For a Few Trees More

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August 2025

Abstract

We develop a model of the illicit mineral trade to explain the persistence of environmental degradation in isolated, bio-sensitive regions. We show that local monopolists with de facto power optimize between global rents and endogenous laundering costs, creating a resilient institutional equilibrium that neutralizes global regulatory shocks through adaptive laundering and supply reallocation. To break this path dependence, we introduce blockchain traceability, which segments the market into verifiable and unverifiable assets, thereby changing the arbitrage and depressing illicit returns. Incorporating Directed Technical Change, we demonstrate that this market segmentation redirects innovation away from illegal mining. Ultimately, the emergence of profitable legal rents shifts local governments' incentives, driving a departure from this extractive equilibrium toward endogenous investments in regional governance and the preservation of isolated ecosystems.

*Université Paris-Dauphine|PSL- The author thanks Gilles Chemla (Imperial College), Joseph Kaboski (University of Notre Dame), Philippe Aghion (LSE, INSEAD, Collège de France), Jerome Dugast (ESSEC), Olivier Tercieux (PSE), Evgenia Passari (Université Paris-Dauphine-PSL), Olivier Darmouni (HEC) for their commentaries and guidance. He also thanks the participants in internal seminars at Notre Dame, Paris-Dauphine and Collège de France for their insights and companionship

1 Introduction

The consensus that has been built around the issue of deforestation is disconnected from the ecological outcomes happening in tropical forests around the world. For over a quarter of a century, their role in providing precipitations and regulating climate, by avoiding extreme weather effects, has been recognized by the scientific community. (Barbier & Burgess, 2001) The dangers of unchecked forestry and resource extraction have been extensively chronicled, particularly in highly sensitive ecosystems such as the Amazon and Indonesia. (Goldammer, Schindele, Seibert, Hoffmann, & Abberger, 1999) (Nobre, Sellers, & Shukla, 1991) Yet, as global awareness has risen, one simple look at the dynamics of deforestation evidence that we haven't really achieved significant progress in hampering the degradation of these biomes. (Geldmann, Manica, Burgess, Coad, & Balmford, 2019)

Despite the urgency of the climate crisis, comprehensive policy efforts to protect these biomes remain paralyzed by coordination failures, as evidenced by the recent stalemates at COP16. For economists, this failure underscores a multi-dimensional challenge. At the extensive margin, deforestation is driven by the expansion of harvested agricultural land, whereas the intensive margin is dominated by clandestine, localized extraction such as artisanal mining. (Farrokhi, Kang, Pellegrina, & Sotelo, 2025) Because both margins generate externalities of similar magnitude, effective regulation requires both macro-level coordination and micro-level enforcement.(Araujo, 2024)(Araujo, Assunção, Hirota, & Scheinkman, 2023) Yet, a profound asymmetry in the global political economy undermines these efforts: sovereign nations that preserve their forests bear the full opportunity cost of foregone extraction, while the rest of the world free-rides on the ecological benefits. This asymmetric payoff structure starves local governments of legal revenues, inadvertently fostering zones of "non-governance" where illicit cartels and guerrilla groups consolidate de facto power and further erode state capacity.

In light of this persistent policy failure, the economics literature has not been able to formulate regulatory mechanisms able to address this deforestation crisis (Reynaert, Souza-Rodrigues, & van Benthem, 2024). The vacuum of enforceability generated by the systemic subsversion of local regulatory agencies, has forced the international community to address these issues through trade policy. Current efforts by the OECD, the UN, and the EU attempt to curtail production by increasing supply chain transparency to dampen

demand for illicit goods (OECD & UN, 2023). Yet, a striking empirical paradox has emerged. Despite the implementation of these transparency frameworks, the production of illicit minerals has actually surged. The irony lies in the exogenous boom in demand for rare earths which are needed for the green transition and with the sharp surge in gold prices in the recent years.(Boer, Pescatori, & Stuermer, 2023) (Baur & Smales, 2025) This generates a double jeopardy, today the fight against global climate change is generating local climate crisis.

The failure of current policies does not stem exclusively from the green transition demand for the minerals, but also from a fundamental lack of microeconomic grounding. The Walrasian framework it is based on incorrectly maps a unilateral demand reduction from developped countries to a contraction in illegal mines outputs. In this paper, we challenge this view by modeling the industrial organization of illegal extraction in bio-sensitive regions. In our model, a criminal organization acts as the sole bottleneck intermediary between the isolated region and the global market, selling extracted minerals via an auction-like mechanism to maximize rents. We demonstrate that this market structure is highly resilient to partial regulatory shocks. When policymakers impose a shock on a subset of buyers, the market responds by reallocating the illicit asset to unaffected, non-compliant actors at a lower price. Because the cartel acts as a pure intermediary, it has no incentive to reduce output as long as the global clearing price exceeds local extraction costs. This resilience is further fortified by the cartel's capacity to self-deal and launder minerals, generating an absolute barrier to traditional policies and leaving the environmental externality entirely unresolved.

To break this oppressive institutional equilibrium, we develop a novel blockchain architecture explicitly designed to segment the market and restore the transmission between demand and production. We integrate legal mineral supply into this blockchain using a Mint-or-Enforce architecture. This system combines a permissioned gateway—where institutions prove the tokenization of legal minerals—with a Byzantine Fault Tolerant state machine that enables permissionless trading thereafter. By digitizing transaction governance through non-reversible strong smart contracts, this partition isolates unverified assets from global liquidity, eroding the criminal organization's rents.

We then trace the macroeconomic implications of this price depression in a North-South model of Directed Technical Change. Stripped of their laundering channels, illicit min-

erals face a globally depressed market size. We argue that cryptographic segmentation provides institutions like the OECD, EU, and UN with the necessary tools to exert truly global effects on mineral prices. As the North subsidizes the clean industry, the resulting technical change outcompetes illegal supply. Ultimately, we characterize a scissor effect in the new steady state: the collapse of the repugnance spread between the illegal asset's price in the general economy and the bio-sensitive region drives illegal miners out of the market. This, in turn optimally redirects local government incentives toward the provision of state capacity in previously isolated regions.

1.1 Review of the Literature

1.1.1 Macroeconomics of Preservation

The issue of climate change is deeply correlated to the issue of deforestation. A brief analysis of a tree's life-cycle evidences that by cutting one, one would emit the stocked carbon of the trunk into the atmosphere whilst also depriving the atmosphere from the plant's CO2 captation capacities.

The literature on deforestation and global conservation of tropical forests have focused on the role of agriculture and trade on deforestation. In a survey, from 2024, products of agriculture, ranging from dairy, bovine meat, soja and more the review(Farrokhi et al., 2025), questions the veracity of Borlaug's hypothesis (Da Silva & Filho, 2016). Indeed, globalization have jeopardized the predictions made during the Green Revolution, that an increase in global agricultural productivity would result in less deforestation. The high substitutability of some crops, like soja, have transferred the land usage from places like the U.S to less productive places like Brazil. As a global effect, these should balance out but the forests from the North and the South are not perfect substitutes. As sub-tropical forests concentrate more biodiversity and hold higher amounts of CO2. Moreover, they are not easily reforesteable as their recovery takes centuries due to their high degree of interconnectedness (Balboni et al., n.d.)

Policy measures at the national level are associated with increasing the price of deforestation: Few papers in the financial literature link farming with carbon prices, yet, in a recent field study, (Assunção, Hansen, Munson, & Scheinkman, 2023), look at carbon pricing as a potential mitigator in the case of deforestation. (Lucio 2024) Shows that

carbon markets, when including farmers, manage deforestation through pricing effects. The profit obtained by expanding exploitations by one more acre shall, at one point, be equal to the price of acquiring one more carbon credit. Yet, incentives, in the form of carbon offsets, displace this equilibrium and permits for more deforestation.
Those policies, while essential are only one face of a coin. The subtropical forests, as complex ecosystems need to be managed at the micro level in order for the whole ecosystem to subsist..

1.1.2 Singularity Points and the Microeconomics of Conservation

In recent years, though, some evidence that global warming might be accelerated due to much more local and restricted damages done the forest has arisen (Lapola et al., 2023). Understanding of evo-transpiration and aerial water circulation (Ruiz-Vásquez, Arias, Martínez, & Espinoza, 2020), has shown that, in a subtropical biome, deforestation in the middle of the ecosystem provokes mayhem down the line. Examples of such has risen for example in Colombia. In Bogota, the country's capital, a centennial drought has kept the city with water restrictions (Ownby, 2024). This drought, expected because of the "El Niño" particularly aggravated by a drought in the Magdalena and Orinocco amplified by the environmental abuse happening in said regions These micro disruption, which create local effects, shall, if not addressed , cause a black swan event known as singularity(Saravia, Doyle, & Bond-Lamberty, 2018). Singularity in the case of tropical forests, is the breaking point in which the biome goes from being a global weather regulator to a global warmer. Indeed, it is the point where the trees gases do not flow in a cycle but is simply released globally in the atmosphere . In the case of old sub-tropical forests, a singularity event would increase the amount of carbon dioxide in the atmosphere by a substantial amount. These patches of degradation are one of the main drivers of this loss in resilience (Boulton, Lenton, & Boers, 2022).
In terms of local policies, the literature is at the crossroads with development economics. Consisting of in field random controlled trials, the preservation literature has focused on incentivization of sustainable agricultural practices. These local programs have found direct incentivization of forestry preservation and agro-forestry to be effective in small communities (Jayachandran et al., 2017) (Wong, Kuralbayeva, Anderson, Pessoa, & Harding, 2022) but hardly scalable (Pattanayak, Wunder, & Ferraro, 2010) and overall costly

(Edwards et al., 2020) in the context of the resources available in countries like Congo, Brazil, Peru...

Recent recognition in international law of these disruptions were done in the COP16 in Cali. In a common declaration, the UN has pinpointed the importance of strategic intervention in communities polluting these bio-sensitive regions as to encourage preservation and sustainable development. A Funds of 8 bn$ was established to accompany those communities in developing sustainable practices in remote regions. Yet, the case of the 200bn$ global fund to accompany the Global South into green development, is only funded at 8bn$ ten years later. There is a certain urgency in dealing swiftly with these issues. Yet, the obstacles to access these zones, both physically and because of conflict make the issue of transforming those practices difficult.

1.1.3 Repugnance and Distance to Global Markets

Repugnance in economics has been largely discussed as the constraints morality have subjected markets to. In a vast review of what constitutes these constraints, Alvin Roth (Roth, 2007) defines a repugnant transaction as a monetary transaction between consenting parts which creates opposition from a third part.

In his analysis, a thorough characterization of what makes a transaction repugnant is impossible, one can see that the multiple ethical dilemmas around them do pose an economic problem. In the case of kidney markets, these transactions exist in parallel to legal markets, without, in turn generating other transactions. They, are for both parts beneficial, whilst creating deep issues about the monetization of the human body. (Fox, 2006) Still, for other, like narcotics, the supply chain resides in mostly legal products and creates negative, measurable externalities for all parts of the transaction.

In the case of subtropical forest, the repugnance of the transaction lies in the damage made to the environment and the human harm made to get it. In the case of artisanal mining for example, the use of mercury, hurts waterways and create neurological diseases in the communities surrounding exploitations. Blood diamonds, generate repugnance because of the abuse of human rights (Zwick et al., 2006). Coltan and cobalt exploitations in the Congo basin generate both.

Repugnance in the case of economic exploitation in bio-sensitive regions is not only due to the negative ecological externalities but because of other factors like armed conflict,

lack of human rights, human trafficking. Moreover, some of these generate more disgust than others for cultural reasons only. An interesting case is the differential coverage made between about ivory poaching and pangolin scale poaching.

Yet, an important point of these repugnant transactions is that they exist despite regulatory and cultural disgust. For mining in bio-sensitive zones, exploitation has rapidly expanded because of the international demand for these minerals (e.g : gold, coltan, lithium...). This demand, is funnily enough, lead by the need to electrify their production and achieve the energy transition by stocking electricity inside batteries. Moreover a characterization of these transactions, in comparison with other repugnant assets, is that their repugnance come neither from their nature or from the monetary nature of the trade. Indeed, minerals trade is legal in all countries and is seen as essential in the global supply trade. It's the fact that the zones in which the minerals are extracted are seen as as holding higher value than their counterparts in less bio-diverse zones (e.g deserts, plains, the ocean...) . A clear example resides in the difference in public's attention between a mine opening in the Atacama, in Chile, or one in the Amazon forest. (find example).

The notion of repugnance and the notion of commons mesh into one another. The idea of shared values and repugnance , join the idea of preserving the environment in multiple points. An example, of which is animal preservation and poaching. Even though, ivory trade has subsisted for centuries, evolving sentiments about the killing of elephants has made the market for horns illegal. Illegality in this case, has made prices skyrocket as a consequence. In parallel feeding the market with incentives to continue the practice. Similarly, repugnance tend to coexist with other morally illicit practice such as market power effects such as coercion and and forced trade.

It is thus surprising, that the OECD, developed guidelines to address these questions of illegal mining (OECD, 2016). Some of the measures of these guidelines were recently adopted by the European Parliament in 2024 and are supposed to be followed for European companies. Even in the context of the rapidly growing EV battery industry. These guidelines are accompanied by joint efforts with the U.N (OECD & UN, 2023) to include the local population and try developing sustainable practices in these regions. Still, they ignore the repugnant nature of these markets in two important aspects. These measures are only effective if all the actors in said zones apply them, and if all actors of the trade

do also. More so, in a fragile environment, reaching its tipping point, voluntary programs don't seem to cut it as all should be undergoing these treatments. A treatment of such would be similar to the one of child-labor, highly illegal in all countries, with multiple international codes and programs to deter and prohibit, yet extremely common. As with child labor, these products still find their way to the global supply chain and would need a profound review of the economic roles and incentives all actors receive in order to properly seize the issue at hand.

More so, the archaic nature of markets inside of bio-sensitive zones, their connection to global markets by, sometimes criminal, intermediaries and the demand coming from global markets shall be studied. The will of the author is first to describe these exchanges, by first describing the market structure inside of bio-sensitive zones, then describe the nature of the intermediary in global trade and finally explaining why repugnance, in the form of guidelines and disgust from northern countries plays a role in maintaining these practices.

In this last part we will generate a significant contribution to the literature by proposing then studying the effects of introducing a clean, distinguishable, blockchain on the mineral trade. This will allow us to draw a parallel with the directed technical change literature ((Acemoglu, 2002), which in recent development have integrated schumpeterian growth to provide with policy answers (Acemoglu, Akcigit, Hanley, & Kerr, 2016)(Acemoglu, Aghion, Bursztyn, & Hemous, 2012). And recognize that these changes might come in pair with institutional changes on par with the state building literature (Acemoglu, 2006)(Acemoglu & Robinson, 2000)

2 Setup

2.1 The flow of illegal goods

Before any characterization of the illegal good and of policy actions let's first define the economy, its actors and its flows. We want to represent the economy as a flow of goods from one firm to another focusing on the illegal goods that were produced in the bio-sensitive zone. We propose the following definition of an economy to study said flows.

Definition 1. *The Economy - We define the general economy's graph $G_E = (V_E, D_E)$, with $V_E = \{X_1, ...X_N\}$ the graph's vortex, with each X_k being a firm, D_E denotes the graphs arcs. G_E. G_E is a directed graph. Each node $X_k \in V_E$ hold some numerical properties:*

1. *$f_{k,j}$ denotes the net flow of illegal good from node j to k*
2. *b_k denotes the net consumption (>0 is a consumption, <0 is a production) of illegal good from firm X_k*
3. *$u_{k,j}$ denotes the flow capacity of each arc (k, j)*
4. *$c_{k,j}$ denotes the cost per unit of flow along the arc (k, j)*

It is natural to impose the following condition on flows:

$$b_k + \sum_{j \in I(k)} f_{k,j} = \sum_{j \in O(k)} f_{k,j} \qquad \forall k \in [1, N]$$
$$0 \leq f_{k,j} \leq u_{k,j}$$

Where $I(k)$ and $O(k)$ represent the incoming and outgoing flow from X_K

In essence, the general economy's graph defines a network for which the sum of all incoming and outgoing flows is null. Meaning that the economy is at equilibrium for the illegal good. Equilibrium is formed at every node with the illegal good's price . The general economy's graph, represents how the illegal good travels from its inception, in a bio-sensitive zone to its consumers.

Definition 2. *Isolated Economy An isolated economy, is a directed subgraph $G_I = (V_I, D_I)$, with $V_I = (X_1, ...X_i)$ and $I \leq N$ of the general economy's graph, G_E, which is connected to G_E through the single node X_I.*

In essence, this defines a geographical bottleneck in the economy. Node V_I works as the only supplier of the illegal good in the legal economy. He holds this monopoly as, either for political reasons, such as conflict, or purely topological reasons, inaccessibility, he is the only one able to move the product from the bio sensitive region to the general

economy.

From this definition of an isolated economy we can infer some first properties of the bottleneck from its network representation :

Property 1. *Isolated Economy*

1. *Cost of transportation $c_{i,k}$ from a node $X_i \in V_{i-1}$ to a node $X_k \in V_E/V_{i-1}$ is equal to ∞*

2. $$b_i = \sum_{k\in[1,i-1]} \sum_{j\in O(k)} f_{k,j} - \sum_{k\in[i+1,N]} \sum_{j\in I(k)} f_{j,k}$$
$$b_i = \sum_{k=1}^{i-1} b_k - \sum_{k=i+1}^{N} b_k$$

3. $$b_k \geq 0 \quad \forall k > i$$

The first condition sets in stone the fact that sellers of the repugnant asset cannot sell directly their good in the economy and require the bottleneck monopolist as an intermediary. This reflects a common reality in these zones, the monopoly of power exercised by the illegal (e.g ELN in Colombia, militias in Congo...) is used to coerce the economy and, in turn, generate a bottleneck monopoly that controls the inflows and outflows of goods, labor and capital inside of bio-sensitive zone .

The second condition highlights the monopolistic nature of the repugnant's asset trade, the inflow of the asset in the regular economy is the residue (positive or negative) of the asset after it got through the bottleneck. We can even go further to say that if $b_i > 0$ the amount of repugnant asset kept by the bottleneck would be laundered and resold in the legal economy.

We call $q_j = f_{k,j}$ the flow of the illegal good from the bottleneck monopolist to a buyer with $j \in [i+1, N]$ and U_j his utility in q_j, twice differentiable. We make the assumption that for all j, $U(.)$ is submodular.

The third condition forces supply of the illegal asset to come from the bio-sensitive zone. General equilibrium arguments for the uniqueness of repugnance by zone is strong. First,

the asset can be different in nature,(e.g. gold, silver, cobalt...), it is different in production methods, in geographies and in repugnance. Said, repugnance is also linked to the prior ecological value derived from the awareness of the ecological and human rights issues at hand. The power held by the bottleneck also comes in the form of the trade mechanism. He has the capacity to set the market, and will deliver packages of the repugnant asset to the buyers. This mechanism determines the allocation of the repugnant asset in the economy. Let's now state our main assumptions on the repugnant asset sale at the bottleneck.

Assumption 1. *Sale Mechanism - We assume that the sale of the repugnant asset through the bottleneck is done in accordance to the following assumption:*

1. *The quantity of illegal mineral allocated to the n buyers of the repugnant asset is equal to the quantity produced divided*
2. *Said quantity is sold through a mechanism M=(Q,μ), of allocation rule M and of payment rule μ.*
3. *The illegal mineral sold via M cannot be distinguished from the legally sourced mineral outside of the bio sensitive-zone. It is a durable and perfectly resalable good*

We'll further prove that in the case of a durable good, a mechanism which maximizing revenue for a durable good must allocate efficiently. Let M be the optimal mechanism. We start from the optimal Myerson mechanism (Myerson, 1981). Under a generalized Mechanism notation, the Myerson is a VCG with a positive reserve price Ψ. For a durable good, a parallel can be drawn between Ψ and the monopoly rent, as they are both profits that are in surplus of the competitive equilibrium price. Under Coasian dynamics, it is possible to prove that the issue of commitment is the same in complete contracts (Ausubel & Deneckere, 1992). As, any detectable deviation from efficiency is detected, coalition building make rent extraction possible by agents. In the paper, this extraction leads to a Myerson of a null reserve price, which is simply a Vickrey mechanism. It is essential to see that Coase's conjecture does not require a good to remain the same for an indefinite amount of time, yet only that it does not degrade between a first and second trading period. This potentially extends the reach of this paper's findings to other assets such as oil...

Further evidence in the literature of the absence of a reserve price on top of the mechanism

designer's private value stems from the perfectly resellable nature of gold (Ausubel & Cramton, 1999). Any informational rent generated, generating misallocation, is offset by the ex-post trading among agents. We call $q_j = f_{k,j}$ the flow of the illegal good from the bottleneck monopolist to a buyer with $j \in [i+1, N]$ and U_j his utility in q_j, twice differentiable with $U(.) \geq 0$ and $U'(.) \geq 0$. This means that being attributed a higher quantity via the mechanism generates a higher utility for the buyer. In truth, this corresponds to one of the consequences of the individual rationality of the mechanism.

Having described trade, we now turn towards the issue of the allocation of the illegal good. The way an efficient mechanism allocates

2.2 One-to-many matching in Isolated economies

As we have determined the optimal mechanism used to trade illegal goods at the border between the bio-sensitive zone and the rest of the economy, understanding the allocation of the illegal good and its matching to its buyers.

The one to many allocation among n buyers in a competitive format differs from the traditional walrasian tatonnement in that identical packages are of integer value. In this rests the interest in studying the one-to-may matching made by the bottleneck monopolist.

Because the VCG is efficient in its allocation the stable matching generated as a consequence of the mechanism is ordered among the highest I types from the n buyers. Such matching is stable as the strategies involved in bidding are weakly dominant. We shall call this the natural matching σ_N

We assume that the n packages are matched, we order them from $[1, 2, ..., n]$ in their order of attribution, Γ is equal to:

$$\Gamma = \begin{array}{cccc} 1 & 2 & ... & \text{n} \\ \hline t_1 & t_2 & ... & t_n \end{array}$$

Where t_j, $j \in [1, n]$ represent the j^{th} highest type among the N mechanism participants. If all participants have a positive, non-zero utility for each package, this means that $N \times N - n$ orders were not fulfilled. Here lies one aspect in the resilience of illegal trade. Ebbing the utility through regulation has a displacement effect on the natural match-

ing, changing the allocation, but not necessarily the quantities. To highlight a change in quantities matched, we define quota, q_n, the total quantity to allocate and Q_n, the last profitable trade for the bottleneck monopolist. A demand shock changes quantities allocated if and only if $Q_n \in Im(\Gamma')$ the ex-post stable matching.

One further nuance lies on the self-dealing nature of the illegal trade. It is often the case that the bottleneck monopolist wishes to cash in some of the profits of the illegal trade by laundering himself the illegal mineral. For metals, such as gold or silver, it is impossible to differentiate between legal and illegal supply outside of the bio-sensitive region (simple elements do not carry location with them). On the other hand, rare earths, such as cobalt, are mostly sourced from one country. This creates extreme hardship in distinguishing the legality of the supply.

Assumption 2. *Illegal Asset Price - The illegal asset is in-differentiable from its legal counterpart at any node $k > i$. Meaning price θ_B, of the illegal asset is equal to θ_E at any node $k > i$*

This makes laundering of illegal mineral equivalent to a vertical integration. In our matching, we need to adjust notations. As b_i denotes the consumption at node i we shall divide it into two notations:

$$b_i = \underbrace{q_u}_{\text{non-profitable quantity}} + \underbrace{q_l}_{\text{self-allocated/laundered quantity}}$$

The self-allocated quantity represents the number of orders from the bottleneck monopolist that are in Γ and are profitable to sell in the general economy. Conversely, Q_n represents the quantity left in the bottleneck monopolists' hands that are unprofitable to sell.

The existence of mineral laundering further increases the challenge in diminishing quantities traded as, discriminatory policies outside of the bio-sensitive regions are hardly possible. One would have to create control on both the producers of the minerals but also on secondary markets. (e.g jewelries, thrift shops...) A second point in discriminatory policies concerning gold is that its in-differentiability is part of its value. Fully policing it, for example with the use of a blockchain, could hurt its use as a safe asset in

times of crisis.

2.3 The Policy environment

We introduce the policy maker G, G's objective is to prevent and defuse the externality generated by human activity in the form of climate change. It also wishes to solve the the human right and political issues stemming from illegal mining.
To proceed with the policy action we shall define the conservation game. The conservation game is defined by its set of outcomes $O = \{G, D\}$ with G denoting the green outcome and D the degraded outcome. The realized outcomes for the economy E_g and E_D are ordered in the following fashion:

$$E_G > E_D \tag{1}$$

The notation extends for any subset of E. We have mentioned in last section the notion of Bio-sensitive region. We define a bio sensitive region in the following fashion
Definition 3. *Bio-sensitive Regions - We define a bio-sensitive region B such as for $B \in E$, such that:*

1. *B is an isolated economy*
2. *With (X_1,...,X_I), the n firms constituting B. Outcome B_G is realized if and only if $\forall X_k, i \in [1, 2, .., n]$, the outcome G dominates outcome D.*
3. *Outcome B_D is realized implies the realization of E_D*

This definition precludes the core of the game by requiring in any coalition of outcome E_G to include outcome B_G for all bio-sensitive regions. On the other hand, the smallest coalition forming outcome E_D is one B_G among all, even more, one firm suffice for the environment to be degraded.
Ecosystems which hold this importance are numerous. The easiest example to observe is that of countries which depend on one river for their water supply (e.g Egypt and the Nile). Any upstream alteration would degrade its economy. On illegal mining, the issues are often dual, practices including patch deforestation alter both the precipitation and the world's environment. Conceptually, for the social planner, avoiding the ecological ex-

ternality becomes the problem of providing a policy that, on top of preventing the Global economy's degradation, must provide the incentives and regulations which would refrain all firms in the bio-sensitive regions to undergo the zone's degradation. This challenge is accrued by the isolation of bio-sensitive regions. In accordance, his policy action, P is implementable only outside of the bio-sensitive zone.
We can now define an effective policy by describing its effects upon implementation:

Definition 4. *Effective Policy - At same net demand $b'_i = b_i$ after policy, we define an effective policy P_E as a policy in the set of feasible policies P which increases the non-allocated quantity Q_n .*

In such case, we say that there a transmission of diminishing demand to the bottleneck monopolist. At this point, this is only a necessary condition for the policy. This means that there should be transmission.
Definition 5. *Transmissive policy - A transmissive policy is a policy P_E such that, a decrease of demands b_e $\forall e \in E$ to demands b'_e implies that the sum flows $\sum_1^{k-1} b'_k \leq \sum_1^{k-1} b_k$*

In plain english, a demand curbing policy is transmissive if the negative shock in demand it generated in the firms' affected by the policy is transmitted upstream via the demand of the bottleneck monopolist. In classic microeconomics, at equilibrium, all policies are transmissive as change in demand lead to changes in marginal utilities of upstream firms. Yet, in the case of integer package selling, the excess demand of competing bids generates transmission and if there are no cost involved, is null. We shall describe the conditions for transmission in this paper.

3 The model

3.1 The State of Nature

Before any policy implementation, there is a trade. The bottleneck monopolist will buy it at price θ_B from the illegal miners in the bio-sensitive zone and will sell the illegal through a mechanism M, which generates a revenue Π_m from buyers [1,...,N]. The order book

$q_m = (q_1, ..., q_N) = (f_{b,1}, ..., f_{b,N})$ represent the allocated quantities given to each agents and the agent's payments for said quantities are given by the vector $p = (p_1, ..., p_N)$. Agents possess private information only on their private value for the possession of a quantity of the illegal mineral $\theta = (\theta_1, ..., \theta_n) \in \Theta = \times_{i=1}^{n} \Theta_i$ We can make some natural inferences on the payment values, the payments and the quantities. First, the bottleneck monopolist does not sell at a loss, and will not sell any package under the price θ_B. Second, without scarcity in the legal economy, the price θ_E represents the upper bound of value for a single package of the illegal asset. As such, buyers would rather to buy the legal asset rather than the illegal. This gives us an important property about price θ_M:

$$\forall p_i \in p \quad \theta_B \times q_i \leq p_i \times q_i \leq \theta_E \times q_i \tag{2}$$

$$\theta_B \times b \leq \Pi_m = \sum_{i=1}^{N} p_i \times q_i \leq \theta_E \times b \tag{3}$$

We now define the payments p_i and the utilities u_i of each of the N agents of the mechanism:

$$p_i(\theta) = \underbrace{\left[\max_{x \in P} \sum_{j \neq i} v_j(x, \theta_j)\right]}_{\text{Welfare of others without i}} - \underbrace{\sum_{j \neq i} v_j(x^*, \theta_j)}_{\text{Welfare of others with } i} \tag{4}$$

$$p_i(\theta) = W_i(N \backslash \{i\}) - \sum_{j \neq i} v_j(x^*, \theta_j) \tag{5}$$

$$u_i(\theta) = v(\theta) - p_i \tag{6}$$

$$u_i(\theta) = W(N) - W(N \backslash \{i\}) \tag{7}$$

A Vickrey mechanism is one where the winning bidder of k units must pay the externality of not serving those units to the rest of the agents. Truth-telling is dominant and as such it is incentive compatible. From this property we further extract a property and a

definition. In the context of the informational universe $\Theta = \theta_1 \times \theta_2 \times ... \times \theta_N = \theta^N$, the private values of the buyers of the illegal assets must range from [0 , θ_E]. Second we can infer that the cost of repugnance for the illegal asset is equal to :

$$R = Q \times (\theta_E - \theta_B) = \underbrace{\sum_{i=1}^{N} p_i(\theta)}_{\text{Payments to the illegal trader}} + \underbrace{\sum_{i=1}^{N} u_i(\theta)}_{\text{utility of the agents}}$$

Repugnance will be shared by the actors who will both receive a part of it to receive a profit, for the bottleneck monopolist. The bottleneck monopolist's profit will be equal to :

$$\Pi_b = \sum_{i=1}^{N} p_i(\theta) - Q \times \theta_B \geq 0$$

The profit from the monopolist represent the necessary condition for trade, the total revenue for the mechanism has to at least balance his payment for the quantity Q of illegal mineral he bought at price θ_B. As the selling mechanism is set by the bottleneck monopolist, he has a desire to maximize his rent. This is evidenced by dynamic strategies adopted by illegal groups. In Colombia, it has been observed that the production of cocaine is inversely dependent on the price of gold, suggesting a profit maximization. Focusing on Gold and cobalt we observe that they are durable goods. Under Coase, reselling makes any bargaining mechanism inefficient, leading rents to zero (Coase, 1960). Two different arguments will based on mechanism design theory points towards an efficient mechanism as the preferred mechanism for selling the repugnant asset

First, under Coase, reselling and waiting are the sources of the rent extraction. Under an efficient mechanism, allocation of any package is given to the agent who values the package the most. Re-selling would always lead to a loss in welfare Second, under the class of Myerson mechanisms, the only mechanism which is IR is the VCG. The durable good trade must be at least IR as the agents cannot be forced to trade.

These two arguments settle the choice of the allocation rule for the optimal trade mechanism of the illegal good in the Vickrey Clarke Groves Mechanism (VCG). The Revenue Equivalent Principle frees us from determining the payment rule of the mechanism and allows us to focus on the mechanism's behavior. Because VCG is strategy proof the types

and private valuations are truthfully revealed ex-post.

3.2 Trading vs laundering

It is implied by the setting of a trade mechanism that the repugnance spread is shared between the bottleneck and downstream agents. It is in the interest of the bottleneck monopolist to expand downstream. First to limit coalition building in the mechanism, which would lead to reduction in profits. Second, to try and recover more of the spread from repugnance, he might want to sell the illegal mineral directly in the legal economy. Assumption 2 provides with the useful characteristic from illegal minerals, outside of the extraction zones the legal from the illegal mineral are indistinguishable. This means that as long as the bottleneck monopolist finds a venue to distribute the illegal asset outside of the bio-sensitive he can expect to sell the asset to price θ_E.

Such action from the bottleneck monopolist means that he must either takeover a firm in [i+1,N] to launder the mineral or he must create a new entity. The most plausible is the former, indeed, this would be the case of an illegal group buying a legal mine or a jewelry. In both, the laundering is simple, lie about purity or quantity of the legal asset to add the illegal asset. Said expansion of the laundered quantity becomes increasingly difficult with scale. There is more scrutiny in large mines than in small and the same can be said about jewelries.

Thus, we introduce the cost function V(q), with $V(.) > 0$, $V'(.) \geq 0$ the cost of vertical integration. The costs of vertical integration are increasing, this comes as scaling laundering operations come with additional costs. In this case, vertical integration is a consequence of repugnance. There is no further cost or change in activity linked to the movement of the selling activity downstream. The bottleneck monopolist's payoff after having laundered a quantity q of illegal asset is :

$$\Pi_V(q) = q \times (\theta_E - \theta_B) - V(q) \tag{8}$$

This new revenue generates an optimization problem on the allocation of the quantities between the bottleneck monopolist and the buyers. The amounts sold are in competition with the amounts laundered. This leads to the following optimization program:

$$\begin{cases} \underset{q_m,q_v}{max}(\Pi_B(q_m,q_v)) = \underset{q_m,q_v}{max}(\Pi_m(q_m)+\Pi_v(q_v)) \\ b = q_m + q_v \end{cases} \tag{9}$$

Where $q_m = \sum_{j\in[i+1,N]} f_{b,j}$ the sum of mineral flows from the bottleneck monopolist to the agents present in the mechanism and $q_v = b_i$ his self allocation. The optimization program represents the balance between selling directly at the mechanism price θ_m or undergoing the vertical integration and generating a revenue of R at cost V. This layer of vertical integration differs from the usual framework as there is no firm competition downstream. This stems from the price taking assumption on the legal mineral. Indeed, the bottleneck monopolist is a pure player and does not have industrial needs for the asset.

The optimal allocation of quantities is a problem in an of itself. If the answer has been studied in incomplete contracts (Chemla, 2003), the literature, to the best of my knowledge, does not address the question of a mechanism designer's option to self-deal. The closest resemblance is the literature on reserve prices. Indeed, reserve prices represent a break-even point where the mechanism's revenue outperforms keeping the object. If in single item auctions, Klemperer finds that the demand reduction generated by reserve prices diminish the expected seller's revenue, the question remains open in generalized mechanisms. (Bulow & Klemperer, 1994) The only consensus is that the variance reduction property mechanisms yield. Still, reserve prices are never seen as moving, nor do they seem to be linked to be endogenized to the mechanism's designer utility function. One could see a reserve price as a self-dealing offer for which the mechanism's designer reveals its own utility. In such case, the mechanism's designer utility changes and becomes quasi-linear too with a self-applied allocation rule.

To complete the literature and generate a program which allows for the efficient allocation of the illegal asset, we design the following self dealing vector:

$$\phi = (\Pi_v(\frac{b}{n}), \Pi_v(\frac{2b}{n}) - \Pi_v(\frac{b}{n}), ..., \Pi_v(\frac{i \times b}{n}) - \Pi_v(\frac{(i-1) \times b}{n}), ..., \Pi_v(b) - \Pi_v(\frac{(n-1) \times b}{n}))^t \tag{10}$$

$$\phi = (\theta_E - \theta_B - V(\frac{b}{n}), \theta_E - \theta_B - (V(\frac{2b}{n}) - V((\frac{b}{n})), ..., \theta_E - \theta_B - (V(b) - V((\frac{(n-1) \times b}{n}))^t \tag{11}$$

The self-dealing vector, has two different interpretations. First, it is a reserve price which guarantees the bottleneck monopolist that selling the illegal mineral is at least as profitable than laundering the asset himself. Second, the bottleneck monopolist gets to measure the demand in excess of what is achievable through pure laundering.

The question of a public or hidden reserve price can be made. The literature has no fixed answer on the issue of the ideal reserve price, the optimal mechanism set by Myerson lays the framework for seller optimal mechanism. (Myerson, 1981) If the assignment rule remains to deliver the goods the highest bidder, Myerson evidences that a positive reserve price is optimal. Yet, issues such as commitment in cases where no bid is higher than the reserve price and issues concerning the assumption that the value distribution of buyers is known ex-ante has generated a literature concerning the robustness of mechanisms. . Klemperer, generates another insight on reserve prices. In a single object auction, a positive reserve price which would exclude even one buyer would decrease the remaining bids value in an amount superior to the rent generated by the setting of the reserve price. (Bulow & Klemperer, 1994) If the result holds for a single object mechanisms, for generalized mechanisms the effects are not clearly laid out. In our case, we can avoid the issue of the reserve price as the self-dealing vector is as much a reserve price than a competing bid. The commitment issue is not present as the payoff for the illegal good in case it is served a quantity i of illegal good is:

$$\text{Payoff} = \underbrace{q \times (\theta_E - \theta_B) - V(q \times \frac{i}{n})}_{Launderingpayoff} + \Pi'_m$$

Due to the properties of the VCG auction. All payments constituting Π'_m the payments made by buyers who were served have to be at least superior to the $(i+1)^{th}$ bid of the

bottleneck monopolist, as they are the price of the externality generated by serving a winning bid. This implies that :

$$\Pi'_m \geq \underbrace{(b-i)(\theta_E - \theta_B) - (V(b) - V(b\frac{i+1}{n}))}_{\text{externality of not serving the rest of the monopolist's bid}}$$

This property effectively excludes the issue of commitment. As, in case he is served, the rest of the payments are always at least higher than his utility had he not entered the mechanism. Moreover, if he is not served, this means that has received no bid that would offset the profits which would happen in the case he had laundered all of the illegal asset.

4 Market resilience against demand curbing policies

Before addressing the policy implication poised by the illegal mining trade in our model, it is necessary to pinpoint that even if the mechanism is efficient among its actors it does not act efficiently for welfare. One could see it as a mechanism where absent agents pay the price of the externality of the agents in the mechanism, this price being the human rights and ecological externalities derived from the illegal trade.

Going back to the policy maker's policies arsenal, he is deeply constrained by his inability to deter the production in bio-sensitive zones directly. Implementation of these policies is made difficult because of the isolated nature of the trade.

As such, his only policy is to curb demand on his constituents by creating new transparency and supply chain control regulation. In the mechanism, we represent this by affecting to share p of buyers in the mechanism, a demand curbing vector $\tau = \tau_1, .., \tau_n$ where $(t_1, ..., t_n)$ with $\tau_1 \leq \tau_2 \leq ... \leq \tau_n$ is a constant tax vector inflicted on the types of the affected buyers . They represent the increased costs (or repugnance) imposed on the buyers due to the implementation of the policy. For any actor under the scope of the policy, their new private value becomes:

$$\tilde{\theta} = max\{0, \theta - \tau\}$$

We remain in the private value context, an agent knows before entering in the mechanism

the amount he will need to pay to be able to launder under the new policy. Non-affected buyer's private value remain unchanged, with their corresponding private value X. The physical properties of the illegal mineral are conserved and once outside of the illegal zone, the price of the mineral is equal to the market price of the mineral θ_E

For the bottleneck monopolist, we can anticipate the following relation for his revenue:

$$\Pi^{N-p} \leq \underbrace{\Pi'}_{\text{payoff after policy shock}} \leq \Pi^N \tag{12}$$

The left hand side of the inequality represents a fully exclusionary policy. It means that the distribution of all affected by the policy is null. The right hand side, represents the opposite extreme case in which the policy is fully ineffective and did not move the private values of the affected buyers. This inequality sets the tone, whilst the revenue for the monopolist has diminished, we shall see that the ebb in demand might not transfer to the allocated quantities.

Before finding the necessary conditions for transmission, we shall describe the strategic actions of the actors after the shock. For both the p agents affected by the regulation and the $n-p$ agents not affected, the optimal bid remains bidding their respective private value vectors $\tilde{\theta}$ and θ that the self-dealing vector remains unchanged. As long as $p < N$, the natural strategy for laundering the illegal mineral is to do it in a region unaffected by the regulator's new policy. As such, we make the assumption that the new self dealing vector $\phi' = \phi$.

4.1 Allocation of the illegal assets after policy shock

To study the profits and allocated quantities after the policy shock, it is convenient to point that the agent's strategy remain truth-telling. Revealing the agent's true type remain the dominant strategy for both the affected and non affected agents. As such, non affected agents will declare their types $\theta_i' \; \forall i \in [1, p]$ and $\theta_i \forall i \in [p, N]$. The information set becomes $\tilde{\Theta} = \Theta_{N-p} \times \tilde{\Theta}_p$, where $\tilde{\Theta}_p = \tilde{\theta}^p$. We shall now direct our attention to the new allocation made by efficient mechanism. The effects of the policies affect classes of agents asymmetrically. We shall first evaluate the allocation and profits of non affected buyers, second we shall study the allocation of affected buyers. Finally, we will conclude with

the self-allocation for the monopolist and determine the conditions for the transmission of the demand curbing to production.

For the non-affected buyer we will first establish that their utility has increased. A buyer non-affected by the policy will have a payment equal to:

$$p_i' \leq \underbrace{\left[\max_x \sum_{\substack{j\neq i \\ j\leq N-p}} v_j(x,\theta_j)\right]}_{\text{Welfare of unaffected without } i} - \underbrace{\sum_{\substack{j\neq i \\ j\leq N-p}} v_j(x^*,\theta_j)}_{\text{Welfare of unaffected with } i} \tag{13}$$

$$+ \underbrace{\left[\max_x \sum_{j>N-p} v_j(x-\tau,\theta_j)\right]}_{\text{Welfare of affected without } i} - \underbrace{\sum_{j>N-p} v_j(x^*,\theta_j)}_{\text{Welfare of affected with } i} \tag{14}$$

Yet, because we know that $X' \leq X$, we know that the externality generated by serving agent $i \in (N-p)$ non affected buyers, must have diminished. This means that there is a decrease in the price paid by the $N-p$ agents. We can now prove that the amount of mineral allocated to the non affected has increased.

Proposition 1. - *Mineral Reallocation after policy shock After policy shock* $\mathbf{T}$ *the quantity of minerals allocated to an unaffected agent has increased on average.*

Proof. The valuation vector present in the mechanism $\tilde{\theta}$ after the tax shock $\mathbf{T}$ is for all agents in [1,...,N]:

$$\tilde{\theta}_j(\omega) = \begin{cases} \max(0, \theta_j(\omega) - \tau) & \text{if } j \in P \\ \theta_j(\omega) & \text{if } j \in U \end{cases} \tag{15}$$

It is immediate that $\forall j \in [1,..,N]$ and all states $\omega \in \Omega$ that:

$$\tilde{\theta}_j(\omega) \leq \theta_j(\omega) \tag{16}$$

From this we build the probability C_t as the $(Q_{total} - t + 1)$-th highest value in the rest

of the bidders $Y_i = \{\theta_j \mid j \neq i\}$.$C_t$ is in reality the $(Q_{total} - t + 1)$-th order statistic of the mechanism describing the threshold required for the t-th bid to be placed by a particular agent.

Because order-statistics are monotonous, non-decreasing functions and $\tilde{\theta}_j(\omega) \leq \theta_j(\omega) \quad \forall j \in [0, ..., N]$ We have:

$$C_t(\tilde{Y}_{-i}) \leq C_t(Y_{-i})$$

This means that to obtain t items in the post policy shock requires a lesser bid than ex-ante. Because non-affected users have had their valuations unchanged, this means that the probability of winning any amount of packages has also increased

To close the proof we shall prove that this dampening in the hurdle rate C_t translates to the stochastic dominance, for an unaffected agent, of the probability of winning t-packages after $\mathbf{T}$.

We define E_t and $\tilde{E}_t$ as the events where agent i wins at least t packages in the pre-shock and post-shock economies, respectively:

$$E_t = \{\omega \in \Omega \mid \theta_i(\omega) > C_t(Y_{-i}(\omega))\}$$

$$\tilde{E}_t = \{\omega \in \Omega \mid \theta_i(\omega) > C_t(\tilde{Y}_{-i}(\omega))\}$$

Our agent belonging to U keeps the same valuation. This proof establishes that for any agent in the non-affected set, must win at least t-objects after it ex-post. This establishes $E_t \subseteq \tilde{E}_t \Rightarrow P(E_t) \leq P(\tilde{E_t})$.

Furthermore, we know that the utility is increasing with the number of assigned objects, meaning:

$$u_i^U(\theta) \leq u_i^U(\tilde{\theta}) \tag{17}$$

This concludes the proof that, after a partial policy shock, non-affected agents, receive

more of the illegal mineral and see their utility increase. □

For affected agents, we shall prove, that their utility $u_i' \quad i \in [0, p]$ has diminished after the tax shock. To prove this, we assume a best-case scenario, the agent does not lose any bid he previously had after the tax shock. This is a best-case as he could not have won more packages. The ordering of his private values among the taxed agents remain the same as they are all taxed the same, and the ordering of his private values among the non-affected can only decrease. Affecting a good can only provide at least positive utility as the mechanism is IR.
In this best-case scenario, the agent's utility for having won the same items would be:

$$u_i' = \underbrace{SW'(N)}_{\text{welfare with the affected agent}} - \underbrace{SW'(N\backslash\{i\})}_{\text{Welfare without the affected agent}}$$

The first term: $SW'(N) = SW(N) - \tau$ is simply the welfare of i after having won the same items after having paid the tax. The welfare without i depends on who the agent made the payment to. We shall bound u_i' by taking the best and worst case scenario in terms of the externalities he has to pay to his competitors.
The best case scenario comes from the case where all the agents he previously paid the externality for his packages (to the bottleneck monopolist of course) were affected and that these did not have their ordering shifted due to the tax shock. Meaning that :

$$u_i' = SW(N) - \tau - (SW(N\backslash\{i\}) - \tau) = u_i \tag{18}$$

$$\Rightarrow u_i' \leq u_i \tag{19}$$

This is enough to say that the utility after the tax for the affected agents have lost some of their utility in the mechanism. Yet, we shall see that there is full transmission of the tax to the utility, only in the worst case scenario. This case comes when the payments he has to make were only to those unaffected, meaning that the externality of serving i has remained constant. We can write this as :

$$u_i' = SW(N) - \tau - SW(N\backslash\{i\}) = u_i - \tau \tag{20}$$

$$\Rightarrow u_i - \tau \leq u_i' \tag{21}$$

We recall this is the best scenario for the agent, where the ordering of his packages have not changed. If the ordering has changed, and he is left with some or all of his packages outside of the n highest bids, his utility can become null. The tax, effectively diminishes the quantity allocated to the affected. Yet, because it is a VCG it will either go to the unaffected For the bottleneck monopolist, payoff has decreased in the mechanism. As we stated when describing the self-serving vector, any allocation made during the mechanism was made because it increased profits. Two corollaries can be evidenced from this observation. Any increase in self-allocation is a decrease in the mechanism's designer profits. The profits and the quantities have shifted towards non-regulated buyers. This rationalizes, in part, the transformation of the minerals supply chain from Europe and the United States towards China and India. (find source) With less regulation, these countries were able to secure their supply chain in gold and cobalt. Moreover, the total quantities of minerals processed in the world have drastically increased in the last decades. The transfer of quantities and profits in the mechanism, as we will show next, are not synonymous with a decreased in total exchanged quantities.

4.2 Resilience of the market

We previously established that self-allocation by the bottleneck monopolist shields him from low offers for his mineral. Crucially, it also shields him from demand reduction. When demand diminishes, we observed that his self-allocation, denoted as b_i, increases. We decompose b_i into two distinct components:

$$b_i = \underbrace{q_u}_{\text{Unprofitable}} + \underbrace{q_l}_{\text{Laundered}} \tag{22}$$

Here, q_u represents the strategic (unprofitable) retention of goods, and q_l represents the

profitable self-allocation. The profitable component q_l is determined by the self-allocation profit function:

$$\Pi_m(q) = q \times (\theta_E - \theta_B) - V(q) \tag{23}$$

where θ_E is the exit valuation, θ_B is the base cost, and $V(q)$ is the cost of vertical integration. As long as Π_m is strictly increasing, the bottleneck monopolist has no incentive to diminish the quantities he purchases from the bio-sensitive zone.

In an extreme case where the bottleneck monopolist's self-allocation profits are increasing over the entire domain $[0, Q]$, T equals b_i everywhere. This implies that the unprofitable component q_u is null, rendering the policy P ineffective.

4.2.1 Market Resilience and Mechanism Design

In light of this, we examine the scenario where the market is not fully resilient. We consider the symmetric extreme case where the policymaker successfully prevents agents under their jurisdiction from participating in the illegal trade by setting a tax $\tau \geq \max_{[\![0,p]\!]} \theta$, corresponding to the highest type among the agents under the government's control. In this scenario, trade occurs without the p affected actors, meaning $N - p$ actors continue to trade.

We have established that the new self-allocation $b'_i \geq b_i$. We now inquire into the value of b'_i which shifts κ into positive territory. We assume there exists a quantity $\bar{q}$ in $[0, Q]$ for which the marginal profit $\Pi'_m(\bar{q}) = 0$. We define $Q_{total} - \bar{q}$ as the non-profitable zone.

For κ (the strategic holding) to be zero, a necessary and sufficient condition relies on the mechanism's revenue. Proceeding by contradiction: let the expected value for the package $i^* = \frac{Q-q}{N} + 1$ be inferior to the total quantity. This implies that the total revenue for the mechanism satisfies:

$$\sum v_{-i} - \sum v_i \leq i^* \times \frac{Q-q}{N} \times \theta_B \tag{24}$$

This represents the break-even value for the illegal miner.

For κ to be positive, the revenue of the mechanism must yield a deficit relative to the miner's valuation. This entails that in the Vickrey-Clarke-Groves (VCG) mechanism—where the unprofitable quantity $Q_{total} - \bar{q}$ is auctioned among $N - p$ agents—the sum of

payments P_{total} must satisfy:

$$P_{total} \leq (Q_{total} - \bar{q}) \times \theta_B \tag{25}$$

As long as the mechanism delivers a profit above this threshold, the bottleneck monopolist will not self-allocate any of the illegal mineral .

4.2.2 Policy Implications

The case of full resilience arises when vertically integrating the whole quantity is profitable for the bottleneck monopolist. In such a case, the illegal trader uses the market only for the extra revenue generated from sales. Returning to the self-supplied quantity:

$$b_i = q_u + T < T(Q) \implies q_u = 0 \tag{26}$$

This indicates that the upper bound of policy action P is a function of the vertical integration function V.

While demand-curbing measures affect the monopolist's self-allocated quantity and decrease his profit, the policy effects are bounded. A maximalist criterion examines if the policy is fully discriminatory, leading to:

$$Q' > Q \tag{27}$$

in the case where the mechanism retains $N - p$ agents.

From these remarks, we derive that b_i is a function of the policy action P, while the profitable component T is not. The negative shift in demand yielded by policy action P depends on market conditions and the policy strength S. The quantity q_u is the residual between b_i and T, and it is non-zero if and only if:

1. There exists a quantity $\bar{q} \leq Q_{total}$ such that:

$$\theta_E - \theta_B \leq V\left(\frac{\bar{q}}{N}\right) - V\left(\frac{\bar{q}+1}{N}\right) \tag{28}$$

2. For the remaining quantity in the non-profit zone, the price for the illegal good is

inferior to θ_B.

These results challenge the notion that reducing demand automatically decreases the amount traded. By utilizing graph-theoretic notation within the mechanism design setting, we capture the nuance between self-allocation and losses, showing that supply chains may simply shift toward non-complying jurisdictions rather than shrinking in volume.

5 Blockchain and Supply Chain Control

Until now, this paper has dealt with resilience. It has offered an understanding on the issues of addressing the illegal trade of minerals by reducing demand of said minerals when such policies are not universally followed. To reestablish some sense of control, we shall address the underlying conditions that have made those markets resilient.

This paper is heavy with assumptions, that are seen as exogenous to the policymaker. The purpose of this section is to break away and allow the policymaker to form policies that modifies the illegal mining market's conditions. The first policy measure we propose is to disrupt the perfect resale of the illegal mineral by designing a blockchain verifying the cleanliness of a mineral. We do so by proposing a tokenized version physical mineral through a Zero-Knowledge Byzantine Fault Tolerant (BFT) consensus, anchored by a permissioned auditing gateway and governed by a "Mint or Enforce" smart contract. We prove this effectively segments the mineral commodity market, under certain institutional conditions, and render the resale implausible. We follow this design by an analysis of the shock generated by this introduction on the clean and the brown mineral prices and market sizes. Following the shock, we observe that the price levels might still allow for illegal trade. In such cases, we add Directed Technical change to the policymaker's arsenal to allow the incentivization of the clean supply chain. This further endogenizes the model by creating levers to direct innovation towards and lead toward a green sustainable steady state.

Then we shall see that incentivizing can be done locally to create the incentives for local governments to break the isolation of bio-sensitive zones. Building state capacity will allow for direct intervention of the government which was previously impossible. We

shall see that this will create further price competition in bio-sensitive zones in turn further disrupting the bottleneck monopolist.

In tandem, these micro and macro policies have the capacity to break the illegal trade of minerals and generate the inclusive institutions which are so heavily absent from the remotes forests of our world.

5.1 Locking the illegal trade with the Blockchain

5.1.1 Addressing the numeraire in the room

The sources of the resilience of the illegal market were dual, laundering and the remaining market. By partitioning the supply chain in two, a legal and an illegal, we shall see that these two sources of resilience are impacted.

The source of resilience lies in R, the repugnance spread, between the illegal assets's . R is the difference between the price of the mieral in the general economy, θ_E and the price in the bio-sensitive region, θ_B . By fragmenting the market, we change the upper bound of the spread θ_E. After introducing a tokenized mineral, with a price θ_C (theta clean), the remaining globa supply, not on the blockchain, supply shall be called, θ'_E.

We shall first establish that if $\theta'_E > \theta_E$, then q', the new non-profitable self-allocated quantity, is superior to q. On the laundering side, we defined quantity $\bar{q}$ the quantity where the marginal utility of laundering becomes null. We shall prove that $\bar{q}(\theta_E, \theta_B)$ is increasing with θ_E.

We have:

$$\bar{q}(\theta_E, \theta_B) = (V')^{-1}(\theta_E - \theta_B) \tag{29}$$

Where $(V')^{-1}$ is correctly defined over $[0, (V')^{-1}(Q)]$ as we have assumed the monotonicity of V over $[0, Q]$.

Taking the partial derivative with respect to θ_E:

$$\frac{\partial \bar{q}(\theta_E, \theta_B)}{\partial \theta_E} = \frac{\partial (V')^{-1}(\theta_E - \theta_B)}{\partial \theta_E} = \frac{1}{\frac{dV'(V^1(\theta_E - \theta_B)}{d\theta_E}} \tag{30}$$

Yet V is increasing and convex over $[0, q]$ (implying $V'' > 0$), which makes the quotient positive and $\bar{q}(\theta_E, \theta_B)$ increasing in θ_E.

In plain english, this means that decreasing the prices on the global market limits the profits made by the bottleneck monopolist when laundering the illegal asset. This in turn reduces the amount that can potentially be intervened by policy.

On the amount that is not allocated, a decrease in the price of the illegal asset in the global markets have a negative effect on the amount allocated during the mechanism. Indeed, the private values X of each agent in the mechanism follow a distribution in $[0, \theta_E]$. If it falls to θ'_E, the distribution of their private values, X', assuming they follow the same distributions, is in $[0, \theta'_E]$. This means that X' is first-order stochastically dominated by X. In this convoluted chains of implies, this in turn means that for every item in the mechanism, the expectation of gain has decreased, meaning that the non-allocated quantity has also decreased.

A policy which would diminish the global prices for brown minerals would yield some success in diminishing quantities. Yet, it is not guaranteed that fragmenting the market leads to a decrease of the brown asset in the global economy...

5.2 Designing the lock on the illegal supply

The path to design a policy enabling a negative shift in the level of the global prices of minerals requires being able to recognize and separate the legal from the legal supply of minerals.

Before such segmentation is born, industrial policies on the legal side of the mineral supply chain is limited. The pooling of legal and illegal minerals in the general economy makes any increase in profitability of the former, increase profitability in the latter. Segmentation becomes an issue of efficiency and of viability for any policy aiming to stop the traffic of minerals.

Before introducing the blockchain, at $\xi = 0$, clean and dirty asset trade at the same price θ_E, this characterizes the perfect resale assumption and is what generates the spread generating the profit in the sale mechanism for the illegal actors. In the following excerpt, we will show how at $\xi = 1$, we can separate the supplies into the clean, tokenized, supply Y_C traded at price θ_C and a dirty supply Y_D exchanged at price θ_D.

5.2.1 From pooled to separate markets

As gold is a physical mineral, the traded gold at this point is pooled into the general gold supply Y. We wish to generate a blockchain which will partition Y perfectly between Y_C and Y_D.

We propose the following caracterization of the segmentation problem to address it by a blockchain.

Definition 6 (Commodity Space)**.** *Let Y be a non-empty set. We postulate a partition*

$$Y = Y_C \sqcup Y_D,$$

where Y_C denotes the verifiable commodity subset and Y_D denotes the unverifiable commodity subset.

The partition of the commodity space is the policy objective at $\xi = 1$. The desire of the policymaker is that the clean supply and the dirty supply be readily identifiable with no overlap between the two.

Definition 7 (Value Semigroup)**.** *Let V be a totally ordered abelian semigroup. Let $v : Y \to V$ be a function satisfying $v(y) > 0$ for all $y \in Y$.*

The second requirement models the need for the tokenized mineral to remain a scarce reserve of value. The abelian nature of the value function, generates a predictable outcome in transactions outside of the new mineral, and allows for its division.

Definition 8 (Commitment Space)**.** *Let $\mathcal{C}$ be a set. A commitment structure is a function*

$$\psi : \mathcal{C} \to \mathcal{P}(Y) \setminus \{\emptyset\}$$

such that $\psi(c)$ is finite for all $c \in \mathcal{C}$. The commitment valuation is defined by

$$v(c) := \sum_{y \in \psi(c)} v(y),$$

which is well-defined since $\psi(c)$ is finite and every $y \in Y$ maps to V.

Here by mapping the tokenized mineral to a digital cryptographic commitment we start building the architecture of the blockchain. Because of the physical nature of the mineral trade, the nature of the verification must stray away from distributed ledgers. Here, ψ,

represents the work the auditing institutions present on the blockchain do to enforce the partition of Y. Furthermore, by placing the payload within a cryptographic commitment space C, we ensure data privacy on all the ends of the blockchain. This preserves the information rents of secondary dealers and institutional market makers, which ensures that trading is liquid.

5.2.2 Transaction Automaton and Dependency Graph

Let Π be a set of zero-knowledge proofs and $\mathcal{E}$ a set of digital signatures.

Definition 9 (Transaction)**.** *A transaction is a 4-tuple*

$$tx = (I, O, \pi, s) \in \mathcal{P}(\mathcal{C}) \times \mathcal{P}(\mathcal{C}) \times \Pi \times \mathcal{E},$$

with I and O finite sets. Denote by $I(tx) = I$ and $O(tx) = O$. Let $\mathcal{T}$ denote the finite set of all transactions.

This definition formalizes the fundamental unit of economic exchange as a cryptographic 4-tuple comprising inputs I, outputs O, zero-knowledge proofs π, and signatures s. From the perspective of Transaction Cost Economics (TCE), this tuple operates as a "strong smart contract," which digitizes the terms of trade such that execution is automated, non-reversible, and mathematically guaranteed. By requiring a zero-knowledge proof π and signature s for every state transition, the mechanism substitutes costly, potentially corrupt, audits by an algorithmic verification. This cryptographic bounding ensures that property rights are securely transferred while eliminating the risk of ex-post opportunism or holdup by illegal miners.

Definition 10 (Dependency Relation)**.** *Define the binary relation $\prec$ on $\mathcal{T}$ by*

$$tx \prec tx' \iff I(tx') \cap O(tx) \neq \emptyset.$$

The dependency relation $\prec$ constructs an absolute provenance graph, this makes the outputs of one transaction the input of the next one. This allow for the spatial and temporal mapping of transactions in the blockchain. By digitizing this provenance graph , the protocol removes most of the auditing and monitoring costs for the clean supply. This comes in tandem with transparency as any market participant is now able to verify

the provenance of the commodity, without the need a centralized intermediary. (Which would be a weak link in the fight against corruption). This is the lock that enforces the strict partition of Y_C and Y_D

Axiom 5.1 (Acyclicity)**.** *The directed graph $(\mathcal{T}, \prec)$ is a finite directed acyclic graph (DAG).*

Acyclicity is there to make the commodity move forward in time and enforces scarcity. It prevents, circling loops of transactions which could be used to inflate and generate leakage of the illegal supply in the blockchain. This makes the blockchain non inflationary and keeps malicious actors from capturing unearned seigniorage rents.

Lemma 1 (Well-foundedness)**.** *The relation $\prec$ on $\mathcal{T}$ is strictly well-founded.*

Proof. By Axiom 1, $(\mathcal{T}, \prec)$ is a finite DAG. Every finite DAG admits a topological ordering; thus no infinite descending chain exists in $\mathcal{T}$, establishing strict well-foundedness. □

The well foundedness lemma proves that the graph we defined has a topological ordering and is a finite DAG. Each transaction can be traced to the token's creation and one can observe it moving from hand to hand. As only an authorized mint agent, can generate a token, there is certitude in the blockchain. This lemma is the proof that our blockchain does partition Y and keep Y_D from leaking in. Because they are partitioned, we can now assume that the prices of the dirty asset and the clean asset are respectively θ_D and θ_C.

5.2.3 System Dynamics and Physical Consistency

Having dealt with the validity of the blockchain's partition we must formalize the process through which the blockchain keeps consistency between the off-chain commodity space and the on-chain ledger accross state transitions. We must provide with the sufficient transaction costs which refrain the illegal actors from forcing their way in the blockchain.

Let $\sigma_G \in \mathcal{E}$ be a distinguished signature verification key. Let $\{S_t\}_{t \in N}$ be a sequence of subsets of $\mathcal{C}$ denoting the ledger state at time t.

Definition 11 (Validity Predicate)**.** *A transaction $tx \in \mathcal{T}$ is valid with respect to S_t if and only if exactly one of the following mutually exclusive conditions holds:*

- ***(Mint):*** *$I(tx) = \emptyset$ and $s = \sigma_G$.*

- ***(Enforce):*** $I(tx) \subseteq S_t$ *and* $v(I(tx)) = v(O(tx))$.

The "Mint-or-Enforce" protocol divides agent in two tiers. Agent validating a mint condition are at the inception of a token(zero inputs, signed by the Gateway σ_G). The Enforce condition, represents the rest of the trades, they have to verify that the token rightly belongs to the chain (inputs belong to the current state, and the input value equals the output value). This is the smart contract governing the global ledger. We remove any human input and in doing so meddling in the chain.

Axiom 5.2 (Gateway Fidelity)**.** *For any valid transaction satisfying the Mint condition:*

$$\bigcup_{c \in O(tx)} \psi(c) \subseteq Y_C.$$

The axiom means that any valid Mint condition must be issued from someone in the clean supply. This introduces the risk for the chain. The agent validating the Mint must be close enough to the supply chain to verify it provenance and have the right incentives to not introduce a dirty mineral. The institution can therefore not be fully located in the OECD countries but also cannot be the miner. The Mint condition must come from reliable auditors. This binds the chain to the physical reality. The degree of leakage will depend on the institutional strength of the organization writing the smart contracts. The entire market segmentation strategy hinges on the integrity of this Gateway; if the Gateway is corrupted and allows Y_D to be minted, the blockchain's internal mathematics cannot prevent the collapse of the verifiability premium.

Axiom 5.3 (Conservation and Provenance)**.** *For any valid transaction satisfying the Enforce condition:*

$$\bigcup_{c \in O(tx)} \psi(c) \subseteq \bigcup_{c \in I(tx)} \psi(c).$$

This condition makes sure that the digital transaction happening under Enforce conditions must be a subset of the physical payloads exchanged. While Definition 3.1 ensures the numerical value is conserved, this axiom ensures the physical mapping is conserved. This condition guarantees that once the commodity is tokenized, illegal actors cannot secretly dilute the clean supply by mixing in dirty gold during a transfer. By strictly tying every output to a verified input, the protocol protects the property rights of the token holders, ensuring that the digital asset retains its macroeconomic utility as a safe,

unadulterated store of value

Axiom 5.4 (Ledger Realizability)**.** *For all $t \in N$ and all $c \in S_t$, there exists a finite chain $(tx_1, tx_2, \ldots, tx_k)$ such that:*

1. *$c \in O(tx_k)$,*
2. *each tx_i is valid with respect to S_{t_i} for some $t_i \leq t$,*
3. *for each $1 < i \leq k$: $tx_{i-1} \prec tx_i$.*

This axiom formalizes the requirement of complete, unbroken auditability. In a traditional supply chain, information asymmetry allows intermediaries to extract rents by hiding the true origin of a good. Ledger realizability ensures that every single tokenized asset currently active in the economy possesses a deterministic, cryptographically verifiable lineage tracing all the way back to its initial Gateway certification. This represents the total collapse of search and monitoring costs regarding provenance. It is this absolute transparency of origin that allows global buyers to trust the asset, justifying the price premium $(\theta_C - \theta_D)$ for clean gold.

Having setup the necessary blockchain and institutional requirement needed to operate a partitioned clean and dirty supply of gold, we look at the effect of the introduction on the prices and market size of the clean and dirty asset.

5.3 A directed transition to a clean supply chain

To model the impact of integrating the legal gold supply in a blockchain, we shift our focus from the bio-sensitive region to the global economy. Having fragmented the market, the policymaker has now fragmented both the supply and the demand of the asset. This fragmentation is an avenue for global institutions to direct investment to the clean supply of minerals. We shall build a model of directed technical change in a schumpeterian growth model to first describe the effect of the shock on illegal markets resilience. This first shock affects the resilience through the reduction of the illegal asset θ'_E which we shall call θ_D in rest of the paper. Then see the dynamic policy possible to reduce this price to almost zero, effectively extinguishing the illegal trade.

5.3.1 The pooled economy and the introduction of the blockchain

In this framework, time is continuous and indexed by $t \in [0, \infty)$. The world economy is partitioned into the North, $\mathcal{N}$, representing countries where policy applies, and the South, $\mathcal{S}$. Both have fixed labor endowments, $L^{\mathcal{N}}$ and $L^{\mathcal{S}}$, such that $L^{\text{pool}} = L^{\mathcal{N}} + L^{\mathcal{S}}$.
Before introduction of the blockchain, the worlds economy produced unique final mineral asset Y, which serves as the numeraire. This mineral is produced uses two intermediate inputs, the clean, Y_C, the dirty, Y_D.
The north and the south economies differ by their taste in the final mineral Y. If possible, $\mathcal{N}$ has infinite disutility for the brown inputs and has already established checks in its production such that $Y_D^{\mathcal{N}} = 0$. On the other hand, the south uses both the brown and the clean supply for its inputs.
We define the traceability structure $\xi \in \{0, 1\}$. In 0, ξ represent the current situation where the inputs are pooled and consumers are bound to buy a pool of clean and dirty. In 1, ξ represents a world with the blockchain where discriminatory buying is now possible. Lack of traceability generated an implicit demand subsidy to the brown supply of illegal mineral. By enforcing blockchain adoption, the segmented market allows final consumers to allocate their demand according to their preference. This profoundly changes, the profitability, the market sizes and the innovation possible in both clean (tokenizable) or brown (non-tokenizable) supplies.
We shall proceed first by describing the shock and its effects on the clean and brown productions underlying today's global production. This part will conclude on the reduction of illegal markets' resilience as part of the sole introduction of the blockchain. Then only we will study the dynamics of the clean vs brown sectors to analyze policy making on a global scale.
We introduce the notations $r = \{N, S\}$, to represent the regions and $j = \{C, D\}$ to represent the clean and the dirty sector. At $\xi = 0$ the final output is producted through a CES (constant elasticty substitution) aggregator:

$$Y^r = \left[\gamma (Y_C^r)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma)(Y_D^r)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{31}$$

With $\varepsilon \in (0, \infty)$ the elasticity of substitution between sectors, and $\gamma \in (0, 1)$ the efficiency of the green sector in relation to the dirty. We shall make the assumption that $\epsilon > 1$,

making the sectors gross substitutes.

Each intermediate good j is produced in a competitive market using a labor intensive technology that uses machines $x_j(i)$:

$$Y_j = \frac{1}{1-\beta}\left(\int_0^1 A_j(i)^\beta x_j(i)^{1-\beta} di\right) L_j^\beta \tag{32}$$

L_j being the labor used in sector j, A_j the quality of the machine line i and $\beta \in (0,1)$ the partial elasticity of output. Machines are supplied by monopolists who face a marginal cost of $\psi \equiv 1-\beta$ units of the final good. We consider the optimal machine supply faced by the monopolist in sector holding the patent for machine i. Let θ_j be the price for the intermediate good j. The inverse demand function for $x_j(i)$ is given by :

$$p_{x,j}(i) = \theta_j A_j(i)^\beta x_j(i)^{-\beta} L_j^\beta. \tag{33}$$

The monopolist follows the maximization program $\pi_j(i) = p_{x,j}(i)x_j(i) - (1-\beta)x_j(i)$. The FOC yields the constant monopoly price $p_x = 1$ which in turn yields the equilibrium quantities and profits:

$$x_j(i) = A_j(i)\theta_j^{1/\beta} L_j, \quad \text{and} \quad \pi_j(i) = \beta\theta_j^{1/\beta} A_j(i) L_j. \tag{34}$$

We can now shift our attention to the derivation of the price in the general economy θ_E at $\xi = 0$. We call $\zeta \equiv (1-\beta)^{-1}$ and $A_j \equiv \int_0^1 A_j(i)d_i$, the aggregate productivity of sector j. Including the equilibrium quantities into the production function for intermediate goods yield:

$$Y_j = \zeta A_j L_j \theta_E^{\frac{1-\beta}{\beta}} \tag{35}$$

In the bundled economy, the buyer receives a mix proportional to the supply $Y_C + Y_D$ the price θ_E is equal to the average marginal product :

$$\theta_E = \frac{Y}{Y_C + Y_D} = \frac{\left[\gamma A_C^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma) A_D^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}}{A_C + A_D} \tag{36}$$

We shall now compare it to the new state of the world when $\xi = 1$ and there is now a separated equilibrium. We shall prove that allowing the north to discriminate against the dirty asset generates a demand leakage which will impact its prices

The equilibrium price for the clean world is still dependant of the global demand. Its value will be :

$$\theta_C = \frac{\partial Y^{World}}{\partial Y_C} = \gamma \left(\frac{Y}{Y_C}\right)^{\frac{1}{\varepsilon}} = \gamma \left[\gamma + (1-\gamma)\left(\frac{Y_D}{Y_C}\right)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{1}{\varepsilon-1}} \tag{37}$$

For the brown asset, on the other hand, the demand now comes only from the south, the maximization problem is now :

$$\max_{Y_C^{\mathcal{S}}, Y_D^{\mathcal{S}}} \left[\gamma (Y_C^{\mathcal{S}})^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma)(Y_D^{\mathcal{S}})^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} - \theta_C Y_C^{\mathcal{S}} - \theta_D Y_D^{\mathcal{S}} \tag{38}$$

The FOC in θ_D yields:

$$\theta_D = (1-\gamma)\left(\frac{Y^{\mathcal{S}}}{Y_D^{\mathcal{S}}}\right)^{\frac{1}{\varepsilon}} = (1-\gamma)\left[\gamma \left(\frac{Y_C^{\mathcal{S}}}{Y_D}\right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma)\right]^{\frac{1}{\varepsilon-1}} \tag{39}$$

We can see that the price $\theta_D \leq \theta_E$ meaning that the introduction of the blockchain has effectively drained the demand subsidy that helped the dirty sector's profits.

Proposition 2. - *Decrease of Resilience after introduction of the blockchain Assuming $\varepsilon > 1$ and $L^{\mathcal{N}} > 0$. The introduction of the blockchain has decreased the price of the dirty asset. In turn, this diminishes the illegal market Resilience.*

In generating a clean sector, we saw that the blockchain has already allowed to hurt the market resilience more than simple policies. We will now see in the schumpeterian model, that the action can be accrued by intervening in the clean market's innovation.

5.3.2 The creative destruction of the blockchain - The creation of a clean supply for the destruction of the dirty

We will now integrate the markets in a dynamic growth setting to motivate the fact that long-term policy can possibly drive illegal markets to bankruptcy by also motivating that this change should be now better than after due to path-dependance

In a standard creative destruction framework, Let s_C and s_D be the share of scientists allocated to the Green and Brown sectors, respectively ($s_C + s_D \leq 1$). The evolution of machine productivity depends on the current state of technology:

$$\dot{A}_C = \eta_C A_C s_C, \quad \dot{A}_D = \eta_D A_D s_D \tag{40}$$

Let $a = A_C/A_D$ be the relative state of technology. We assume that before the shock:

$$\eta_C = \bar{\eta} a^{\kappa}, \quad \eta_D = \bar{\eta} a^{-\kappa} \tag{41}$$

where $\kappa \geq 0$ governs the intensity of state dependence. If $\kappa > 0$, it is easier to innovate in the sector that is already advanced

In such an economy, we expect scientist to re-allocate themselves to the sector with the highest profit as they are those who have the profitability require to offer a relatively higher wage. By introducing $\Phi \equiv \pi_C/\pi_D$ and injecting it into (33) we get:

$$\Phi = \frac{\pi_C}{\pi_D} = \frac{\beta \theta_C^{1/\beta} A_C L_C}{\beta \theta_D^{1/\beta} A_D L_D} = \left(\frac{\theta_C}{\theta_D}\right)^{\frac{1}{\beta}} \frac{A_C}{A_D} \frac{L_C}{L_D} \tag{42}$$

Proposition 3. *Reallocation of innovation By introducing the blockchain, the incentive to innovate in the clean technology is higher*

Proof. We compare Φ under the two regimes.

Before the shock with $\xi = 0$: Prices are equalized ($\theta_C = \theta_D = \theta_E$). Assuming symmetric labor allocation in production ($L_C \approx L_D$), the incentive ratio is driven purely by the technology gap:

$$\Phi_0 \approx \frac{A_C}{A_D}.$$

After the shock, with $\xi = 1$: Prices diverge. Furthermore, the market size for innovation differs. Green innovations can be used by the entire world ($\bar{L}$), whereas Brown innovations are effectively restricted to the South ($L^{\mathcal{S}}$). Substituting these relevant market sizes into (8):

$$\Phi_1 = \underbrace{\left(\frac{\theta_C}{\theta_D}\right)^{\frac{1}{\beta}}}_{\text{Price Effect}} \times \underbrace{\frac{A_C}{A_D}}_{\text{Tech Effect}} \times \underbrace{\frac{\bar{L}}{L^{\mathcal{S}}}}_{\text{Market Size Effect}}.$$

From Theorem 1, we established that $\frac{\theta_C}{\theta_D} > 1$. Since $\beta \in (0, 1)$, the term $(\theta_C/\theta_D)^{1/\beta}$ is significantly greater than 1. Additionally, $\bar{L} > L^{\mathcal{S}}$. Therefore, every term in the transition from Φ_0 to Φ_1 strictly increases the value of Green innovation.

$\Phi_1 > \Phi_0$. □

This theorem provides the central transmission mechanism: the regulatory shock works through both a Price Effect, clean goods increase in their price in relation to brown goods and a Market Size Effect, the market for brown goods shrink. Both forces push the economy toward the tokenizable industry.

5.3.3 Path Dependence and policy Intervention

Theorem 2 gives us a positive outlook on the state of the world. If the productivity of the clean sector after the technology shock is sufficiently high, this will drive the market towards a clean equilibrium without illegal mining. Without any further policy implementation. Nonetheless, if the reverse scenario is true and the brown sector is highly productive, we must study how directed technical change must be implemented to re-balance the equation.

To operate this discussion we first study the dynamics of the relative technologies. We introduce the notation $a_t \equiv A_c(t)/A_D(t)$. The relative innovation rate is:

$$\frac{\dot{a}_t}{a_t} = \bar{\eta} a_t^{\kappa} s_C(t) - \bar{\eta} a_t^{-\kappa}(1 - s_C(t)) \tag{43}$$

We saw that scientists migrate to the clean sector only if it is relatively the most profitable meaning:

$$\frac{\Pi_C}{\Pi_D} \equiv \frac{\pi_C \eta_C}{\pi_D \eta_D} > 1. \tag{44}$$

We now turn to general equilibrium to determine the adjustment of prices after an adjustment in the state of technology a_t. Using the ex-post shock prices of the clean and dirty assets we get:

$$\frac{\theta_C}{\theta_D} = \frac{\gamma}{1-\gamma}\left(\frac{Y_C}{Y_D}\right)^{-\frac{1}{\varepsilon}}. \tag{45}$$

Injecting the previous equation in the profit ratio:

$$\frac{\pi_C}{\pi_D} = \left[\frac{\gamma}{1-\gamma}\left(a_t \frac{\bar{L}}{L^{\mathcal{S}}}\right)^{-\frac{1}{\epsilon}}\right]^{\frac{1}{\beta}} \cdot a_t \cdot \frac{\bar{L}}{L^{\mathcal{S}}} = \Lambda \cdot a_t^{1-\frac{1}{\beta\epsilon}} \tag{46}$$

With the scale $\Lambda \equiv \left(\frac{\gamma}{1-\gamma}\right)^{\frac{1}{\beta}} (\frac{\bar{L}}{L^{\mathcal{S}}})^{1-\frac{1}{\beta\epsilon}}$ capturing market size and preferences. From here we build the stability condition that allows for a clean path towards sustainability. To say the profitability ratio $\Pi_C/\Pi_D > 1$ is equivalent to say :

$$\frac{\Pi_C}{\Pi_D} = \Lambda \cdot a_t^{1-\frac{1}{\beta\epsilon}} \cdot a_t^{2\kappa} = \Lambda \cdot a_t^{\sigma}, \tag{47}$$

With, $\sigma \equiv 1 + 2\kappa - \frac{1}{\beta\epsilon}$ being the net elasticity of substitution. At the foundation of the policy, a_0 must be such that :

$$\Lambda \cdot a_0^{\sigma} > 1 \Leftrightarrow a_0 > \Lambda^{-\frac{1}{\sigma}}$$

This is the policy intervention threshold. If it fulfilled, the policymaker can have a laissez-faire policy as both the market size and the price of the dirty asset will shrink. Under, there is a dirty path where the dirty mining survives and keep its dominance...
As the north does not consume the dirty asset, the traditional scissor policy of tax and subsidy is not possible. Here it relies solely on a subsidy g to incite clean innovation.

We call the green path threshold $e = \Lambda^{-\frac{1}{\sigma}}$. Using the clean subsidy g, the profitability of the green sector for a green path must be :

$$(1+g)\frac{\Pi_C}{\Pi_D}(a_0) > 1.$$
$$\Leftrightarrow (1+g)e^{-\sigma}a_0^{\sigma} > 1.$$

This condition simply states that the subsidy must be high enough for the clean sector to be able to incentivize scientist to troop in the sector. This yield the final condition.

Proposition 4. *In the case where the relative state of technology at the start of the policy a_0 is inferior to the required green path threshold. Then the policy maker must provide with a subsidy g that generates:*

$$(1+g) > \left(\frac{\omega^*}{a_0}\right)^{\sigma}.$$

This section has studied the impact of the introduction and the long-term policies that foster the conditions for the disappearance of the illegal mineral trade using blockchain. Yet, this policy is long-termed and the path dependence mean that if there is a lapse during the policy, there might be a point of no return for the world's environment. Yet an understudied effect of directed technical change in this case is that it might be the platform that generates durable political change in regions with illegal mining issues.

5.4 Building state capacity through the blockchain - Work in progress

We have explored the effects of generating a clean mineral sector on the market's resilience by exploring how it changes the numeraire price which stands at the center of those markets resilience. Yet, we have not explored the effects how the introduction of the clean asset might incentivize changes of governance in the bio-sensitive regions.

Before jumping to the analysis, we must ease two assumptions characterizing isolation. First, local governments have no capacity to intervene. The literature on institutional economics seem to point at a political choice for this non intervention. The work of

Acemoglu, Johnson and Robinson has pointed that extractive (synonymous with oppressive) institutions are often characterized by the roughness of geographical conditions in a region. (Acemoglu, Johnson, & Robinson, 2001) They equate these to the lack of incentives for governments to undertake the cost of developing inclusive institutions in the region. This generates a game where building state capacity in the totality of territory becomes endogenous with that territory's capacity to generate the political incentives to be developed. Second, we hypothesized that there was no sustainable way to mine in bio-sensitive regions (might have been implicit). Examples of traditional mining, usually using techniques preceding mercury extractions, have resurfaced under the guidance of NGOs and international institutions. These traditional mining are severely less productive than their polluting counterparts but are much cleaner and are not implemented with deforestation.

To model this, we first model the decision to build state capacity for a social planner with an infinite timeline. This social planner can plan his economy on an infinite timeline and must make the decision today to either build state capacity in the bio-sensitive region or not. The decision to build state capacity allows him to perceive tax revenue from the clean industry he will create, the decision to not pursue it allows him to keep the bribe he perceives from illegal mining.

Building state capacity requires an investment, from the part of the social planner. State capacity is a risky investment as their is no certainty of success. To improve the certainty of success, the social planner has a choice of investment on k, the cost of building state capacity, which increases the profitability, P(.), the government can defeat the cartel and put a clean mine in the bio-sensitive zone. In case he succeeds he can now tax the legal mine at rate τ, generating value V^{BSC} at date t:

$$V_S^{BSC}\theta_C, A_{C,t}) = \sum_{i=1}^{+\infty} \delta^i \times \tau \times \Pi_C^i \tag{48}$$

$$V_S^{BSC}(\theta_C, A_{C,t}) = \tau \sum_{s=1}^{\infty} \delta^s \beta \theta_C^{1/\beta} (1+\mu_C)^s A_{C,t} L_C \tag{49}$$

We call the discount rate δ, the tax rate for the legal mining industry, τ. As before, we use $A_{C,t}$ to denote the technology level in the country at date t. Its law of motion changes

as the decision is taken at each start of the year :

$$A_{C,t+1} = (1 + \mu_C)A_{C,t}, \quad \mu_C = \eta_C s_C \tag{50}$$

We keep $\eta_C > 0$ the sector specific innovation efficiency and s_C the share of scientists directed toward legal mining. This equates for $V^B SC$ to be equal in case of success to:

$$V_S^{BSC}(\theta_C, A_C) = \frac{\gamma(1+\mu_C)}{1-\gamma(1+\mu_C)}]\beta\theta_C^{1/\beta} A_C L_C \tag{51}$$

If he fails to achieve BSC (Building state capacity), his revenue from the bio-sensitive region is null. This means that at any period the optimization program followed by a social planner pursuing BSC is :

$$V_B SC(\theta_C) = \max_k\{-k + P(k)[\frac{\gamma(1+\mu_C)}{1-\gamma(1+\mu_C)}]\beta\theta_C^{1/\beta} A_C L_C\} \tag{52}$$

On the other hand, we consider that the social planner might receive part of the revenue of the illegal miner in the form of a bribe.

$$r_b = \theta_D \times b \times q \tag{53}$$

Where r_b is the bribe's revenue, θ_D the price of the dirty mineral, b the total flow of mineral exiting the bio-sensitive zone and q the share that goes to the social planner
To chose the bribe means that he gets to keep the bribe for this period and at the same time keep the option to pursue building state capacity in the future. This means that he get to choose next period between the value of the bribe V^D and the value of building state capacity V^{BSC}:

$$V_D(\theta_C) = r_b + \delta \max\{V_D(\theta_C), V_I(\theta_C)\} \tag{54}$$

Due to the North Directed technical change policy, the price of the clean asset increases.

Because of the form of the social planners Bellman, there must be a threshold price for the clean mineral at which:

$$V^D(\theta_C^*) = V^{BSC}(\theta_C^*)$$

This threshold is expressed as :

$$\theta_C^* = \frac{\frac{q\theta_D b}{1-\delta} + (1-\delta)k^*}{\Phi(k^*, \mu_C, A_C)} \tag{55}$$

6 Conclusion

Isolated, bio-sensitive regions have long been trapped in an extractive equilibrium. This paper has explored the microeconomic foundations of this institutional persistence, demonstrating how armed cartels and guerrilla factions leverage the global demand for minerals to finance coercion and environmental devastation. We have established that international sanctions alone cannot break this path dependence; the unobservability of the supply chain allows these illicit organizations to seamlessly launder their output, effectively transforming global moral repugnance into a lucrative private rent. Breaking this cycle requires a technological shock to the informational architecture. By adopting blockchain traceability, the global market can strictly segment legal from illegal supply, systematically stripping illicit extraction of its profitability. Crucially, this static shock alters the macroeconomic growth trajectory through Directed Technical Change, permanently shifting global investment toward clean technologies. As the rents from illegal extraction collapse, the local political economy is forced into a fundamental transition. By bankrupting the financial foundation of de facto cartel power, this mechanism provides a structural pathway for vulnerable regions to escape the resource curse, replacing cycles of violence and ecological ruin with sustainable, inclusive governance.

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