c_\ell, \text{ for all } \ell \in \mathcal{L}.$$

Using Lemma EC.8, we will show that this outcome is in the core, and by Lemma EC.6 all Compensation Outcomes must be in the core as well. Note that $\eta < \eta_2(\pi^{\mathcal{F}}) = \infty$, which by Lemma 2 implies that $0 \in T(\pi^{\mathcal{F}})$. We proceed then to show that this outcome is undominated.

First, note that no family $F \in \pi^{\mathcal{F}}$ would profitably deviate from any No-Deforestation Outcome (and thus also from a Compensation Outcome) when $\phi_F > \delta_F$, because any No-Deforestation Outcome already provides the largest possible welfare for F, that is, $\sum_{\ell\in F} J_\ell(0,\text{yes})$.

Now, consider any coalition $S \subset \mathcal{L}$ that forms partition $\pi_S \in \Pi_S$. We show that this configuration cannot dominate the Compensation Outcome. For any such coalition S, we have $|\mathcal{L}\setminus S| \in [1, |\mathcal{L}|-1]$, and by Lemma EC.8, we have $1 \in A(\mathcal{L}\setminus S;\pi_S)$. Hence, for any (sub)coalition $S_i \in \pi_S$,

$$\min_{d^*\in A(\mathcal{L}\setminus S;\pi_S)} w(S_i;d^*) \leq w(S_i;1) = \sum_{\ell\in S}\big(J_\ell(1,\text{no}) - c_\ell\big) \leq \sum_{\ell\in S} a_\ell.$$

Therefore, the coalition S with partition π_S cannot derive strictly larger welfare under pessimism, proving that the Compensation Outcome is un-dominated and must belong to the core. □

Lemma EC.17. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F < \delta_F$ *for some* $F \in \pi^{\mathcal{F}}$*, the core does not contain Compensation Outcomes.*

Proof of Lemma EC.17. The proof is immediate from the definition of a compensation outcome. If $\phi_F < \delta_F$, then, by definition, in any No-Deforestation Outcome, $\sum_{\ell\in F} a_\ell = \sum_{\ell\in F} J_\ell(0,\text{yes}) < \sum_{\ell\in F} J_\ell(1,\text{no}) - c_\ell$, where the last inequality comes from $\phi_F < \delta_F$ and implies that the core cannot contain a Compensation Outcome. □

Lemma EC.18. *Consider the area no-use condition $\bar{\mathbb{U}}$ in the cooperative game with transferable utility defined in §3.2. If $\eta > \eta_3^{\mathrm{TU}} = \max_{F\in\pi^{\mathcal{F}}} \phi_{F\cap\mathcal{G}} - \delta_{F\cap\mathcal{G}}$, then any No-Deforestation Outcome in the core must be a Compensation Outcome.*

Proof of Lemma EC.18. Assume by contradiction that there is a No-Deforestation Outcome in the core such that $a_\ell < J_\ell(1,\mathrm{no}) - c_\ell$, for some $\ell \in \mathcal{L}\setminus\mathcal{G}$. Then, ℓ can deviate towards a deforestation equilibrium all by himself. This is because, for any partition of the remaining locals $\pi_{\mathcal{L}\setminus\{\ell\}} \prec \pi^{\mathcal{F}}$,

$$\eta_2(\pi_{\mathcal{L}\setminus\{\ell\}} \cup \{\{\ell\}\}) \leq \max_{F\in\pi^{\mathcal{F}}} \phi_{F\cap\mathcal{G}} - \delta_{F\cap\mathcal{G}} < \eta,$$

which, by Lemma 2, implies that $\{1\} = T(\pi_{\mathcal{L}\setminus\{\ell\}} \cup \{\{\ell\}\})$ and thus $\{1\} = A(\mathcal{L}\setminus\{\ell\}; \{\{\ell\}\})$ and

$$w(\{\ell\}; d^*) > a_\ell, \text{ for every } d^* \in A(\mathcal{L}\setminus\{\ell\}; \{\{\ell\}\}).$$

This proves that $\{\ell\}$ can deviate and improve his allocation, and therefore, every $\ell \in \mathcal{L}\setminus\mathcal{G}$ must have an allocation that satisfies

$$a_\ell \geq J_\ell(1,\mathrm{no}) - c_\ell. \qquad \square$$

Lemma EC.19. *Consider the area no-use condition $\bar{\mathbb{U}}$ in the cooperative game with transferable utility defined in §3.2. If $\phi_F > \delta_F$, for every $F\in\pi^{\mathcal{F}}$ and $\eta < \overline{\eta}_2^{\mathrm{TU}} = \max_{F,S:F\in\pi^{\mathcal{F}},S\subset F,S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$, then the core contains no Compensation Outcomes.*

Proof of Lemma EC.19. Assume by contradiction that there is a Compensation Outcome in the core. The allocations $\{a\}_{\ell\in\mathcal{L}}$ should then satisfy $a_\ell \geq J_\ell(1,\mathrm{no}) - c_\ell$, for all $\ell\in\mathcal{L}\setminus\mathcal{G}$. We prove that this outcome is dominated.

First, note that $\eta < \max_{F,S:F\in\pi^{\mathcal{F}},S\subset F,S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$ implies that there exists $F\in\pi^{\mathcal{F}}$ and $S\subset F$ such that

$$(\phi_S - \delta_S) > \eta|\mathcal{L}\setminus S|. \tag{EC.22}$$

Without loss of generality, we can assume $F\cap\mathcal{G}\subseteq S$, and therefore $F\setminus S\subseteq\mathcal{L}\setminus\mathcal{G}$. We will show that S can deviate from the Compensation Outcome.

For any partition $\pi_{\mathcal{L}\setminus S}\in\Pi_{\mathcal{L}\setminus S}$, with $\pi_{\mathcal{L}\setminus S}\prec\pi^{\mathcal{F}}$, equation (EC.22) implies that $\eta\leq\eta_1(\{S\}\cup\pi_{\mathcal{L}\setminus S})$, which by Lemma 2 implies that $T(\{S\}\cup\pi_{\mathcal{L}\setminus S}) = \{0\}$. Because this holds for every partition $\pi_{\mathcal{L}\setminus S}$, then $A(\mathcal{L}\setminus S;\{S\}) = \{0\}$.

Because the Compensation Outcome is a No-Deforestation Outcome, we know that

$$\sum_{\ell\in S} a_\ell + \sum_{\ell\in F\setminus S} a_\ell = w(F;0).$$

But then,

$$\begin{aligned}\sum_{\ell\in S} a_\ell &= w(F;0) - \sum_{\ell\in F\setminus S} a_\ell \\ &\le w(F;0) - \sum_{\ell\in F\setminus S}\big(J_\ell(1,\text{no}) - c_\ell\big) \\ &= w(S;0) + (\phi_{F\setminus S} - \delta_{F\setminus S}) \\ &< w(S;0),\end{aligned}$$

where the first inequality comes from the outcome being a Compensation Outcome, and the second (strict) inequality comes from $F \setminus S \subseteq \mathcal{L} \setminus \mathcal{G}$, which implies that $(\phi_{F\setminus S} - \delta_{F\setminus S}) < 0$. But then, we have shown that $\sum_{\ell\in S} a_\ell < w(S;d^*)$, for every $d^* \in A(\mathcal{L}\setminus S;\{S\})$, which completes the proof that the Compensation Outcome is dominated. □

LEMMA EC.20. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. If* $\phi_F > \delta_F$ *for some* $F \in \pi^{\mathcal{F}}$ *and* $\eta \in (\eta_1^{\text{TU}}, \underline{\eta}_2^{\text{TU}})$*, where* $\eta_1^{\text{TU}} := \min_{S\subseteq F, F\in\pi^{\mathcal{F}}:\phi_S<\delta_S} \sup\left\{\eta : \sum_{H\in\pi^{\mathcal{F}}:\phi_{H\setminus S}>\delta_{H\setminus S}} \left\lfloor \frac{\phi_{H\setminus S}-\delta_{H\setminus S}}{\eta}\right\rfloor > |S|\right\}$ *and* $\underline{\eta}_2^{\text{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}},S\subseteq F,\phi_F>\delta_F,S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$*, then the core may be empty.*

Proof of Lemma EC.20. Consider the following example with partial ability to cooperate $\mathcal{L} = \{\ell, g, h, e\}$, $\pi^{\mathcal{F}} = \{\{\ell, g, h\}, \{e\}\}$, and:

$$\phi_\ell - \delta_\ell = \phi_g - \delta_g > 0, \quad \phi_h < \delta_h, \quad \phi_e - \delta_e < \frac{\phi_g - \delta_g}{2}, \quad \phi_{\mathcal{L}} > \delta_{\mathcal{L}}, \tag{EC.23a}$$

$$(\phi_h - \delta_h) + (\phi_g - \delta_g) < 0, \quad (\phi_h - \delta_h) + \phi_\ell < \delta_\ell. \tag{EC.23b}$$

Finally, consider η such that:

$$\eta_1^{\text{TU}} = \frac{(\phi_\ell - \delta_\ell)}{2} = \frac{(\phi_g - \delta_g)}{2} < \eta < \underline{\eta}_2^{\text{TU}} = \frac{(\phi_\ell - \delta_\ell) + (\phi_g - \delta_g)}{2} = (\phi_\ell - \delta_\ell) = (\phi_g - \delta_g). \tag{EC.24}$$

Let us assume by contradiction that there is an outcome in $C(\mathcal{L};\emptyset)$, with allocations $\{a_\ell, a_g, a_h, a_e\}$. We show that these allocations would have to satisfy the following infeasible system of inequalities:

$$a_\ell + a_g + a_h = J_\ell(0,\text{yes}) + J_g(0,\text{yes}) + J_h(0,\text{yes}) \tag{EC.25a}$$

$$a_\ell + a_g \ge J_\ell(0,\text{yes}) + J_g(0,\text{yes}) \tag{EC.25b}$$

$$a_h \ge J_h(0,\text{yes}) \tag{EC.25c}$$

$$a_\ell + a_h \ge J_\ell(1,\text{no}) - c_\ell + J_h(1,\text{no}) - c_h \tag{EC.25d}$$

$$a_g + a_h \ge J_g(1,\text{no}) - c_g + J_h(1,\text{no}) - c_h. \tag{EC.25e}$$

First, we show that the above system is indeed infeasible. For this, note that (EC.25a)-(EC.25c) imply that $a_h = J_h(0, \text{yes})$. This, together with (EC.25d)-(EC.25e) and (EC.23b), implies that $a_\ell > J_\ell(0, \text{yes})$ and $a_g > J_g(0, \text{yes})$. So we get $a_\ell > J_\ell(0, \text{yes})$, $a_g > J_g(0, \text{yes})$, and $a_h = J_h(0, \text{yes})$, contradicting (EC.25a).

The equality in (EC.25a) comes from Lemma EC.5, which applies because $\eta < \underline{\eta}_2^{\text{TU}}$, and states that all outcomes in the core should be No-Deforestation Outcomes. Thus, the sum of all allocations should be equal to $w(\mathcal{L}, 0) = J_\ell(0, \text{yes}) + J_g(0, \text{yes}) + J_h(0, \text{yes})$.

Inequality (EC.25b) comes from the plausible deviation of ℓ and g, where they cooperate to block any production by h or e (note that the only feasible partition $\pi_{\{e,h\}} \prec \pi^{\mathcal{F}}$ is $\pi_{\{e,h\}} = \{\{h\}, \{e\}\}$). This applies because in our case

$$\eta_1(\{\{\ell, g\}, \{h\}, \{e\}\}) = (\phi_g - \delta_g), \tag{EC.26}$$

which together with (EC.24) implies that $\eta < \eta_1(\{\{\ell, g\}, \{h\}, \{e\}\})$, which by Lemma 2 implies that $T(\{\{h\}, \{\ell, g\}, \{e\}\}) = A(\{h, e\}; \{\{\ell, g\}\}) = \{0\}$. This in turn implies that if ℓ and g were to form the coalition $\{\ell, g\}$, they could block h and e and ensure a No-Deforestation Outcome where they would get welfare $J_\ell(0, \text{yes}) + J_g(0, \text{yes})$, so $a_\ell + a_g$ must satisfy (EC.25b).

The inequality (EC.25c) comes from Lemma EC.3 and $h \in \mathcal{L} \setminus \mathcal{G}$.

The two inequalities (EC.25d)-(EC.25e) come from two plausible deviations of $\{\ell, h\}$ and $\{g, h\}$, respectively. Because ℓ and g are symmetric in our example, we show this for $\{\ell, h\}$. Note that the only feasible partition of $\{g, e\}$ is $\{\{g\}, \{e\}\} \prec \pi^{\mathcal{F}}$. We have that

$$\eta_2\big(\{\{g\}, \{\ell, h\}, \{e\}\}\big) = \frac{(\phi_g - \delta_g)}{2}, \tag{EC.27}$$

which together with (EC.24) implies that $\eta > \eta_2(\{\{g\}, \{\ell, h\}, \{e\}\})$, which by Lemma 2 implies that $\{1\} = T(\{\{g\}, \{\ell, h\}, \{e\}\}) = A(\{g, e\}; \{\{\ell, h\}\})$, which implies that $\{\ell, h\}$ could deviate to a Deforestation Outcome. A symmetric argument for $\{g, h\}$ implies that any outcome in the core $C(\mathcal{L}; \emptyset)$ must satisfy (EC.25d)-(EC.25e), which proves the lemma for the case when locals have partial ability cooperate.

Finally, we note that the same instance but with full ability to cooperate and $\mathcal{L} = \{\ell, g, h\}$ would also lead to an empty core, as long as η satisfies:

$$\eta_1^{\text{TU}} = \min_{S \subseteq \mathcal{L}, \phi_S < \delta_S} \frac{(\phi_{\mathcal{L}\setminus S} - \delta_{\mathcal{L}\setminus S})}{|S|} = \frac{(\phi_\ell - \delta_\ell)}{2} = \frac{(\phi_g - \delta_g)}{2} < \eta < (\phi_{\mathcal{G}} - \delta_{\mathcal{G}}) = 2(\phi_\ell - \delta_\ell) = 2(\phi_g - \delta_g) = \underline{\eta}_2^{\text{TU}}.$$

The proof is identical to the one above, except that $\eta_1(\{\{\ell, g\}, \{h\}\})$ takes value $(\phi_{\mathcal{G}} - \delta_{\mathcal{G}})$ in (EC.26). $\square$

Lemma EC.21. *Consider the area no-use condition $\bar{\mathbb{U}}$ in the cooperative game with transferable utility in §3.2. If $\phi_F > \delta_F$ for some $F \in \pi^{\mathcal{F}}$, $\underline{\eta}_2^{\mathrm{TU}} \le \eta_1^{\mathrm{TU}} < \overline{\eta}_2^{\mathrm{TU}}$, and $\eta \in (\eta_1^{\mathrm{TU}}, \overline{\eta}_2^{\mathrm{TU}})$, where*

$$\eta_1^{\mathrm{TU}} := \min_{S\subseteq F, F\in\pi^{\mathcal{F}}:\phi_S<\delta_S} \sup\left\{\eta : \sum_{H\in\pi^{\mathcal{F}}:\phi_{H\setminus S}>\delta_{H\setminus S}} \left\lfloor \frac{\phi_{H\setminus S}-\delta_{H\setminus S}}{\eta}\right\rfloor > |S|\right\}$$

$$\underline{\eta}_2^{\mathrm{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}}, S\subseteq F, \phi_F>\delta_F, S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|},$$

$$\overline{\eta}_2^{\mathrm{TU}} := \max_{F,S:F\in\pi^{\mathcal{F}}, S\subseteq F, S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|},$$

then the core may be empty.

Proof of Lemma EC.21. If $\underline{\eta}_2^{\mathrm{TU}} \le \eta_1^{\mathrm{TU}} < \overline{\eta}_2^{\mathrm{TU}}$, then, locals must have partial ability to cooperate. Consider the following example, with $\mathcal{L} = \{\ell, h, g, e\}$, $\pi^{\mathcal{F}} = \{\{\ell, g, h\}, \{e\}\}$,

$$\phi_{\ell,g,h} < \delta_{\ell,g,h},\ \phi_e > \delta_e,\ \phi_g = \phi_h > \delta_g = \delta_h,\ \phi_g - \delta_g > \phi_e - \delta_e \tag{EC.28a}$$

$$\underline{\eta}_2^{\mathrm{TU}} = (\phi_e - \delta_e)/3 = \eta_1^{\mathrm{TU}} < \phi_e - \delta_e < \eta < \overline{\eta}_2^{\mathrm{TU}} = \phi_g - \delta_g. \tag{EC.28b}$$

We will show that the core is empty, $C(\mathcal{L};\emptyset) = \emptyset$. Assume by contradiction that there an outcome in $C(\mathcal{L};\emptyset)$, with allocation $\{a_\ell, a_g, a_h, a_e\}$. We show that these allocations would have to satisfy the following infeasible system:

$$a_\ell + a_g + a_h = J_\ell(1,\mathrm{no}) - c_\ell + J_g(1,\mathrm{no}) - c_g + J_h(1,\mathrm{no}) - c_h \tag{EC.29a}$$

$$a_g + a_h \ge J_g(0,\mathrm{yes}) + J_h(0,\mathrm{yes}) > J_g(1,\mathrm{no}) - c_g + J_h(1,\mathrm{no}) - c_h \tag{EC.29b}$$

$$a_\ell + a_g \ge J_\ell(1,\mathrm{no}) - c_\ell + J_g(1,\mathrm{no}) - c_g \tag{EC.29c}$$

$$a_\ell + a_h \ge J_\ell(1,\mathrm{no}) - c_\ell + J_h(1,\mathrm{no}) - c_h. \tag{EC.29d}$$

First, we show that the system is infeasible. For this, note that summing (EC.29b)-(EC.29d) we have that $2(a_\ell + a_g + a_h) > 2(J_\ell(1,\mathrm{no}) - c_\ell + J_g(1,\mathrm{no}) - c_g + J_h(1,\mathrm{no}) - c_h)$, which contradicts (EC.29a).

Equation (EC.29a) must hold, because otherwise $\{\ell, g, h\}$ could deviate and form partition $\{\{\ell, g, h\}\}$. Note that $\eta > (\phi_e - \delta_e)/3 = \eta_2(\{\{\ell, g, h\}, \{e\}\})$, Lemma 2 implies that $\{1\} = A(\{e\}; \{\{\ell, g, h\}\})$. Hence, $\{\ell, g, h\}$ could profitability deviate from any No Deforestation Outcome, and (EC.29a) must hold.

The first inequality in (EC.29b) holds because otherwise $\{g, h\}$ could deviate from any Deforestation Outcome and form coalition $\{\{g, h\}\}$. Note that $\eta < \overline{\eta}_2^{\mathrm{TU}} = \phi_g - \delta_g = \eta_1(\{\{\ell\}, \{g, h\}, \{e\}\})$, implies that $\{0\} = A(\{\ell, e\}; \{\{g, h\}\})$, by Lemma 2. The second inequality in (EC.29b) holds because $\phi_{g,h} > \delta_{g,h}$.

Both (EC.29c) and (EC.29d), hold because otherwise $\{\ell, g\}$ and $\{\ell, h\}$ could deviate. Notice that $\eta > \phi_e - \delta_e = \eta_2(\{\{g\}, \{\ell, h\}, \{e\}\}) = \eta_2(\{\{h\}, \{\ell, g\}, \{e\}\})$, which implies by Lemma 2 that

$\{1\} = A(\{g,e\};\{\ell,h\}) = A(\{h,e\};\{\ell,g\})$. Which proves that the infeasible system must hold in any Outcome in the core. □

LEMMA EC.22. *Consider the area no-use condition* $\bar{\mathbb{U}}$ *in the cooperative game with transferable utility defined in §3.2. The core may be empty if* $\phi_F < \delta_F$*, for every* $F \in \pi^{\mathcal{F}}$.

Proof of Lemma EC.22. Consider an example with three locals $\mathcal{L} = \{\ell, g, h\}$ and full ability to cooperate ($\pi^{\mathcal{F}} = \{\mathcal{L}\}$) in which exactly one local g prefers the incentive ($\mathcal{G} = \{g\}$), the other two locals prefer deforestation to the extent that:

$$(\phi_g - \delta_g) + (\phi_\ell - \delta_\ell) < 0, \; (\phi_g - \delta_g) + (\phi_h - \delta_h) < 0, \tag{EC.30}$$

and the cost of blocking is sufficiently low that

$$\eta < (\phi_g - \delta_g)/2. \tag{EC.31}$$

The core cannot contain an outcome with a partition in which the local g forms a singleton coalition because (EC.31) and Lemma 2 imply that for any partition of the other two locals $\pi_{\{\ell,h\}} \in \Pi_{\{\ell,h\}}$, $T(\{\{g\}\} \cup \pi_{\{\ell,h\}}) = \{0\}$, so any such outcome must have an allocation that satisfies

$$\sum_{\ell \in \mathcal{L}} a_\ell = \sum_{\ell \in \mathcal{L}} J_\ell(A_\ell, 0, \text{yes}),$$

and would therefore be dominated by the formation of the grand coalition $\{\mathcal{L}\}$. Observe that (EC.30) implies $T(\{\mathcal{L}\}) = \{1\}$ which guarantees strictly higher aggregate welfare of $\sum_{\ell \in \mathcal{L}}(J_\ell(1, \text{no}) - c_\ell)$.

If a local $h \in \mathcal{L} \setminus \mathcal{G}$ forms a singleton coalition, we claim that the core $C(\mathcal{L} \setminus \{h\}; \{\{h\}\})$ for the residual game for locals $R = \mathcal{L} \setminus \{h\}$ is non-empty and contains all outcomes that satisfy

$$\pi_R = \{R\} \tag{EC.32}$$

$$d^* = 1 \tag{EC.33}$$

$$\sum_{\ell \in R} a_\ell = \sum_{\ell \in R} \big[J_\ell(1, \text{no}) - c_\ell\big] \tag{EC.34}$$

$$a_\ell \geq J_\ell(0, \text{yes}) \;\; \text{for all } \ell \in R. \tag{EC.35}$$

We distinguish two cases, depending on whether the outcomes in $C(R; \{\{h\}\})$ involve the grand coalition $\{R\}$ or the partition of singletons (this is exhaustive since $|R| = 2$). For any outcomes corresponding to the grand coalition $\{R\}$, Lemma 2, (EC.30) and $h \in \mathcal{L} \setminus \mathcal{G}$ imply that $T(\{\{R\}\} \cup \{\{h\}\}) = \{1\}$, and therefore (EC.33) and (EC.34) hold. These outcomes are undominated if and only if they satisfy (EC.35); this follows since the only possible deviations from R are by a (sub)coalition consisting of one local, leading to a game with singleton coalitions and $a_\ell = J_\ell(0, \text{yes})$ for all $\ell \in R$, due to (EC.31) and $g \in R$. Finally, (EC.30) also implies that the set of allocations satisfying (EC.34)-(EC.35) is non-empty. The argument above also shows that all the outcomes corresponding to the partition of singletons are dominated: these outcomes have $a_\ell = J_\ell(0, \text{yes})$ for all $\ell \in R$ and are dominated by outcomes that satisfy (EC.35) with a strict inequality for every $\ell \in R$, which exist in view of (EC.30).

Similar arguments to those above show that under partial ability to cooperate ($\pi^{\mathcal{F}} \neq \mathcal{L}$), the instance with $\mathcal{L} = \{\ell, g, h, e\}$, with $\pi^{\mathcal{F}} = \{\{\ell, g, h\}, \{e\}\}$, $\mathcal{G} = \{g\}$, $e \in \mathcal{L} \setminus \mathcal{G}$, $\eta < (\phi_g - \delta_g)/3$, and ℓ, g, h satisfying (EC.30), the core must be empty as well. □

EC.3.1. Proofs for the Results In §4

In this section, we maintain Assumption 2 (which implies $\phi_\ell \geq 0$ for every $\ell \in \mathcal{L}$), but we relax some of the other working assumptions in §2. Specifically, condition 4 is relaxed to allow for $\mathcal{G} = \mathcal{L}$. Additionally, when characterizing the idiosyncratic payments $\{\phi_\ell\}_{\ell \in \mathcal{L}}$ that minimize the total payment $\sum_{\ell \in \mathcal{L}} \phi_\ell$, i.e., minimize the cost of providing the incentive, we also relax the requirement that either $\phi_\ell > \delta_\ell$ or $\phi_\ell < \delta_\ell$ to allow for $\phi_\ell = \delta_\ell$ (to obtain closed sets and the existence of optimal solutions in the optimization problems). Lastly, in conjunction with allowing idiosyncratic payments for cost-minimization we also allow for idiosyncratic conditions, i.e., a hybrid of various forest protection conditions in the area.

Proposition 1. Consider the setting with coordination and utility transfer from §3.2, where locals have full ability to cooperate ($\pi^{\mathcal{F}} = \{\mathcal{L}\}$) and any incentive satisfying $\phi_\ell \geq 0$ for every $\ell \in \mathcal{L}$.

(i) The incentives that guarantee that the No-Deforestation condition $\bar{\mathbb{D}}$ *prevents deforestation* (and *achieves compensation*, respectively) are all the $\{\phi_\ell\}_{\ell \in \mathcal{L}}$ that satisfy:

$$\sum_{\ell \in \mathcal{L}} \phi_\ell > \sum_{\ell \in \mathcal{L}} \delta_\ell. \tag{EC.36}$$

(ii) The infimum total payment to *prevent deforestation with compensation* under the area no-deforestation condition $\bar{\mathbb{D}}$ is $\sum_{\ell \in \mathcal{L}} \delta_\ell$.

(iii) The incentives that guarantee that the No-Use condition $\bar{\mathbb{U}}$ *prevents deforestation* are all the $\{\phi_\ell\}_{\ell \in \mathcal{L}}$ that satisfy (EC.36).

(iv) The incentives that guarantee that the No-Use condition $\bar{\mathbb{U}}$ *prevents deforestation with compensation* are all the $\{\phi_\ell\}_{\ell \in \mathcal{L}}$ that satisfy:

$$\begin{cases} \sum_{\ell \in \mathcal{L}} \phi_\ell > \sum_{\ell \in \mathcal{L}} \delta_\ell \text{ and } \sum_{\ell \in \mathcal{G}} \phi_\ell < \eta + \sum_{\ell \in \mathcal{G}} \delta_\ell, \text{ where } \mathcal{G} = \{\ell \in \mathcal{L} : \phi_\ell > \delta_\ell\}, & \text{if } \exists \ell \in \mathcal{L} : \phi_\ell < \delta_\ell \\ \sum_{\ell \in \mathcal{L}} \phi_\ell > \sum_{\ell \in \mathcal{L}} \delta_\ell \text{ and } \phi_\ell > \delta_\ell \text{ for all } \ell \in \mathcal{L} & \text{otherwise.} \end{cases} \tag{EC.37}$$

(v) The incentives that guarantee that the Individual condition $\mathbb{I}$ *prevents deforestation* (and *achieves compensation*, respectively) are all the $\{\phi_\ell\}_{\ell \in \mathcal{L}}$ that satisfy $\phi_\ell > \delta_\ell$, for all $\ell \in \mathcal{L}$.

Proof. (i) If $\mathcal{L} \neq \mathcal{G}$, by Theorem 1, the core with $\bar{\mathbb{D}}$ only contains Compensation Outcomes if and only if $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, which is equivalent to $\sum_{\ell \in \mathcal{L}} \phi_\ell > \sum_{\ell \in \mathcal{L}} \delta_\ell$ in this setting.

We show that the core contains only Compensation Outcomes if $\mathcal{L} = \mathcal{G}$. First, we note that the core contains only No-Deforestation Outcomes. This follows because $\mathcal{L} = \mathcal{G}$ implies $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, so Lemma 2 implies that $0 \in A(\emptyset, \{\mathcal{L}\})$ and the grand coalition would always profitably deviate from any Deforestation Outcome. Second, we show that any No-Deforestation Outcome in the core must satisfy $a_\ell \geq J_\ell(1, \text{no}) - c_\ell$, for all $\ell \in \mathcal{L}$. Assume to reach a contradiction that $a_i < J_i(1, \text{no}) - c_i$; but then, $\{i\}$ would deviate because $w(\{i\}, d) > a_i$ for any $d \in \{0, 1\}$ (because $\phi_i > \delta_i$). This shows that the core contains only Compensation Outcomes if $\mathcal{L} = \mathcal{G}$.

(ii) The proof is immediate from (i): a set of minimizing incentives can be obtained by considering $\phi_\ell = \delta_\ell + \epsilon$ in the limit as $\epsilon \to 0$.

(iii) If $\mathcal{L} \neq \mathcal{G}$, then, by Theorem 2, when $\pi^{\mathcal{F}} = \{\mathcal{L}\}$, the area No-Use condition $\bar{\mathbb{U}}$ prevents deforestation if and only if $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, or equivalently $\sum_{\ell \in \mathcal{L}} \phi_\ell > \sum_{\ell \in \mathcal{L}} \delta_\ell$. On the other hand, if $\mathcal{L} = \mathcal{G}$, then the core can only contain No-Deforestation Outcomes, as any Deforestation Outcome would be dominated by a deviation of the grand coalition $\mathcal{L}$. Finally, $\mathcal{L} = \mathcal{G}$ implies that $\sum_{\ell \in \mathcal{L}} \phi_\ell > \sum_{\ell \in \mathcal{L}} \delta_\ell$, and therefore, in both cases, $\bar{\mathbb{U}}$ prevents deforestation if and only if $\sum_{\ell \in \mathcal{L}} \phi_\ell > \sum_{\ell \in \mathcal{L}} \delta_\ell$.

(iv) If $\mathcal{G} \neq \mathcal{L}$ (or equivalently, there exists $\ell \in \mathcal{L}$ such that $\phi_\ell < \delta_\ell$), by Theorem 2, when $\pi^{\mathcal{F}} = \{\mathcal{L}\}$, the core contains only Compensation Outcomes under $\bar{\mathbb{U}}$ if and only if $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ and $\eta > \eta_3^{\text{TU}} = (\phi_{\mathcal{G}} - \delta_{\mathcal{G}})$, where $\mathcal{G} = \{\ell \in \mathcal{L} : \phi_\ell > \delta_\ell\}$. Rewriting these two conditions in terms of the incentives ϕ_ℓ, we obtain $\sum_{\ell \in \mathcal{L}} \phi_\ell > \sum_{\ell \in \mathcal{L}} \delta_\ell$ and $\sum_{\ell \in \mathcal{G}} \phi_\ell < \sum_{\ell \in \mathcal{G}} \delta_\ell + \eta$. On the other hand, if $\mathcal{L} = \mathcal{G}$, then, as shown in (iii), the regeneration condition $\bar{\mathbb{U}}$ prevents deforestation, and therefore, as $\phi_\ell > \delta_\ell$, for all $\ell \in \mathcal{L}$, it prevents deforestation with compensation as well.

(v) As in §2, $\mathbb{I}$ prevents deforestation with compensation if and only if $\phi_\ell > \delta_\ell$ for all $\ell \in \mathcal{L}$. ☐

Proposition 2. Consider the setting with coordination and utility transfer from §3.2 where locals have partial ability to cooperate ($\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$), and any incentive satisfying $\phi_\ell \geq 0$ for every $\ell \in \mathcal{L}$.

(i) The incentives that guarantee that the No-Use condition $\bar{\mathbb{U}}$ *prevents deforestation* are all the $\{\phi_\ell\}_{\ell \in \mathcal{L}}$ that satisfy:

$$\sum_{\ell \in F} \phi_\ell > \sum_{\ell \in F} \delta_\ell, \text{ for some } F \in \pi^{\mathcal{F}} \tag{EC.38a}$$

$$\sum_{i \in S} \phi_i > \eta \cdot (|\mathcal{L}| - |S|) + \sum_{i \in S} \delta_i, \text{ for some } S \subseteq F. \tag{EC.38b}$$

(ii) The incentives that minimize the total payment $\sum_{\ell \in \mathcal{L}} \phi_\ell$ and guarantee that $\bar{\mathbb{U}}$ *prevents deforestation* are all the $\{\phi_\ell\}_{\ell \in \mathcal{L}}$ that satisfy:

$$\sum_{\ell \in F} \phi_\ell > \sum_{\ell \in F} \delta_\ell, \text{ for some } F \in \pi^{\mathcal{F}} \text{ and} \tag{EC.39a}$$

$$\sum_{i\in S}\phi_i > \eta\cdot(|\mathcal{L}|-|S|)+\sum_{i\in S}\delta_i \text{ for some } S\subseteq F \tag{EC.39b}$$

$$\sum_{\ell\in\mathcal{L}}\phi_\ell = \min_{F\in\pi^{\mathcal{F}}}\max\Big\{\eta\cdot(|\mathcal{L}|-|H|)+\big(\sum_{i\in H}\delta_i\big),\sum_{\ell\in\mathcal{L}}\delta_\ell\Big\},\ \text{for } H=\{\ell\in F:\delta_\ell<\eta\}\cup\{i\} \text{ for some } i\in\arg\min_{j\in F}\delta_j. \tag{EC.39c}$$

(iii) The incentives that guarantee that $\bar{\mathbb{U}}$ *prevents deforestation with compensation* are all the $\{\phi_\ell\}_{\ell\in\mathcal{L}}$ that satisfy:

$$\phi_\ell\ge\delta_\ell,\ \text{for all } \ell\in\mathcal{L}, \tag{EC.40a}$$

$$\sum_{\ell\in F}\phi_\ell>\sum_{\ell\in F}\delta_\ell,\ \text{for some } F\in\pi^{\mathcal{F}} \tag{EC.40b}$$

$$\sum_{i\in S}\phi_i>\eta\cdot(|\mathcal{L}|-|S|)+\sum_{i\in S}\delta_i,\ \text{for some } S\subseteq F. \tag{EC.40c}$$

(iv) The incentives that minimize the total payment $\sum_{\ell\in\mathcal{L}}\phi_\ell$ and guarantee that $\bar{\mathbb{U}}$ *prevents deforestation with compensation* are the $\{\phi_\ell\}_{\ell\in\mathcal{L}}$ that satisfy:

$$\phi_\ell\ge\delta_\ell,\ \text{for all } \ell\in\mathcal{L}, \tag{EC.41a}$$

$$\sum_{\ell\in\mathcal{L}}\phi_\ell=\min_{F\in\pi^{\mathcal{F}}}\sum_{H\in\pi^{\mathcal{F}},H\neq F}\delta_H+\max\Big\{\eta\cdot(|\mathcal{L}|-|S|)+\big(\sum_{i\in S}\delta_i\big),\sum_{\ell\in F}\delta_\ell\Big\},\ \text{for } S=\{\ell\in F:\delta_\ell<\eta\}\cup\{i\} \text{ for some } i\in\arg\min_{j\in F}\delta_j. \tag{EC.41b}$$

(v) The incentives that guarantee that the Individual condition $\mathbb{I}$ *prevents deforestation* (and *achieves compensation*, respectively) are all the $\{\phi_\ell\}_{\ell\in\mathcal{L}}$ that satisfy $\phi_\ell>\delta_\ell$, for all $\ell\in\mathcal{L}$.

Proof. (i) Notice that Lemma EC.5 and EC.9 do not require Assumption 4, and together imply that under the area regeneration condition $\bar{\mathbb{U}}$, the core contains only No-Deforestation Outcomes if and only if $\eta<\underline{\eta}_2^{\mathrm{TU}}=\max_{F,S:F\in\pi^{\mathcal{F}},S\subseteq F,\phi_F>\delta_F,S\neq\mathcal{L}}\frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$ and $\phi_F>\delta_F$ for some $F\in\pi^{\mathcal{F}}$. It is immediate to see then that these two conditions are equivalent to (EC.38a)-(EC.38b).

ii) By part (i), the problem of minimizing the monetary cost to the interested party while preventing deforestation can be written as:

$$\begin{array}{lll}\min\limits_{\{\phi_\ell\}_{\ell\in\mathcal{L}}} & \sum_{\ell\in\mathcal{L}}\phi_\ell & \\ \text{subject to} & \phi_\ell\ge 0, & \text{for all } \ell\in\mathcal{L} \\ & \sum_{\ell\in F}\phi_\ell\ge\sum_{\ell\in F}\delta_\ell & \text{for some } F\in\pi^{\mathcal{F}} \\ & \sum_{i\in H}\phi_i\ge\eta\cdot(|\mathcal{L}|-|H|)+\sum_{i\in H}\delta_i, & \text{for some } H\subseteq F.\end{array} \tag{EC.42}$$

First, we show that any optimal solution to (EC.42) satisfies conditions (EC.39b)-(EC.39c). Clearly, (EC.39b) and (EC.39a) must hold, as the optimal solution must be feasible. To see that (EC.39c) must hold, consider that for each $F\in\pi^{\mathcal{F}}$, the minimum value of $\eta\cdot(|\mathcal{L}|-|H|)+\big(\sum_{i\in H}\delta_i\big)$ over $H\subseteq F$ is achieved at $H=\{\ell\in F:\delta_\ell<\eta\}$, if there exists any $\ell\in F$, such that $\delta_\ell<\eta$, and $H=\{\ell\}$ for any $\ell\in\arg\min_{i\in F}\delta_i$ otherwise. Because we need that $\sum_{\ell\in F}\phi_\ell\ge\sum_{\ell\in F}\delta_\ell$, consider then the family $F\in\pi^{\mathcal{F}}$

that minimizes $\max\{\sum_{\ell\in F}\delta_\ell, \eta\cdot(|\mathcal{L}|-|H|)+\big(\sum_{i\in H}\delta_i\big)\}$, with H defined above. This means that $\sum_{\ell\in F}\phi_\ell \geq \max\{\sum_{\ell\in F}\delta_\ell, \eta\cdot(|\mathcal{L}|-|H|)+\big(\sum_{i\in H}\delta_i\big)\}$, but in particular, because $\sum_{\ell\in\mathcal{L}}\phi_\ell \geq \sum_{\ell\in F}\phi_\ell$, we have that

$$\sum_{j\in\mathcal{L}}\phi_j \geq \max\{\sum_{\ell\in F}\delta_\ell, \eta\cdot(|\mathcal{L}|-|H|)+\big(\sum_{i\in H}\delta_i\big)\}.$$

To show that the optimal value must be exactly this maximum, we can observe that setting

$$\sum_{i\in H}\phi_i = \max\Big\{\eta\cdot(|\mathcal{L}|-|H|)+\big(\sum_{i\in H}\delta_i\big), \sum_{\ell\in F}\delta_\ell\Big\},$$

and $\phi_j = 0$, for any $j\in\mathcal{L}\setminus H$, is always a feasible solution to (EC.42) that achieves the desired objective. Therefore, any optimal solution must satisfy (EC.39b)-(EC.39c). Vice versa, any solution that satisfies these conditions is feasible and achieves the optimal objective value in (EC.42), so it must be optimal.

iii) Theorem 2 implies that when $\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$, condition $\bar{\mathbb{U}}$ cannot prevent deforestation with compensation if $\mathcal{G}\neq\mathcal{L}$ (condition 4 holds) or $(\phi_F-\delta_F)\leq 0$ for each $F\in\pi^{\mathcal{F}}$[3]. Additionally, Lemma EC.9 implies that every non-empty core under $\bar{\mathbb{U}}$ contains Deforestation Outcomes if $\eta \geq \underline{\eta}_2^{\mathrm{TU}} = \max_{F,S:F\in\pi^{\mathcal{F}},S\subseteq F,\phi_F>\delta_F,S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$ (even if $\mathcal{G}=\mathcal{L}$ holds). Therefore, if the incentive prevents deforestation with compensation under $\bar{\mathbb{U}}$, it must satisfy that $\mathcal{L}=\mathcal{G}$, $\phi_F>\delta_F$ for some $F\in\pi^{\mathcal{F}}$, and $\eta<\underline{\eta}_2^{\mathrm{TU}}$. These three conditions are equivalent to (EC.40a)-(EC.40c).

We only need to show then that (EC.40a)-(EC.40c) imply that $\bar{\mathbb{U}}$ prevents deforestation with compensation. By Lemma EC.5, which holds even if condition 4 does not, (EC.40b) and (EC.40c) imply that the core contains only No-Deforestation Outcomes. But then, because (EC.40a) implies that $\mathcal{L}=\mathcal{G}$, we have $a_\ell \geq \min\{J_\ell(0,\text{yes}), J_\ell(1,\text{no})-c_\ell\} = J_\ell(1,\text{no})-c_\ell$, for every $\ell\in\mathcal{L}$ and any allocation $\{a_\ell\}_{\ell\in\mathcal{L}}$ of any outcome in the core. Therefore, the core contains only No-Deforestation Outcomes that satisfy $a_\ell \geq J_\ell(1,\text{no})-c_\ell$, which implies that $\bar{\mathbb{U}}$ prevents deforestation with compensation.

iv) By part iii), the problem of minimizing the monetary cost to the interested party while preventing deforestation with compensation (and allowing for $\phi_\ell=\delta_\ell$) can be written as:

$$\begin{array}{lll} \min\limits_{\{\phi_\ell\}_{\ell\in\mathcal{L}}} & \sum_{\ell\in\mathcal{L}}\phi_\ell & \\ \text{subject to} & \phi_\ell\geq\delta_\ell, & \text{for all } \ell\in\mathcal{L} \\ & \sum_{\ell\in F}\phi_\ell > \sum_{\ell\in F}\delta_\ell & \text{for some } F\in\pi^{\mathcal{F}} \\ & \sum_{i\in H}\phi_i \geq \eta\cdot(|\mathcal{L}|-|H|+|\mathcal{E}|)+\sum_{i\in H}\delta_i, & \text{for some } H\subseteq F. \end{array} \tag{EC.43}$$

First, we show that the optimal objective value in (EC.43) is exactly $\sum_{\ell\in\mathcal{L}}\phi_\ell = \sum_{\ell\in\mathcal{L}}\delta_\ell$. Combining (EC.40a) and (EC.40b), we obtain that $\sum_{\ell\in\mathcal{L}}\phi_\ell \geq \sum_{\ell\in\mathcal{L}}\delta_\ell$. Moreover, (EC.40b) and (EC.40c) imply that for some $F\in\pi^{\mathcal{F}}$, $\sum_{\ell\in F}\phi_\ell \geq \max\{\sum_{\ell\in F}\delta_\ell, \min_{S\subseteq F}\sum_{i\in S}\delta_i+\eta\cdot(|\mathcal{L}|-|S|)$. By the proof of (iii),

[3] Note that Lemmas EC.9 and EC.19 can be readily extended to show that when $\phi_{\mathcal{L}}=\delta_{\mathcal{L}}$ and $\pi^{\mathcal{F}}\neq\{\mathcal{L}\}$, condition $\bar{\mathbb{U}}$ cannot prevent deforestation with compensation.

we know that the $\min_{S\subseteq F}\sum_{i\in S}\delta_i+\eta\cdot(|\mathcal{L}|-|S|)$ is obtained at $H=\{\ell\in F:\delta_\ell<\eta\}\cup\{i\}$, for some $i\arg\min_{k\in F}\delta_k$. But then, because this must hold for some $F\in\pi^{\mathcal{F}}$, we have that

$$\sum_{\ell\in\mathcal{L}}\phi_\ell\geq\min_{F\in\pi^{\mathcal{F}}}\sum_{H\in\pi^{\mathcal{F}},H\neq F}\delta_H+\max\Big\{\eta\cdot(|\mathcal{L}|-|S|)+\big(\sum_{i\in S}\delta_i\big),\sum_{\ell\in F}\delta_\ell\Big\},\ \text{for } S=\{\ell\in F:\delta_\ell<\eta\}\cup\{i\}$$
$$\text{for some } i\in\arg\min_{j\in F}\delta_j.$$

We provide a feasible solution that exactly obtains this objective value. For this, consider a family $F\in\pi^{\mathcal{F}}$ that minimizes the right hand side of (EC.41b) $\phi_i=\delta_i$, for all $i\in\mathcal{L}$, and for this family, consider the set H defined above. Set then $\phi_\ell=\delta_\ell$, for all $\ell\in\mathcal{L}\setminus H$, and $\sum_{\ell\in H}\phi_\ell=\max\{\sum_{\ell\in H}\delta_\ell,\eta\cdot(|\mathcal{L}|-H)\}$. By construction, $\sum_{\ell\in\mathcal{L}}\phi_\ell$ is equal to the right hand side in (EC.41b). This distribution is feasible for (EC.43). We have shown then that the optimal objective value for (EC.43) is exactly the right hand side of (EC.41b), which implies that (EC.41b) must hold for any optimal solution. Requirement (EC.41a) must hold as well, as it is required for $\bar{\mathbb{U}}$ to prevent deforestation with compensation, as shown in (iii).

Finally, any set of incentives that satisfy (EC.41a) and (EC.41b) is readily feasible in problem (EC.43) (taking F that minimizes the right hand side of (EC.41b) and the corresponding H as the $S\subseteq F$ for (EC.40c)), which also implies that these are optimal.

(v) As in §2, $\mathbb{I}$, prevents deforestation with compensation if and only if $\phi_\ell>\delta_\ell$ for all $\ell\in\mathcal{L}$. □

EC.3.2. Hybrid Conditions

Recall the definition of hybrid incentives from §4.3, which we repeat for convenience. We consider two hybrid schemes. The first involves individual incentives for each local $\ell\in\mathcal{L}$ but based on any condition $\mathbb{C}_\ell\in\{\mathbb{I},\bar{\mathbb{D}},\bar{\mathbb{U}}\}$, whereby each area condition $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$ applies to the entire area (containing all locals in $\mathcal{L}$). The second scheme allows partitioning the area into subareas and applying distinct conditions for all locals in each subarea; formally, we define the following subarea conditions:

1. *Subarea No-Deforestation Condition*, $\bar{\mathbb{D}}^H$. Each local $\ell\in H\subseteq\mathcal{L}$ receives the incentive if and only if no local in H engages in deforestation: $\bar{\mathbb{D}}^H_\ell(d,B)=\text{yes}\Leftrightarrow d_i=0,\forall i\in H$.
2. *Subarea No-Use Condition*, $\bar{\mathbb{U}}^H$. Each local $\ell\in H\subseteq\mathcal{L}$ receives the incentive if and only if no local in H generates income on deforested land: $\bar{\mathbb{U}}^H_\ell(d,B)=\text{yes}\Leftrightarrow d_i(1-\max_{g\in\mathcal{L}}B_{gi})=0,\forall i\in H$.

Proposition 3 shows that if locals have full ability to cooperate, neither of these hybrid approaches can prevent deforestation (or achieve compensation) at lower cost than what would be incurred by applying a uniformly condition $\bar{\mathbb{D}}$ with $\phi_{\mathcal{L}}>\delta_{\mathcal{L}}$, as recommended in §4.2.

Proposition 3. If locals have full ability to cooperate ($\pi^{\mathcal{F}}=\{\mathcal{L}\}$), then no set of incentives and conditions $\{\phi_\ell,\mathbb{C}_\ell:\ell\in\mathcal{L}\}$, with $\mathbb{C}_\ell\in\{\mathbb{I},\bar{\mathbb{D}},\bar{\mathbb{U}}\}\cup\{\bar{\mathbb{D}}^H:H\subseteq\mathcal{L}\}\cup\{\bar{\mathbb{U}}^H:H\subseteq\mathcal{L}\}$, can prevent deforestation (or achieve compensation) at lower total cost than $\mathbb{C}_\ell=\bar{\mathbb{D}}$ for all $\ell\in\mathcal{L}$ with $\phi_{\mathcal{L}}\searrow\delta_{\mathcal{L}}$.

Proof of Proposition 3. If locals have full ability to cooperate, then to prevent deforestation, all locals must prefer the incentive in aggregate ($\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$). Otherwise, any No-Deforestation Outcome would have a deviation towards deforestation of the grand coalition $\mathcal{L}$, in which all locals could be transferred utility to prefer the Deforestation Outcome. This holds regardless of the conditions imposed on the locals and is driven solely by the ability to transfer utility in the community. Therefore, even if $\mathbb{C}_\ell \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\} \cup \{\bar{\mathbb{D}}^H : H \subseteq \mathcal{L}\} \cup \{\bar{\mathbb{U}}^H : H \subseteq \mathcal{L}\}$, there is no set of incentives that can achieve a lower total cost than applying $\bar{\mathbb{D}}$ for all $\ell \in \mathcal{L}$. □

In contrast, Proposition 4 shows that such hybrid conditions *can* reduce the costs of an optimal incentive when locals have partial ability to cooperate.

Proposition 4. If locals have partial ability to cooperate ($\pi^{\mathcal{F}} \neq \{\mathcal{L}\}$) and there exists a family $H \in \pi^{\mathcal{F}}$ such that $\delta_H < \eta|H|$, then a hybrid condition $\{\phi_\ell, \mathbb{C}_\ell : \ell \in \mathcal{L}\}$ with $\mathbb{C}_\ell \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\} \cup \{\bar{\mathbb{D}}^H : H \subseteq \mathcal{L}\} \cup \{\bar{\mathbb{U}}^H : H \subseteq \mathcal{L}\}$ could prevent deforestation with a lower total-cost:

$$\phi_{\mathcal{L}} = \delta_H + \min_{F \in \pi^{\mathcal{F}} \setminus \{H\}} \max\Big\{\delta_F, \min_{S \subseteq F, S \neq \emptyset} \big(\delta_S + \eta(|\mathcal{L}| - |S| - |H|)\big)\Big\}.$$

This can be achieved by applying $\mathbb{C}_\ell = \mathbb{I}$ for all $\ell \in H$ and $\mathbb{C}_\ell = \bar{\mathbb{U}}$ for all $\ell \in \mathcal{L} \setminus H$, or alternatively by applying $\mathbb{C}_\ell = \bar{\mathbb{D}}^H$ or $\mathbb{C}_\ell = \bar{\mathbb{U}}^H$ for all $\ell \in H$ and $\mathbb{C}_\ell = \bar{\mathbb{U}}^{\mathcal{L} \setminus H}$ for all $\ell \in \mathcal{L} \setminus H$.

Proof of Proposition 4. When assigning either $\mathbb{C}_\ell = \mathbb{I}$ and $\phi_\ell \searrow \delta_\ell$ or $\mathbb{C}_\ell = \bar{\mathbb{U}}^H_\ell$ and $\phi_H \searrow \delta_H$ to all locals in $\ell \in H$, we ensure that all locals in H would choose not to deforest $d_\ell = 0$, in all outcomes in the core. But then, we can replicate the same analysis in §4.2 with the smaller group of locals $\mathcal{L} \setminus H = \mathcal{L}'$. For this $\mathcal{L}'$, we have that both the area no-use condition $\bar{\mathbb{U}}$ and the Sub-area no-use condition $\bar{\mathbb{U}}^{\mathcal{L}'}$ are equal in equilibria, as no local in H would either deforest or block any other local. But then, by the results in §4.2, we have that both these conditions prevent deforestation at a minimum cost when

$$\phi_{\mathcal{L}'} = \phi_{\mathcal{L} \setminus H} \searrow \min_{F \in \pi^{\mathcal{F}} \setminus \{H\}} \max\{\delta_F, \min_{S \subseteq F, S \neq \emptyset} (\delta_S + \eta(|\mathcal{L}| - |S| - |H|))\}.$$

And, because $\delta_H < \eta|H|$,

$$\phi_{\mathcal{L}} = \phi_H + \phi_{\mathcal{L} \setminus H} < \min_{F \in \pi^{\mathcal{F}}} \max\{\delta_F, \min_{S \subseteq F, S \neq \emptyset} (\delta_S + \eta(|\mathcal{L}| - |S|))\}.$$

Thus, if $\min_{F \in \pi^{\mathcal{F}}} \max\{\delta_F, \min_{S \subseteq F, S \neq \emptyset} (\delta_S + \eta(|\mathcal{L}| - |S|))\} < \delta_{\mathcal{L}}$, which is the minimum cost incentive when applying $\mathbb{I}$ to every $\ell \in \mathcal{L}$, the proposed hybrid conditions can reduce the total cost, in comparison with the best uniform condition. □

EC.4. Modeling Extensions

This section examines several important extensions of the main model.

EC.4.1. Optimistic Recursive Core

Next, we define the *optimistic* Recursive Core and show that any outcome in the optimistic Recursive Core must also be in the pessimistic Recursive Core. This implies that if the forest is protected and locals are better off in all pessimistic Recursive Core outcomes, then the same is true in all optimistic Recursive Core outcomes.

Definition EC.1 (Optimistic Recursive Core). Suppose that for an integer $k \in [1, |\mathcal{L}|-1]$, the *optimistic* core $C_o(R;\pi_{\mathcal{L}\setminus R})$ is defined for every residual game in which a set of locals $R \subset \mathcal{L}$ with $|R| \in [1,k]$ respond to a partition of the other locals $\pi_{\mathcal{L}\setminus R} \in \Pi_{\mathcal{L}\setminus R}$ (with $\pi_{\mathcal{L}\setminus R} \prec \sigma$). For $k=1$, the residual game has a single local $R=\{\ell\}$ and the core $C_o(\{\ell\};\pi_{\mathcal{L}\setminus\{\ell\}})$ is the set of triples of partition, equilibrium indicator, and allocations of the form $\big(\{\{\ell\}\}, d^*, a_\ell\big)$ with $a_\ell = w\big(\{\ell\},\{\{\ell\}\};d^*\big)$ and $d^* \in T(\{\{\ell\}\}\cup\pi_{\mathcal{L}\setminus\{\ell\}})$. For a residual game with $|R|=k+1$, the core $C_o(R;\pi_{\mathcal{L}\setminus R})$ is the set of *un-dominated* outcomes, where an outcome with allocation $\{a_\ell\}_{\ell\in R}$ and partition π_R is *dominated* if there exists a coalition $H \subseteq R$ forming partition $\pi_H \in \Pi_H$ so that

$$w\big(S, \hat{\pi}_{R\setminus H}\cup\pi_H\cup\pi_{\mathcal{L}\setminus R}; \hat{d}\big) > \textstyle\sum_{\ell\in S} a_\ell \qquad \text{(EC.44)}$$

for **every** coalition $S\in\pi_H$, **at least one** sub-partition $\hat{\pi}_{R\setminus H}\in\Pi_{R\setminus H}$ with $\hat{\pi}_{R\setminus H}\prec\sigma$, and equilibrium indicator $\hat{d}$ and real values $\{\hat{a}_\ell\}_{\ell\in R\setminus H}$ satisfying:

$$\begin{cases} \big(\hat{\pi}_{R\setminus H}, \hat{d}, \{\hat{a}_\ell\}_{\ell\in R\setminus H}\big) \in C_o(R\setminus H; \pi_H\cup\pi_{\mathcal{L}\setminus R}) & \text{if } H\subset R \text{ and } C(R\setminus H;\pi_H\cup\pi_{\mathcal{L}\setminus R})\neq\emptyset \\ \hat{d}\in T(\hat{\pi}_{R\setminus H}\cup\pi_H\cup\pi_{\mathcal{L}\setminus R}) & \text{otherwise.} \end{cases} \qquad \text{(EC.45)}$$

The *optimistic* Recursive Core of the TU cooperative game among all locals is then given by $C_o(\mathcal{L};\emptyset)$.

Notice that the optimistic core $C_o(\mathcal{L};\emptyset)$ differs from the pessimistic core defined in (3) only in the notion of dominance: While in a pessimistic core a coalition set would have to be better off in all outcomes of the remaining locals $(R\setminus H)$, in the optimistic core, deviating coalitions need only be better off for one feasible outcome. It is then immediate by the definition that any optimistic outcome would also be pessimistic, as any dominated outcome in the pessimistic sense would have to be dominated in the optimistic sense. Our next proposition shows this rigorously using the recursive definitions of both core concepts.

Proposition 5. Given any cooperative game with transfer of utilities as defined in §2, the optimistic core $C_o(\mathcal{L};\emptyset)$ must be included in the pessimistic core $C(\mathcal{L};\emptyset)$ defined in (3).

Proof of Proposition 5.

We will prove that for every $R\subseteq\mathcal{L}$, and partition $\pi_{\mathcal{L}\setminus R}$, $C_o(R;\pi_{\mathcal{L}\setminus R})\subseteq C(R;\pi_{\mathcal{L}\setminus R})$, which, taking $R=\mathcal{L}$, implies the proposition. We then proceed by induction in $|R|$. For $|R|=1$, note that $C_o(R;\pi_{\mathcal{L}\setminus R}) = C(R;\pi_{\mathcal{L}\setminus R})$, because both definitions coincide when the residual game is of size 1.

Thus, our inductive assumption is that $C_o(R;\pi_{\mathcal{L}\setminus R})\subseteq C(R;\pi_{\mathcal{L}\setminus R})$, for any set $R\subseteq\mathcal{L}$ and (sub)partition $\pi_{\mathcal{L}\setminus R}$, such that $|R|\le k$.

Let $R \subseteq \mathcal{L}$ such that $|R| = k+1$. Assume by contradiction that there is an outcome in $C_o(R;\pi_{\mathcal{L}\setminus R})$ that is not in $C(R;\pi_{\mathcal{L}\setminus R})$, for some (sub)partition $\pi_{\mathcal{L}\setminus R}$, with allocation $\{a^*_\ell\}_{\ell\in\mathcal{L}}$. But this implies that this outcome must be *dominated* according to the pessimistic definition in (3), which implies that there exists a coalition $H \subseteq R$ that forms the partition $\pi_H \in \Pi_H$ that would prefer to deviate from all the outcomes of the remaining locals in $R\setminus H$. But, because $|R\setminus H| \le k$, the inductive assumption implies that H must also have a positive deviation under the optimistic definition. This leads to a contradiction, as the outcome being in $C_o(R;\pi_{\mathcal{L}\setminus R}$ implied that it was undominated under the optimistic definition. Therefore, we have proved the case for $|R| = k+1$ and the proposition. □

EC.4.2. Family-Dependent Blocking Cost

We assume in §2 that the blocking cost η is homogeneous across all farmers. In this section, we relax this assumption to allow for the blocking cost to depend on the family to which the blocking farmer belongs and show that our main results can be readily generalized.

Consider the cooperative game with transfer of utilities defined in § 2, but with blocking costs η_F, for each $\ell \in F$, and $F \in \pi^{\mathcal{F}}$, and the net income (5) for a coalition $S \subseteq F$ redefined as:

$$\sum_{\ell\in S}\left[J_\ell\Big(d_\ell\cdot\big(1-\max_{i\in\mathcal{L}} B_{i\ell}\big), \mathbb{C}_\ell(d,B)\Big) - c_\ell\cdot d_\ell - \eta_F\cdot\sum_{i\in\mathcal{L}} B_{\ell i}\right]. \tag{EC.46}$$

Proposition 6 generalizes Corollary 1 to this setting.

Proposition 6. When locals have full ability to cooperate, $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$ prevent deforestation if and only if locals collectively prefer the incentive ($\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$); in this case, both $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$ prevent deforestation, $\bar{\mathbb{D}}$ achieves compensation, and $\bar{\mathbb{U}}$ achieves compensation if $\eta_{\mathcal{L}} > (\phi_{\mathcal{G}} - \delta_{\mathcal{G}})$. When locals have partial ability to cooperate, $\bar{\mathbb{D}}$ cannot prevent deforestation, whereas $\bar{\mathbb{U}}$ prevents deforestation if and only if there $\eta_F < \underline{\eta}_2^{\mathrm{TU}}(F)$ for some $F \in \pi^{\mathcal{F}}$ such that $\phi_F > \delta_F$, where $\underline{\eta}_2^{\mathrm{TU}}(F) = \max_{S\subseteq F}\frac{\phi_S-\delta_S}{|\mathcal{L}\setminus S|}$.

Proof of Proposition 6. When locals have full ability to cooperate, there is only one value of η_F, and the result follows from Theorem 1 and Theorem 2. When locals have partial ability to cooperate, the result for $\bar{\mathbb{D}}$ does not depend on the blocking cost, and follows as before. So, we need only to show that when locals have partial ability to cooperate, $\bar{\mathbb{U}}$ prevents deforestation if and only if $\eta_F < \underline{\eta}_2^{\mathrm{TU}}(F)$ for some $F \in \pi^{\mathcal{F}}$ such that $\phi_F > \delta_F$.

First, we show that if $\eta_F < \underline{\eta}_2^{\mathrm{TU}}(F)$ for some $F \in \pi^{\mathcal{F}}$ such that $\phi_F > \delta_F$, then $\bar{\mathbb{U}}$ prevents deforestation. For this, notice that the same arguments as in Lemma EC.5 can be used to show that every Deforestation Outcome is dominated by a coalition $S \subseteq F$ such that

$$\phi_S - \delta_S > \eta_F|\mathcal{L}\setminus S| \ge 0,$$

deviating towards a No-Deforestation Outcome. Therefore, there can only be No-Deforesation Outcomes in the core.

We show that if $\eta_F \geq \underline{\eta}_2^{\mathrm{TU}}(F)$ for all $F \in \pi^{\mathcal{F}}$ such that $\phi_F > \delta_F$, then $\bar{\mathbb{U}}$ cannot prevent deforestation. For this, the same arguments as in Lemma EC.9 prove that for any $R \subseteq \mathcal{L}$, if $0 \in A(R; \pi_{\mathcal{L}\setminus R})$, and $(\pi'_R, d' = 0, \{a'_\ell\}) \in A(R; \pi_{\mathcal{L}\setminus R})$ is a No-Deforestation Outcome, then the Deforestation Outcome (EC.11a)-(EC.11d) must be in $A(R; \pi_{\mathcal{L}\setminus R})$. Intuitively, all locals in families that prefer to deforest receive a higher allocation than in the No-Deforestation Outcome. And because there is no coalition from a family that prefers the incentive that can block all other locals, then they receive their income from deforestation and cannot deviate, and guarantee only No-Deforestation Outcomes in the residual core. Therefore, $\bar{\mathbb{U}}$ cannot prevent deforestation, which concludes the proof. □

EC.4.3. When Some Farmers Would Not Benefit From Deforestation

We assume in §2 that all farmers would deforest absent the incentive ($\delta_\ell > 0$, for all $\ell \in \mathcal{L}$). In this section, we generalize our main results for the case where $\delta_\ell = 0$ for some $\ell \in \mathcal{L}$. We assume that $c_\ell > 0$ even if $\delta_\ell = 0$; in other words, even though ℓ would not benefit from deforestation, engaging in deforestation would still be costly for him.[4], and both conditions $\bar{\mathbb{U}}$ and $\bar{\mathbb{D}}$ are still defined with respect to all locals in $\mathcal{L}$, that is, if $d_\ell = 1$, no incentive is provided under $\bar{\mathbb{D}}$, and if $d_\ell(1 - \max_{i \in \ell} B_{i\ell}) = 1$, then no incentive is provided under $\bar{\mathbb{U}}$. We assume that $\delta_\ell > 0$ for at least one $\ell \in \mathcal{L}$ (i.e., there is at least one local that would deforest). For this, we first show the generalizations of Lemma 1 and Lemma 2, and using these, we generalize our main results.

Lemma EC.23. *For every partition $\pi \in \Pi_{\mathcal{L}}$ and condition $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$, $\mathcal{Q}(\pi, \mathbb{C})$ is non-empty and any subgame-perfect equilibrium in $\mathcal{Q}(\pi, \mathbb{C})$ has $B^*(d^*) = 0$ and either $d^*_\ell = 0$ for all $\ell \in \mathcal{L}$ or $d^*_\ell = 1$ for all $\ell \in \{i \in \mathcal{L} : \delta_i > 0\}$.*

To prove this lemma, we proceed as before and show the following intermediate results:

Lemma EC.24. *For the cooperative game with transferable utility, assuming $\delta_\ell \geq 0$ for all $\ell \in \mathcal{L}$, and $\delta_i > 0$ for some $i \in \mathcal{L}$, consider a partition $\pi \in \Pi_{\mathcal{L}}$, with $\pi \prec \pi^{\mathcal{F}}$. Any subgame-perfect equilibria $(d^*, B^*(d)) \in \mathcal{Q}(\pi, \mathbb{C})$ satisfies that $d^*_S = 0$ (i.e., $d^*_\ell = 0$, for every $\ell \in S$) or $d^*_\ell = 1$, for every $\ell \in S$ such that $\delta_\ell > 0$, for every coalition $S \in \pi$, and any forest protection condition $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$. Note that this result does not require condition 4.*

Proof of Lemma EC.24. Assume by contradiction that there is an equilibrium $(d^*, B^*(d)) \in \mathcal{Q}(\pi, \mathbb{C})$ such that for a coalition $S \in \pi$ there are $d^*_g = 0$, $d^*_\ell = 1$, for some $\ell, g \in S$, such that $\delta_g > 0$ and $\delta_\ell = 0$.

Under $\bar{\mathbb{D}}$, we note first that, because $\bar{\mathbb{D}}_\ell(d, B)$ does not depend on B, but blocking is costly (as expressed in (6) by the blocking cost η), then in equilibria, $B^* = 0$. But then, $\bar{\mathbb{D}}_g(d, B) = $ no, and

[4] We also conducted the analysis under the alternative assumption that if $\delta_\ell = 0$, then local ℓ would not deforest in any equilibria and would not incur any cost c_ℓ. The qualitative insights are the same and are omitted for brevity.

because g would gain from deforestation ($\delta_g > 0$ by (3)), then (7) can be improved by setting $d_g^* = 1$, which contradicts $(d^*, B^*(d))$ being an equilibrium.

Under $\bar{\mathbb{U}}$, if $\max_{i\in\mathcal{L}} B_{i\ell}^*(d^*) = 1$, then local ℓ is being blocked. But then, because deforestation is costly, (7) can be increased by c_ℓ by setting $d_\ell^* = 0$. If, on the other hand, $\max_{i\in\mathcal{L}} B_{i\ell}^*(d^*) = 0$, then, by the definition of the No-Use Condition, $\bar{\mathbb{U}}_g(d^*, B^*(d^*)) = \text{no}$, and, as before, the coalition S could increase its net income in (7) by setting $d_g^* = 1$. Therefore, in any equilibrium, either $d_\ell = 0$ for all $\ell \in S$, or $d = 1$ for all $\ell \in S$ such that $\delta_\ell > 0$. □

We can then denote $d_S = 0$ when $d_\ell = 0$ for all $\ell \in S$, and $d_S = 1$, when $d_\ell = 1$ for at least one $\ell \in S$.

LEMMA EC.25. *For the cooperative game with transferable utility, consider a partition $\pi \in \Pi_{\mathcal{L}}$, with $\pi \prec \pi^{\mathcal{F}}$. Under the area no-deforestation condition $\bar{\mathbb{D}}$, if $\pi = \{\mathcal{L}\}$, and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, then $\mathcal{Q}(\pi, \bar{\mathbb{D}})$ contains a no-deforestation equilibrium ($d^* = 0$); otherwise, $\mathcal{Q}(\pi, \bar{\mathbb{D}})$ contains a deforestation equilibrium ($d^* = 1$). Under the area no-use condition $\bar{\mathbb{U}}$, if*

$$\eta < \eta_1(\pi) = \sup\{\eta : \exists S \in \pi \text{ with } (\phi_S - \delta_S) > \eta\,|\mathcal{L} \setminus S|\},$$

the set of equilibria, $\mathcal{Q}(\pi, \bar{\mathbb{U}})$ contains a no-deforestation equilibrium ($d^* = 0$); otherwise, $\mathcal{Q}(\pi, \bar{\mathbb{U}})$ contains a deforestation equilibrium ($d^* = 1$). Note that this result does not require condition 4.

Proof of Lemma EC.25. Under $\bar{\mathbb{D}}$, we will consider three cases. First, if $\pi = \{\mathcal{L}\}$, and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, then there are only two options, either $d_{\mathcal{L}}^* = 1$, or $d_{\mathcal{L}}^* = 0$ (by Lemma EC.24). Because $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, the optimal decision in (7) is $d_{\mathcal{L}}^* = 0$, resulting in a no-deforestation equilibrium. Second, if $\pi = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} \le \delta_{\mathcal{L}}$, the solution to the maximization in (7) must include $d_{\mathcal{L}}^* = 1$, and $\mathcal{Q}(\pi, \bar{\mathbb{D}})$ includes a deforestation equilibria. Finally, if $\pi \neq \{\mathcal{L}\}$, then there are at least two coalitions S_1, and S_2, in π. Hence, if we consider a deforestation equilibrium, with $d_\ell^* = 1$ foer very $\ell \in S_1$, and $d_\ell^* = 1$ for every $\ell \in S_2$, we can see that $\bar{\mathbb{D}}(\pi, d^*, B^*) = \text{no}$, and no unilateral deviation of any $S \in \pi$ can change this, which implies that, absent any reward, each coalition will engage in deforestation and therefore, $\mathcal{Q}(\pi, \bar{\mathbb{D}})$ contains a deforestation equilibrium.

Under $\bar{\mathbb{U}}$, if $\eta < \eta_1(\pi)$, then there exists $S \in \pi$ such that $\phi_S - \delta_S > \eta|\mathcal{L} \setminus S| \ge 0$. Thus, a no-deforestation equilibrium (d^*, B^*) must be in $\mathcal{Q}(\pi, \bar{\mathbb{U}})$ because in such an equilibrium, if any coalition S' unilaterally deviates and sets $d_{S'} = 1$, then coalition S would block all individuals who deviated in the second stage.

On the other hand, if $\eta \ge \eta_1(\pi)$, no coalition S exists so that $(\phi_S - \delta_S) > \eta|\mathcal{L} \setminus S|$. We consider two (sub)cases, the first with $|\pi| = 1$ and the second with $|\pi| \ge 2$.

First, if $\pi = \{\mathcal{L}\}$, then $\eta \ge \eta_1(\pi)$ implies that $\phi_{\mathcal{L}} \le \delta_{\mathcal{L}}$ or equivalently

$$\sum_{\ell\in\mathcal{L}} J_\ell(0, \text{yes}) \le \sum_{\ell\in\mathcal{L}} J_\ell(1, \text{no}) - c_\ell.$$

Therefore, $B^*_{\mathcal{L}i} = 0$ is an optimal solution in (6) for each $i \in \mathcal{L}$, conditional on $d^*_{\mathcal{L}} = 1$, which in turn implies that these deforestation decisions are optimal in (7), which proves that this deforestation equilibrium is in $\mathcal{Q}(\{\mathcal{L}\}, \bar{\mathbb{U}})$.

Assume now that $\eta \geq \eta_1(\pi)$ and $|\pi| \geq 2$. Let S_1, and S_2 be two coalitions in π. Consider a deforestation equilibrium, where $d^*_\ell = 1$ for $\ell \in S$ and $B^*_{Si} = 0$, for every $S \in \pi$, $i \in \mathcal{L}$. In this case, $\kappa^{\bar{\mathbb{U}}}(\pi, d^*, B^*) = \text{no}$, and there is no profitable deviation of any one coalition that can change this: for instance, coalition S_1 would not change its second stage blocking decision because $\eta \geq \eta_1(\pi)$ implies that it would not be strictly profitable to block all other locals in $\mathcal{L} \setminus S_1$, and the compliance indicator would not change even if $d_{S_1} = 0$ because there are at least two coalitions, and $d^*_\ell = 1$ for every $\ell \in S_2$. Therefore, this deforestation equilibrium must be in $\mathcal{Q}(\pi, \bar{\mathbb{U}})$. □

Proof of Lemma EC.23. By Lemma EC.25, we know that $\mathcal{Q}(\pi, \mathbb{C}) \neq \emptyset$ for $\mathbb{C} \in \{\bar{\mathbb{D}}, \bar{\mathbb{U}}\}$ and any partition $\pi \in \Pi_{\mathcal{L}}$. By Lemma EC.24, we know that for every coalition $S \in \pi$ either $d^*_\ell = 0$ for all $\ell \in S$ or $d^*_\ell = 1$, for all $\ell \in S$ such that $\delta_\ell > 0$. Hence, we must only prove that any equilibrium in $\mathcal{Q}(\pi, \mathbb{C})$ is either a deforestation equilibrium (with $d^*_\ell = 1$ for all $S \in \pi$ and $\ell \in S$ such that $\delta_\ell > 0$) or a no-deforestation equilibrium (with $d^*_\ell = 0$ for all $S \in \pi$ and $\ell \in S$).

If $|\pi| = 1$, the result is immediate by the definition of the game, as the single coalition in π can only choose $d^*_\ell = 0$ for all $\ell \in \mathcal{L}$ or $d^*_\ell = 1$ for all $\ell \in \mathcal{L}$, with $\delta_\ell > 0$, corresponding to a no-deforestation equilibrium and deforestation equilibrium respectively. Thus, we consider below only the case with $|\pi| \geq 2$.

We first show the result for the area no-deforestation condition $\bar{\mathbb{D}}$. Assume by contradiction that there exists an equilibrium such that $d^*_\ell = 1$ for all $\ell \in S_1$, with $\delta_\ell > 0$ and $d^*_{S_2} = 0$, for $S_1 \neq S_2$, and both $S_1, S_2 \in \pi$. By definition, $\bar{\mathbb{D}}_\ell(\pi, d^*, B^*) = \text{no}$ for every $\ell \in \mathcal{L}$, as there is at least one coalition that engages in deforestation (and blocking decisions do not matter with $\bar{\mathbb{D}}$). But without rewards, it is a profitable for all $\ell \in S_2$ with $\delta_\ell > 0$ to set $d_\ell = 1$. Therefore, no equilibrium can exist in $\mathcal{Q}(\pi)$ with $d^*_{S_1} = 1$ and $d^*_{S_2} = 0$.

We now show the result for the area no-use condition $\bar{\mathbb{U}}$. Assume by contradiction that there exists an equilibrium such that $d^*_{S_1} = 0$ and $d^*_\ell = 1$ for all $\ell \in S_2$ such that $\delta_\ell > 0$, for $S_1 \neq S_2$, and both $S_1, S_2 \in \pi$. Consider then the second stage blocking decisions; there are two possible scenarios, either all locals in S_2 that engage in deforestation are blocked in the second stage (i.e., $\max_{i \in \mathcal{L}} B_{i\ell} = 1$, for every $\ell \in S_2$ with $\delta_\ell > 0$), or at least one local in S_2 is not blocked (i.e., $\max_{i \in \mathcal{L}} B_{i\ell} = 0$, for some $\ell \in S_2$). In the former case, coalition S_2 has a profitable deviation by changing $d^*_{S_2} = 0$ and not incurring the deforestation costs $\sum_{\ell \in S_2 : \delta_\ell > 0} c_\ell$. In the latter case, $\bar{\mathbb{U}}_h(\pi, d^*, B^*) = \text{no}$, for every $h \in S_1$, as at least one local from S_2 is engaging in deforestation and not being blocked by any other local. Hence, S_1 has a profitable deviation by either changing $B_{hf} = 1$ for some $h \in S_1$, and block the unblocked local $\ell \in S_2$ (depending on the magnitude of the blocking cost η) or setting $d^*_h = 1$ for all $h \in \S_1$ with $\delta_h > 0$. In all cases, there is a profitable deviation, and therefore every equilibrium must either be a deforestation equilibrium or a no-deforestation equilibrium. Note we do not use condition 4 to prove these results, and therefore they hold even if $\mathcal{L} = \mathcal{G}$. □

We now show Lemma 2 for this extension. We note $T \subseteq 0,1$, where here $0 \in T$ implies that $(d_\ell^* = 0, B_\ell^* = 0)$ is an equilibrium in $\mathcal{Q}(\pi)$, while $1 \in T$ implies that $\mathcal{Q}(\pi)$ contains an equilibria with $B_\ell^* = 0$ for all $\ell \in \mathcal{L}$, and $d_\ell^* = 1$, for all $\ell \in \mathcal{L}$ such that $\delta_\ell > 0$.

LEMMA EC.26. *In the setting where $\delta_\ell \geq 0$ for all $\ell \in \mathcal{L}$, and $\delta_\ell > 0$ for at least one $\ell \in \mathcal{L}$, consider a partition $\pi \in \Pi_{\mathcal{L}}$. With the area no-deforestation condition $\bar{\mathbb{D}}$,*

$$T(\pi, \bar{\mathbb{D}}) = \begin{cases} \{0\} & \text{if } \pi = \{\mathcal{L}\} \text{ and } \phi_{\mathcal{L}} > \delta_{\mathcal{L}} \\ \{1\} & \text{if } \phi_S < \delta_S \text{ for some coalition } S \text{ in } \pi \\ \{0,1\} & \text{otherwise.} \end{cases}$$

With the area no-use condition $\bar{\mathbb{U}}$, there exist thresholds (on the cost of blocking) $\eta_1(\pi), \eta_2(\pi)$ so that $\eta_1(\pi) \leq \eta_2(\pi)$ and

$$T(\pi, \bar{\mathbb{U}}) = \begin{cases} \{0\} & \text{if } \eta < \eta_1(\pi) \\ \{1\} & \text{if } \eta > \eta_2(\pi) \\ \{0,1\} & \text{otherwise.} \end{cases}$$

Proof of Lemma EC.26. We begin by showing the results under the area no-deforestation condition $\bar{\mathbb{D}}$. We have shown in Lemma EC.23 that $T(\pi)$ can take only values $\{0\}$, $\{1\}$, or $\{0,1\}$, so we only need to prove that a) $T(\pi) = \{0\}$ if and only if $\pi = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, and b) $T(\pi) = \{1\}$ if and only if $\phi_S < \delta_S$ for some $S \in \pi$.

Lemma EC.25 implies that $T(\pi) = \{0\}$ (i.e., *only* no-deforestation equilibria) can occur only if $\pi = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$. Conversely, if $\pi = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$ then $d_{\mathcal{L}}^* = 0$ is the unique solution to (7) by definition of $\phi_{\mathcal{L}}$ and $\delta_{\mathcal{L}}$, which implies that $T(\pi) = \{0\}$.

If $\phi_S < \delta_S$ for some $S \in \pi$, then $d_\ell^* = 1$ for all $\ell \in S$, for *any* equilibrium in $\mathcal{Q}(\pi, \bar{\mathbb{D}})$, as this is the only solution to (7). But then, Lemma EC.23 implies $T(\pi) = \{1\}$. Conversely, if $\phi_S \geq \delta_S$ for all $S \in \pi$, then any no-deforestation equilibrium will be in $\mathcal{Q}(\pi, \bar{\mathbb{D}})$, because when $\kappa^{\bar{\mathbb{D}}}(\pi, d^*) = \text{yes}$, then $d_S^* = 0$ is the only solution to (7), which implies that no coalition would want to deviate from a no-deforestation equilibrium if they all prefer not to deforest. Therefore, $T(\pi) = \{1\}$ if and only if $\phi_S < \delta_S$ for some $S \in \pi$.

Under the area no-use condition $\bar{\mathbb{U}}$, we showed in Lemma EC.25 that if $\eta < \eta_1(\pi) = \sup\{\eta : \exists S \in \pi \text{ with } (\phi_S - \delta_S) > \eta\,|\mathcal{L} \setminus S|\}$, then $0 \in T(\pi)$; and if $\eta \geq \eta_1(\pi)$, then $1 \in T(\pi)$. Because

$$\eta_1(\pi) \leq \eta_2(\pi) := \inf\left\{\eta : \sum_{S \in \pi : \phi_S > \delta_S} \left\lfloor \frac{(\phi_S - \delta_S)}{\eta} \right\rfloor < \max_{H \in \pi : \phi_H < \delta_H} |H| \right\},$$

we need only to show that $\eta < \eta_1(\pi)$ implies $1 \notin T(\pi)$ and that $\eta > \eta_2(\pi)$ implies $0 \notin T(\pi)$.

To see that $\eta < \eta_1(\pi)$ implies $1 \notin T(\pi)$, assume by contradiction that $1 \in T(\pi)$. If $\eta < \eta_1(\pi)$, there exists a coalition $S \in \pi$, such that $(\phi_S - \delta_S) > \eta|\mathcal{L} \setminus S|$. Thus, given any deforestation equilibrium, S will have a profitable deviation of setting $d_S = 0$, and $\sum_{j \in S} B_{ji} = 1$, for every $i \in \mathcal{L} \setminus S$, blocking all locals outside of S that deforest. This implies that $\mathcal{Q}(\pi, \bar{\mathbb{U}})$ cannot contain a deforestation equilibrium.

To see that $\eta > \eta_2(\pi)$ implies $0 \notin T(\pi)$, assume by contradiction that $0 \in T(\pi)$. As η is finite, it follows from the definition of $\eta_2(\pi)$ that there exists some coalition $H \in \pi$ with $\phi_H < \delta_H$. Consider $H \in \arg\max_{S' \in \pi : \phi_{S'} < \delta_{S'}} |S|$. In any no-deforestation equilibrium, H could deviate by setting $d_H = 1$ and because $\eta > \eta_2(\pi)$, the locals in H cannot be blocked by the coalitions $S \in \pi$ with $\phi_S \geq \delta_S$. It follows that there cannot be a no-deforestation equilibrium in $\mathcal{Q}(\pi, \bar{\mathbb{U}})$ if $\eta > \eta_2(\pi)$. Note we do not use condition 4 to prove these results, and therefore they hold even if $\mathcal{L} = \mathcal{G}$. □

Because we have in this extension that Lemma 2 is extended without any changes to the thresholds, then all subsequent results that depend on these thresholds would hold. Note that in these results, a deforestation outcome does not necessarily mean that all locals are deforesting, but only that all locals who would benefit from deforestation are deforesting.

Proposition 7. The area conditions $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$ prevent deforestation only if at least one family of locals prefers the incentive ($\phi_F > \delta_F$ for some $F \in \pi^{\mathcal{F}}$), in which case: (a) With full ability to cooperate, $\bar{\mathbb{D}}$ and $\bar{\mathbb{U}}$ prevent deforestation; $\bar{\mathbb{D}}$ achieves compensation and $\bar{\mathbb{U}}$ achieves compensation if $\eta > \sum_{\ell \in \mathcal{L} : \delta_\ell > 0 \text{ and } \phi_\ell > \delta_\ell} (\phi_\ell - \delta_\ell)$; (b) With partial ability to cooperate, $\bar{\mathbb{D}}$ cannot prevent deforestation, whereas $\bar{\mathbb{U}}$ prevents deforestation if $\eta < \max_{S, F : S \subseteq \{\ell \in F : \delta_\ell > 0\}, F \in \pi^{\mathcal{F}}, \phi_F > \delta_F} \frac{(\phi_S - \delta_S)}{|\{\ell \in \mathcal{L} : \delta_\ell > 0\} \setminus S|}$.

The proof involves the same line of arguments as in the main text and is omitted for brevity.

EC.4.4. Maximizing Standing Forest Cover.

Although our focus has been on preventing *any* deforestation, our results can also inform a party seeking to maximize the amount of standing forest cover. Let d_ℓ^a denote the optimal amount of forest converted by local $\ell \in \mathcal{L}$ and assume that the incentive budget B is insufficient to prevent deforestation in the area (i.e., B is strictly lower than the minimum incentive cost in Figure 4.3). Moreover, we also recall the definition of the hybrid incentives in §4.3, which allow offering an incentive and condition focused on a subarea, to a subset of locals active therein.

If locals have full ability to cooperate, one can maximize the forest cover in the area by providing an incentive $\phi_S \searrow \delta_S$ with a single (sub)area no-deforestation condition $\bar{\mathbb{D}}^S$ to that subset of locals S satisfying $\delta_S < B$ that maximizes $\sum_{\ell \in S} d_\ell^a$. So the optimal set of locals S would thus be given by a solution to a knapsack problem:

$$\max_{x_\ell \in \{0,1\}} \sum_{\ell \in \mathcal{L}} x_\ell \cdot d_\ell^a$$
$$\text{such that } \sum_{\ell \in \mathcal{L}} x_\ell \cdot \delta_\ell \leq B.$$

If locals only have partial ability to cooperate, one should subdivide the area and its locals, as discussed in §4.3, and apply (sub)area conditions for several families $\mathcal{H} \subseteq \pi^{\mathcal{F}}$ and individual conditions for some other locals $G \in \mathcal{L} \setminus \cup_{H\in\mathcal{H}} H$, chosen to maximize $\sum_{\ell \in G} d^a_\ell + \sum_{H\in\mathcal{H}} \sum_{\ell\in H} d^a_\ell$. Some families $H \in \mathcal{H}$ with $\delta_H < \eta|H|$–i.e., for which it is more cost-effective to provide the incentive rather than block them–would be treated separately, with each offered payment $\phi_H \searrow \delta_H$ with a sub-area condition $\bar{\mathbb{D}}^H$ (or $\bar{\mathbb{U}}^H$, equivalently). The other families $\mathcal{F} \subseteq \mathcal{H}$ would be treated together as a local community $\bar{\mathcal{L}} = \cup_{H\in\mathcal{H}} F$, receiving a total payment corresponding to (16) (with $\pi^{\mathcal{F}}$ replaced by $\mathcal{F}$ and $\mathcal{L}$ replaced by $\bar{\mathcal{L}}$) and condition $\bar{\mathbb{U}}^{\bar{L}}$. The individuals in $\mathcal{G}$ would be selected so that other members of their family would not be able to pay them off to entice them to engage in deforestation.

These results can be formalized, but we omit details for space considerations.

EC.5. Illustration in Indonesia

East Kalimantan, Indonesia, has extensive forests at risk of conversion to palm oil farms. To gauge whether a conditional price premium for palm-fruit bunches could both prevent deforestation and achieve compensation, we conducted detailed household surveys in several villages. This section describes the resulting dataset and explains, step by step, how we deploy our analytical framework–offering a template for practitioners who wish to replicate the approach elsewhere.

In §EC.5.1, we describe the survey data and other datasets needed for our study. In §EC.5.2, we develop a procedure to estimate each farmer's value with deforestation and the incentive. In §EC.5.3, we apply our model separately for each village, with the incentive being a price premium and area conditions based on each village's perimeter. For each village, with $\mathcal{L}$ denoting the set of all locals in that village, we consider two cases: a case with full ability to cooperate ($\pi^{\mathcal{F}} = \{\mathcal{L}\}$) and an extreme case with *no* ability to cooperate, where each family is a singleton ($\pi^{\mathcal{F}} = \{\{\ell\} : \ell \in \mathcal{L}\}$). §EC.5.4 then examines a special case with partial ability to cooperate of practical importance, where $\pi^{\mathcal{F}} = \{S\} \cup \{\{\ell\} : \ell \in \mathcal{L} \setminus S\}$; here, locals in S form a tight-knit group (e.g., residents of the same village, members of the same cooperative) whereas all others can be thought of as "outsiders entrants" who are unable to cooperate with the tight-knit group or among themselves. This configuration allows us to examine the robustness of the area no-use condition with respect to entry by those outside the community. §EC.5.4 also conducts a few other important robustness checks.

EC.5.1. Description of the data

Our survey included 60 villages in two regencies of East Kalimantan, Indonesia, mapped in Figure EC.1 (the figure shows all villages in East Kalimantan, and those in our survey). In total, 420 farmers were surveyed, but we retain a subset of 391 farmers from 58 villages for our study. These are all farmers in our data with total land less than 20 hectares (ha) and all villages with at least two observations.

Table EC.2 provides brief summary statistics and Figure EC.2 shows histograms for all data fields. Each farmer in the data has multiple plots. We replace missing prices, costs, and interest rate values

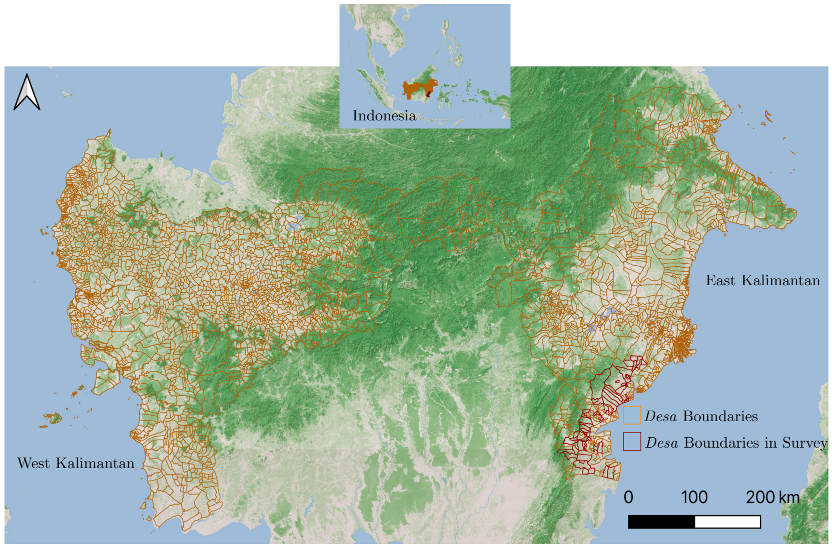

Figure EC.1 Map of East and West Kalimantan, Indonesia, showing the divisions into all rural villages (*desa*) in orange, and those in the survey in red. Darker shades of green denote more forest cover.

for each farmer with the median of the corresponding field over all the available data. Finally, because some farmers reported overly optimistic production values in our survey, we limit their maximum production quantities using the maximum attainable yields for palm trees in Indonesia (as a function of the age of the trees) according to Hoffmann et al. (2014).

Definition	Mean	Range
plot area $A_{\ell,i}$ (hectares)	2	0.3-17.5
tree age $a_{\ell,i}$ (years)	9.9	1-40
production $q_{\ell,i}$ (tFFB/year)	41.3	0.5-480
price $p_{\ell,i}$ (USD/tFFB)	90	51-129
transport cost $\tau_{\ell,i}$ (USD/tFFB)	11.8	1-29.6
harvest cost $h_{\ell,i}$ (USD/tFFB)	16	0.2-29.6
interest rate β_ℓ (% /year)	16.5	2.6-102

Table EC.2 Data by farmer-plot pairs (ℓ, i): The 391 survey participants produce palm fruit on 683 separate plots: $i \in \mathcal{P}_\ell$ indicates that plot i is among farmer ℓ's plots.

Additional Data Sources. Palm fruit production varies with tree age. Production is zero for the first two years after planting, peaks after eight years, and declines thereafter. We use yield data from Hoffmann et al. (2014) to account for the change in productivity over the whole time horizon. Based on this, Figure EC.3 shows a *normalized* value of the yield y_a as a function of the tree age a (i.e., years elapsed after replanting). This normalized measure takes values between 0 and 1 and is obtained by dividing the yield for trees of age a by the maximum attainable yield (at age 8 years).

To generate maps (as in Figure EC.1 and the future Figure EC.8), we combine global data on forest canopy cover from Potapov et al. (2021) with the village boundaries extracted from the sub-national administrative boundaries for Indonesia from OCHA (2020).

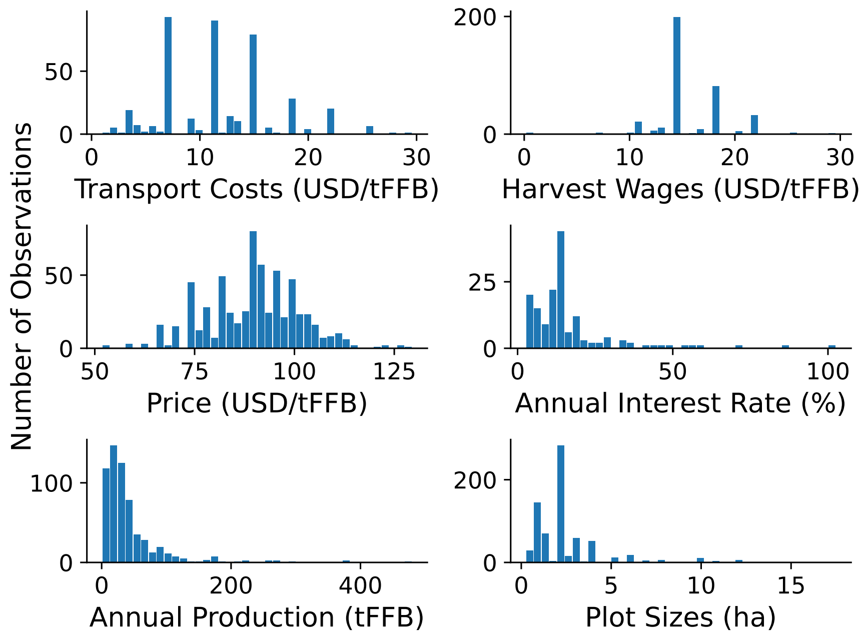

Figure EC.2 Distributions of key parameters in our data set. Each observation corresponds to a particular farmer and plot, except for the interest rates, where each observation corresponds to a specific farmer.

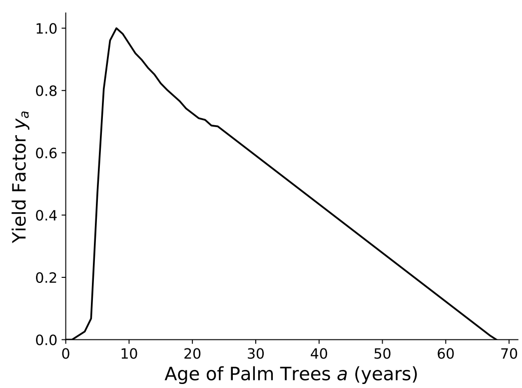

Figure EC.3 Yield Multiplier: The normalized attainable yield for palm oil in Indonesia as a function of tree age a. We calculate this by dividing the attainable yield in year a with the maximum attainable yield, which occurs at age 8 years.

EC.5.2. Model Calibration

A local ℓ is a palm farmer. Recall that his value from engaging in deforestation is $\delta_\ell := J_\ell(1,\text{no}) - c_\ell - J_\ell(0,\text{no})$ and his value from the incentive is $\phi_\ell := J_\ell(0,\text{yes}) - J_\ell(0,\text{no})$, where $J_\ell(0,\text{no})$ represents his status quo income, $J_\ell(0,\text{yes})$ his income with no deforestation and the incentive, and $J_\ell(1,\text{no}) - c_\ell$ his net income with deforestation. We develop a structural model to calibrate these model parameters for each ℓ so as to be representative of one of the 391 palm farmers in our survey. (These are all farms in the 58 villages, with the number of farmers $|\mathcal{L}|$ per village ranging from 35 to 295.) We apply robust Data Envelope Analysis (DEA) to *overestimate* each farmer's idiosyncratic value with deforestation δ_ℓ, so as to be conservative in predicting the performance of an incentive and condition.

Table EC.2 describes and assigns notation for the data we use from our survey. We use plot-level data because half of the surveyed farmers have more than one plot, and tree ages, production yields, and (in some cases) selling prices and production costs differ among a farmer's plots. Production is measured in metric tons of fresh fruit bunches (tFFB). Farmers generally reported their significant production costs as those for harvest labor and transport of fruit from the plot to the mill for sale. Half of the surveyed farmers did not report an interest rate to borrow money, so we substitute the median reported interest rate for β_ℓ; we use an analogous procedure in the few cases that the price, transport cost, or harvest cost is missing for a plot.

Lastly, we assume that any farmer can convert forest to a new plot by incurring cost $c^{\text{def}} = 375$ USD per hectare, comprised of the costs to clear forest by fire (5 USD/ha, per Falcon et al. 2022) and to plant saplings (2.96 USD/sapling and 125 saplings per hectare, per our survey).

Status Quo Income from Existing Plots. We estimate the net cash flow for farmer ℓ from existing plot $i \in \mathcal{P}_\ell$ in a future year when the trees reach age $a \geq a_{\ell,i}$ and with fruit price p as

$$I^e_\ell(i,a,p) = (p - h_{\ell,i} - \tau_{\ell,i}) \cdot q_{\ell,i} \cdot y_a / y_{a_{\ell,i}}, \text{ for any } a \geq a_{\ell,i}. \tag{EC.47}$$

Here, $y_a/y_{a_{\ell,i}}$ accounts for the predictable variation in fruit production with the age of the trees. We thus estimate the farmer's status-quo income without deforestation and without the incentive as

$$J_\ell(0,\text{no}) = \sum_{t=1}^{T} (1+\beta_\ell)^{-t} \sum_{i\in\mathcal{P}_\ell} I^e_\ell(i, a_{\ell,i}+t, p_{\ell,i}). \tag{EC.48}$$

We assume that a farmer discounts cash flows according to his interest rate to borrow money and uses a finite planning horizon T. All results in this section are for $T = 20$ years, and §EC.5.4.1 shows that (due to discounting) the results exhibit remarkably little variation with any choice of planning horizon larger than T=15. We assume a farmer's expected future prices and costs are the same as those he reported in the survey. This is not an unreasonable representation of information available to a smallholder farmer.

Income from Existing Plots with the Incentive. The incentive is a *price premium* p^* per tFBB (ton of FFB), so we estimate farmer ℓ's income without deforestation and with the incentive as

$$J_\ell(0,\text{yes}) = \sum_{t=1}^{T} (1+\beta_\ell)^{-t} \sum_{i\in\mathcal{P}_\ell} I^e_\ell(i, a_{\ell,i}+t, p_{\ell,i}+p^*), \tag{EC.49}$$

and his value from the incentive as

$$\phi_\ell(p^*) = J_\ell(0,\text{yes}) - J_\ell(0,\text{no}) = p^* \cdot \sum_{t=1}^{T} (1+\beta_\ell)^{-t} \sum_{i\in\mathcal{P}_\ell} q_{\ell,i} \cdot y_{(a_{\ell,i}+t)}/y_{a_{\ell,i}}. \tag{EC.50}$$

The maximum RSPO price premium contemporaneous with our survey is 30 USD/tFFB.

Income with Deforestation. We conservatively *overestimate* the area of forest x_ℓ that farmer ℓ would convert to a palm farm, and his resulting net income $J_\ell(1,\text{no}) - c_\ell$.

The first step is to estimate an efficient production frontier $u(A)$: maximum annual production quantity of palm fruit for a farmer with *total* land area A and trees at peak productive age 8 years. Scaling up the production quantity $q_{\ell,i}$ reported by farmer ℓ (for trees aged $a_{\ell,i}$) by a factor $y_8/y_{a_{\ell,i}} = 1/y_{a_{\ell,i}} \geq 1$, we estimate the *total peak production quantity* that farmer ℓ could have produced on all his existing plots if the trees were at the peak productive age:

$$\hat{q}_\ell := \sum_{i \in \mathcal{P}_\ell} q_{\ell,i}/y_{a_{\ell,i}}. \tag{EC.51}$$

Each point in Figure EC.4 (left) plots a farmer's total peak production quantity $\hat{q}_\ell$ and total land $A_\ell = \sum_{i \in \mathcal{P}_\ell} A_{\ell,i}$. The estimated efficient production frontier $u(A)$ (blue line) is the robust concave envelope of those points calculated by m-estimator robust DEA, as detailed below.

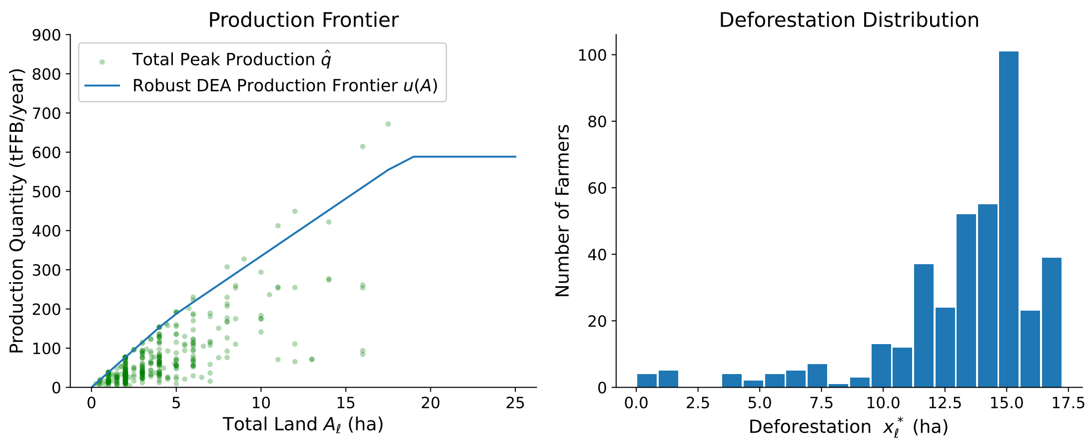

Figure EC.4 (Left) Scatter plot of each farmer's total peak production quantity $\hat{q}_\ell$ and total land $A_\ell = \sum_{i \in \mathcal{P}_\ell} A_{\ell,i}$, with $u(A)$, the robust efficient production frontier of these points estimated using m-estimator DEA. (Right) Histogram of a farmer's estimated optimal area to deforest x^*.

Second, we use that efficient production frontier to *overestimate* the net income that farmer ℓ could generate by deforesting a plot of area x_ℓ. The estimated annual production quantity for farmer ℓ from the deforested plot of area x_ℓ with trees at peak productive age is:

$$\hat{q}_\ell^{\text{def}}(x_\ell) := u\left(\sum_{i \in \mathcal{P}_\ell} A_{\ell,i} + x_\ell\right) - u\left(\sum_{i \in \mathcal{P}_\ell} A_{\ell,i}\right), \tag{EC.52}$$

and with trees of arbitrary age a it is $\hat{q}_\ell^{\text{def}}(x_\ell) \cdot y_a$. Hence, in the a^{th} year after deforesting the land and planting seedlings, the estimated net cash flow from the new plot is:

$$I_\ell^d(x_\ell, a) = (\overline{p}_\ell - \underline{h}_\ell - \underline{\tau}_\ell) \cdot \hat{q}_\ell^{\text{def}}(x_\ell) \cdot y_a, \text{ for any } a \geq 0, \tag{EC.53}$$

where $\overline{p}_\ell := \max_{i \in \mathcal{P}_\ell} p_{\ell,i}$, $\underline{h}_\ell := \min_{i \in \mathcal{P}_\ell} h_{\ell,i}$, and $\underline{\tau}_\ell := \min_{i \in \mathcal{P}_\ell} \tau_{\ell,i}$ denote the largest price obtained and lowest costs incurred by farmer ℓ on his existing plots, respectively.

Finally, we *overestimate* the net income for ℓ with deforestation and without the incentive by

$$J_\ell(1,\text{no}) - c_\ell = \max_{x_\ell \geq 0} \Big\{ \textstyle\sum_{t=1}^{T} (1+\beta_\ell)^{-t} \Big[\textstyle\sum_{i \in \mathcal{P}_\ell} I_\ell^e(i, a_{\ell,i}+t, p_{\ell,i}) + I_\ell^d(x_\ell, t) \Big] - c^{\text{def}} \cdot x_\ell \Big\}, \tag{EC.54}$$

and the value from deforestation δ_ℓ as,

$$\delta_\ell = J_\ell(1,\text{no}) - c_\ell - J_\ell(0,\text{no}) = \textstyle\sum_{t=1}^{T} (1+\beta_\ell)^{-t} I_\ell^d(x_\ell^*, t) - c^{\text{def}} \cdot x_\ell^*, \tag{EC.55}$$

where $c^{\text{def}} = 375$ USD/hectare is the cost to clear forest and plant seedlings. With x_ℓ^* denoting the solution to (EC.54), Figure EC.4 (right) shows the distribution of x_ℓ^* among farmers. Nearly all farmers (387 out of 391) would benefit from clearing some forest. None would clear more than 20 ha.

Data Envelope Analysis. To obtain the production frontier while systematically accounting for outliers, we use m-estimator Data Envelope Analysis from Aragon et al. (2005). We obtain the production frontier $u(A)$ by applying Algorithm 1 to the set of points $\{(A_\ell, \hat{q}_\ell) : \ell \in \cup_j \mathcal{L}_j\}$, where $\cup_j \mathcal{L}_j$ is the union of all the villages in the dataset.

Algorithm 1 Production Frontier $u(x)$

Require: $x \geq 0$, $\{(A_\ell, \bar{v}_\ell) : \ell \in \mathcal{L}\}$

procedure U(x)
  for $A \in \cup_{\ell \in \cup_j \mathcal{L}_j} A_\ell$ **do**
    for $b = 1$ to B **do**
      $\{q_b^1, ..., q_b^m\} \leftarrow$ A random sample with replacement of size m from $\{\bar{v}_\ell : A_\ell \leq A\}$
      $h_b(A) \leftarrow \max\{q_b^1, ..., q_b^m\}$
    end for
    $h(A) \leftarrow \frac{1}{B} \sum_{b=1}^{B} h_b(A)$
  end for
  $\{(A, \hat{h}(A))\} \leftarrow$ convex hull of $\{(A, h(A)) : A \in \cup_{\ell \in \cup_j \mathcal{L}_j} A_\ell\}$
  if $x \leq \max_{\ell \in \cup_j \mathcal{L}_j} A_\ell$ **then**
    $u(x) \leftarrow$ linear interpolation of $\{(A, \hat{h}(A))\}$ at x
  else
    $u(x) \leftarrow u(\max_{\ell \in \cup_j \mathcal{L}_j} A_\ell)$
  end if
end procedure

The procedure for obtaining the production frontier $u(x)$, for any $x \geq 0$ detailed in Algorithm 1 works in three parts: (i) first, it obtains the expected value of the DEA frontier defined by a sub-sample of m points with total area $A_\ell \leq x$. It uses a Monte-Carlo simulation, sampling B times and taking the average. We set $B = 500$, and $m = 150$. (ii) Because the sampling procedure in (i) need not produce a concave function, this step computes the convex hull of the points obtained. (iii) Finally, a linear interpolation of the points in the convex hull leads to the value of $u(x)$. We assume the production would be constant for any x larger than the maximum total land registered in our dataset.

Blocking Cost. We consider a range of blocking cost values $\eta \in (0, 3000]$ USD. Given the difficulty of estimating the cost of preventing deforestation by fire in the Indonesian context, we focus on the cost of blocking palm production. The upper bound of 3000 USD is the cost to use bulldozers and excavators to clear 20 hectares of light forest (Falcon et al. 2022). Lower blocking cost could be achieved, for instance, by cutting palm seedlings with a chainsaw (Villadiego 2017).

EC.5.3. Performance of a Price Premium Conditional on $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$

For each village in the dataset, we apply the results in §3 with the price premium as the incentive and with each condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$. Importantly, we treat the farmers in our sample within that village as the entire population of the village; provided that this is a representative sample, this should not bias our results. (Proposition 8 in §EC.5.5 formalizes this result.)

Figure EC.5 illustrates the *mismatch* inherent in a price premium incentive to prevent deforestation: the largest value from the incentive goes to farmers with the least value from deforestation, whereas farmers with the least land and largest value from deforestation gain the least value from the incentive. Due to this mismatch and the low value of the RSPO price premium $p^* = 30$ USD/tFFB, 94% of the farmers prefer deforestation (have $\phi_\ell < \delta_\ell$).

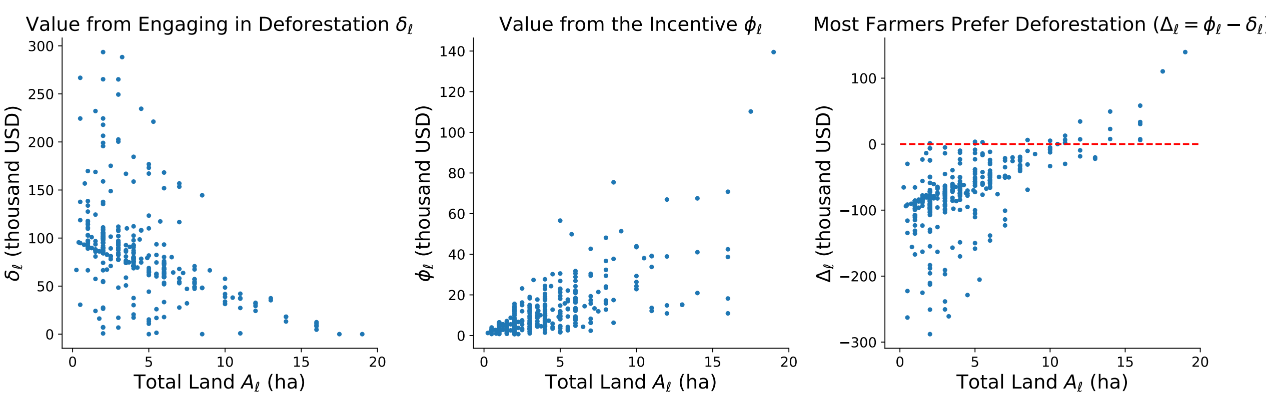

Figure EC.5 Scatter plots of a farmer's value δ_ℓ from engaging in deforestation, value ϕ_ℓ from a price premium $p^* = 30$ USD/tFFB, and preference for deforestation $\Delta_\ell = (\phi_\ell - \delta_\ell)$ as a function of the farmer's total land A_ℓ.

We apply the area No-Deforestation Condition $\bar{\mathbb{D}}$ and area No-Use Condition $\bar{\mathbb{U}}$ at a village level. In each of the 58 villages, all palm farmers in the village get the price premium on all their production if and only if the specified condition holds for that village. For each of those villages, §EC.5.1 reports the number of households in the village that are palm farmers, estimated from Indonesia census data, and we set $|\mathcal{L}|$ for the village to that number. We assume that the surveyed farmers from each village are representative of the other farmers in their village and replicate their model parameters to characterize the set of farmers $\ell \in \mathcal{L}$ in the village.

With the RSPO price premium $p^* = 30$ USD/tFFB, only the area no-use condition $\bar{\mathbb{U}}$ can possibly prevent deforestation. In each of the 58 villages, farmers collectively prefer deforestation ($\phi_{\mathcal{L}} < \delta_{\mathcal{L}}$), so $\bar{\mathbb{U}}$ can prevent deforestation in a village *only* if the farmers don't have full ability to cooperate, as shown by Theorem 2. In the case where families consist of singletons $\pi^{\mathcal{F}} = \{\{\ell\} : \ell \in \mathcal{L}\}$, $\bar{\mathbb{U}}$ prevents deforestation in 23 villages if the blocking cost $\eta \leq 10$ USD, in only one village at $\eta = 500$ USD, and in none for $\eta \geq 1,060$ USD.

What is the minimum (uniform) price premium that would prevent deforestation and achieve compensation, respectively, in *all* 58 villages? From (EC.50), the value of the incentive $\phi_\ell(p^*)$ to each farmer ℓ increases linearly with the price premium p^*. Depending on the condition $\mathbb{C} \in \{\mathbb{I}, \bar{\mathbb{D}}, \bar{\mathbb{U}}\}$ and the setting, we determine the minimum value of p^* that satisfies the necessary requirements in (13), (14), or (15a)-(15b) respectively, for all villages. Figure EC.6 shows the minimum price premium for each condition and case considered (except $\bar{\mathbb{D}}$ in the setting with no ability to cooperate, where $\bar{\mathbb{D}}$ cannot prevent deforestation). The minimum price premium to prevent deforestation is much lower for area No-Use Condition $\bar{\mathbb{U}}$ (and $\bar{\mathbb{D}}$ with full ability to cooperate) than for the individual condition $\mathbb{I}$. For $\bar{\mathbb{U}}$ it is lower with full ability to cooperate than in the case with no ability to cooperate if and only if the blocking cost η exceeds 630 USD. As in §4, full ability to cooperate reduces the cost to prevent deforestation if and only if the blocking cost is sufficiently large. For $\bar{\mathbb{U}}$ and no ability to cooperate, the minimum price premium to prevent deforestation increases with η, from 471 USD/tFFB at η=1 USD to 2496 USD/tFFB at η=3000 USD. For $\bar{\mathbb{U}}$ with full ability to cooperate, the minimum price premium is invariant with η. To achieve compensation, the minimum price premium is the same for $\bar{\mathbb{U}}$ and $\mathbb{I}$, and (under full ability to cooperate) is much lower for $\bar{\mathbb{D}}$.

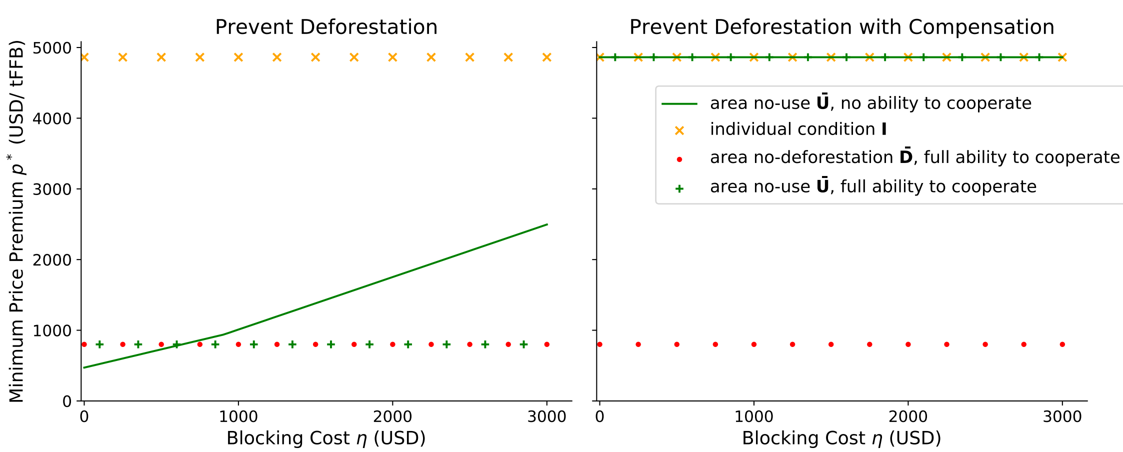

Figure EC.6 Minimum uniform price premium to prevent deforestation (left) and achieve compensation (right) in all villages.

Figures EC.7 and EC.8 depict the *village-specific* minimum price premiums to prevent deforestation and achieve compensation, respectively, which differ among the villages. If farmers have full ability to cooperate, a price premium below 250 USD prevents deforestation (with $\bar{\mathbb{U}}$) and achieves compensation (with $\bar{\mathbb{D}}$) in most villages. That is less than a third of the 800 USD/tFFB *uniform* price premium needed to prevent deforestation in all villages, which suggests that village-specific price premiums can meaningfully reduce the cost of preventing deforestation (and achieving compensation).

Taken together, our findings in this section indicate that–even under deliberately conservative opportunity-cost assumptions–area-based conditions, especially when coupled with tailored area-specific incentives, remain a powerful instrument for curbing deforestation.

Two caveats about our results also deserve highlighting. First, we discourage practitioners from applying our estimated price premiums verbatim, because those figures are probably inflated by the assumptions used to value deforestation benefits in (EC.54). A real-world application should start with richer, site-specific data to construct a localized efficiency frontier and may also adopt production-function estimation techniques that are less conservative. Second, we acknowledge that although implementing *village-specific* price premiums in practice may face some practical challenges, such as side-selling and equity concerns (particularly when villages neighbor each other). However, REDD+ projects have recently been successfully implemented in Indonesia at a sub-national jurisdictional level, including village-specific projects (see Irawan et al. 2019, Wahyudi et al. 2024), which shows that such conditional incentives may remain viable.

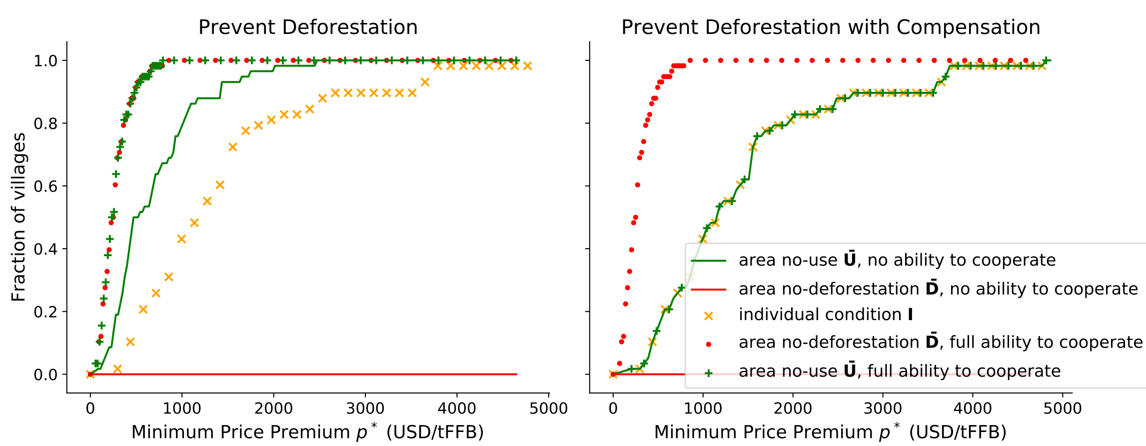

Figure EC.7 Fraction of villages in which a condition prevents deforestation (left) and achieves compensation (right) as a function of the price premium. For $\bar{\mathbb{U}}$, this is at $\eta = 3,000$ USD; the fraction of villages would be higher at lower blocking cost.

EC.5.4. Robustness Checks

We conduct a few important robustness checks for these empirical results.

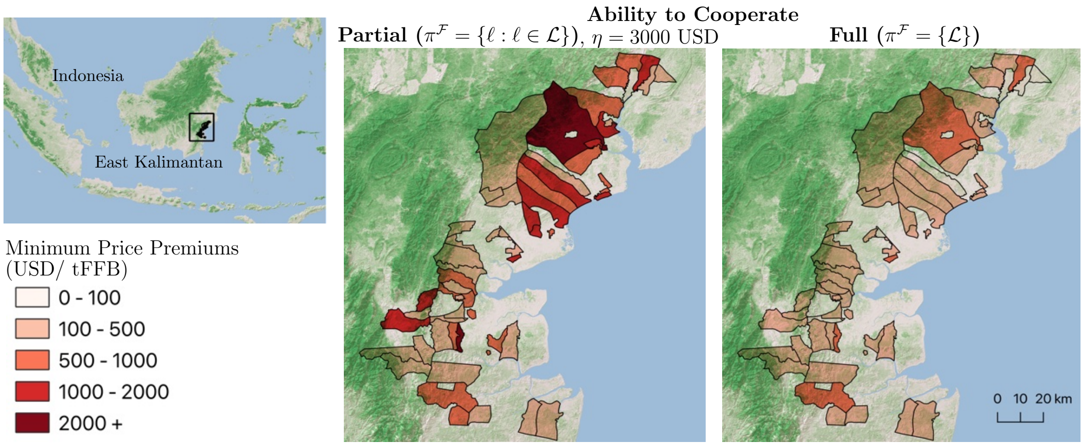

Figure EC.8 Minimum price premium to prevent deforestation and, with $\bar{\mathbb{D}}$, and full ability to cooperate, achieve compensation.

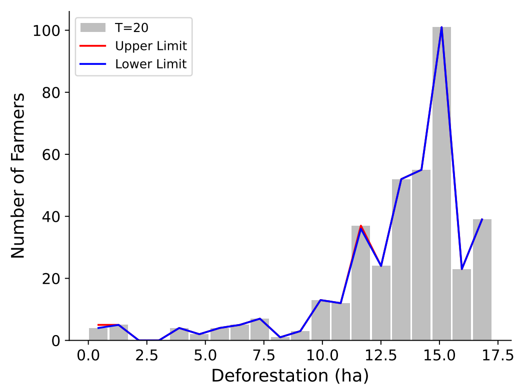

Figure EC.9 Histogram of the estimated optimal area to deforest x^* at $T = 20$ years, with upper limit (lower limit) showing the maximum (minimum) number of farmers in each bin for $T \in [15, 60]$ years.

EC.5.4.1. Robustness with respect to the planning horizon T. Our base analysis considered a planning horizon of $T = 15$. We now relax this assumption and consider larger values of T. Due to the heavy discounting, this does not carry much impact on the results presented in §EC.5. We re-computed all our results with $T \in [15, 60]$ and Figure EC.9 shows that the deforestation distribution remains virtually identical for any T in that range. While Figures EC.10 and EC.11 show that the uniform and village-specific minimum prices would also remain virtually unchanged. The most meaningful change is in the uniform minimum price that would prevent deforestation with compensation in all 58 villages under the individual incentive; this changes from 4,456 USD/tFFB at $T = 15$ years to 5,193 USD/tFFB at $T = 60$ years.

EC.5.4.2. Deterring Entrants: Robustness of area no-use condition $\bar{\mathbb{U}}$. We now consider a special case with partial ability to cooperate of practical significance. Specifically, we take the partition of families as $\pi^{\mathcal{F}} = \{S\} \cup \{\{\ell\} : \ell \in \mathcal{L} \setminus S\}$ and we only consider incentives with $\phi_\ell = 0$ for all $\ell \in \mathcal{L} \setminus S$. This emulates a practical setting where a tight-knit group S (e.g., suppliers to a commodity

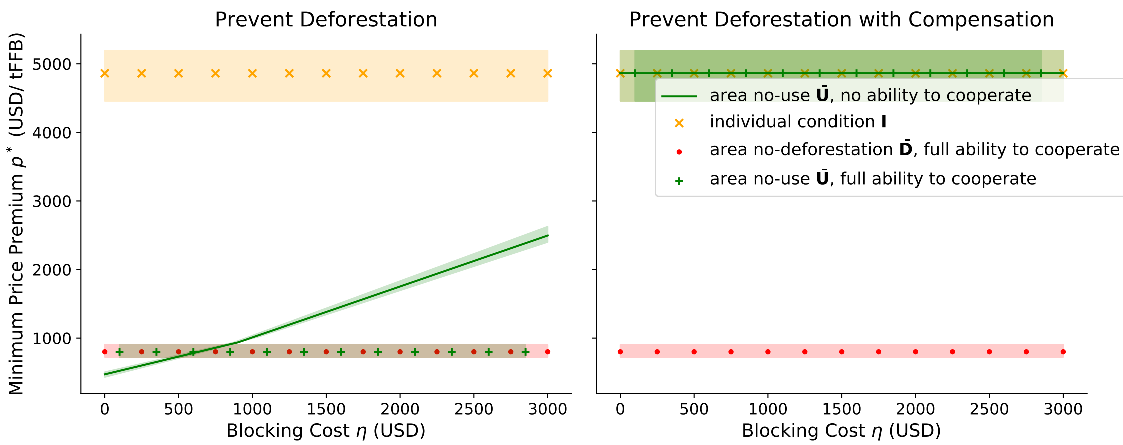

Figure EC.10 Minimum price premium p^* that would prevent deforestation (left) and achieve compensation (right) in all villages, for $T = 20$ years, together with shaded areas showing the variation for $T \in [15, 60]$ years.

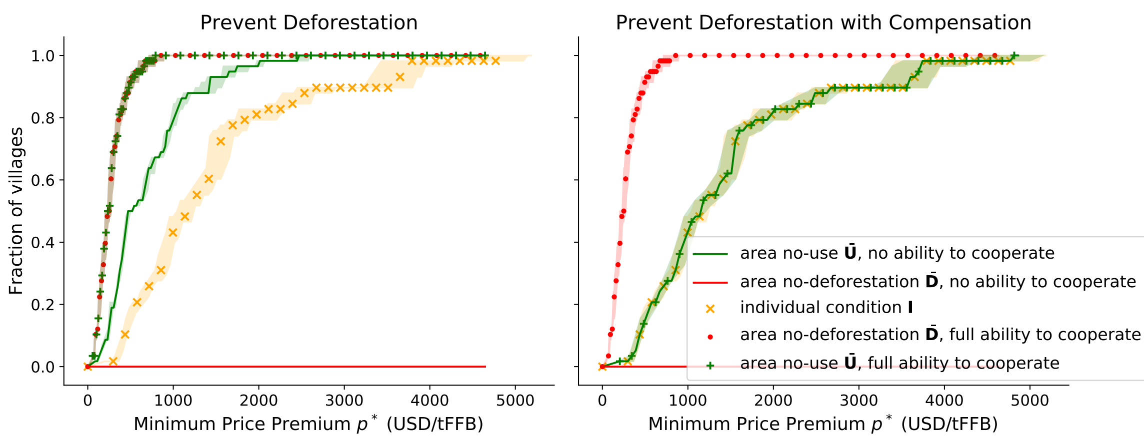

Figure EC.11 Fraction of villages in which each condition prevents deforestation (left) and achieves compensation (right) as a function of the price premium p^*, considering $\eta = 3,000$ USD and $T = 20$ years. The shaded areas show the variation of these curves for $T \in [15, 60]$ years.

buyer, residents of the same village, members of the same cooperative) are the only ones who receive the incentive, whereas locals in $\mathcal{L} \setminus S$ are "outsiders" who cannot receive any incentive and cannot cooperate with the tight-knit group. We refer to locals in $\mathcal{L} \setminus S$ as *entrants.*[5]

In many settings, it is challenging to determine the number of entrants in a community. So instead of trying to estimate this number, we show that even if the price premium p^* is calculated *as if there are no entrants*–so under the assumption that $\mathcal{L} = S$–the resulting incentive with $\bar{\mathbb{U}}$ will still prevent deforestation even for a large number of entrants. To that end, to compute the minimum price premiums, we assume that $S = \mathcal{L}$, and we then calculate the number of entrants that would still be in the community while preventing deforestation under $\bar{\mathbb{U}}$.

[5] That entrants cannot cooperate among themselves is irrelevant in what follows: taking an arbitrary partition of entrants into families would not change any results.

One can readily verify Theorem 2 implies that if a price premium p^* conditional on $\bar{\mathbb{U}}$ prevents deforestation without any entrants, it also prevents deforestation with up to

$$M := \left\lfloor \sum_{\ell \in H} \Big(\phi_\ell(p^*) - \delta_\ell\Big)/\eta \right\rfloor - |S| + |H| \text{ with } H = \{\ell \in S : \phi_\ell(p^*) > \delta_\ell - \eta\} \tag{EC.56}$$

entrants. Similarly, if a price premium p^* achieves compensation, it would prevent deforestation with compensation, with up to

$$\bar{M} := \left\lfloor \sum_{\ell \in S} \Big(\phi_\ell(p^*) - \delta_\ell\Big)/\eta \right\rfloor \geq M \tag{EC.57}$$

entrants. The maximum number of entrants deterred (M or $\bar{M}$ depending on the setting) grows infinitely large as the blocking cost η decreases towards zero, decreases with the blocking cost η, and increases with the price premium p^*.

Estimating the number of farmers in the village. Recall that in view of Proposition 8, our analysis so far could ignore the precise number of farmers in each village (as long as our sample was properly stratified and representative). However, the number of farmers in each village matters here because the number of entrants that can be deterred grows with that value.

Our approach in this section will be to assume that the full population of palm farmers in the village can be obtained by suitably duplicating the farmers in our dataset from that village. (That is, if the village has N palm farmers and we have n farmers in our dataset, we simply duplicate each farmer in the dataset $\lceil N/n \rceil$ times.) To that end, we must estimate the number of palm farmers in each village. Because each farmer really represents a farming household, we first estimate the number of households in each village: we divide the total population of each district by the number of villages in the district (to estimate an average village population) and then divide that value by 5.12, which is the average household size in East Kalimantan according to BPS, Indonesia (2010). Finally, we multiply the estimated number of households by 38%, which is the mean fraction of households that farm palm, according to BPS, Indonesia (2013). Table EC.3 shows our estimates.

Results. The maximum number of entrants that could be deterred is remarkably *large*, even if the *minimum* price premium was obtained assuming no entrants. In Table EC.4, "uniform p^*" refers to the minimum uniform price premium conditional on $\bar{\mathbb{U}}$ that prevents deforestation and achieves compensation, respectively, in *all* 58 villages, assuming no entrants. See Figure EC.6 for the exact values. Analogously, "village-specific p^*" refers to each village's minimum price premium conditional on $\bar{\mathbb{U}}$ to prevent deforestation and achieve compensation, respectively, assuming no entrants. For each village, we calculate the maximum number of entrants deterred (M or $\bar{M}$ depending on the setting) at blocking cost values $\eta = 1000$ and $\eta = 3000$. The table shows the range over all villages in each setting. Achieving compensation or using a uniform price premium for all villages requires a higher price premium, which increases the maximum number of entrants deterred. With the uniform p^*, M is large except for the one village whose village-specific minimum price premium to prevent

District	District Population (people)	Number of Villages	Village Population (people)	Village Households	Palm Households $\|\mathcal{L}\|$
Tanah Grogot	63,311	16	3,957	773	295
Waru	15,643	4	3,911	764	292
Penajam	66,983	23	2,912	569	217
Batu Sopang	22,540	9	2,504	489	187
Babulu	29,434	12	2,453	479	183
Sepaku	30,863	15	2,058	402	154
Pasir Belengkong	23,543	15	1,570	307	117
Kuaro	23,934	13	1,841	360	137
Long Ikis	36,701	26	1,412	276	105
Tanjung Harapan	7,720	7	1,103	215	82
Batu Engau	11,662	13	897	175	67
Muara Samu	4,221	9	469	92	35

Table EC.3 District and village information, including the estimated number of palm farming households, which we take as the total number of locals $|\mathcal{L}|$ in the village for our model.

deforestation exactly equals that uniform p^*. With village-specific p^*, M is large with price premiums that achieve compensation, except in the 13 villages where these prices match the corresponding minimum price premiums needed to prevent deforestation with no entrants. M and $\bar{M}$ are very large in all settings and all villages; the village with the least farmers (only 35 farmers) consistently has the least M and $\bar{M}$, and yet even with maximum blocking cost η=3,000 USD and the village-specific minimum price that prevents deforestation assuming no entrants, that small village deters up to $M = 194$ entrants, over five times the number of farmers in the cooperative S!

How does cooperation in S make the performance of a price premium conditional on $\bar{\mathbb{U}}$ so highly robust to potential entrants? A price premium conditional on $\bar{\mathbb{U}}$ must be large enough that

$$\textstyle\sum_{\ell \in S}(\phi_\ell(p^*) - \delta_\ell) > 0 \tag{EC.58}$$

to prevent deforestation. In each of the 58 villages, at the village-specific minimum price premium to prevent deforestation (determined by EC.58), the subset of farmers $H = \{\ell \in S : \phi_\ell(p^*) > \delta_\ell - \eta\}$ have large $\sum_{\ell \in H}(\phi_\ell(p^*) - \delta_\ell)$ and hence a credible threat to block all the other farmers plus a large number of potential entrants, even at the maximum blocking cost $\eta = 3000$ USD. This entry deterrence rests on the heterogeneity of the farmers. Additionally, for any price premium that satisfies (EC.58), cooperation and utility transfer enable farmers to deter more entrants. Without cooperation in S, blocking of entrants would have to be done by just one farmer with the greatest $\phi_\ell(p^*) - \delta_\ell$, whereas through cooperation and utility transfer, farmers can pool their resources to block, which deters more entrants. This echoes the observation in §4 that the ability to cooperate reduces the cost to prevent deforestation when the blocking cost is not too large.

The results show quite convincingly that a conditional incentive that uses a village-specific price premium and a village-area no-use condition $\bar{\mathbb{U}}$ would prevent a large number of outsiders from clearing forest and voiding the incentive for the local community.

Prevent Deforestation		Achieve Compensation	
$\eta = 1,000$	$\eta = 3,000$	$\eta = 1,000$	$\eta = 3,000$
2,744 - 264,362	905 - 88,120	27,775 - 1,707,419	9,258 - 569,139
626 - 15,261	194 - 4,918	2,470 - 357,614	823 - 119,204

Table EC.4 Range among villages of the maximum number of entrants deterred, with the minimum price premium calculated assuming no entrants $S = \mathcal{L}$.

EC.5.4.3. Robustness with respect to village size. Our analysis in §EC.5 considers all villages in our dataset, with number of locals $|\mathcal{L}|$ varying from 35 to 295. Although there are many agricultural cooperatives in Indonesia with memberships within these ranges–in particular, the first cooperative to be RSPO certified in 2021 consists of 209 farmers (RSPO 2021)–it is reasonable to expect that having full ability to cooperate would be simpler in smaller villages. So this section repeats our analysis for those villages that have fewer locals (from fewer than 200 to fewer than 50).

Table EC.5 shows the size of the reduced dataset, considering only villages with a smaller number of oil-palm farmers. Our full dataset includes 58 villages with 391 observations. As we restrict the maximum number of oil palm farmers in the villages, we reduce the total number of observations. We observe only 3 villages with fewer than 50 oil palm farmers, and for these three villages, we have only 18 observations. This reduced number of observations reduces the ability to generalize results drawn from these smaller datasets.

max $|\mathcal{L}|$	**200**	**150**	**100**	**50**
number of villages	47	29	9	3
number of observations	313	194	56	18

Table EC.5 Number of villages in our dataset with fewer than 200, 150, 100, and 50 palm farmers and the total number of observations across all of these villages.

Table EC.6 and Figures EC.12-EC.14 summarize the results, namely the minimum uniform price premiums p^* required to prevent deforestation (and achieve compensation in the cases of the individual condition $\mathbb{I}$ and the area no-deforestation condition $\bar{\mathbb{D}}$ with full ability to cooperate) in villages with fewer than 200, 150, 100, and 50 oil palm farmers.

We can see that when filtering based on fewer than 200 or fewer than 150 locals, respectively, the minimum price premiums are identical, and almost the same as in the full dataset. The only difference is that for the area No-Use condition $\bar{\mathbb{U}}$, when locals have partial ability to cooperate, the price premium increases faster for higher values of η in the full dataset, reaching 2496 USD at $\eta = 3000$, as opposed to the 2022 USD for the reduced dataset.

Considering only villages with fewer than 100 locals, the minimum price premium to prevent deforestation under $\mathbb{I}$ (and achieve compensation under $\bar{\mathbb{U}}$) is the same as in the full dataset (4863USD). While the minimum prices to prevent deforestation under $\bar{\mathbb{U}}$ and achieve compensation under $\bar{\mathbb{D}}$

max $\lvert\mathcal{L}\rvert$	**200**	**150**	**100**	**50**
min p^*, $\mathbb{I}$ (USD/tFFB)	4863	4863	4863	2494
min p^*, $\bar{\mathbb{D}}$, full ability to cooperate (USD/tFFB)	800	800	561	434
min p^*, $\bar{\mathbb{U}}$, $\eta = 1$USD, partial ability to cooperate (USD/tFFB)	471	471	334	185
min p^*, $\bar{\mathbb{U}}$, $\eta = 3000$USD partial ability to cooperate (USD/tFFB)	2022	2022	935	427

Table EC.6 Minimum homogeneous prices that prevent deforestation under each condition and ability to cooperate (where $\pi^{\mathcal{F}} = \{\{\ell\} : \ell \in \mathcal{L}\}$ when locals have partial ability to cooperate), considering only villages with fewer than 200, 150, 100, and 50 oil palm farmers. Under the individual condition $\mathbb{I}$ and the area no-deforestation condition $\bar{\mathbb{D}}$, these prices prevent deforestation with compensation as well.

and full ability to cooperate are lower. While it is to be expected that the values are lower (we are considering a subset of the villages), the values are still in the same order of magnitude as those obtained using the whole dataset. Moreover, we consistently observe the same relationship between the prices for $\mathbb{I}$ and both area conditions; to prevent deforestation, both area conditions are significantly lower than the individual, and for low blocking costs (below 1130USD) $\bar{\mathbb{U}}$ with partial ability to cooperate (and $\pi^{\mathcal{F}} = \{\{\ell\} : \ell \in \mathcal{L}\}$) results in lower price premiums, while to achieve compensation, $\bar{\mathbb{D}}$ with full cooperation results in the lowest price premium.

Considering only villages with fewer than 50 locals, reduces the dataset to only 3 villages and 18 observations. Nevertheless, the main observations from the whole dataset are preserved, although the estimated minimum prices are lower. In particular, we see that for $\eta < 3050$USD, $\bar{\mathbb{U}}$ results in lower price premiums to prevent deforestation when locals have partial ability to cooperate (and $\pi^{\mathcal{F}} = \{\{\ell\} : \ell \in \mathcal{L}\}$). It is, nevertheless, hard to draw conclusions from this reduced dataset, as it includes a very small number of villages and observations.

We conclude then that our main observations in §EC.5 are robust to considering only villages with a small number of locals.

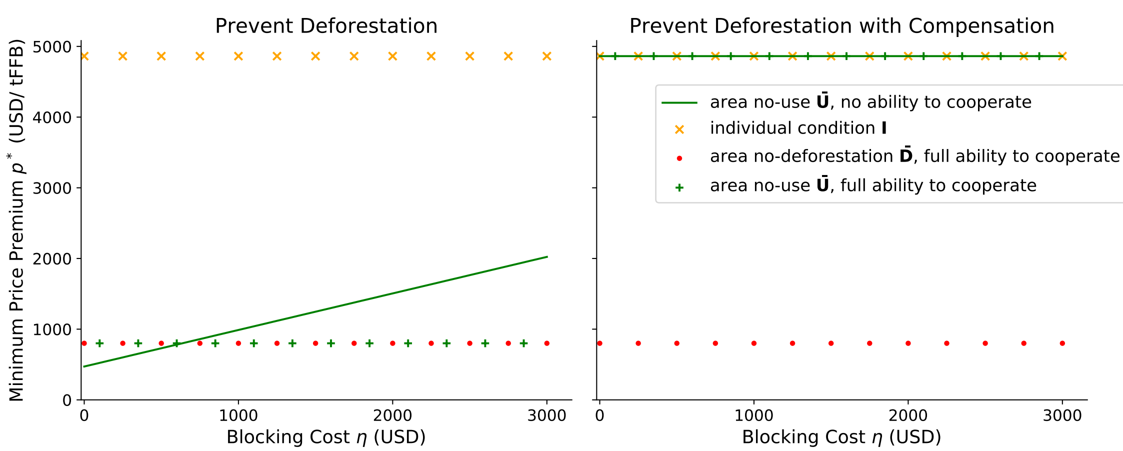

Figure EC.12 Minimum uniform price premium to prevent deforestation (left) and achieve compensation (right) in all villages with fewer than 150 oil palm farmers (the same prices apply when considering all villages with fewer than 200 oil palm farmers).

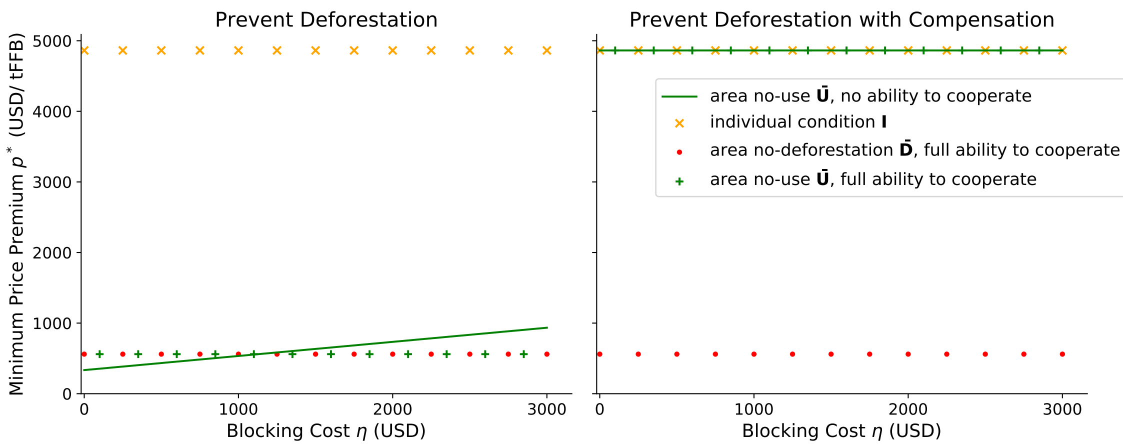

Figure EC.13 Minimum uniform price premium to prevent deforestation (left) and achieve compensation (right) in all villages with fewer than 100 oil palm farmers.

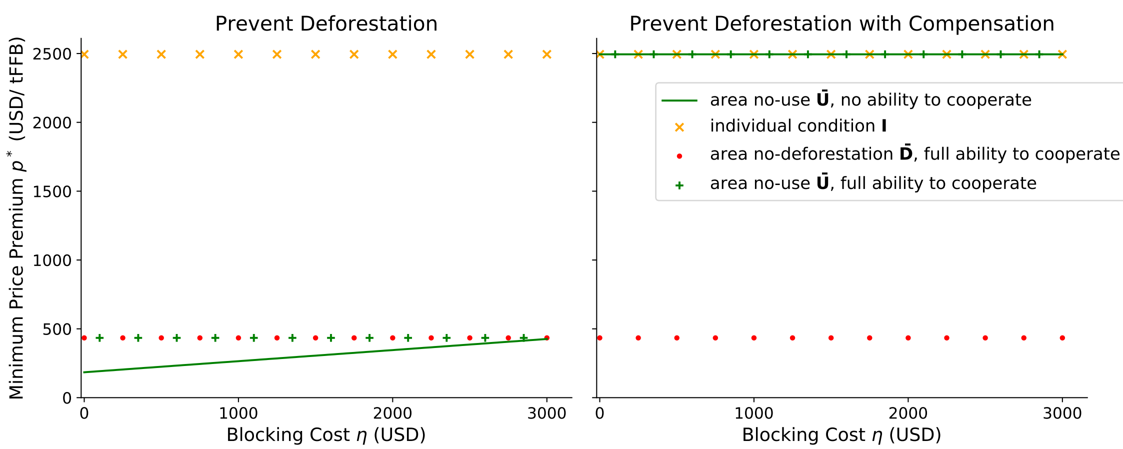

Figure EC.14 Minimum uniform price premium to prevent deforestation (left) and achieve compensation (right) in all villages with fewer than 50 oil palm farmers.

EC.5.5. Technical Supplement

The results in §EC.5.3 implicitly assumed that the surveyed locals in each village represent *all* palm-farmers in that village. We show here that our results are consistent, provided the surveyed sample is representative. In particular, we show that given any problem instance, a condition prevents deforestation (and achieves compensation) in this instance if and only if it does so in the instance arising from duplicating the original instance k times (for any positive integer k).

PROPOSITION 8. Consider a problem instance characterized by $\mathcal{L} = \{1, 2, \ldots, |\mathcal{L}|\}$, $\pi^{\mathcal{F}}$, and given $\{\phi_\ell\}_{\ell \in \mathcal{L}}$, $\{\delta_\ell\}_{\ell \in \mathcal{L}}$. For a positive integer k, consider a new problem instance obtained by duplicating the original instance k times, that is, where the set of locals is $\tilde{\mathcal{L}} := \{1, 2, \ldots, k \cdot |\mathcal{L}|\}$, the partition into families is $\tilde{\pi^{\mathcal{F}}} = \{\bigcup_{i \in \{1,\ldots,k} F_i,\ \text{for } F \in \pi^{\mathcal{F}}\}$, where for each $i \in \{1, \ldots, k\}$ $F_i = \{1 + j + |\mathcal{L}| i \text{ for all } j \in F\}$, and the values from the incentives and from deforestation are $\tilde{\phi_h} = \phi_{1+((h-1) \bmod |\mathcal{L}|)}$, $\tilde{\delta_h} = \delta_{1+((h-1) \bmod |\mathcal{L}|)}$ for all $h \in \tilde{\mathcal{L}}$.

(i) The individual condition $\mathbb{I}$ *prevents deforestation* (*and achieves compensation*, respectively) for the problem instance with $\mathcal{L}$, $\pi^{\mathcal{F}}$ and $\{\phi_\ell\}_{\ell\in\mathcal{L}}$, $\{\delta_\ell\}_{\ell\in\mathcal{L}}$ if and only if it prevents deforestation (*and achieves compensation*, respectively) for the problem instance with $\tilde{\mathcal{L}}$, $\tilde{\pi^{\mathcal{F}}}$, $\{\tilde{\phi}_i\}_{i\in\tilde{\mathcal{L}}}$, and $\{\tilde{\delta}_i\}_{i\in\tilde{\mathcal{L}}}$.

(ii) The area No-Deforestation condition $\bar{\mathbb{D}}$ *prevents deforestation* (and *achieves compensation*, respectively) for the problem instance with $\mathcal{L}$, $\pi^{\mathcal{F}}$, $\{\phi_\ell\}_{\ell\in\mathcal{L}}$, and $\{\delta_\ell\}_{\ell\in\mathcal{L}}$ if and only if it prevents deforestation (*and achieves compensation*, respectively) for the problem instance with $\tilde{\mathcal{L}}$, $\tilde{\pi^{\mathcal{F}}}$, $\{\tilde{\phi}_i\}_{i\in\tilde{\mathcal{L}}}$, and $\{\tilde{\delta}_i\}_{i\in\tilde{\mathcal{L}}}$.

(iii) The area No-Use condition $\bar{\mathbb{U}}$ *prevents deforestation* (and *achieves compensation*, respectively) for the problem instance with $\mathcal{L}$, $\pi^{\mathcal{F}}$, $\{\phi_\ell\}_{\ell\in\mathcal{L}}$, $\{\delta_\ell\}_{\ell\in\mathcal{L}}$, and a blocking cost of η if and only if it prevents deforestation (*and achieves compensation*, respectively) for the problem instance with $\tilde{\mathcal{L}}$, $\tilde{\pi^{\mathcal{F}}}$ and $\{\tilde{\phi}_i\}_{i\in\tilde{\mathcal{L}}}$, $\{\tilde{\delta}_i\}_{i\in\tilde{\mathcal{L}}}$, and a blocking cost of η.

Proof: (i) As discussed in §2, the individual condition $\mathbb{I}$ prevents deforestation (and also *achieves compensation*) if and only if $\phi_\ell > \delta_\ell, \forall\, \ell \in \mathcal{L}$, which holds if and only if $\phi_{\ell^i} > \delta_{\ell^i}, \forall\, \ell^i \in \tilde{\mathcal{L}}$.

(ii) By Theorem 1, $\bar{\mathbb{D}}$ prevents deforestation (and achieves compensation, respectively) in the problem instance with $\mathcal{L}$, $\pi^{\mathcal{F}}$, $\{(\phi_\ell,\delta_\ell)\}_{\ell\in\mathcal{L}}$ if and only if $\pi^{\mathcal{F}} = \{\mathcal{L}\}$ and $\phi_{\mathcal{L}} > \delta_{\mathcal{L}}$, which occurs if and only if $\tilde{\pi^{\mathcal{F}}} = \{\tilde{\mathcal{L}}\}$ and $\tilde{\phi}_{\tilde{\mathcal{L}}} > \tilde{\delta}_{\tilde{\mathcal{L}}}$, which gives the desired result.

(iii) By Theorem 2, $\bar{\mathbb{U}}$ prevents deforestation in the problem instance with $\mathcal{L}$, $\pi^{\mathcal{F}}$, $\{(\phi_\ell,\delta_\ell)\}_{\ell\in\mathcal{L}}$ if and only if $\eta < \underline{\eta}_2^{\mathrm{TU}} = \max_{F,S:F\in\pi^{\mathcal{F}},S\subseteq F,\phi_F>\delta_F,S\neq\mathcal{L}} \frac{(\phi_S-\delta_S)}{|\mathcal{L}\setminus S|}$, or equivalently,

$$(\phi_S - \delta_S) > \eta\cdot(|\mathcal{L}| - |S|) \text{ for some } S\subseteq F \text{ and } F\in\pi^{\mathcal{F}} \text{ such that } \phi_F > \delta_F. \tag{EC.59}$$

Similarly, $\bar{\mathbb{U}}$ prevents deforestation for the instance with $\tilde{\mathcal{L}}, \tilde{\pi^{\mathcal{F}}}$, $\{\tilde{\phi}_i\}_{i\in\tilde{\mathcal{L}}}$, and $\{\tilde{\delta}_i\}_{i\in\tilde{\mathcal{L}}}$ if and only if

$$\tilde{\phi}_{\tilde{S}} - \tilde{\delta}_{\tilde{S}} > \eta\cdot(|\tilde{\mathcal{L}}| - |\tilde{S}|) \text{ for some } \tilde{S}\subseteq\tilde{F}, \text{ and } \tilde{F}\in\tilde{\pi^{\mathcal{F}}}, \text{ such that } \tilde{\phi}_{\tilde{F}} > \tilde{\delta}_{\tilde{F}}. \tag{EC.60}$$

We will show that (EC.59) and (EC.60) are equivalent. That (EC.59) implies (EC.60) is immediate, simply by taking the set $\tilde{S} = \{\ell + n\cdot|\mathcal{L}| : \ell\in S,\, n\in\{0,\dots,k-1\}\}\subseteq\tilde{\mathcal{L}}$. To show that (EC.60) implies (EC.59), we first argue that if (EC.60) holds for some $\tilde{F}\in\pi^{\mathcal{F}}$ and $\tilde{S}\subseteq\tilde{F}$, it must hold for $\tilde{F}$ and $\tilde{H} = \{\ell + n\cdot|\mathcal{L}| : \ell\in H,\, n\in\{0,\dots,k-1\}\}$ where $H = \{\ell\in F : (\phi_\ell - \delta_\ell) > -\eta\}$ and $F = \{i\in\tilde{F} : i \le |\tilde{F}|/k\}$, that is, F is the family in $\pi^{\mathcal{F}}$ that scales to $\tilde{F}$, and H is the subset in F that scales to $\tilde{H}$. From this, it is immediate that H must satisfy (EC.59).

Assume $\tilde{S}\not\subseteq\tilde{H}$, consider then $f\in\tilde{S}\setminus\tilde{H}$. We have that $(\phi_{\tilde{S}\setminus\{f\}} - \delta_{\tilde{S}\setminus\{f\}}) > \eta\cdot(|\tilde{\mathcal{L}}| - |\tilde{S}|) - (\phi_f - \delta_f) \ge \eta\cdot(|\tilde{\mathcal{L}}| - |\tilde{S}\setminus\{f\}|)$, where the last inequality comes from $f\notin\tilde{H}$, which implies that $\delta_f \ge \phi_f + \eta$. But then, $\tilde{S}\setminus f$ satisfies (EC.60) as well. We can thus assume that $\tilde{S}\subseteq\tilde{H}$.

If $\tilde{S}\subset\tilde{H}$, consider $f\in\tilde{H}\setminus\tilde{S}$. Because $f\in\tilde{H}$ and $\tilde{S}$ satisfies (EC.60), then $(\phi_{\tilde{S}} - \delta_{\tilde{S}}) + (\phi_f - \delta_f) > \eta\cdot(|\tilde{\mathcal{L}}| - |\tilde{S}|) + (\phi_f - \delta_f) > \eta\cdot(|\tilde{\mathcal{L}}| - |\tilde{S}\cup\{f\}|)$. Therefore, any $f\in\tilde{H}\setminus\tilde{S}$ can be included and (EC.60) would still hold, showing that $\tilde{H}$ must satisfy (EC.60).

Finally, by Proposition 2, $\bar{\mathbb{U}}$ would prevent deforestation with compensation for the instance with $\mathcal{L}$, $\pi^{\mathcal{F}}$ and $\{(\phi_\ell, \delta_\ell)\}_{\ell\in\mathcal{L}}$ if and only if (EC.59) holds and $\phi_\ell > \delta_\ell$ for every $\ell \in \mathcal{L}$, which is equivalent to (EC.60) and $\tilde{\phi}_i > \tilde{\delta}_i$, for every $i \in \tilde{\mathcal{L}}$, implying the desired result. □

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