Rigid Institutions, Irreversible Technology*

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Abstract

Why are rigid institutions sometimes reformed without crisis? We develop a framework of technology-induced institutional change centered on two forces: *institutional rigidity*, whereby status-quo beneficiaries can coordinate to block direct reform, and *technological irreversibility*, whereby a new technology, once adopted, cannot be costlessly unwound. Facing institutional rigidity, a reform-minded government can pursue change indirectly by promoting an irreversible new technology. Decentralized adoption and dispersed information create strategic uncertainty: each incumbent who receives a sufficiently favorable private signal finds it individually rational to adopt, for fear of being stranded on the losing side, even though collective resistance would leave every incumbent better off. This splits the incumbent class, making the technology viable at scale and reshaping the political landscape: adopters, locked in, cannot profit without reform; new actors, spawned by the technology, cannot thrive without reform; and resisters, their rents already eroded, lack the incentive to fight. At a tipping point, reform becomes irresistible, ratifying the new economic reality. Empirically, agricultural mechanization in China causally increased land consolidation at scales incompatible with the household-based tenure system, followed by nationwide land-rights reform. The framework also explains uneven reform across sectors in high-rigidity settings.

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Keywords: Technology-induced institutional change; Irreversible technology; Institutional rigidity; Strategic uncertainty; Gradual reform

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1 Introduction

Economic reform is politically difficult when its losers are concentrated, organized, and able to act collectively. A well-resourced incumbent class can coordinate to block changes that would raise aggregate welfare, even when the inefficiency of the status quo is widely recognized (Olson, 1982; Fernandez and Rodrik, 1991). The political economy of reform literature has identified several pathways past this obstacle. Reform-minded governments can pursue gradualism that builds constituencies through early winners (Dewatripont and Roland, 1992, 1995) or adopt dual-track liberalization that protects incumbent rents (Lau, Qian, and Roland, 2000). Alternatively, exogenous shocks—wars, fiscal crises, revolutionary threats—can overwhelm resistance outright (Acemoglu and Robinson, 2006; North, 1990). Yet a distinct pathway has received less formal attention. In a number of consequential episodes, particularly at the sectoral level, rigid economic institutions have been reformed following government-promoted technological shifts, without crisis, without Pareto improvement, and without incumbents being deceived about what was coming.[1]

Consider three cases from China's recent reform experience. The household-based rural land system, resistant to direct reform for decades despite well-documented efficiency losses, was restructured after the government subsidized agricultural machinery whose efficient use required larger and more consolidated holdings. The state monopoly on payment clearing was restructured after mobile-payment technology, initially tolerated within the existing regulatory framework, grew to dominate everyday commerce. Centralized power dispatch accommodated market-based trading after renewable-energy technology created producers whose economic viability hinged on a different institutional arrangement. In each case, the proximate trigger was not a political crisis but a technological shift actively promoted—or at least permitted—by the government.[2]

This paper proposes a formal framework for understanding this pathway, which we call *technology-induced institutional change*. The framework centers on the interaction of two forces: *institutional rigidity*—the political infeasibility of directly reforming an entrenched institution because its beneficiaries can coordinate to block change—and *technological irreversibility*—the fact that a new technology, once adopted, generates scale economies, network effects, and altered production practices that cannot

[1] We study sectoral economic institutions: the formal rules and governance structures that govern production and exchange within a sector (North, 1990), such as land tenure systems, payment clearing architectures, and power dispatch rules. Like national political institutions, sectoral economic institutions can be self-reinforcing: their beneficiaries form distributional coalitions that organize to protect them (Olson, 1982), making direct reform politically infeasible even when the status quo is widely recognized as inefficient.

[2] Each of these sectoral arrangements—land tenure (土地承包制度), payment clearing (支付清算制度), and power dispatch (电力调度制度)—is an institution in the precise sense of North (1990): a formal, state-enforced rule system that allocates property rights over decades and is defended by organized beneficiaries. China's planned power dispatch administratively assigns generation hours to each power plant, effectively allocating electricity revenue rights, which is backed by provincial authorities and actively defended by coal-power incumbents whose profitability depends on guaranteed utilization hours. UnionPay's exclusive clearing mandate, established by the State Council in 2002, grants a single entity the legal monopoly over interbank card settlement—a property-rights allocation no less formal than a land-tenure rule. All these arrangements were long-standing, and altering any of them required action at the State Council or National People's Congress level.

be costlessly reversed. We interpret technology broadly to include not only physical technologies but also new production methods and market arrangements that exhibit similar dynamics of decentralized adoption and irreversibility.

The core logic can be stated as a sequence: technology changes production; production changes interests; changed interests change politics; and law follows by ratifying the new economic reality. When direct reform is politically blocked, the government can promote or permit a new technology that can begin operating within the existing institutional framework—agricultural machinery, for example, can be deployed on existing farmland under the existing land tenure system. Once adoption spreads, the technology reshapes the economic interests of the very incumbents who benefit from the status quo: it alters relative returns, making the old arrangement less attractive to some incumbents who once had every reason to defend it. At the same time, it spawns new economic actors whose livelihoods hinge on new institutional arrangements compatible with the new technology. Once adoption crosses a tipping point, technological irreversibility forecloses reversion: the technology has generated sunk investments, network effects, and production practices that cannot be costlessly unwound. The shifted incumbents and the new actors the technology has spawned together constitute a reform constituency that did not previously exist. Institutional change at this point is less a political victory over the old order than the legal ratification of a new economic reality. The technology-induced pathway thus simultaneously installs new productive capacity and dislodges the old institution.

This argument, however, raises an immediate question: if the institutional implications of a new technology are foreseeable, why do incumbents not coordinate to block it preemptively? After all, collective resistance would leave every incumbent better off than the post-reform outcome. The key lies in strategic uncertainty among incumbents under decentralized adoption. Because each incumbent's adoption decision is private, no incumbent can observe how many others have shifted allegiance; even tiny uncertainty about the technology's fundamental potential generates large uncertainty about others' behavior. Each incumbent, fearing being stranded on the losing side of an irreversible shift in which the old institution is reformed and resisters lose everything, finds it individually rational to adopt the technology. This coordination failure has the logic of a prisoners' dilemma: each incumbent's individually rational choice collectively undermines the group. It is this coordination failure—not deception, crisis, or Pareto improvement—that explains why incumbents cannot preemptively block a technology even when its institutional implications are understood in advance.

This mechanism, coordination failure under decentralized adoption, therefore simultaneously addresses three questions in the political economy of reform. First, it overcomes the preemptive-blocking logic of Acemoglu and Robinson (2000): dispersed private information destroys the common knowledge that coordinated resistance requires. Second, it endogenizes constituency formation, developing Dewatripont and Roland (1992, 1995): the pro-reform coalition is not presupposed but created by technology adoption that endogenously splits the incumbent class before any reform is

attempted. Third, it shows how non-Pareto-improving reform becomes feasible, extending Lau, Qian, and Roland (2000): when losers cannot coordinate, reform need not be Pareto-improving to proceed.

We formalize this idea in a two-stage game. In Stage 1, a unit mass of incumbents simultaneously decide whether to adopt, based on private signals about the technology's fundamental potential. This stage adapts the global-games framework (Morris and Shin, 1998; Goldstein and Pauzner, 2005) to a technology-adoption setting. In Stage 2, conditional on the technology achieving viability, meaning that enough incumbents adopt in Stage 1 for the technology to operate as a viable alternative, a political contest over institutional reform takes the form of a Tullock contest between a Challenger coalition (comprising adopters and technology-spawned new entrants) and a Defender coalition (resisters). Each coalition's aggregate stake is the product of its size and the per-capita payoff difference each member faces between reform passing and failing. These aggregate stakes, in turn, determine the equilibrium reform probability. The two stages are strategically linked: Stage 1 adoption determines the coalition structure and stakes in Stage 2, while the anticipated reform probability in Stage 2 feeds back into adoption incentives in Stage 1, generating a self-reinforcing loop.

The model delivers a sharp contrast between two informational environments. Under perfect information of the technology's potential, incumbents can always coordinate on collective resistance: the "all resist" profile is the Pareto-dominant equilibrium from the incumbents' perspective, regardless of how transformative the technology is (Proposition 1). Under dispersed private information, by contrast, the "all resist" equilibrium unravels. A unique threshold equilibrium emerges in which each incumbent adopts whenever his private signal exceeds a cutoff (Proposition 2). The technology achieves viability and reform occurs with positive probability, whenever the fundamental exceeds a finite threshold. The wedge between these two results arises entirely from strategic uncertainty: even arbitrarily small dispersion in private information destroys the incumbents' ability to coordinate on collective resistance. The equilibrium adoption threshold can be remarkably low because a feedback loop operates between the two stages. Higher adoption swells the Challenger coalition, spawns new entrants, shrinks the Defender bloc, and erodes defensive rents, thereby raising the equilibrium reform probability. The higher reform probability in turn amplifies the expected cost of resistance, inducing further adoption. What primarily drives individual adoption is not the prospect of gain from being on the winning side, but the fear of catastrophic loss from being caught on the losing side.

Conceptually, technological irreversibility functions as a commitment device. By foreclosing ex-post reversion, it makes the future political landscape depend on today's adoption choices, and this is what gives strategic uncertainty its bite: each incumbent must weigh the cost of being stranded in a transformed world against the cost of adoption. Without irreversibility, dispersed information alone would not break coordination, because incumbents could simply wait the disturbance out.

Ex ante at Stage 0, a reform-minded government whose objective is to maximize social welfare decides whether to promote the technology by paying the upfront cost of building initial infrastructure.

The government optimally promotes whenever the expected welfare gain exceeds the infrastructure cost. The welfare gain decomposes into a *technology dividend* (net productive surplus from the new technology), and an *institutional dividend* (the welfare gain from escaping the value-destroying status quo). Because the institutional dividend is positive even when the technology's standalone productive surplus is modest, the government may rationally back a technology whose direct productivity effects alone would not justify the investment. This provides a justification for certain industrial policies that appear disproportionate if judged only by their standalone technological returns.

We further extend the model to compare technology-induced reform with radical reform (corresponding to "big-bang" reform in Dewatripont and Roland, 1995). Radical reform bypasses decentralized technology adoption: the government directly assembles a Challenger coalition through fiscal expenditure. Because no incumbent has defected, the full incumbent class remains intact as Defenders, and the resulting political contest becomes a head-on battle that is costly and resource-intensive even when the Challenger prevails. Technology-induced reform operates differently: decentralized adoption splits the incumbent class before the contest begins, so that by the time reform is contested, the opposition is depleted and divided. The two-stage structure also functions as a real option: the costly political contest is entered only if decentralized adoption reveals favorable fundamentals. Technology-induced reform dominates when ex ante uncertainty about the technology's potential is substantial, the incumbent class is well-resourced, and the private cost of adopting the new technology is small relative to the fiscal cost of directly building a pro-reform coalition. The tradeoff favoring radical reform is speed.

We provide empirical evidence for the central link of the theory using agricultural mechanization and rural land reform in China. In this setting, the rigid institution is *China's household-based land tenure system* and the irreversible technology is *agricultural machinery*. Our empirical analysis focuses on Lemma 1 of the model, which predicts the sequence technology adoption → production reorganization → institutional change. Applied to this empirical setting, the testable implication for the first sub-link, technology adoption → production reorganization, is that scale-biased mechanization causes operational land consolidation at scales incompatible with the existing household-based tenure system. To identify this effect, we exploit the staggered rollout of agricultural machinery purchase subsidies across counties beginning in 2004. We show that mechanization causally increased household land-rental expenditure, our proxy for operational consolidation. Crucially, this effect operated through large and medium tractors, machinery whose efficient use requires contiguous land at scale, rather than through small tractors compatible with fragmented household farming. This pattern confirms that what matters is not generic modernization but scale-biased technological change that alters the returns to land consolidation. The second sub-link, production reorganization → legal codification, is supported by institutional narrative and the chronology of subsequent reforms: the "Three Rights Separation" framework (2014–2016) and the 2018 amendment to the Rural Land Contracting Law

codified the production reorganization that mechanization had set in motion.

Our empirical analysis identifies the causal effect of mechanization on land-rental activity—the first sub-link of Lemma 1. We do not directly test the government's strategic intent (Proposition 3) or the incumbents' adoption coordination problem (Propositions 1 and 2). The machinery subsidy was introduced primarily as productivity-enhancing industrial policy (see, e.g., Liu and Xu, 2026), and the institutional consequence appears largely unintended. Crucially, the model's positive prediction that technology adoption irreversibly restructures production and triggers institutional adjustment (Stages 1–2) holds regardless of whether the government intentionally deploys technology as an institutional strategy (Stage 0), and does not depend on how decentralized adoption arises (Stage 1). Strategic intent is the province of Stage 0, which delivers the model's normative implication; it is not a premise of the positive mechanism tested here.

Our framework also generates cross-sectional predictions about where reform is more likely to advance and where it is more likely to stall. Not every technological advance induces institutional change.[3] We call a technology *institutionally irreversible* when it satisfies two conditions. First, adoption must *reorganize production* in ways the old institution cannot efficiently accommodate at scale, as when large and medium tractors achieve efficiency only on contiguous blocks that fragmented household plots cannot provide. Adopters retool around the new technology, a supporting ecosystem of parts suppliers, repair networks, operator training, and upstream and downstream manufacturing emerges around it, and the rents sustaining the old institution erode through competition from this new ecosystem. Second, this reorganization must be *locked in*: once it has occurred at scale, it cannot be costlessly unwound even if reform does not proceed. Both elements are necessary: reorganization without lock-in is a temporary disturbance that incumbents can wait out, while lock-in without reorganization leaves the old institution unchallenged because nothing of consequence has been locked in. This pattern appears consistent with China's cross-sector reform experience: agricultural mechanization, mobile payments, and renewable energy each exhibit the full constellation of conditions and have seen substantial institutional restructuring in land tenure, payment clearing, and power dispatch, respectively, while sectors lacking a suitable technological vehicle have proved more resistant to change. The framework may also offer lessons for other developing economies facing similar rigidities.

The remainder of the paper is organized as follows. Section 2 reviews the related literature and positions our contribution. Section 3 presents the model. Section 4 analyzes the equilibrium. Section 5 studies radical reform within our model framework. Section 6 tests the model with agricultural mechanization and rural land reform in China. Section 7 provides the discussion. Section 8 concludes.

[3]For instance, Hornbeck (2010) shows that barbed wire substituted for formal legal property rights on the American Plains: by lowering the cost of enforcing boundaries, it directly addressed the property-rights problem and made formal institutional reform less necessary. In such cases, technology acts as a *substitute* for institutional change rather than a *trigger*.

2 Related Literature

This paper connects to five strands of literature.

Institutional persistence and change. A large literature emphasizes that institutions persist because they are self-reinforcing and because beneficiaries of the status quo have both incentives and capacity to block change. Foundational contributions include North (1990), Acemoglu, Johnson, and Robinson (2001, 2005), Acemoglu and Robinson (2006, 2012), and Greif (2006). In many accounts, institutional change follows large shocks that alter political constraints or the distribution of coercive power: revolutionary threats induce elites to extend political rights (Acemoglu and Robinson, 2001, 2006), wars and fiscal needs reshape state capacity (Tilly, 1990; Besley and Persson, 2011), and colonial disruptions transplant institutional arrangements (Acemoglu, Johnson, and Robinson, 2001). Olson (1982) argues that absent such shocks, distributional coalitions accumulate and institutional sclerosis deepens over time. Most directly relevant to our setting, Acemoglu and Robinson (2000) show that cohesive elites may block beneficial technologies whose adoption would erode their political position. Yet permanent blocking is historically the exception: most viable technologies eventually diffuse even when their institutional implications are foreseeable (Mokyr, 1990). Our paper identifies a distinct mechanism: decentralized adoption of an irreversible technology generates strategic uncertainty among incumbents about others' resistance decisions, dissolving the coordination that would otherwise block reform—without requiring an exogenous crisis.

Political economy of reform and gradualism. Our paper is closely related to the literature on gradual reform. Dewatripont and Roland (1992, 1995) make the canonical case for gradual over "big bang" reform: gradualism builds political constituencies for further reform by creating early winners, while preserving the option to reverse course if outcomes disappoint. Roland (2000) develops this into a comprehensive framework for understanding transition economies. Our paper provides a microfoundation for the constituency-building mechanism: it shows how an organized incumbent bloc that can collectively block reform is fractured from within, so that the "first move" becomes feasible. Specifically, decentralized technology adoption endogenously splits incumbents and shifts some of them from the Defender to the Challenger coalition, while simultaneously spawning new entrants whose existence is tied to the reformed institution. In their framework, the political virtue of gradualism is reversibility—the ability to abandon reform if early results are unfavorable, which secures ex ante political support. Complementing theirs, in ours technology irreversibility, working as a *commitment device*, is the engine of change: once adoption is sunk, the coalition shift that drives reform is locked in, and the option to revert is foreclosed; ex ante, even slight uncertainty about other incumbents' adoption decisions makes each incumbent wary of blocking the new technology, for fear of being stranded on the losing side.[4]

[4]Fernandez and Rodrik (1991) show that individual-specific uncertainty about who gains from reform generates status-quo bias. The informational friction on new technology in our paper is different in kind and opposite in effect: uncertainty is

Lau, Qian, and Roland (2000) show how dual-track liberalization in China created "reform without losers" by expanding market opportunities while protecting plan-track rents—a mechanism that is Pareto-improving by construction. Our setting extends beyond their Pareto-improving case, which is more likely to apply in the early stages of reform, to the non-Pareto-improving case: reform inevitably creates losers among incumbents. In this case, what makes reform feasible is not the absence of losers but the failure of collective resistance after technology adoption has split the defending coalition. More broadly, our paper advances the literature on Chinese economic reform (Naughton, 1995, 2007; Qian, 2003; Qian and Xu, 1993; Lin, 2009; Xu, 2011) by offering a unified logic for China's uneven reform experience across sectors in recent years: why reform has advanced where a suitable technological vehicle exists and stalled where it does not.

Technology and institutional change. Existing work shows that technology adoption is closely tied to institutional and political conditions. Historical accounts emphasize that technological progress depends on supporting institutions and the accumulation of useful knowledge (Schumpeter, 1942; Mokyr, 1990, 2002). The reverse channel—from technology to institutions—is emphasized by Hayami and Ruttan (1985), who compare the agricultural development paths of the US and Japan and argue that new technologies create demand for complementary institutional arrangements. Cross-country evidence links the pace of technology diffusion to institutional and policy environments (Comin and Hobijn, 2004, 2010). Other empirical studies document how specific technologies reshaped economic organization, effective property rights, and political alignments: the printing press and early commercial practices in Europe (Dittmar, 2011), barbed wire and the enforcement of property rights on the American Plains (Hornbeck, 2010), railroads and market integration in colonial India (Donaldson, 2018), financial asset ownership and political alignments in seventeenth-century England (Jha, 2015), agricultural mechanization and the erosion of coercive labor institutions in the American South (Hornbeck and Naidu, 2014), and labor-saving machinery and rural unrest in nineteenth-century England (Caprettini and Voth, 2020). Building on this evidence, our theoretical contribution is to formalize when the adoption of an irreversible technology becomes an active force for institutional change and to identify the mechanism through which such adoption generates political pressure for reform. Our empirical contribution is to causally identify how technology adoption reorganized production, and to link this reorganization to subsequent land-tenure reforms in China, where the prevailing institution had resisted efficiency-improving reform for decades despite well-documented efficiency losses.

Global games and political contests. Methodologically, our model features a two-stage game: a global game of decentralized technology adoption followed by a Tullock contest over institutional reform. The adoption stage builds on Carlsson and Van Damme (1993) and Morris and Shin (1998, 2003)

strategic—about others' adoption decisions—and dissolves rather than reinforces the status quo. Alesina and Drazen (1991) argue that distributional conflict over who bears adjustment costs leads to a war of attrition that delays stabilization.

to capture the central friction in our setting: even tiny uncertainty about the technology's fundamentals generates strategic uncertainty among incumbents about how many others will shift allegiance. This logic has been applied in political economy to problems of collective action, protest, and regime change (e.g., Bueno de Mesquita, 2010; Shadmehr and Bernhardt, 2011, 2015; Edmond, 2013). Our setting reverses the usual focus: the coordination problem is not among citizens challenging a regime, but among incumbents seeking to defend a rigid institution. The closest methodological connection is Goldstein and Pauzner (2005), whose bank-run model also lacks a natural upper-dominance region; following their approach, we introduce a vanishing standalone return to adoption that restores global-game uniqueness without altering the substantive economics. Our model features two-way feedback between the two stages: adoption reshapes the political contest that follows, while the anticipated contest outcome feeds back into adoption incentives, making the two stages mutually reinforcing rather than analytically separate.

Rural land-rights reform in China. Empirically, our paper is closely related to a growing literature documenting that insecure or incomplete rural land rights in China generated substantial efficiency losses—distorting land allocation, depressing agricultural productivity, impeding migration, and slowing structural transformation (Benjamin and Brandt, 2002; Deininger and Jin, 2005; Ngai et al., 2019; Adamopoulos and Restuccia, 2020; Chari et al., 2021; Adamopoulos et al., 2024). This literature also shows that reforms strengthening land security and transferability improved allocation, raised productivity, and facilitated labor mobility (e.g., Chari et al., 2021; Adamopoulos et al., 2024; Chen et al., 2026; Tian et al., 2026). We take these findings as given but ask a logically prior question: if such reforms were efficiency-enhancing, why were they politically feasible in the first place? Standard theories of institutional persistence predict that incumbents who benefit from the status quo will resist restructuring (North, 1990; Acemoglu and Robinson, 2006). Our theory resolves this tension by showing how adoption of an irreversible technology induces production reorganization that makes subsequent land-rights reform politically feasible. We provide empirical evidence consistent with this technology-induced institutional-change channel.

3 The Model

We present the model and begin by defining the status quo and the source of institutional rigidity.

3.1 Status Quo and Institutional Rigidity

Failing Status Quo. Consider an economy with two groups: incumbents (mass normalized to one) and citizens. Under the prevailing institution, payoffs are

$$\pi_I^{SQ} = R_0 > 0, \qquad \pi_C^{SQ} = R_1 < 0, \qquad \Pi^{SQ} = R_0 + R_1 < 0.$$

The old institution was once efficient but is now mismatched with the economic environment. Incumbents still extract positive rents R_0, yet citizens bear losses R_1, and aggregate surplus is negative.

Intuitively, the status quo amounts to a forced negative-NPV project. Citizens are compelled to invest resources worth $|R_1|$—in the form of taxes, mandatory procurement, or surrendered property rights—and incumbents capture the project's entire payoff R_0. The project's net present value, $R_0 - |R_1| < 0$, is precisely the social surplus: negative by assumption. The system destroys value but persists because those who benefit from it have both the power and the incentive to maintain it. This status quo is the starting point for the two cases that follow.

Marginal Institutional Reform. Marginal reform eliminates institutional frictions while leaving the technological base unchanged. If implemented, payoffs become

$$\pi_I^{MR} = 0, \qquad \pi_C^{MR} \gtrless 0, \qquad \Pi^{MR} = \pi_I^{MR} + \pi_C^{MR} \gtrless 0.$$

The reform improves social surplus by

$$\Delta = \Pi^{MR} - \Pi^{SQ} > 0.$$

It brings the economy from negative to approximately zero surplus—stopping the bleeding. Intuitively, the reform frees citizens from the forced negative-NPV project: they are no longer compelled to invest $|R_1|$ into a value-destroying activity, so their net payoff rises to slightly above zero as they redeploy resources to modest outside activities. Incumbents, however, lose their entire rent R_0. Although the reform is Kaldor–Hicks efficient, it is not Pareto-improving: incumbents are strictly worse off. We assume that frictions such as commitment problems preclude Coasean bargaining between the two groups. Given this, incumbents, who possess the de facto decision right, block the reform.

The central insight of this paper is that a reform-minded government facing institutional rigidity can promote a new technology whose irreversible adoption realigns the economic interests of a critical mass of incumbents and ultimately induces institutional change. We formalize this through a two-stage game: a technology adoption stage (modelled as a global game of regime change) followed by a political contest over reform. This two-stage structure—in which stage 1 coordination shapes the stakes of stage 2, and anticipation of stage 2 feeds back into stage 1 incentives—is a key feature of our model.

3.2 Stage 0: Government Technology Promotion

The government's objective is to maximize the social surplus. It has the opportunity to promote a new technology, whose fundamental, denoted by θ, is drawn from $\theta \sim N(\bar{\theta}, \sigma_\theta^2 = \tau_\theta^{-1})$. The government has no private information about θ. Promotion requires an upfront investment I (for example, the cost of building initial infrastructure). If the government promotes the technology, the game proceeds to Stage 1.

3.3 Stage 1: Technology Adoption Game

This stage of the game adapts the global-games regime-change framework (e.g., Morris and Shin, 2003; Goldstein and Pauzner, 2005) to a setting in which technology adoption is integrated with a

subsequent political contest.

Players and actions. The central government initiates the adoption of the new technology at Stage 0, but viability requires incumbents to cooperate in its implementation. A unit mass of incumbents $i \in [0, 1]$ simultaneously choose $a_i \in \{0, 1\}$: action $a_i = 1$ represents adoption (cooperation, engagement) and $a_i = 0$ represents resistance (shirking). Each incumbent's action is unobservable to other incumbents. Let $A_1 \equiv \int_0^1 a_i \, di$ denote the aggregate adoption.

Information structure. Each incumbent privately observes a noisy signal about the technology's transformative potential θ:

$$x_i = \theta + \varepsilon_i,$$

where $\varepsilon_i \overset{i.i.d.}{\sim} N(0, \sigma_x^2 = \tau_x^{-1})$. No incumbent observes θ directly. Each forms beliefs about both θ and crucially about how many other incumbents will adopt, based solely on his private signal.

Viability condition. The technology achieves viability if and only if

$$\theta + \kappa A_1 \geq T,$$

where $T > 0$ is the viability threshold and $\kappa > 0$ measures the strategic complementarity between the technology's fundamental potential and aggregate adoption. We maintain $T > \kappa$, which ensures that viability requires a strictly positive fundamental ($\theta > T - \kappa > 0$ whenever $A_1 \leq 1$).

Payoff structure. Table 1 presents the payoff to an individual incumbent as a function of his action and whether the technology achieves viability.

Table 1: Payoff Structure of Technology Adoption Game

	Resist ($a_i = 0$)	Adopt ($a_i = 1$)
Not Viable ($\theta + \kappa A_1 < T$)	R_0	$-c$
Viable ($\theta + \kappa A_1 \geq T$)	$\Lambda_D(A_1)$	$-c + \Lambda_C(A_1)$

Here $c > 0$ is the adoption cost.[5] When viability fails, the status quo persists: adopters bear the sunk cost c while resisters retain their rent R_0. When viability obtains, the game proceeds to Stage 2, where the reform contest determines payoffs. The adopter's stage 2 payoff $\Lambda_C(A_1)$ and the resister's stage 2 payoff $\Lambda_D(A_1)$ will be derived from the Tullock contest (see equations (3) and (4) below).

Strategies. We consider monotone (threshold) equilibria in which each incumbent follows a cutoff rule:

$$x_i \longmapsto \begin{cases} Resist, & x_i < x^*, \\ Adopt, & x_i \geq x^*, \end{cases}$$

[5] A farmer who dismantles his small-plot operation to prepare for mechanized farming has fundamentally altered his productive assets. If mechanized agriculture does not take off locally, he cannot instantly reconstitute his old setup. The $-c$ payoff captures this total loss of position.

where x_i is the signal received by incumbent i and x^* is the adoption threshold, which is common among incumbents.

3.4 Stage 2: Reform Contest

Conditional on the technology achieving viability, the economy is disrupted, triggering a contest over institutional reform. Adopters and new entrants form a *Challenger* coalition favoring reform; resisters form a *Defender* coalition opposing it.

Coalition structure and stakes. The adoption level A_1 determines both the size and the per-capita stakes of each coalition. Technology adoption spawns $\mu(A_1)$ new entrants who join the pro-reform coalition, so the Challenger coalition comprises the A_1 adopters together with $\mu(A_1)$ new entrants. The Defender coalition consists of the $1 - A_1$ resisters.

Each defender retains a per-capita rent $R(A_1) \in (0, R_0]$ if reform fails and receives zero if reform passes, so the per-capita stake of each Defender is $R(A_1)$.

Each adopter retains the rent of R_0 if reform passes and a reduced rent of βR_0 if reform fails, where $\beta \in (0, 1)$. Hence the per-capita stake of each adopter in the reform contest is $(1 - \beta)R_0$. Note that the adoption cost c that was paid in the first stage is a sunk cost.

Each new entrant receives a base technology payoff $\theta > 0$ regardless of the reform outcome. If reform passes, each new entrant additionally receives a per-capita reform bonus $V(A_1) > 0$; if reform fails, this bonus is zero. Hence the per-capita stake of each new entrant is $V(A_1)$.

Table 2 gives the complete payoff structures for two stages.

Table 2: Complete Payoff Structures for Two Stages

		Resister (size $1 - A_1$)	Adopter (size A_1)	New entrant (size $\mu(A_1)$)
Not Viable ($\theta + \kappa A_1 < T$)		R_0	$-c$	
Viable ($\theta + \kappa A_1 \geq T$)	No Reform	$R(A_1)$	$-c + \beta R_0$	θ
	Reform	0	$-c + R_0$	$\theta + V(A_1)$

The aggregate stakes of the two coalitions are therefore

$$\Pi_D(A_1) = (1 - A_1)R(A_1), \qquad \Pi_C(A_1) = A_1(1 - \beta)R_0 + \mu(A_1)V(A_1). \tag{1}$$

We impose the following regularity conditions on the primitives.

Assumption 1. *The functions μ, V, and R are continuously differentiable on $[0, 1]$ and satisfy:*

1. *$\mu(0) = 0$ and $\mu'(A_1) > 0$: new-entrant creation is strictly increasing in the scale of adoption, with no entrants absent adoption.*

2. $V(0) = 0$ *and* $V'(A_1) > 0$*: the per-capita reform bonus is positive and increasing in the scale of adoption.*

3. $R(0) = R_0$ *and* $R'(A_1) < 0$*: the per-capita defensive rent is strictly decreasing in adoption, starting from the full rent* R_0*.*

Conditions 1 and 3 are intuitive. Condition 2 states that the per-capita value of reform to new entrants rises with the adoption base: a compatible institution is more valuable when the new technology is widely used, because larger adoption creates thicker markets, stronger network effects, and more valuable shared infrastructure, so that each new entrant benefits more from reform when surrounded by many complementary adopters. The strict inequality $V'(A_1) > 0$ is not necessary for our results; the model works qualitatively even when $V(A_1)$ is a positive constant. Regarding Condition 3, the model also works under the weaker assumption that $R(0) = bR_0$ with $b \leq 1$, provided b is sufficiently close to 1—specifically, $b > \beta - c/R_0$.

Under Assumption 1, Π_C is strictly increasing in A_1 with $\Pi_C(0) = 0$, and Π_D is strictly decreasing in A_1 with $\Pi_D(1) = 0$.

Importantly, inspection of equation (1) reveals four reinforcing channels through which higher adoption A_1 tilts the political balance toward reform. On the Challenger side, (i) the adopter component $A_1(1-\beta)R_0$ grows linearly in A_1 as more incumbents switch allegiance, and (ii) the new-entrant component $\mu(A_1)V(A_1)$ grows faster than linearly, since both the number of entrants μ and their per-capita stakes V are increasing in A_1 (Assumption 1). On the Defender side, (iii) the pool of resisters $1 - A_1$ shrinks, and (iv) the per-capita defensive rent $R(A_1)$ falls as A_1 increases. In short, a higher adoption A_1 simultaneously swells the Challenger coalition, attracts new entrants, shrinks the Defender bloc, and erodes defensive rents. Because the Challenger's aggregate stake is convex in A_1 while the Defender's is convex in $(1 - A_1)$, a small increase in adoption near a critical threshold that results in viability produces a discrete shift in the equilibrium reform probability.

Economic foundation. The payoffs in Table 2 rest on a single organizing principle: *technologies and institutions are complementary*. Table 3 makes this transparent by pairing each institutional regime with the technologies operating under it.

Table 3: Technology–Institution Complementarity

	Resister (old tech)	Adopter (new tech)	New entrant (new tech)
Old Institution + (old tech, new tech)	$R(A_1)$	βR_0	θ
New Institution + (old tech, new tech)	0	R_0	$\theta + V(A_1)$

Once adoption is viable, the economy moves into the first row—the mismatched, transitional regime in which the old institution coexists with both technologies. The old institution prevents the new

technology from reaching its potential; the old technology, meanwhile, is eroded by competition but not yet eliminated, because the old institution still partially shields it. Distribution follows directly: the resister, de facto owner of the old technology, earns $R(A_1)$, declining as competitive erosion intensifies; the new entrant, de facto owner of the new technology, operates under hostile institutions and is limited to θ; the adopter, allied with the new entrant through the same technological bet, faces the same institutional mismatch and earns only βR_0.

If reform passes, the economy moves into the second row—a regime in which the new institution is paired with the new technology alone. The new institution allows the new technology to realize its full potential; the old technology, stripped of institutional protection, is exposed to full competitive pressure and driven to extinction—not by fiat, but through open-market competition. Distribution follows the same logic in reverse: the adopter, de facto owner of the now-unleashed new technology, earns $R_0 > \beta R_0$; the new entrant, operating the same technology under its compatible institution, realizes his full value $\theta + V(A_1)$; the resister, de facto owner of the now-unprotected old technology, earns zero.

Table 3 also encodes ***technological irreversibility***, which combines production reorganization with its lock-in. Production reorganization shows up through three features. First, adopters have restructured production around the new technology; their payoff under the old institution is permanently degraded to $\beta R_0 < R_0$, so they cannot costlessly revert. Second, the $\mu(A_1)$ new entrants called into existence by the technology populate the first row and persist—they are economic actors that cannot be legislated away. Third, each resister's defensive rent $R(A_1)$ is strictly decreasing in adoption: it suffers irreversible erosion due to competition from the rising new technology. Lock-in then means that this reorganization persists even if reform does not proceed. The mismatched regime (the first row) is therefore self-undermining. The very suppression of productive potential, which defines the distance between the two rows, creates the motive for reform and converts economic loss into political pressure. Reform—the move from the first row to the second—remains a contest, but the material stakes of that contest have already been determined by the production structure.

The Tullock contest. We model the political competition as a Tullock contest between the two coalitions, each acting as a unitary player. The Challenger coalition chooses aggregate lobbying effort $e_C \geq 0$ and the Defender coalition chooses $e_D \geq 0$. The probability that reform is enacted is given by the contest success function

$$p(e_C, e_D) = \frac{e_C}{e_C + e_D} \quad \text{if } e_C + e_D > 0,$$

and $p = \frac{1}{2}$ otherwise. Each coalition maximizes its aggregate expected payoff net of effort costs. The Challenger solves

$$\max_{e_C \geq 0} \ \frac{e_C}{e_C + e_D} \Pi_C - e_C,$$

and the Defender solves

$$\max_{e_D \geq 0} \frac{e_D}{e_C + e_D} \Pi_D - e_D.$$

Under Assumption 1, for any $A_1 \in (0,1)$ the Tullock contest has a unique Nash equilibrium with efforts

$$e_C^* = \frac{\Pi_C^2 \Pi_D}{(\Pi_C + \Pi_D)^2}, \qquad e_D^* = \frac{\Pi_C \Pi_D^2}{(\Pi_C + \Pi_D)^2},$$

and equilibrium reform probability

$$p^*(A_1) = \frac{\Pi_C(A_1)}{\Pi_C(A_1) + \Pi_D(A_1)}. \tag{2}$$

Substituting $\Pi_C(A_1)$ and $\Pi_D(A_1)$ from (1) into (2), and using Assumption 1 (which implies $\Pi_C'(A_1) > 0$ and $\Pi_D'(A_1) < 0$), we obtain the following result.

Lemma 1. *Under Assumption 1, the equilibrium reform probability $p^*(A_1)$ is strictly increasing in $A_1 \in [0,1]$, with $p^*(0) = 0$ and $p^*(1) = 1$.*

Lemma 1 formalizes the technology-to-politics linkage of our theory: it encapsulates the sequence technology adoption → production reorganization → institutional change, which is the focus of our empirical test in Section 6. As technology adoption A_1 rises, production reorganizes in the manner depicted in Table 3: adopters retool around the new technology, new entrants emerge, and the per-capita rents sustaining the old institution erode. This reorganization translates monotonically into a higher probability of institutional change through $p^*(A_1)$.

Per-capita equilibrium payoffs. Within each coalition, effort costs are allocated in proportion to individual stakes (Nitzan, 1991). Consider a Challenger member whose individual stake is s_i and whose floor payoff (the amount retained regardless of the reform outcome) is f_i. His expected gross prize from the contest is $p^* s_i$, since reform passes with probability p^* and, conditional on passage, he captures s_i. Under proportional cost sharing, the member bears effort $(s_i/\Pi_C)e_C^*$. The net contest gain is therefore

$$p^* s_i - \frac{s_i}{\Pi_C} e_C^* = s_i \left(p^* - \frac{e_C^*}{\Pi_C} \right) = (p^*)^2 s_i,$$

where the last equality uses $p^* \Pi_C - e_C^* = (p^*)^2 \Pi_C$. His total Stage 2 payoff is $f_i + (p^*)^2 s_i$. An analogous derivation applies to Defender members, with winning probability $1 - p^*$.

For an adopter ($f_i = \beta R_0$, $s_i = (1-\beta)R_0$),

$$\Lambda_C(A_1) = \beta R_0 + \left(p^*(A_1)\right)^2 (1-\beta) R_0. \tag{3}$$

For a new entrant ($f_i = \theta$, $s_i = V(A_1)$), stage 2 payoff is $\theta + \left(p^*(A_1)\right)^2 V(A_1)$. For a resister ($f_i = 0$, $s_i = R(A_1)$),

$$\Lambda_D(A_1) = \left(1 - p^*(A_1)\right)^2 R(A_1). \tag{4}$$

The squared-probability terms reflect the standard Tullock rent-dissipation result: each side's gross expected prize is discounted by the equilibrium cost of lobbying.

A notable feature of this payoff structure is that the adopter's Stage 2 payoff $\Lambda_C(A_1)$ depends only on the adoption level A_1—not on the technology fundamental θ, similar to the payoff structure of the current attack in Morris and Shin (1998). The parameter θ governs whether the new economic reality materializes (through the viability condition $\theta + \kappa A_1 \geq T$ and the new entrants' base payoff), while A_1 governs what that new reality looks like—who has switched coalitions, how large the Challenger bloc is, and how eroded the Defenders' rents are. This separation yields a clean closed-form characterization of the adoption threshold and tractable comparative statics. If θ entered Λ_C directly, the global-game machinery would still deliver a unique threshold equilibrium, and the additional channel would only reinforce adoption incentives.

Assumption 2 (Standalone Value)**.** *An adopter receives a small standalone productivity gain $\alpha\theta$ from the technology, with $\alpha > 0$, regardless of whether the technology achieves viability or reform succeeds. We focus on the limiting case $\alpha \to 0$ throughout the paper.*

Assumption 2 captures the fact that any superior technology generates some private return—through learning, efficiency gains, or direct productivity improvement—independent of the institutional environment. The extreme case $\alpha = 0$, in which the technology has zero value outside the reformed institution, is a knife-edge. We treat α as arbitrarily small and normalize all payoff expressions to the limiting case $\alpha \to 0$; the standalone term therefore does not appear in the payoff tables or closed-form expressions that follow. Its analytical role is to ensure that, for sufficiently high θ, adoption is a strictly dominant action—establishing an *upper dominance region* that the global-game uniqueness argument requires (Goldstein and Pauzner, 2005). Formally, for $\theta > \bar{\theta}(\alpha) \equiv (R_0 + c)/\alpha$, an adopter's payoff exceeds a resister's under every strategy profile of other incumbents, so that resistance cannot be part of any equilibrium. As $\alpha \to 0$, $\bar{\theta}(\alpha) \to \infty$, but for any fixed $\alpha > 0$ the upper dominance region exists and—together with the lower dominance region already present in the model—the equilibrium under dispersed information is globally unique (Proposition 2).

Linear specification. For tractability and to generate closed-form comparative statics, we adopt the following linear parameterisation:

$$V(A_1) = vA_1, \quad v > 0; \qquad R(A_1) = R_0(1 - A_1); \qquad \mu(A_1) = \eta A_1, \quad \eta > 0.$$

These satisfy Assumption 1 and imply coalition sizes $n_C = (1 + \eta)A_1$ and $n_D = 1 - A_1$. The aggregate stakes become

$$\Pi_C(A_1) = (1 - \beta)R_0A_1 + v\eta A_1^2, \qquad \Pi_D(A_1) = R_0(1 - A_1)^2. \tag{5}$$

Define the new-entrant leverage parameter:

$$\gamma \equiv \frac{v\eta}{R_0}.$$

This parameter summarizes the political weight of new entrants relative to defensive rents. The Challenger's aggregate stake can then be written compactly as $\Pi_C(A_1) = R_0 A_1 \big[(1-\beta) + \gamma A_1\big]$, and the equilibrium reform probability becomes

$$p^*(A_1) = \frac{(1-\beta)A_1 + \gamma A_1^2}{(1-\beta)A_1 + \gamma A_1^2 + (1-A_1)^2}. \tag{6}$$

By Lemma 1, $p^*(A_1)$ is strictly monotonically increasing in $A_1 \in [0,1]$; the linear specification delivers the explicit S-shape illustrated in Figure 1. Writing $\Sigma(A_1) \equiv (1-\beta)A_1 + \gamma A_1^2 + (1-A_1)^2$ for the common denominator, the per-capita equilibrium payoffs in the contest reduce to

$$\Lambda_C(A_1) = R_0 \left[\beta + \frac{(1-\beta)\big[(1-\beta)A_1 + \gamma A_1^2\big]^2}{\Sigma(A_1)^2}\right], \qquad \Lambda_D(A_1) = \frac{R_0(1-A_1)^5}{\Sigma(A_1)^2}. \tag{7}$$

Together with the reform premium $1-\beta$, the leverage parameter γ fully determines the political balance in the linear case. Intuitively, as the aggregate adoption A_1 increases, the reform probability $p^*(A_1)$ follows an S-shaped trajectory; this dynamic drives the adopter's expected payoff $\Lambda_C(A_1)$ strictly upward while steeply eroding the resister's defensive payoff $\Lambda_D(A_1)$. Figure 1 illustrates the functions under a set of parameter values.

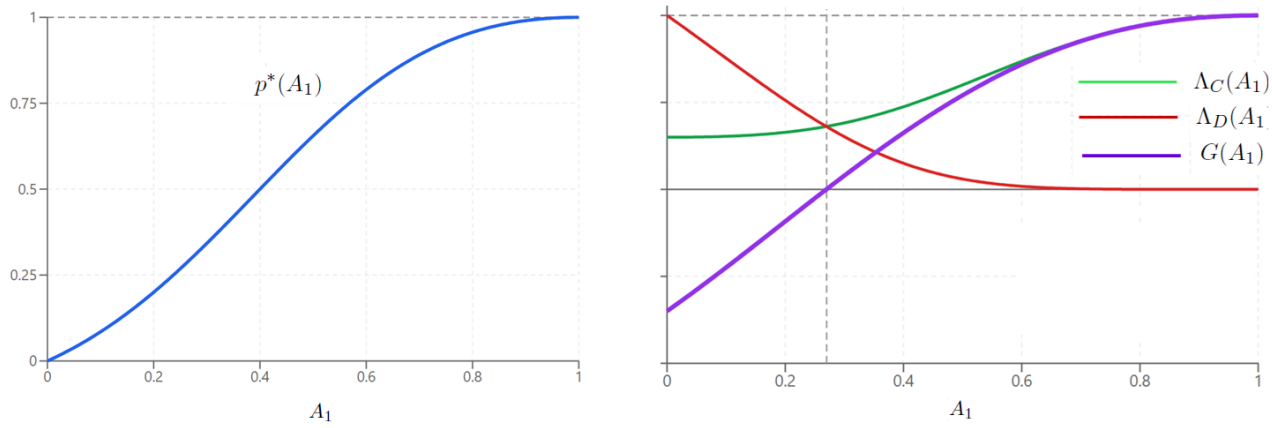


Figure 1: Functions p^*, Λ_C, Λ_D, and $G(A_1) \equiv \Lambda_C(A_1) - \Lambda_D(A_1)$

4 Equilibrium Analysis

We find the equilibrium using backward induction. First, we solve the equilibrium in Stage 1 using the endogenous payoff structure determined in Stage 2. Then, we move to Stage 0 to study the government's optimal decision.

4.1 Perfect-Information Benchmark

We begin by characterizing the equilibrium of the adoption game at stage 1 when the technology fundamental θ is common knowledge among all incumbents. This benchmark establishes that, absent

informational frictions, incumbents can always coordinate to block the technology regardless of how high θ is.

Proposition 1 (Perfect-Information Benchmark)**.** *Suppose θ is common knowledge among all incumbents. Then:*

(i) For all θ, the strategy profile in which every incumbent resists ($A_1 = 0$) is a Nash equilibrium, yielding payoff R_0 to every incumbent.

(ii) For sufficiently high θ such that $\theta \geq T - \kappa$, "all adopt" ($A_1 = 1$) is also a Nash equilibrium, yielding payoff $R_0 - c$ to every incumbent.

(iii) The "all resist" equilibrium strictly Pareto-dominates every other Nash equilibrium from the perspective of incumbents. Under Pareto-dominant equilibrium selection, the technology is never adopted regardless of θ.[6]

Proof: We first establish a payoff bound that applies to every strategy profile and every value of θ. Consider any strategy profile with aggregate adoption $A_1 \in [0, 1]$. If the viability condition $\theta + \kappa A_1 \geq T$ fails, the game ends at stage 1; each resister retains R_0 and each adopter receives $-c$. If viability holds, the game continues to Stage 2, where the reform contest determines payoffs. A resister receives at most R_0 and an adopter receives at most $R_0 - c$. This follows because reform never makes incumbents better off than the status quo, and adoption always costs c.

Part (i). Suppose all incumbents resist, so $A_1 = 0$. We consider two cases. If $\theta < T$, the viability condition is not satisfied: $\theta + \kappa \cdot 0 = \theta < T$, so the game ends at Stage 1 and each resister retains R_0. If $\theta \geq T$, viability holds but the technology lacks any adoption base: $\mu(0) = 0$, so the reform probability is $p^*(0) = 0$ and each resister again receives R_0. In both cases, a deviation imposes the adoption cost c, making the deviator strictly worse off, so "all resist" is a Nash equilibrium yielding R_0 to every incumbent.

Part (ii). Suppose all incumbents adopt, so $A_1 = 1$, and assume $\theta \geq T - \kappa$. The viability condition is satisfied: $\theta + \kappa \cdot 1 \geq (T - \kappa) + \kappa = T$. The Challenger coalition encompasses all incumbents while the Defender coalition has measure zero, so the reform probability is $p^*(1) = 1$. Each adopter receives $R_0 - c$. A deviation to resistance is not optimal, since the lone resister finds himself on the losing side of a certain reform with zero payoff.

Part (iii). By the payoff bound, no incumbent can receive more than R_0 in any equilibrium. The "all resist" equilibrium delivers exactly R_0 to every incumbent, thereby attaining this upper bound simultaneously for all players. Consider any other Nash equilibrium. In such an equilibrium, a

[6] With $\alpha > 0$ (Assumption 2), "all resist" ceases to be a Nash equilibrium for $\theta > \bar{\theta}(\alpha)$, since adoption becomes strictly dominant in that region. Because $\bar{\theta}(\alpha) \to \infty$ as $\alpha \to 0$, the statement in Proposition 1 in the text describes the limiting case analyzed throughout the paper.

positive-measure set of incumbents must adopt, and each adopter receives at most $R_0 - c < R_0$. Hence every adopter is strictly worse off than under "all resist," while no resister can be better off. It follows that "all resist" strictly Pareto-dominates every alternative Nash equilibrium. Under Pareto-dominant equilibrium selection, the technology is therefore never adopted, regardless of θ. Q.E.D.

Proposition 1 delivers a stark result: when θ is common knowledge, incumbents sustain collective resistance and the technology is completely blocked, no matter how transformative it may be. What sustains the "all resist" equilibrium is the coordination power enabled by common knowledge. We will next replace common knowledge with dispersed information or beliefs.

Remark (Negative externality and coordination failure). The Pareto-dominance result in part (iii) reveals a *negative externality* at the heart of the model. An individual adoption decision exerts a positive externality on fellow adopters: a larger Challenger coalition raises the reform probability p^*, increasing each adopter's Stage 2 payoff Λ_C. Simultaneously, it exerts a negative externality on resisters: the same increase in p^* reduces each resister's payoff Λ_D, while the shrinking Defender coalition further erodes their political leverage. The net effect on the incumbent class as a whole is unambiguously negative. To see this, note that by the first part of proof of Proposition 1, no incumbent's payoff can exceed R_0 under any strategy profile, and the "all resist" profile delivers exactly R_0 to everyone. Any profile with $A_1 > 0$ therefore makes every adopter strictly worse off (each pays c) while making no incumbent better off. Aggregate incumbent welfare is maximized at $A_1 = 0$ and strictly declining thereafter. This has the flavor of a prisoners' dilemma—each incumbent may find it individually rational to adopt, even though collective resistance would leave every incumbent strictly better off. Common knowledge of θ resolves this dilemma by enabling coordination on "all resist." We now study how dispersed information destroys this coordination and allows the technology to fracture the incumbent bloc from within.

4.2 Equilibrium under Dispersed Information

We now return to the global-game environment in which each incumbent observes only a private signal about θ.

The equilibrium is characterized by two thresholds (θ^*, x^*): a fundamental threshold θ^* such that the technology achieves viability if and only if $\theta \geq \theta^*$, and a signal threshold x^* such that incumbent i adopts if and only if $x_i \geq x^*$. These two thresholds are jointly determined by a viability equation and an indifference equation.

When all incumbents use the threshold x^*, the fraction who adopt given fundamental θ is

$$A_1(\theta) = \Pr(x_i \geq x^* \mid \theta) = 1 - \Phi\left(\frac{x^* - \theta}{\sigma_x}\right),$$

where $\Phi(\cdot)$ stands for the c.d.f. of the standard normal and $\phi(\cdot)$ denotes its p.d.f. The fundamental threshold θ^* is the value of θ at which the technology just achieves viability. At θ^*, the viability

condition binds:

$$\theta^* + \kappa \left[1 - \Phi\left(\frac{x^* - \theta^*}{\sigma_x}\right)\right] = T. \tag{8}$$

For $\theta \geq \theta^*$, enough incumbents adopt that the technology is viable; for $\theta < \theta^*$, too few adopt and the technology fails.

The signal threshold x^* is pinned down by the indifference condition of the marginal incumbent—the one who receives exactly signal $x_i = x^*$. The technology is viable when $\theta \geq \theta^*$ and fails when $\theta < \theta^*$. Using the payoffs from Table 1, the expected net gain from adopting rather than resisting is zero from the perspective of the marginal incumbent, that is,

$$\mathbb{E}_{\theta|x_i}\left[(-c - R_0)\mathbf{1}_{\theta<\theta^*} + (G(A_1(\theta)) - c)\,\mathbf{1}_{\theta\geq\theta^*} \,|\, x_i = x^*\right] = 0, \tag{9}$$

where $\mathbb{E}_{\theta|x_i}(\cdot|x_i)$ is the conditional expectation operator over θ, and we define the contest net gain function

$$G(A_1) \equiv \Lambda_C(A_1) - \Lambda_D(A_1) = \beta R_0 + \left(p^*(A_1)\right)^2 (1-\beta)R_0 - \left(1 - p^*(A_1)\right)^2 R(A_1),$$

which has the monotonic property

$$\frac{dG(A_1)}{dA_1} > 0 \qquad \text{for } A_1 \in [0,1],$$

implying that strict strategic complementarity holds. The two equations (8) and (9) jointly determine the equilibrium pair (θ^*, x^*).

As signals become arbitrarily precise ($\sigma_x \to 0$ or $\tau_x \to +\infty$), we prove that the system of equations (8) and (9) is transformed into

$$\theta^* = x^* \tag{10}$$

and

$$x^* = T - \kappa a^*, \tag{11}$$

where a^* is the unique solution to

$$\int_{a^*}^{1} G(A_1)\, dA_1 - (c + R_0 a^*) = 0. \tag{12}$$

The intuition behind (11) and (12) is as follows. In making his adoption decisions, an individual incumbent faces *fundamental uncertainty* as well as *strategic uncertainty* (i.e., he does not know how many peers will adopt). As $\sigma_x \to 0$, *fundamental uncertainty* disappears (i.e., $x_i \to \theta$). Thus, for the marginal incumbent who receives signal $x_i = x^*$, his inference of θ is $\theta = x^*$ and so he is almost sure that the technology will achieve viability if and only if aggregate adoption A_1 exceeds a^* where a^* solves $x^* = T - \kappa a^*$. However, strategic uncertainty does not disappear as $\sigma_x \to 0$. By the Laplacian property, the marginal incumbent perceives that A_1 (i.e., the proportion of peers choosing to adopt) is

uniformly distributed on $[0, 1]$. He can therefore evaluate his expected net gain from adopting rather than resisting given by the left-hand side of (9); setting this net gain to zero yields the indifference condition (12). Figure 2 illustrates the intuition, where the blue area minus the brown area equals c.

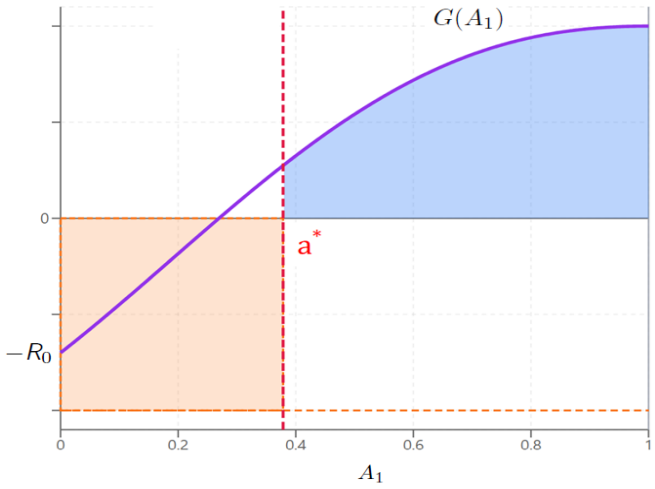


Figure 2: The Global-Games Unique Equilibrium under Dispersed Information

Proposition 2 (Equilibrium under Dispersed Information)**.** *Suppose* $\int_0^1 G(A_1)\,dA_1 > c$ *holds. In the limit as* $\sigma_x \to 0$*, the two-stage game possesses a unique equilibrium.*[7] *An incumbent adopts if and only if* $x_i \geq x^* = T - \kappa a^*$*, where* $a^* \in (0, 1)$ *is the unique solution to (12). The technology achieves viability if and only if* $\theta \geq \theta^* = T - \kappa a^*$*. Conditional on viability, institutional reform succeeds with probability* $p^*(A_1)$ *given by (6).*

The equilibrium adoption threshold x^* can be remarkably low, owing to a self-reinforcing feedback between technological adoption and institutional reform (Stage 1 $\to$ Stage 2 $\to$ Stage 1). In the forward direction, the adoption level A_1 shapes Stage 2 through the four reinforcing channels identified earlier: higher adoption simultaneously swells the Challenger coalition, attracts new entrants, shrinks the Defender bloc, and erodes defensive rents, all of which raise the equilibrium reform probability $p^*(A_1)$. In the backward direction, the anticipated reform probability feeds back into Stage 1, amplifying each incumbent's incentive to adopt. The dominant force behind individual adoption is defensive rather than opportunistic: each incumbent's main concern is the downside loss of ending up as a loser rather than the upside gain of ending up as a winner.

This fear is self-reinforcing. As more incumbents adopt in anticipation of reform, p^* rises, which

[7] Assumption 2 ensures the existence of an upper dominance region: for $\theta > \bar{\theta}(\alpha)$, adoption is strictly dominant. Together with the lower dominance region (for sufficiently low θ, resistance is strictly dominant since the technology is unviable and the standalone value is negligible), the standard global-game iterated-dominance argument (Morris and Shin, 2003; Goldstein and Pauzner, 2005) eliminates all equilibria except the threshold equilibrium—including the "all resist" profile that would otherwise survive as an equilibrium when $\alpha = 0$. In the limit $\alpha \to 0$, the equilibrium threshold θ^* and all comparative statics are unaffected, because the indifference condition of the marginal incumbent is continuous in α.

magnifies the expected penalty for resistance, which induces still more adoption. The resulting positive feedback loop—adoption raises reform probability, which raises the cost of resistance, which accelerates adoption—drastically pushes down the equilibrium threshold x^* and θ^*. The technological irreversibility embedded in the payoff structure (see Table 2) plays a complementary role: once adoption is sunk, the coalition shift that drives reform is locked in, converting a strategic gamble into a fait accompli.

Propositions 1 and 2 together deliver the central theoretical result. The punchline is almost paradoxical: incumbents are not fooled about the technology—they understand perfectly well that it threatens their rents. What they lack is certainty about each other's behavior. That strategic uncertainty alone is sufficient to break their coordination and allow the technology to penetrate the institutional wall. Under perfect information, incumbents coordinate to block the technology for all θ—institutional rigidity is absolute. Under dispersed information, the threshold drops to a finite level: for $\theta \geq \theta^*$, positive adoption emerges, viability is achieved, and reform occurs with positive probability. The wedge between the two regimes arises entirely from *strategic uncertainty*. Each incumbent observes only a noisy signal of θ and cannot be sure whether sufficiently many others will resist. The "all resist" equilibrium unravels because an incumbent receiving a high signal rationally fears that others are also receiving high signals and choosing to adopt. This higher-order reasoning—"I think that others think that still others might adopt"—is precisely what common knowledge of θ would eliminate, and precisely what dispersed information preserves.

The Role of Irreversibility. The mechanism in Proposition 2 depends critically on technological irreversibility. To see this, consider a *fully reversible* technology: if reform does not proceed, adopters costlessly retool back to the old technology ($\beta \to 1$), new entrants costlessly exit ($\mu \to 0$), and per-capita rents are restored ($R \to R_0$). The economy reverts to the pre-adoption configuration, so $\Pi_C(A_1) = 0$ on that path, which gives $p^* = 0$ and $G(A_1) = 0$. The unique equilibrium is "all resist" for all θ, regardless of the informational environment.

Corollary 1 (Reversible-Technology Benchmark)**.** *Under a fully reversible technology, dispersed information cannot break incumbent coordination. The unique equilibrium is $a^* = 0$ for all θ: technology adoption never occurs and reform is impossible.*[8]

The intuition is immediate. Strategic uncertainty among incumbents is still present but inconsequential: because adoption leaves no lasting trace, no incumbent fears being stranded on the losing side, and those who hold out can simply wait the disruption out at no cost. Dispersed information provides the *mechanism* for coordination failure; irreversibility provides the *fuel*, ensuring that adoption generates the asymmetric payoff consequences that make coordination failure consequential. Neither alone suffices.

[8]With $\alpha > 0$ (Assumption 2), adoption becomes strictly dominant for $\theta > \bar{\theta}(\alpha) = (R_0 + c)/\alpha$, so the literal statement "adoption never occurs" describes the limiting case $\alpha \to 0$ analyzed throughout the paper.

Conceptually, technological irreversibility functions as *a commitment device*: by foreclosing ex-post reversion, it makes tomorrow's political landscape depend on today's adoption choices, so that each incumbent must weigh the cost of being stranded in a transformed world against the cost of adoption itself. It is this commitment property that lets dispersed information bite; absent it, waiting out the disturbance would be a credible best response and the "all resist" profile would survive.

Production reorganization and lock-in. It is useful to separate two ideas that "irreversibility" bundles together, corresponding to the two conditions used in the introduction. The first is *production reorganization*: the joint movement of (β, μ, R) away from $(1, 0, R_0)$ as A_1 rises. By Lemma 1, adopters retool ($\beta < 1$), entrants emerge in the supporting ecosystem ($\mu(A_1) > 0$), and rents sustaining the old institution erode ($R'(A_1) < 0$). These are not independent dials but co-products of the same diffusion process, and the model treats them as a single bundle. The second is *lock-in*, a temporal property of this bundle: conditional on having occurred at scale A_1, reorganization persists even absent reform—retooling cannot be undone, entrants cannot costlessly exit, and eroded rents cannot be restored. Full reversibility (Corollary 1) is the polar opposite; the body of the paper assumes lock-in.

Institutional change of the kind we study requires both elements. Reorganization generates the political stakes; lock-in makes them permanent, converting a transient diffusion of technology into a lasting change in the political landscape that incumbents cannot undo by collective inaction. Reorganization without lock-in is a disturbance that resolves itself; lock-in without reorganization is vacuous. Together, these two properties define an institutionally irreversible technology. A further enabling condition is a particular time profile of institutional compatibility: the technology must be *initially compatible*—able to enter and operate without prior reform—but *eventually incompatible* at scale, so that once diffusion crosses a threshold, the old institution becomes a binding constraint that cannot be costlessly reinstated.

4.3 Comparative Statics

Let $F(a^*)$ denote the left-hand side of the indifference condition (12), so the equilibrium critical mass a^* is defined by $F(a^*) = 0$. Because F is strictly decreasing in a^*, any parameter change that uniformly raises (lowers) F increases (decreases) the equilibrium critical mass a^* and thereby lowers (raises) the equilibrium viability threshold $\theta^* = T - \kappa a^*$.

A decrease in the adoption cost c uniformly shifts F upward. Consequently, a^* rises and θ^* falls. Intuitively, cheaper adoption induces more incumbents to adopt at any given signal, allowing the technology to achieve viability under weaker fundamental conditions.

An increase in the new-entrant leverage γ has a similar effect. A politically stronger entrant sector amplifies the Challenger coalition's advantage, strictly raising the net contest gain $G(A_1)$ for all $A_1 \in (0, 1)$. This shifts F upward, raising a^* and lowering θ^*.

An increase in the reform premium $1 - \beta$ yields an ambiguous effect on θ^*. While a higher premium

increases the reform prize captured by the Challenger coalition, it simultaneously lowers the guaranteed floor payoff βR_0 that adopters receive if reform fails. For interior adoption levels where the reform probability p^* is low, the negative floor effect can dominate, reducing $G(A_1)$. The net impact on a^* and θ^* thus depends on the specific parameterization.

Finally, an increase in the viability threshold T does not affect a^* because the indifference condition (12) is independent of T. However, it raises the signal threshold $x^* = T - \kappa a^*$ one-for-one, requiring a proportionately higher technology fundamental to sustain the same adoption pattern.

4.4 Government's Promotion Decision and Welfare

The government knows the model parameters and, by Proposition 2, can compute the equilibrium thresholds (θ^*, x^*). It does not observe the realized θ and evaluates expected welfare under the prior $\theta \sim N(\bar{\theta}, \sigma_\theta^2)$. Its decision is whether the expected social-welfare gain from making the technology available justifies the upfront infrastructure cost I.

Social welfare. If the government does not promote, the status quo persists and social welfare is $\Pi^{SQ} = R_0 + R_1 < 0$: the forced negative-NPV project described continues to destroy value.

If the government promotes, social welfare depends on the realized θ through the equilibrium adoption and reform outcomes. Working in the limit $\sigma_x \to 0$ (Proposition 2), the equilibrium is effectively deterministic conditional on θ. When $\theta < \theta^*$, aggregate adoption is $A_1 = 0$, the technology fails to achieve viability, and the status quo persists at welfare Π^{SQ}. When $\theta \geq \theta^*$, aggregate adoption is $A_1 = 1$, the viability condition $\theta + \kappa \geq T$ is satisfied, the Defender coalition vanishes ($\Pi_D(1) = 0$), and reform passes with certainty ($p^*(1) = 1$) at zero contest cost. Social welfare in this case aggregates payoffs across the three groups in the economy:

$$W(\theta) = \underbrace{R_0 - c}_{\text{incumbents}} + \underbrace{\eta(\theta + v)}_{\text{new entrants}} + \underbrace{\pi_C^{TR}}_{\text{citizens}}, \qquad \text{for } \theta \geq \theta^*, \tag{13}$$

where $\pi_C^{TR} \geq 0$ denotes citizens' aggregate payoff under the reformed institution with the new technology in place. Since reform frees citizens from the forced negative-NPV project, we have $\pi_C^{TR} \geq \pi_C^{MR} \gtrsim 0 > R_1$.

The three terms merit interpretation. Incumbents collectively earn $R_0 - c$: each pays the transition cost c but retains the rent level R_0 under the reformed institution. While this level coincides with the status-quo rent, its source is fundamentally different. Under the status quo, R_0 derives from institutional extraction—the forced negative-NPV project that compels citizens to invest $|R_1|$ into an activity whose total return is $R_0 + R_1 < 0$. Under the reformed institution, R_0 derives from productive participation in the new technological regime: incumbents have retooled their assets and operate within an institutional framework compatible with the new technology. The reform does not confiscate incumbents' economic capacity; it redirects it from extraction to production.

Technology adoption spawns $\mu(1) = \eta$ new entrants—economic actors who owe their existence to the technology. Under the reformed institution each earns $\theta + v$, reflecting the technology's full potential when paired with its compatible institutional environment. These agents represent pure surplus creation: they did not exist under the status quo and cannot exist without the technology.

Citizens see their payoff improve from $R_1 < 0$ to $\pi_C^{TR} \geq 0$. The mechanism is the dismantling of the institutional arrangement that forced them to fund the negative-NPV project. Freed from this obligation, citizens at minimum recover to approximately zero and may additionally benefit from spillovers of the new technology.

Summarizing,

$$W(\theta) = \begin{cases} R_0 + R_1, & \text{if } \theta < \theta^*, \\ (R_0 - c) + \eta(\theta + v) + \pi_C^{TR}, & \text{if } \theta \geq \theta^*. \end{cases} \tag{14}$$

Dual-dividend decomposition. Subtracting status-quo welfare from (14) yields no welfare gain when the technology fails ($\Delta W(\theta) = 0$ for $\theta < \theta^*$), and the following welfare gain conditional on success:

$$\Delta W(\theta) \equiv W(\theta) - \Pi^{SQ} = \underbrace{\eta(\theta + v) - c}_{\text{technology dividend}} + \underbrace{(\pi_C^{TR} - R_1)}_{\text{institutional dividend}}, \qquad \text{for } \theta \geq \theta^*. \tag{15}$$

The *technology dividend*, $\eta(\theta + v) - c$, is the net productive surplus created by the new technology: η new entrants each generating value $\theta + v$, less the aggregate adoption cost c borne by incumbents. This term captures the upgrade of the economy's productive capacity. The *institutional dividend*, $\pi_C^{TR} - R_1$, is the welfare gain to citizens from escaping the failing institution. Since $R_1 < 0$ and $\pi_C^{TR} \geq 0$, this term is at least $|R_1|$ and is strictly positive even if the technology confers no direct benefit on citizens. This term reflects the abandonment of the old value-destroying system. Technology promotion thus achieves "one stone, two birds."

Promotion condition. The government's expected welfare gain from promotion net of the infrastructure cost I must be greater than 0. Using (15) yields

$$\mathbb{E}_\theta[\Delta W(\theta)] - I = \Pr(\theta \geq \theta^*) \left[\eta \left(\mathbb{E}[\theta \mid \theta \geq \theta^*] + v\right) - c + (\pi_C^{TR} - R_1)\right] - I \geq 0. \tag{16}$$

Proposition 3 (Government's Promotion Decision)**.** *In the limit $\sigma_x \to 0$, the benevolent government promotes the technology if and only if condition (16) holds. The promotion condition can equivalently be written as*

$$\Pr(\theta \geq \theta^*) \left[\eta \left(\mathbb{E}[\theta \mid \theta \geq \theta^*] + v\right) - c + \pi_C^{TR}\right] \geq I - \Pr(\theta \geq \theta^*)|R_1|. \tag{17}$$

Since $|R_1| > 0$ and $\Pr(\theta \geq \theta^*) > 0$, the effective hurdle for promotion is $I - \Pr(\theta \geq \theta^*)|R_1| < I$: the government backs a technology whose expected gross surplus may fall short of the infrastructure cost, provided the shortfall is smaller than the expected institutional dividend.

The equivalent form (17) provides a justification for certain industrial policies. When the status quo is sufficiently wasteful, the government may find it optimal to promote a technology even if the technology's standalone productive surplus is modest, because the institutional dividend alone justifies the investment.

Remark (Distributional consequences). Technology-induced reform generates a distinctive distributional pattern. Table 4 compares payoffs across the three regimes in the sharp-signal limit, conditional on $\theta \geq \theta^*$.

Table 4: Payoff Comparison across Regimes

	Status Quo	Marginal Reform	Tech-Induced Reform
Incumbents	R_0	0	$R_0 - c$
Citizens	$R_1 < 0$	$\gtrsim 0$	$\pi_C^{TR} \geq 0$
New Entrants	—	—	$\eta(\theta + v) > 0$
Total Surplus	$R_0 + R_1 < 0$	$\gtrsim 0$	$(R_0 - c) + \eta(\theta + v) + \pi_C^{TR}$

Relative to the status quo, technology-induced reform is Kaldor–Hicks efficient but not Pareto-improving: incumbents bear the adoption cost $c > 0$, while citizens and new entrants are strictly better off. This non-Pareto feature is precisely the obstacle that also blocks marginal reform—incumbents can identify that they will lose and coordinate to resist. What technology-induced reform overcomes is not the distributional problem itself but the mechanism of strategic uncertainty that prevents incumbents from sustaining collective resistance (Proposition 2). Relative to marginal reform, however, technology-induced reform is strictly Pareto-superior: incumbents earn $R_0 - c > 0$ instead of 0, citizens earn $\pi_C^{TR} \geq \pi_C^{MR}$, and new entrants—who would not exist under marginal reform—earn $\theta + v > 0$.

5 Extension: Toward A Unified Framework

This section shows that the model nests two alternatives—marginal institutional reform and radical institutional reform—as special cases. Radical institutional reform corresponds to what Dewatripont and Roland (1995) term "big-bang" reform. All three paths conclude with the same Tullock contest but differ in the coalition structure that enters it.

5.1 Three Reform Paths and Contest Stakes

All three paths conclude with a Tullock contest between a Challenger coalition C and a Defender coalition D, with reform probability $p = \Pi_C/(\Pi_C + \Pi_D)$. They differ in what precedes the contest.

Marginal institutional reform (MR) proposes a change in institutional rules with no prior technological disruption and no investment in building a new constituency. This corresponds to $A_1 = 0$ and $\mu = 0$: the Challenger coalition is empty and reform fails with certainty ($p^{MR} = 0$).

Radical institutional reform (RR) bypasses technology adoption. The government directly assembles a Challenger coalition of size μ at fiscal cost $C(\mu)$, where C is increasing and convex. The full incumbent class remains as Defenders ($A_1 = 0$). The government commits to μ without knowing θ.

Technology-induced reform (TR) is the main case of the paper. The government invests I to introduce the new technology, triggering the global coordination game of Section 4. The equilibrium adoption level $A_1^*(\theta)$ splits the incumbent class and organically generates new entrants of size $\mu = \eta A_1$.

Under TR, adoption precedes the contest. Incumbents have already been split and new entrants spawned; the stakes are given in equation (1) based on Table 2.

Under RR, no incumbent has defected. The full incumbent class retains its rent R_0 and defends as a unified bloc. The government-created entrants cannot operate productively under the old institution; their value materializes only if reform passes. Conditional on viability ($\theta + \kappa\mu \geq T$), the payoff structure is presented in Table 5.

Table 5: Payoff Structure under Radical Reform

	Incumbent (Defender) (size 1)	New entrant (Challenger) (size μ)
No reform	R_0	0
Reform	0	$\theta + v\mu$

The aggregate stakes and equilibrium reform probability are

$$\Pi_D^{RR} = R_0, \qquad \Pi_C^{RR}(\mu) = \mu(\theta + v\mu), \qquad p^{RR}(\mu, \theta) = \frac{\mu(\theta + v\mu)}{\mu(\theta + v\mu) + R_0}.$$

Two structural differences are immediate. First, the Defender's stake under RR is the constant R_0—the full, undiluted capacity of the entire incumbent class—whereas under TR it is $R_0(1 - A_1)^2$, decaying quadratically as adoption proceeds. Second, for a given Challenger size, the payoff gap between reform and no-reform is larger under RR (each entrant's entire value is at stake) than under TR (where adopters contest only the premium $(1 - \beta)R_0$). Both features imply that the RR contest is fiercer and more resource-intensive.

5.2 Comparing TR and RR

The government does not observe θ when selecting its strategy. Four economic forces govern the choice between TR and RR.

Force 1: Direct cost (Favors TR). Under TR, the government pays infrastructure cost I and private agents bear adoption cost c. Under RR, the government pays $C(\mu)$ to create the new class directly. Reasonably, the total cost is higher in RR than in TR.

Force 2: Contest efficiency (Favors TR). The deadweight loss of a Tullock contest is

$$DWL = e_C^* + e_D^* = \frac{\Pi_C \Pi_D}{\Pi_C + \Pi_D},$$

which vanishes when either side's stake approaches zero and is maximized when stakes are symmetric.

Under TR with high adoption ($A_1 \to 1$), $\Pi_D^{TR} = R_0(1 - A_1)^2 \to 0$, so $DWL^{TR} \to 0$. Reform passes as ratification at negligible contest cost. Under RR, $\Pi_D^{RR} = R_0$ regardless of Challenger size, so

$$DWL^{RR} = \frac{\mu(\theta + v\mu)R_0}{\mu(\theta + v\mu) + R_0} \longrightarrow R_0 \quad \text{as } \mu \to \infty.$$

Even when RR achieves high reform probability, it does so through a costly head-on battle against an intact opponent.

The deeper principle is that TR serves a dual purpose: adoption simultaneously creates productive value and erodes the opposition. Under RR, these are separate activities—the government first pays $C(\mu)$ to build a coalition, then that coalition expends further resources fighting the contest.

Force 3: Information revelation and option value (Favors TR). Under TR, the adoption game serves as an endogenous screening mechanism. If $\theta < \theta^*$, incumbents do not adopt, viability fails, and the economy remains at the status quo. The game never enters Stage 2: no contest takes place, and the only loss is I. If $\theta \geq \theta^*$, adoption succeeds and reform follows. The two-stage structure thus functions as a real option: the government pays I to purchase the option of reform, exercised only when fundamentals are favorable.

Under RR, no such screening operates. The government commits $C(\mu)$ without knowing θ. If θ is low, either spending is insufficient for viability—in which case $C(\mu)$ is wasted—or viability is achieved but the Challenger is outmatched, burning resources in a losing contest.

The option-value advantage of TR is increasing in σ_θ^2. When uncertainty about the technology's potential is large, the ability to let decentralized decisions reveal θ before committing to political battle is particularly valuable.

Force 4: Speed (Favors RR). Technology-induced reform requires time. In the model, TR's payoff is realized only after Stage 2, whereas RR resolves at Stage 1. Introducing a discount factor $\delta < 1$ between stages, TR's welfare gain is discounted relative to RR's. Outside the model, the economy inhabits a mismatched regime during the transition—the old institution coexists with the new technology, suppressing both—generating flow losses that accumulate until reform is enacted. In crisis settings where the status quo is acutely destructive, speed dominates efficiency.

5.3 When Does Each Path Dominate?

TR dominates when: ex ante uncertainty about θ is substantial (high option value of screening); the incumbent class is well-resourced (R_0 large, making head-on contest costly); and organic adoption is cheap relative to direct coalition-building ($I + c \ll C(\mu)$ for comparable coalition sizes).

RR dominates when: the prior on θ is strongly favorable (screening has low value); the fiscal cost $C(\mu)$ is low; and the status quo is acutely destructive ($|R_1|$ large), so that every period of delay inflicts severe harm and speed is the binding constraint.

In short, the three paths form a hierarchy. MR is blocked by the absence of any Challenger. RR creates a Challenger through fiscal expenditure that must fight the full, undisrupted incumbent class. TR exploits decentralized adoption to split incumbents, erode rents, and generate an organic Challenger—achieving feasibility at the cost of time, but with structural advantages in screening and contest efficiency.

Reform as Ratification. The fundamental advantage of TR is not merely that it creates a Challenger—RR does that too—but that it *simultaneously degrades the opposition*. Under RR, the government builds a force to fight intact incumbents. Under TR, by the time the contest arrives, adoption has already split the incumbent class, eroded per-capita rents, and generated new actors tied to reform. The Defender arrives depleted, divided, and facing an opponent that includes former allies. This explains why technology-induced reform often appears anticlimactic. China's "Three Rights Separation" reform of 2018 merely codified land-transfer arrangements that mechanization had already made ubiquitous. The contest was over before the legislative process began, because the coalition that would have defended household plots had been transformed by the economics of mechanized agriculture. Reform as ratification—not revolution—is the distinguishing signature of TR.

6 Empirical Analysis: Agricultural Mechanization and Rural Land Reform in China

This section tests Lemma 1 using agricultural mechanization and rural land reform in China. The setting maps directly onto the model's structure: the rigid institution is *China's household-based land tenure system*, which assigned small, fragmented plots to individual households and proved politically resistant to reform despite widely recognized efficiency losses; the irreversible technology is *agricultural machinery*—particularly large and medium tractors—whose adoption involves sunk investment and scale complementarities and whose efficient use requires larger, more contiguous operational holdings. The government's subsidization of mechanization beginning in 2004 provides quasi-experimental variation that we exploit to identify the technology's causal effect on production reorganization.[9]

What we test and what we do not. Our theory posits the following causal chain (which is also the timeline of the model):

[9]Hayami and Ruttan (1985) document the broad historical correlation between agricultural technology and institutional forms across the U.S. and Japan. Our empirical test differs in three respects: we exploit quasi-experimental variation rather than cross-country comparison; we identify the causal effect of technology on a specific institutional reform rather than documenting co-evolution; and we trace the concrete political-economic environment under which technology-induced institutional change happens. Taking into account this environment is important: a growing literature (reviewed in Section 2) has documented that rural land rights in China generated substantial efficiency losses for decades, yet efficiency-improving reform did not follow automatically.

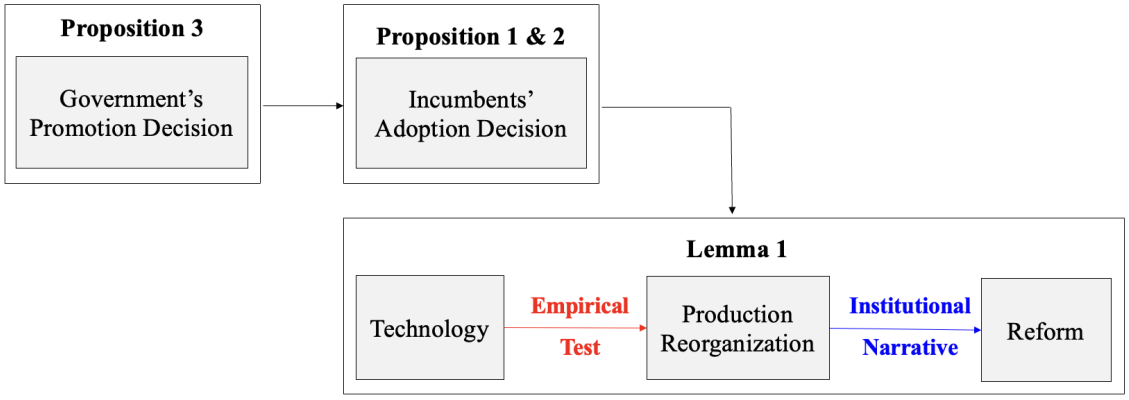


Figure 3: Model Timeline (Theoretical Causal Chain)

This paper's empirical contribution focuses on testing Lemma 1, which itself comprises two sub-links: from technology to production reorganization, and from production reorganization to institutional reform. For the first sub-link in **red**, we identify the causal effect of mechanization (technology) on land-rental activity (production reorganization), using the staggered rollout of agricultural machinery purchase subsidies. For the second sub-link in **blue**—from production reorganization to legal codification—we rely on institutional narrative, including official legislative explanations, policy documents, and the chronological fact that production reorganization preceded legal codification. We do not test incumbents' adoption decisions (Propositions 1 and 2), which involve a coordination problem, nor whether the government's promotion was strategically intended (Proposition 3). This empirical strategy—theorizing a multi-step causal chain while causally identifying one key link—follows standard practice in political economy (see, e.g., Hornbeck and Naidu, 2014; Jha, 2015; Nunn, 2008). On the question of intent, the machinery subsidy was introduced primarily as productivity-enhancing industrial policy (see, e.g., Liu and Xu, 2026); the institutional consequence appears largely unintended.[10]

Section 6.1 documents the institutional setting and provides narrative evidence for the second sub-link of Lemma 1 (production reorganization → legal codification). Section 6.2 provides causal evidence for the first sub-link (technology → production reorganization).

6.1 Institutional Background and Narrative Evidence

This subsection documents the institutional setting, the technology shock, and the sequence from production reorganization to legal ratification.

The old institution and its rigidity. China's post-1978 rural land regime rested on collective ownership and household contracting. Under the Household Contract Responsibility System (HRS), village collectives allocated land-use rights to individual households on an egalitarian per-capita basis.

[10] In this respect, other Chinese episodes—such as renewable energy and mobile payments—may differ: the government's technology promotion plausibly reflected an awareness that diffusion would eventually force institutional restructuring.

Because land quality varied even within a village, allocations were further equalized by assigning each household multiple non-contiguous plots. The result was extreme fragmentation: by the mid-2000s, the average farm comprised approximately 0.5–0.6 hectares of cultivated land, subdivided into five to seven separate, non-contiguous plots scattered across different locations (Wan and Cheng, 2001; Tan, Heerink, and Qu, 2006).

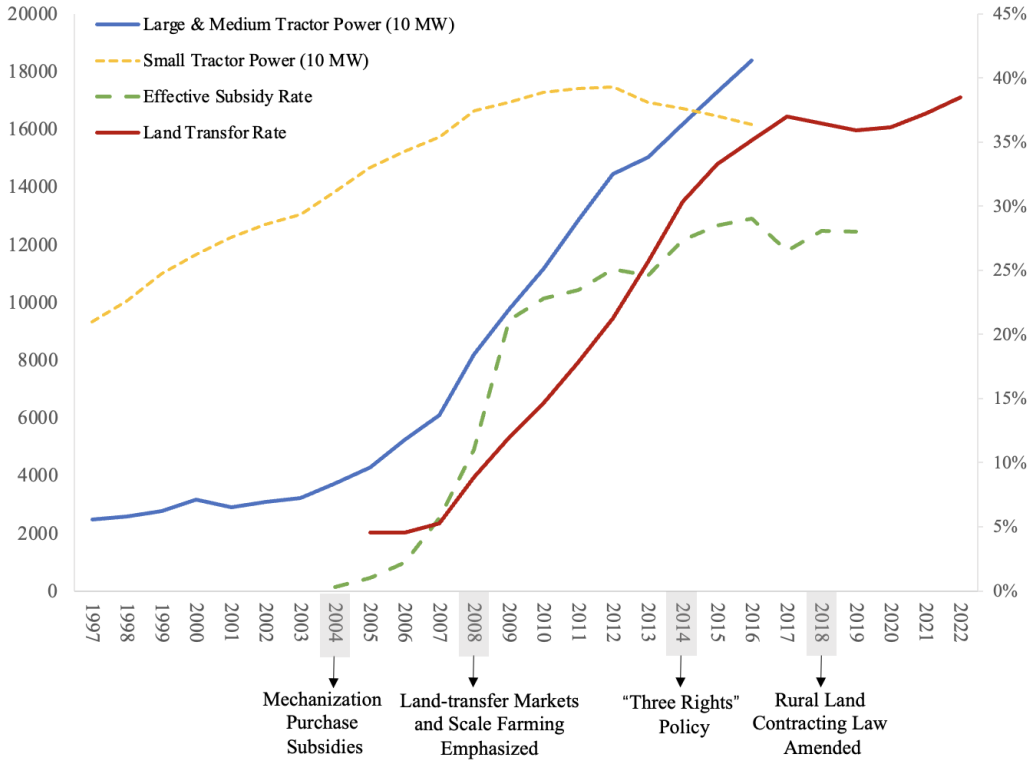


Figure 4: Mechanization, Land Transfers, and the Timing of Rural Land Reform

Notes: This figure plots national trends in agricultural mechanization, land-transfer rates, and mechanization subsidies from 1997 to 2022. The left vertical axis reports tractor power in units of 10 megawatts (10 MW), corresponding to the official statistical unit of 10,000 kilowatts. The right vertical axis reports the farmland-transfer rate and the effective subsidy rate, where the farmland-transfer rate is defined as the area of contracted farmland transferred through rental, subcontracting, cooperative, or other arrangements, divided by total contracted farmland area, and the effective subsidy rate is defined as the ratio of total subsidy funds for machinery purchase to total expenditure in agricultural machinery purchase. Following the classification used in Chinese agricultural statistics, large and medium tractors are defined as tractors with engine power above 14.7 kilowatts (kW), whereas small tractors are defined as tractors with engine power between 2.2 and 14.7 kW. The vertical policy markers indicate the introduction of agricultural machinery purchase subsidies, the 2008 policy emphasis on farmland-transfer markets and moderate-scale operation, the 2014 "Three Rights" policy turn, and the 2018 amendment to the Rural Land Contracting Law. *Data source:* Chinese National Bureau of Statistics, and Chinese Ministry of Agriculture and Rural Affairs.

The Rural Land Contracting Law, adopted in 2002 and effective in 2003, codified this household-based arrangement. Its core purpose was to secure household contract rights against administrative reallocation by village cadres. The law permitted certain forms of land circulation, including sub-contracting, leasing, exchange, and swap. The transferee's claim, however, was treated as derivative of the original contractor's right rather than as an independent property right: it was not separately

registrable, was difficult to enforce over long horizons, and could not serve as collateral. The 2003 law thus protected smallholders from losing their land while offering no legal infrastructure for production organized at larger and more consolidated scales.

A growing empirical literature has documented that this arrangement generated substantial efficiency losses by distorting land allocation, depressing agricultural productivity, impeding labor mobility, and slowing structural transformation (Benjamin and Brandt, 2002; Deininger and Jin, 2005; Ngai et al., 2019; Adamopoulos and Restuccia, 2020; Chari et al., 2021; Adamopoulos et al., 2024). Why, then, did the institution persist?

The answer lies in a layered support base for the status quo. Different actors favored the existing arrangement for different reasons. Although they were not centrally coordinated, their combined effect was to make any direct legal restructuring politically difficult.

First, village cadres and local officials had direct material and administrative stakes in the arrangement. Under the household contract system, land allocation decisions were a primary source of village-level administrative authority. Cadres who controlled periodic land adjustments, mediated disputes, and managed collective assets had direct material and political stakes in preserving the institutional arrangement that sustained their position. Any reform that marketized land rights would displace their allocative role. These actors were few in number but strategically positioned because they controlled the bureaucratic machinery through which any land reform would have to be implemented.

Second, policy elites and scholars whose authority and reputation were invested in egalitarian land ideology constituted a broader intellectual-political coalition. China's household contracting system was not merely an administrative convenience; it also embodied the principle that every rural citizen deserved equal access to collectively owned land. Officials and academics who had built careers defending this principle had reputational stakes in its preservation and could frame opposition to reform in terms of social justice, food security, and rural stability. This framing resonated strongly with the top leadership.

Third, and most consequentially in terms of scale, hundreds of millions of smallholder households passively supported the status quo. These households were not organized opponents of reform in the Olson (1982) sense. For approximately seventy percent of China's farming households, the contracted plot functioned primarily as social insurance—a guaranteed fallback in the event of job loss, illness, or old age, rather than as a productive asset to be traded. Before mechanization raised the returns to scale, most smallholders had little private benefit from a land market and no demand for an independent operating right. Their rational preference was therefore for the security of the status quo. Moreover, their fear of reform was not irrational. Historical episodes of forced land transfers by local governments, in which households lost effective control under the guise of "voluntary circulation," made the promise that "you can choose not to transfer" non-credible. Smallholders understood that once management rights could be independently registered, mortgaged, and financialized, large operators, banks, and

local governments might acquire new leverage over their land. In particular, what they feared was not the stated provisions of any specific reform but the institutional trajectory it could set in motion.

These layers reinforced one another. Cadres and policy elites articulated smallholders' diffuse anxiety as organized political resistance. The government's own risk aversion, especially its concern about backlash from an institution serving as social insurance for hundreds of millions, provided the final seal. The result was institutional rigidity that did not require active coordination among smallholders: mutual reinforcement between passive household preference, cadre interest, ideological commitment, and leadership caution was sufficient to block reform for decades. Any proposal to formalize a transferable operating right competing with the household contract right would have had to confront this layered base simultaneously.

The technology shock: agricultural machinery subsidies. The decisive break came not from land policy but from technology policy. By 2003, the agricultural sector faced acute pressures. Rapid labor outflow to cities, the Grain-for-Green Program's conversion of marginal cropland, and the slow pace of mechanization had combined to reduce grain output from roughly 512 million tons in 1998 to approximately 431 million tons in 2003, heightening concerns about food security. Land abandonment emerged in high-outflow regions because remaining farmers lacked the capacity to cultivate all available land using traditional production methods.

In 2004, the central government launched the agricultural machinery purchase subsidy program. Its stated purpose was to modernize agricultural production. The Agricultural Mechanization Promotion Law, adopted in the same year, established a legal framework for encouraging the use of advanced and suitable agricultural machinery.[11] Why was government intervention via subsidy needed if markets allocate efficiently on their own? Liu and Xu (2026) provide a theoretical rationale rooted in an adoption externality created by land fragmentation, with the subsidy serving to correct this market failure.[12]

The subsidy program began with 66 pilot counties in 2004 and expanded rapidly to 500 counties in 2005, 1,126 in 2006, 1,716 in 2007, and 2,653 in 2008, before reaching nationwide coverage by 2009.[13] A notable design feature was the subsidy catalog, which restricted eligibility to machinery meeting specified quality, safety, and environmental standards. The catalog favored medium and large machinery. "Large and medium-sized tractors" were listed as a key eligible category, whereas small tractors were often excluded or given lower priority (Zhang, 2021). The subsidy rate was typically

[11] See the Agricultural Mechanization Promotion Law (中华人民共和国农业机械化促进法).

[12] Under the HRS, land had been distributed in small, scattered parcels, yet medium and large tractors achieve their efficiency only on contiguous blocks (集中连片). Because each farmer's return to mechanization depends on his neighbors' choices, the market on its own fails to internalize this adoption externality—a classic coordination failure that leaves the economy stuck with low aggregate machinery productivity. A purchase subsidy breaks the deadlock by lowering the price of mechanized plowing services: more farmers switch, animal power and manual labor are crowded out, and mechanized plots come to abut one another, letting tractors work contiguous blocks without interruption. By 2004, rising wages relative to machinery prices had pushed adoption close to the tipping point, making it the right moment for a moderate subsidy to strategically amplify market momentum by internalizing the adoption externality.

[13] See the 2005 Interim Measures on Agricultural Machinery Purchase Subsidy Funds, Ministry of Agriculture and Ministry of Finance.

capped at 30 percent of the retail price. Cumulative funding grew from 70 million yuan in 2004 to more than 20 billion yuan by 2012; between 2004 and 2020, total expenditure reached 238.5 billion yuan and subsidized 48.6 million units of machinery (Zhang, 2021).

Figure 4 shows the resulting expansion in mechanization. Total tractor power rose steadily, but the increase in large and medium tractor power became especially pronounced after 2004. Large and medium tractors, defined in Chinese agricultural statistics as tractors with engine power above 14.7 kilowatts, grew much more rapidly than small tractors, defined as tractors with engine power between 2.2 and 14.7 kilowatts. The subsidy policy therefore shifted the composition of the machinery stock toward scale-compatible equipment.

Production reorganization. Machinery adoption was initially compatible with the old land regime—machinery could be purchased, rented, or hired through custom services without disturbing households' contracted plots. The mismatch became binding only at scale. The economic logic of large and medium agricultural machinery was fundamentally at odds with the fragmented production structure created by the household contract system. Combine harvesters, deep-tillage machines, and large tractors achieved economies through continuous operation over large contiguous areas. Their fixed costs, with purchase prices for large tractors often exceeding 100,000 RMB and combine harvesters considerably more, could only be amortized over substantial acreage. Operating on a typical household's five to six scattered plots of one to two mu each meant frequent turning, high transfer costs between non-adjacent parcels, and inability to coordinate planting schedules with neighboring households whose plots intervened.

Contemporaneous news reports from the late 2000s and early 2010s show that this constraint was already visible to local actors well before the Three-Rights reform of 2014–2018. In Heilongjiang, one of China's major grain-producing provinces, the Dayong machinery cooperative—established in Hulan, Harbin in 2003 as an early provincial pilot—soon ran into what its members called the problem of "small plots, large machines": fragmented household plots prevented continuous operation and inflated idle travel, turning time, and operating costs. The cooperative's response was to assemble land. Beginning in 2005, it rented contiguous blocks from neighboring households and scaled up mechanized operation accordingly.[14] A similar pattern emerged in Feicheng, Shandong, where a machinery operator responded to small, non-contiguous plots by leasing land from several hundred villagers and investing in combine harvesters and no-till seeders.[15] Local policy discussions before 2014 echoed the same logic, describing contiguous land operation as a precondition for deploying large machinery, standardized cultivation, and modern agricultural services.[16]

[14] *China Economic Weekly*, "Six-province survey of rural land transfers," December 8, 2008.

[15] National Development and Reform Commission, "A machinery operator's farm experiment in Feicheng, Shandong," December 1, 2008.

[16] See, for example, a 2012 report on Suihua, Heilongjiang, which framed contiguous land operation as necessary for large agricultural machinery, large-scale water-control projects, and standardized agricultural technology. *China Daily*, "Building modern agriculture and the northern granary," March 4, 2012.

These accounts do not themselves identify the causal effect; that role is played by the staggered subsidy rollout examined below. Yet narrative evidence of this kind has its own evidentiary weight: it shows the mechanism unfolding in real economic settings, with a level of concreteness and contextual fidelity that econometric estimates, however well identified, cannot fully convey. Large machinery could enter under the household-contracting system, but its efficient use required larger and more contiguous operational holdings. Once farmers, cooperatives, and service providers had invested in such equipment, land consolidation became the organizational response through which the new technology could be used effectively.

Crucially, this reorganization was not easily reversed. ***Irreversibility*** came not only from the sunk investment in machinery purchase. Operating large machinery at scale reorganized production into contiguous-block farming, multi-household rental contracts, and machinery-service networks that kept expensive equipment in continuous use. Around this new mode of production, a supporting ecosystem of parts suppliers, repair workshops, operator training, and upstream and downstream manufacturing emerged, each part viable only because the others existed at scale. Reverting to small-plot cultivation would therefore have required unwinding not just individual equipment purchases (which a tractor's resale market could in principle absorb) but the entire network of complementary investments, contracts, and organizational practices. Adoption therefore restructured the productive base in ways that persisted whether or not formal institutional reform followed.

These pressures translated into a visible reorganization of agricultural production after 2004. The technology did not merely raise productivity within the existing organizational structure; it called into existence entirely new forms of agricultural organization whose viability depended on institutional arrangements that the old system could not provide.[17] Specialized grain-growing households expanded operations by renting land from neighbors, often assembling operational holdings of hundreds or thousands of mu. Agricultural machinery cooperatives emerged as service providers whose profitability depended on serving concentrated and contiguous client areas. Family farms, formally recognized as a policy category from 2013 onward, operated at scales far exceeding traditional household plots. Agricultural machinery manufacturers saw their market expansion tied directly to the spread of scale-oriented farming. By 2010, the Ministry of Agriculture reported that transferred farmland had reached approximately 270 million mu (about 18 million hectares), covering roughly 20 percent of total contracted arable land, compared with less than 10 percent before the mechanization subsidy program. These transfers occurred largely through informal or semi-formal arrangements within the permissive but weakly defined space allowed by the 2003 law.

Demand for institutional change and legal ratification (2008–2018). These new actors shared a common institutional need that the existing land-rights framework could not satisfy. Large-scale

[17]The relevant policy categories include specialized grain-growing households, agricultural machinery cooperatives, family farms, and machinery manufacturers such as YTO Group and Lovol Heavy Industry.

operators, machinery cooperatives, and equipment manufacturers whose livelihoods depended on mechanized agriculture required long-term, legally secure, and financeable access to consolidated land. The 2003 law permitted transfer in principle, but the transferee's operational position lacked standalone legal protection. Land management rights could not be independently registered, their long-term enforceability against the original contractor remained uncertain, and they could not serve as collateral for the equipment financing that mechanized operations required. A machinery cooperative investing millions in combines needed assurance that the land it served would remain consolidated for years, assurance that the existing legal architecture could not credibly provide.

At the same time, households that had already transferred out their land discovered that the arrangement suited their needs. They retained contract rights, preserving the social-insurance function of land, while receiving rental income and freeing labor for off-farm employment. Households that had invested in machinery and expanded operations now stood on the opposite side, seeking legal infrastructure for management rights they had already acquired in practice. By the early 2010s, a growing share of rural households participated in land transfer in one capacity or another, whether as lessors collecting rent, operators cultivating consolidated holdings, or machinery-service providers working across multiple plots. The traditional smallholder cultivating only within household boundaries, with little practical stake in the legal status of transferred management rights, was becoming less central to the organization of commercial agricultural production.

Figure 4 shows that the major policy and legal milestones arrived after this behavioral transformation was already underway. The sequence proceeded in distinct stages.

In 2008, the Decision of the Third Plenum of the 17th Central Committee called for strengthening the management and service of land contractual management-right circulation, establishing land-transfer markets, and developing multiple forms of moderate-scale operation.[18] This was not yet a reconstruction of property rights; it was an acknowledgment that transfer practices had become economically significant and required administrative infrastructure.

In 2014, the central government's policy language shifted decisively. The 2014 Central No. 1 Document stated that rural land policy should "stabilize household contract rights while activating land management rights."[19] Later that year, the General Offices of the CPC Central Committee and the State Council issued the Opinion on Guiding the Orderly Circulation of Rural Land Management Rights. Its opening paragraph is revealing: it explicitly attributed the acceleration of land-management-right transfers to industrialization, urbanization, rural labor reallocation, and "the continuous improvement of agricultural material and technical equipment."[20] The document adopted the formulation of separating ownership, contract rights, and management rights, a framework that would become the

[18] See the 2008 Decision of the Third Plenum of the 17th Central Committee.
[19] See the 2014 Central No. 1 Document.
[20] See the 2014 Opinion on Guiding the Orderly Circulation of Rural Land Management Rights.

backbone of subsequent legal reform.

In 2016, the State Council issued the Opinion on Improving the Separation of Rural Land Ownership Rights, Contract Rights, and Management Rights. This document described the Three-Rights Separation as "a major innovation in China's rural reform" and specified the operative principle: "implement collective ownership, stabilize household contract rights, and activate land management rights."[21]

In 2018, the National People's Congress amended the Rural Land Contracting Law. The revised law formally separated the land management right as an independent legal category. A household could retain its contract right while transferring the management right to another operator; the management right could be registered, and the law authorized the use of management rights for financing guarantees.[22] Legislative explanations framed the revision as a codification of practices that had already emerged: rural labor had moved out of agriculture, new agricultural business entities had expanded, land transfers had reached massive scale, and local experimentation with Three-Rights Separation needed to be "summarized and elevated into formal legal rules."[23] Official agricultural policy commentary stated that reform followed "the objective law that production relations must adapt to changes in productive forces."[24]

Summary. The chronology shown in Figure 4 encapsulates the paper's central empirical claim. The machinery subsidy began in 2004. Large and medium tractor power then rose sharply, land-transfer rates accelerated from below 10 percent to more than 35 percent, and the major policy and legal milestones in 2008, 2014, 2016, and 2018 follow thereafter. The decisive legal reconstruction of management rights followed, rather than preceded, the expansion of mechanized scale operation. The 2018 amendment did not create a land market; rather, it formalized and protected a management right that mechanized scale operation had already made economically essential. The temporal pattern underlying both sub-links of Lemma 1—mechanization followed by production reorganization, and production reorganization followed by legal ratification—is already visible in the institutional record. What remains to be established causally is the first link itself: that the technology shock drove the reorganization rather than merely preceding it. That is the task of the next subsection.

6.2 Causal Evidence on Technology to Production Reorganization

The empirical challenge is that the key institutional reforms after 2014 were nationwide changes and therefore cannot be evaluated using a conventional treated-versus-untreated comparison. The staggered

[21] See the 2016 Opinion on Improving the Separation of Rural Land Ownership Rights, Contract Rights, and Management Rights.

[22] See the 2018 amended Rural Land Contracting Law.

[23] See He Baoyu (Director, Office of the NPC Agriculture and Rural Affairs Committee), official explanation of the 2018 amendment to the Rural Land Contracting Law, as reported in People's Forum, 2019.

[24] See Han Changfu (Minister of Agriculture), press conference on the Opinion on Improving the Separation of Rural Land Ownership Rights, Contract Rights, and Management Rights, State Council Information Office, November 3, 2016, as reported in Guancha, 2016.

rollout of mechanization subsidies between 2004 and 2009 instead allows us to identify the intermediate behavioral responses emphasized by the theory. The empirical analysis asks whether exposure to the technology shock altered land-market behavior under the existing institutional arrangement before formal institutional reconstruction occurred. We then examine whether the mechanism operated specifically through scale-compatible machinery and whether the effect was strongest in environments where the inherited household-scale production structure was initially most restrictive.

6.2.1 Model Implications

Three testable implications organize the empirical analysis below.

Implication 1 (Behavioral response under the old institution). Exposure to the machinery subsidy should raise household land-market activity *before* formal legal codification, because mechanization at scale raises the returns to operating larger and more contiguous plots. We use household land-rental expenditure as the outcome: it captures whether households increasingly used markets to access operational land beyond their contracted allocation while the household-contracting system still formally dominated. This implication is tested in the baseline difference-in-differences estimates of Section 6.2.4.

Implication 2 (Scale-biased mechanization). The response should be driven by machinery whose efficient use is incompatible with fragmented household plots, not by mechanization in general. The reversible-technology benchmark in Corollary 1 clarifies that ordinary productivity improvements need not generate institutional pressure. Large and medium tractors require contiguous and predictably available land and are therefore complementary to land rental and consolidation; small tractors remain compatible with fragmented cultivation. The land-market response should track the former, not the latter. This implication is tested through the machinery-composition evidence in Section 6.2.6 and the supplementary IV evidence in Section 6.2.8.

Implication 3 (Where the mismatch binds). The effect should be strongest where the mismatch between the technology's scale requirements and the old institution's constraints is most binding. We examine three predetermined conditions: smaller pre-treatment operated land, a lower pre-treatment share of large and medium tractors, and pre-treatment plot fragmentation. The first two should amplify the response. The effect of fragmentation is potentially non-monotone: it raises the gains from consolidation, but extreme fragmentation can attenuate the immediate effect by making large machinery hard to deploy and rental coordination costly in the short run. This implication is tested in the heterogeneity analysis of Section 6.2.7.

6.2.2 Data and Measurement

The empirical analysis combines three sources of data: household-level survey data from the National Fixed Point (NFP) Survey, policy data on the staggered rollout of agricultural mechanization subsidy pilots, and city-level data on the composition of agricultural machinery. Appendix Table A.1 reports selected summary statistics for the main variables used in the analysis.

Household data. The main household data come from the National Fixed Point Survey, a longitudinal rural household survey conducted by the Research Center for the Rural Economy under China's Ministry of Agriculture. The survey follows villages and households over time and contains information on household demographics, agricultural production, land use, income, assets, and expenditures. For this paper, the key outcome is household expenditure on agricultural land rental.

Land-rental expenditure is informative because it captures market-mediated access to operational land. A household that expands cultivation through rental markets must make rental payments, and larger or more stable rental transactions are reflected in higher payments. At the same time, land-rental expenditure is not a pure measure of land consolidation. It combines an extensive margin, a quantity margin, and potentially a price margin. We therefore interpret the outcome as a measure of land-market activity and demand for operational land, rather than as a direct measure of rented-in acreage alone. This distinction is important for the theory: the empirical analysis identifies whether mechanization changed land-use behavior under the old institutional arrangement, not whether it directly measured every component of consolidation.

Policy data. The policy variation comes from the rollout of the agricultural machinery purchase subsidy program. The program was introduced in 2004 and expanded rapidly across counties before reaching nationwide coverage by 2009. The first pilot cohort covered 66 counties in 2004; the program then expanded to 500 counties in 2005, 1,126 counties in 2006, 1,716 counties in 2007, and 2,653 counties in 2008. Using the county-level rollout, we construct city-level measures of exposure.

Our baseline treatment variable, $Pilot_{ct}$, equals one once any county or district within city c is covered by the subsidy pilot in year t. This "any-county" definition is appropriate in this setting because mechanization is not confined to the administrative boundary of the treated county. Machinery can move across nearby counties, custom-hiring services operate in broader local markets, and information about subsidies and machine services diffuses across county borders. A city-level exposure measure therefore captures the relevant local-equilibrium effect more naturally than a narrowly defined own-county indicator. In robustness checks, we use alternative measures: the treated share of counties within a city, an indicator for at least half of counties treated, and an indicator for at least two-thirds of counties treated.

Machinery data. To examine the mechanism, we construct city-level data on the composition of agricultural machinery. Because no unified electronic database reports city-level information on tractor composition in China, we manually collected and digitized data on the number of large and medium tractors and small tractors by systematically reviewing provincial statistical yearbooks province by province and city by city. These data allow us to distinguish between scale-compatible machinery and machinery that remains compatible with fragmented household cultivation. Large and medium tractors involve higher fixed costs and operate more efficiently over larger areas, whereas small tractors can be used on small and fragmented plots. This distinction is central to the empirical test because the theory predicts institutional pressure only from technologies that require a different organization of production.

Sample period. The main sample covers 2001–2009. The pre-policy years 2001–2003 provide a baseline period for assessing pre-trends. The years 2004–2009 correspond to the staggered rollout of the subsidy program. The sample ends in 2009 because the program had reached nationwide coverage, leaving little untreated comparison variation after that point. The window is also conceptually important: it precedes the 2014 policy turn and the 2018 amendment to the Rural Land Contracting Law. The empirical analysis therefore studies behavioral adjustment before formal legal reconstruction, exactly the intermediate mechanism emphasized by the model.

6.2.3 Empirical Strategy

The identifying variation comes from the staggered administrative rollout of mechanization subsidy pilots across cities. The baseline specification is

$$LandRent_{ict} = \alpha + \beta\, Pilot_{ct} + X'_{ict}\gamma + \mu_c + \lambda_t + \varepsilon_{ict}, \tag{18}$$

where i indexes households, c cities, and t years. The outcome $LandRent_{ict}$ is the inverse-hyperbolic-sine transformation of household land-rental expenditure.[25] The treatment indicator $Pilot_{ct}$ equals one after city c becomes exposed to the subsidy pilot. The vector X_{ict} includes household size, education, and skill level. The terms μ_c and λ_t denote city and year fixed effects. Standard errors are clustered at the city level, the level of treatment variation.

This subsidy policy was not assigned by lottery, so the empirical strategy does not rely on unconditional random assignment. Instead, identification comes from a DID design under a conditional parallel-trends assumption. City fixed effects absorb time-invariant differences in geography, historical land institutions, agricultural suitability, and local market structure, while year fixed effects absorb aggregate national shocks. In more demanding specifications, province-by-year fixed effects further

[25] We use the inverse hyperbolic sine transformation to retain households with zero expenditure while preserving a log-like interpretation for positive values. Because the dependent variable includes many zeros, the coefficient should be interpreted as a log-point-like effect rather than as a literal percentage change for every household. Continuous variables are winsorized at the 1st and 99th percentiles to reduce the influence of extreme observations.

absorb time-varying provincial policies, agricultural market conditions, weather shocks, and fiscal capacity.

The primary identification concern is that cities exposed to the subsidy program earlier may already have been experiencing differential trends in land-market development prior to treatment. We address this concern in several ways. First, the event-study estimates reported below show no evidence of differential pre-trends between treated and untreated cities. Second, we conduct placebo exercises using both fictitious treatment timing and in-time placebo treatments constructed from pre-treatment observations only. Third, the baseline results remain robust to a range of alternative specifications aimed at addressing potential concerns about policy selection, treatment definition, and functional-form dependence, including alternative treatment measures, Poisson pseudo-maximum-likelihood estimation, specifications with baseline-characteristic trends, and regressions excluding the earliest 2004 pilot cohort.

6.2.4 Baseline Results

Table 6 reports the baseline estimates. Column (1) includes city and year fixed effects. Column (2) adds household controls and serves as our preferred specification. Column (3) replaces year fixed effects with province-by-year fixed effects.

The coefficient on $Pilot_{ct}$ in Column (2) is 0.114 and statistically significant at the 1 percent level. The estimate indicates that exposure to the mechanization subsidy increased land-rental expenditure and thereby intensified households' use of land markets to expand operational scale. This finding is economically meaningful because the subsidy policy itself did not directly reform land rights, and the sample period largely predates the national institutional reforms associated with Three-Rights Separation. The technology shock nevertheless altered production behavior under the existing institutional arrangement by increasing the returns to larger and more consolidated operational holdings. The evidence therefore suggests that production reorganization began before formal institutional reconstruction and that mechanization generated pressure for subsequent adjustment of the land-rights system.

6.2.5 Identification and Robustness Checks

Dynamic effects and pre-trends. To assess the parallel-trends assumption, we estimate the event-study specification:

$$LandRent_{ict} = \sum_{k \neq -1} \beta_k \mathbf{1}\{t - T_c = k\} + X'_{ict}\gamma + \mu_c + \lambda_t + \varepsilon_{ict}, \tag{19}$$

where T_c is the first year in which city c is exposed to the subsidy pilot. Event time $k = -1$ is the omitted reference period, and the tails are binned at $k \leq -4$ and $k \geq 3$.

Figure 5 reports the dynamic estimates. The pre-treatment coefficients are economically small and statistically indistinguishable from zero, and the joint test of the pre-treatment coefficients yields a

Table 6: Mechanization Subsidy Pilots and Land-Rental Expenditure

	(1) Land rental	(2) Land rental	(3) Land rental
$Pilot_{ct}$	0.115***	0.114***	0.115**
	(0.042)	(0.042)	(0.047)
Household controls	No	Yes	Yes
City fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	No
Province × year fixed effects	No	No	Yes
R^2	0.23	0.23	0.24
Observations	126,095	125,988	125,985

Notes: The dependent variable is household expenditure on agricultural land rental. $Pilot_{ct}$ refers to an indicator equal to one once any county or district within a city becomes covered by the mechanization subsidy pilot. Household controls include household size, education level, and skill level. Standard errors clustered at the city level are shown in parentheses. The superscript ***, **, or * indicates statistical significance at the 1%, 5% or 10% level, respectively.

p-value of 0.189. There is therefore no evidence that treated cities were already experiencing differential trends in land-market activity prior to pilot exposure. Following treatment, the coefficients become positive and increase gradually over time. This dynamic pattern is consistent with the mechanism emphasized in the paper: mechanization adoption, adjustment of operational scale, and reorganization of cultivation practices are unlikely to occur instantaneously, but instead unfold progressively as machinery diffusion deepens and households adapt production decisions to the new technological environment.

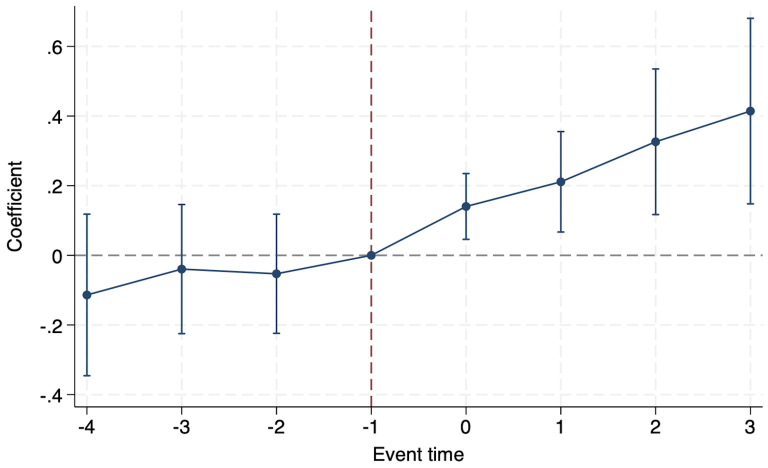


Figure 5: Dynamic Effects of Mechanization Subsidies on Land-Rental Expenditure

Notes: This figure reports dynamic treatment effects of mechanization subsidy pilots on household expenditure on agricultural land rental. Event time -1 is the omitted reference period and is plotted at zero without a confidence interval. The tails are binned at $k \leq -4$ and $k \geq 3$. All specifications include household controls, city fixed effects, and year fixed effects. Standard errors are clustered at the city level. The pre-treatment coefficients are jointly insignificant with $p = 0.189$.

Because staggered-adoption DID estimators can be sensitive to treatment-effect heterogeneity, Appendix Figure A.1 reports corresponding estimates using the estimator of Callaway and Sant'Anna (2021). The results are qualitatively similar: pre-treatment coefficients remain close to zero and post-treatment effects increase after rollout, suggesting that the main findings are not driven by heterogeneous-treatment-effect bias in the two-way fixed-effects specification.

Placebo tests. Appendix Table A.2 reports placebo exercises. The first column replaces the true pilot timing with fictitious treatment timing. The estimated placebo effect is small and statistically insignificant. Columns (2) and (3) use only pre-treatment observations and assign fake treatment one or two years before the actual rollout. These in-time placebo coefficients are also statistically insignificant. Together, these tests indicate that treated cities were not already experiencing a comparable increase in land-rental activity before the subsidy was introduced.

We also examine placebo outcomes that are not directly tied to agricultural land reorganization, including total income, net income, household expenditure, and off-farm wage income. Appendix Table A.3 shows no comparable pattern across these outcomes. The purpose of this exercise is not to prove an exclusion restriction, but to assess whether the baseline effect simply reflects a broad local income shock, a general investment boom, or unobserved local policy activism. The evidence suggests that the effect is concentrated on land-rental activity rather than on broad household economic outcomes.

Alternative treatment definitions and functional forms. Appendix Table A.4 shows that the baseline result is robust to alternative treatment definitions: at least half of counties treated, at least two-thirds of counties treated, and the treated share of counties within a city. Appendix Table A.5 further reports a Poisson pseudo-maximum-likelihood (PPML) specification using land-rental expenditure in levels. Because the outcome is nonnegative, skewed, and contains many zeros, PPML provides a useful alternative to the inverse-hyperbolic-sine specification. The PPML estimate remains positive and statistically significant, suggesting that the result is not an artifact of the transformation used to handle zeros and skewness.

Pilot selection and early cohorts. The earliest 2004 pilot cohort is a natural source of concern because it may have had stronger agricultural fundamentals or administrative capacity. Appendix Table A.5 shows that the result remains positive and statistically significant after excluding cities first treated in 2004. The result is also robust to specifications that allow richer time trends. These checks support the view that the baseline effect is not driven solely by the first pilot cohort or by simple differential trends associated with early selection into the program.

6.2.6 Mechanism: Scale-Biased Mechanization

The baseline result shows that pilot exposure increased land-market activity. The theory, however, does not predict that any form of agricultural capital should generate institutional pressure. What matters is whether the technology changes the economically viable organization of production. The relevant technologies are therefore those that are lumpy, scale-compatible, and difficult to use efficiently on small and fragmented plots. Large and medium tractors fit this description. They involve substantial fixed costs, operate more efficiently over larger and more contiguous areas, and are complementary to stable operational control over land. Small tractors, by contrast, remain broadly compatible with fragmented household cultivation and therefore do not fundamentally alter the production organization supported by the existing land system. The distinction between large and medium tractors and small tractors therefore provides a particularly sharp test of the mechanism: if the baseline effect reflects the scale incompatibility emphasized by the theory, the response should be concentrated in machinery that raises the returns to larger and more contiguous operational holdings.

To examine this channel, we estimate the following equation on the household panel after merging in city-year machinery outcomes:

$$M_{ct} = \alpha + \theta Pilot_{ct} + X'_{ict}\gamma + \mu_c + \lambda_t + \nu_{ict}, \tag{20}$$

where M_{ct} denotes a city-year machinery outcome assigned to household i in city c and year t: the log number of all tractors, the share of large and medium tractors, the log number of large and medium tractors, or the log number of small tractors. The vector X_{ict} includes the same household controls as in the baseline land rental regressions.[26]

Table 7 reports the main machinery-composition results using the household panel after merging in city-year machinery outcomes. Because the machinery variables vary at the city-year level, these estimates are best interpreted as household-weighted local-equilibrium first-stage evidence: whether households in treated local markets were exposed to a different local machinery environment. Pilot exposure increases the stock of large and medium tractors and raises the share of large and medium tractors in the local tractor stock. The effect on small tractors, by contrast, is small and statistically insignificant.

This asymmetry is central. If the baseline result merely reflected generic agricultural modernization or a broad increase in agricultural capital, small tractors should display a similar policy response. Instead, the policy shifted the machinery stock toward the type of equipment most complementary to scale.

[26] Appendix Table A.6 collapses the data to the city-year level and shows the same pattern, confirming that the result is not an artifact of merging city-level machinery outcomes to the household panel.

Table 7: Mechanization and the Composition of Agricultural Machinery

	(1) All tractors	(2) Share	(3) Large & medium	(4) Small
$Pilot_{ct}$	0.080***	0.034***	0.285***	0.050
	(0.025)	(0.006)	(0.051)	(0.036)
Household controls	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
R^2	0.968	0.897	0.953	0.967
Observations	91,357	91,357	91,357	91,357

Notes: The dependent variables are city-level machinery outcomes merged to the household panel. Column (1) uses the log number of all tractors; Column (2) uses the share of large and medium tractors in the local tractor stock; Column (3) uses the log number of large and medium tractors; and Column (4) uses the log number of small tractors. The specification includes the same household controls as the baseline land-rental regressions; because the machinery variables vary at the city-year level, the coefficients can be interpreted as household-weighted local-equilibrium first-stage estimates. Standard errors clustered at the city level are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

6.2.7 Heterogeneous Effects

The theory also predicts where the effect should be strongest. Technology-induced institutional pressure arises when the new technology changes the economically viable organization of production under the existing institutional arrangement. In the agricultural setting, the land-market response should therefore be strongest where household-scale cultivation is initially most constraining and where the subsidy has greater scope to shift machinery adoption toward scale-compatible equipment. We examine this implication using predetermined local characteristics: operated land size, the pre-treatment share of large and medium tractors, and pre-treatment plot density.

We estimate the following equation:

$$Y_{ict} = \alpha + \beta_0 Pilot_{ct} + \beta_1 (Pilot_{ct} \times H_c) + X'_{ict}\gamma + \mu_c + \lambda_{pt} + \varepsilon_{ict}, \tag{20}$$

where H_c is a predetermined heterogeneity indicator and λ_{pt} denotes province-by-year fixed effects. The coefficient β_1 measures whether the pilot effect is larger in the group indicated by $H_c = 1$.

Table 8 reports three related patterns consistent with the mechanism. First, the interaction with low pre-treatment operated land is positive and statistically significant, implying that the pilot effect is stronger in areas where households initially cultivated smaller operational holdings. This result is consistent with the argument that large-scale mechanization increases the returns to expanding operational scale. Where the inherited household-scale production structure was more restrictive, the mechanization shock generated a larger behavioral response through the land-rental market.

Second, the interaction with low pre-treatment large-tractor share is also positive and statistically significant. In areas where large and medium tractors were initially scarce, the subsidy represented a

Table 8: Heterogeneous Effects by Initial Production Conditions

	(1)	(2)	(3)
$Pilot_{ct}$	0.0896*	0.0621	0.161***
	(0.0517)	(0.0629)	(0.0578)
$Pilot_{ct} \times$ Low initial operated land	0.0637**		
	(0.0290)		
$Pilot_{ct} \times$ Low initial large-tractor share		0.0923**	
		(0.0456)	
$Pilot_{ct} \times$ High initial plot density			-0.0949*
			(0.0487)
Household controls	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes
Province × year fixed effects	Yes	Yes	Yes
R^2	0.239	0.264	0.240
Observations	123,350	83,142	120,897

Notes: This table reports heterogeneous effects of mechanization subsidy pilots on land-rental expenditure. The dependent variable is household expenditure on agricultural land rental. Each column interacts $Pilot_{ct}$ with a predetermined heterogeneity indicator. Household controls include household size, education level, and skill level. Standard errors clustered at the city level are shown in parentheses. $Pilot_{ct}$ is an indicator equal to one once any county or district within a city becomes covered by the mechanization subsidy pilot. The superscript ***, **, or * indicates statistical significance at the 1%, 5% or 10% level, respectively.

larger shock to local machinery composition and therefore had greater scope to alter the economically viable scale of cultivation. This result reinforces the machinery-composition evidence: land-market activity increased more precisely where the policy induced greater adoption of scale-compatible machinery.

Third, the interaction with high pre-treatment plot density is negative and statistically significant. This pattern qualifies rather than contradicts the mechanism. Plot density captures not only the demand for consolidation, but also the physical and transactional difficulty of deploying large machinery on highly fragmented land. Fragmentation therefore has two opposing effects: it increases the potential gains from consolidation while simultaneously making mechanized operation and land-rental coordination more difficult in the short run. The negative interaction suggests that scale-biased mechanization generates the strongest immediate land-market response where household-scale production is restrictive but fragmentation has not yet become so severe that large-scale machinery is difficult to deploy efficiently.

6.2.8 Supplementary Instrumental-Variables (IV) Evidence

The DID estimates are the primary source of identification. As a supplementary exercise, we also use pilot exposure as an instrument for local machinery composition. The purpose of this exercise is

not to establish a separate identification strategy for the full mechanism, but to examine whether the policy-induced component of machinery composition displays the same scale asymmetry documented in the reduced-form results.[27] In this sense, the IV analysis provides an additional way to assess whether the behavioral response is concentrated in machinery that is complementary to larger and more consolidated operational holdings.

With the IV specification, the first-stage equation is

$$M_{ct} = \pi \, Pilot_{ct} + \mu_c + \lambda_t + \eta_{ct}, \tag{21}$$

and the second-stage equation is

$$LandRent_{ict} = \beta \, \widehat{M}_{ct} + X'_{ict}\gamma + \mu_c + \lambda_t + \varepsilon_{ict}. \tag{22}$$

The endogenous variable M_{ct} is alternatively the share of large and medium tractors, the log number of large and medium tractors, and the log number of small tractors.

Table 9 reports the results. The first stage is strong for the share of large and medium tractors and for the log number of large and medium tractors, with first-stage F-statistics of 39.65 and 36.03, respectively. The corresponding second-stage coefficients are positive and statistically significant. By contrast, the small-tractor specification has a weak first stage, with an F-statistic of only 0.99, and the corresponding second-stage coefficient is statistically insignificant.

Table 9: IV Estimates: Mechanization Composition and Land-Rental Expenditure

	(1) Large/medium share	(2) Large & medium	(3) Small
Second-stage coefficient	2.866**	0.329**	3.051
	(1.424)	(0.156)	(3.146)
First-stage F-statistic	39.65	36.03	0.99
Household controls	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	82,943	82,943	82,943

Notes: The dependent variable in the second stage is household expenditure on agricultural land rental. The endogenous variable is the local machinery outcome listed at the top of each column, instrumented by pilot exposure. Household controls include household size, education, and skill level. Standard errors clustered at the city level are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Taken together, the IV estimates reinforce the scale-biased mechanism emphasized throughout the paper. The policy-induced component of large and medium machinery is associated with higher

[27] The exclusion restriction is demanding in this setting because the subsidy policy may affect land markets not only through measured tractor stocks, but also through machinery-service networks, information diffusion, liquidity effects, and complementary local investments. The IV estimates should therefore be interpreted as mechanism-oriented evidence rather than as the paper's primary source of causal identification.

land-market activity, whereas the corresponding small-tractor specification exhibits neither a strong first stage nor a significant second-stage effect. Even without treating the IV exercise as the paper's primary identification strategy, the results preserve the central empirical asymmetry predicted by the theory: the relevant behavioral response is concentrated in machinery that changes the economically viable scale of agricultural production.

6.2.9 Interpretation and Relation to Institutional Change

The empirical analysis identifies one causal link: exposure to the mechanization subsidy raised household land-rental activity under the household-contracting regime. This is the first sub-link of Lemma 1—technology adoption to production reorganization—estimated before the formal management-right reforms of 2014 – 2018. The remaining steps, from production reorganization to legal codification and onward to broader institutional change, rest on the institutional narrative in Section 6.1. The 2014 policy turn and the 2018 amendment to the Rural Land Contracting Law were nationwide changes with no clean comparison group, and we do not attempt to estimate their causal effects.

Within the link we do identify, the mechanism evidence is central. The results do not merely indicate that subsidies raised capital intensity: they point specifically to scale-biased mechanization. The land-market response is concentrated in large and medium tractors (whose efficient use requires larger, more stable, and more contiguous operational holdings) and is absent for small tractors (which remain compatible with fragmented household cultivation). The heterogeneity results reinforce this reading: effects are strongest where the inherited household-scale production structure was initially most restrictive and where the subsidy had greater scope to shift adoption toward scale-compatible equipment.

Placed back into the sequence in Section 6.1, these findings support the paper's interpretation of technology-induced institutional change. Scale-biased mechanization reorganized land use while the household-contracting regime was still legally dominant. The subsequent policy sequence is therefore better read not as an exogenous redesign of rural land rights, but as the legal ratification of a production structure that decentralized technology adoption had already brought into being, through a compromise that preserved collective ownership and household contract rights while activating management rights.

7 Discussion: Cross-Sector Predictions and China's Uneven Reform Experience

The empirical analysis in Section 6 tests the model's intermediate mechanism in one setting. This section briefly illustrates how the framework maps to several sectors in which technology-induced institutional change appears to have advanced, and then discusses settings in which the mechanism is less likely to operate.

Three Sectors. Table 10 identifies the model's key objects in each case.

Table 10: Technology-Induced Institutional Change in Three Sectors

Model object	Agriculture	Electricity	Payments
Old institution	Household-based tenure: contract right equals operating right	Planned generation dispatch: annual quota allocation to coal plants	UnionPay exclusive clearing mandate (State Council, 2002)
Incumbents	Village cadres; officials and scholars tied to egalitarian tenure; smallholders relying on land as social insurance[a]	Coal-power generators with guaranteed utilization hours; grid companies; provincial regulators; coal-dependent provinces	UnionPay; commercial banks; traditional acquirers; regulatory officials tied to bank-centered clearing
Government lever	Machinery purchase subsidy (2004)	Fixed feed-in tariff for renewables (2006)	Payment licenses and tacit permission for pilots (2011)
Technology	Large and medium tractors	Solar PV and wind turbines	Mobile payment: QR-code, account-based
New actors	Large grain growers; machinery cooperatives; agricultural service firms; machinery manufacturers	PV manufacturers; renewable generators; green-power buyers	Alipay; WeChat Pay; e-commerce platforms; small merchants; consumers
New institution	Three-Rights Separation (2014–2018)	Electricity spot markets and renewable consumption mandates (2015–2021)	NetsUnion and the "disconnect direct connections" mandate (2017–2018)

[a] Smallholder households were not active opponents of reform but passive supporters of the status quo. Although the inseparability of contract and operating rights generated substantial aggregate efficiency losses, the arrangement was privately rational for many smallholders because land functioned as social insurance. Before mechanization raised the returns to scale, most smallholders had little private demand for transferring management rights, and historical episodes of forced land transfers made the implementation of reform promises uncertain and the reform trajectory unpredictable. Their role in institutional rigidity therefore came from limited private demand for change, rational fear of an uncontrollable reform trajectory, and availability for mobilization by other actors with stronger vested interests.

Across the successful cases, the same underlying logic appears repeatedly. The technology was initially compatible with the existing institutional arrangement: agricultural machinery could operate on existing plots, solar generation could feed into the existing grid, and mobile payments could function through the existing bank-account infrastructure. Yet diffusion at scale gradually made the old institutional arrangement increasingly incompatible with the new mode of production. Large tractors required larger and more consolidated operational holdings; large-scale renewable generation required dispatch systems compatible with decentralized electricity supply and market-based trading; and trillions of mobile-payment transactions required a clearing architecture beyond the traditional bank-centered system. Initial compatibility made decentralized adoption politically feasible at the outset, while eventual incompatibility at scale generated pressure for institutional adjustment by changing production organization and creating new economic actors whose viability depended on a different institutional arrangement.

Where Has Reform Stalled? The framework also suggests where technology-induced reform is less likely to emerge. The mechanism requires a technology that can diffuse before institutional reform occurs, that generates irreversible and scale-dependent reorganization, and that eventually becomes difficult to reconcile with the old institutional arrangement. Where these conditions are absent, institutional rigidity may persist even when the status quo is widely recognized as inefficient.

Healthcare and education illustrate the limits imposed by weak technological irreversibility. Although digital technologies have affected service delivery in both sectors, no widely adopted technology has yet generated a comparable large-scale reorganization of production capable of irreversibly restructuring the underlying institutional arrangement. The household registration (*hukou*) system illustrates a different limit. Hukou primarily governs access to administrative entitlements, such as local schooling, healthcare, and social insurance, rather than the organization of production itself. While technological change may indirectly affect migration patterns and labor mobility, no decentralized technological adoption process has yet created a large class of economic actors whose viability depends directly on dismantling the hukou system. Local government dependence on land-transfer revenue reflects a similar logic. No technology currently available to decentralized private actors makes land finance structurally obsolete in the same way that mobile payments weakened the traditional clearing architecture or mechanization weakened fragmented household cultivation. In these settings, reform may therefore require alternative political pathways—including fiscal crisis, centralized administrative restructuring, or top-down political intervention—rather than technology-induced coalition realignment.

8 Conclusion

This paper develops a theory of technology-induced institutional change. Rigid institutions persist because their beneficiaries can coordinate to block reform. Yet decentralized adoption of an irreversible technology can break this coordination by generating strategic uncertainty among incumbents, splitting the incumbent coalition, spawning new entrants, and eroding the rents that sustain the status quo. Once adoption passes a tipping point, institutional reform becomes a ratification of economic reality rather than a direct assault on the old order.

The Chinese rural land case illustrates this mechanism. Agricultural mechanization did not rewrite land law when subsidies began in 2004. But it changed the returns to land consolidation, induced greater land-market activity, and shifted machinery composition toward scale-compatible forms. The major policy and legal changes that followed—the Three-Rights Separation framework and the 2018 amendment to the Rural Land Contracting Law—did not create this new production structure; they ratified one that decentralized adoption had already brought into being.

More generally, directly reforming economic institutions is politically difficult; it is sometimes more effective to develop productive capacity first—even ahead of what the existing institutions can accommodate, and then allow the new productive base to reshape those institutions. Technology can first change production, production can change interests, and law can follow by codifying the new equilibrium.

This logic resonates with a recurring feature of China's transition experience, in which market practices grew within the planned economy before institutional reform ratified them (Naughton, 1995).

Whether this broader pattern—in which the boundary between "technology" and "institution" is less sharp—can be formalized within the same theoretical structure is a direction for future work.

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APPENDIX

A. Variable Construction and Summary Statistics

Our main outcome variable is household land-rental expenditure. Because this variable is non-negative, highly skewed, and equal to zero for many households, the baseline regressions use the inverse hyperbolic sine transformation. The transformation retains zero observations while approximating a logarithmic transformation for moderate and large positive values. We therefore interpret the coefficients as log-point-like changes in land-market activity rather than as literal percentage changes for every household. Other variables are transformed according to their economic meaning and distributional properties. Tractor counts are expressed in logarithms, while the share of large and medium tractors is kept in levels.

Table A.1 reports selected summary statistics for the variables most relevant to the empirical analysis. The table deliberately reports both the raw land-rental expenditure variable and an indicator for positive land-rental expenditure.

The large number of zero values is not a data problem. Instead, it reflects the fact that, before the institutional reforms examined in the paper, most smallholders did not participate in land-rental markets in a given year. This sparsity motivates the inverse-hyperbolic-sine transformation and the PPML robustness check reported below.

Table A.1: Summary Statistics for Main Variables

Variable	Observations	Mean	SD	p25	Median	p75
Land-rental expenditure (yuan)	126,095	57.65	335.47	0.00	0.00	0.00
Operated cultivated land (mu)	120,527	7.802	10.516	2.30	4.60	9.00
Household size	139,814	3.994	1.535	3.00	4.00	5.00
High-school educated members	139,814	0.204	0.484	0.00	0.00	0.00
Technically skilled members	139,812	0.103	0.346	0.00	0.00	0.00
Pilot exposure: any county treated	140,352	0.528	0.499	0.00	1.00	1.00
Treated-county share	140,352	0.300	0.363	0.00	0.111	0.571
Pilot exposure: majority treated	140,352	0.301	0.459	0.00	0.00	1.00
Pilot exposure: at least two-thirds treated	140,352	0.214	0.410	0.00	0.00	0.00

Notes: This table reports selected variables from the 2001–2009 analysis sample. Land-rental expenditure is the raw yuan value before the inverse-hyperbolic-sine transformation used in the baseline regressions. The reported pilot variables are city-year exposure measures constructed from the county-level rollout of agricultural machinery purchase subsidies.

B. Robustness Checks

B1. Callaway and Sant'Anna (2021) Estimate

Because staggered-adoption designs can be sensitive to treatment-effect heterogeneity, we also implement the estimator of Callaway and Sant'Anna (2021). Let G_i denote the first treatment cohort for unit i. The group-time average treatment effect is

$$ATT(g,t) = \mathbb{E}\left[Y_t(1) - Y_t(0) \mid G_i = g\right], \tag{A.1}$$

which can then be aggregated by event time $e = t - g$. Figure A.1 presents the corresponding dynamic estimates. The pattern is broadly consistent with the two-way fixed-effects results: the pre-treatment coefficients are noisier, but the post-treatment effects rise after policy rollout. This strengthens the conclusion that the baseline result does not simply reflect spurious pre-trends.

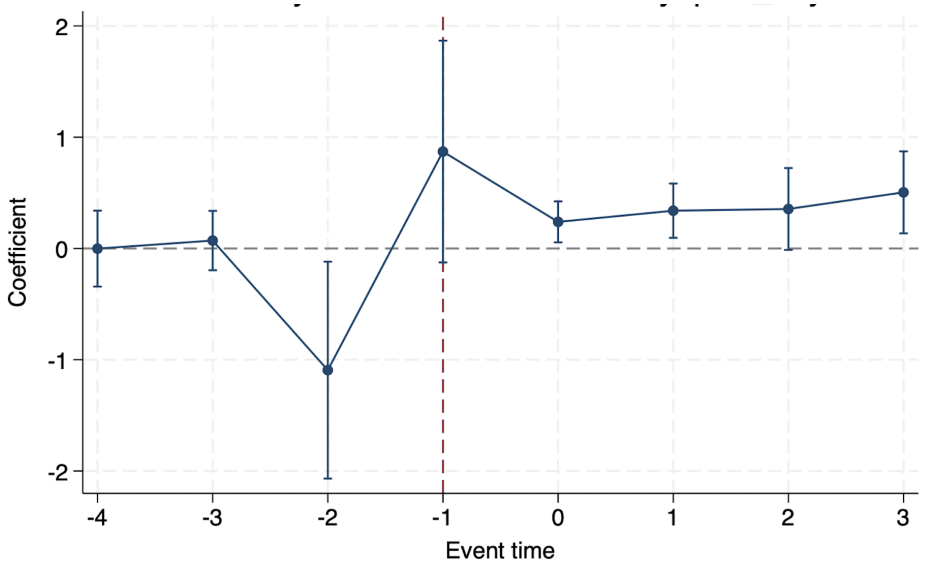


Figure A.1: Dynamic Effects of Mechanization Subsidies on Land-Rental Expenditure (Callaway and Sant'Anna (2021) Estimator)

Notes: This figure reports dynamic treatment effects of mechanization subsidy pilots on household expenditure on agricultural land rental using the Callaway and Sant'Anna group-time average treatment effect estimator. The effects are aggregated by event time relative to the first year of pilot exposure. The comparison group consists of not-yet-treated cities. Standard errors are clustered at the city level.

B2. Placebo Tests

We conduct three placebo tests. First, we replace the actual implementation year of the pilot with fictitious treatment timing. Second, using only pre-treatment observations, we assign fake treatment one or two years before the actual rollout. Third, we examine household outcomes not directly tied to land reorganization. These exercises test whether the baseline effect reflects arbitrary timing, anticipatory trends, or broad local income shocks rather than land-market adjustment. Table A.2 presents the corresponding results.

B3. Alternative Treatment Measures

To ensure that the baseline finding is not driven by the treatment definition $Pilot_{ct}$, we replace it with alternative exposure measures: an indicator equal to one when at least half of counties/districts

Table A.2: Placebo Tests: Fake Treatment Timing and In-time Placebo

	(1) Fake timing	(2) Pre-two-year	(3) Pre-one-year
$Pilot_{ct}$	0.055	0.0169	0.0619
	(0.044)	(0.0848)	(0.0947)
Household controls	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	133,434	52,076	52,076

Notes: The dependent variable is household expenditure on agricultural land rental. Column (1) replaces the true pilot timing with fictitious treatment timing. Columns (2) and (3) use only pre-treatment observations and assign placebo treatment one or two years before the actual rollout. Household controls include household size, education, and skill level. Standard errors are clustered at the city level.

Table A.3: Placebo Tests: Other Household Outcomes

	(1) Total income	(2) Net income	(3) Expenditure	(4) Off-farm wage
$Pilot_{ct}$	0.0186	0.0348	-0.0120	0.115
	(0.0199)	(0.0300)	(0.0568)	(0.171)
Household controls	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	139,570	138,981	128,008	139,812

Notes: This table reports placebo tests using household outcomes that are not directly tied to land reorganization, including total household income, net income, household expenditures, and off-farm wages. Household controls include household size, education, and skill level. Standard errors are clustered at the city level.

are treated, an indicator equal to one when at least two-thirds are treated, and the treated share of counties or districts within a city. Table A.4 shows that the estimates remain positive and statistically significant across these definitions.

Table A.4: Alternative Treatment Measures

	(1) Baseline	(2) ≥ Half	(3) ≥ Two-thirds	(4) Share
$Pilot_{ct}$	0.114***	0.097**	0.107**	0.285***
	(0.042)	(0.045)	(0.046)	(0.091)
Household controls	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	125,988	125,988	125,988	125,988

Notes: The dependent variable is household expenditure on agricultural land rental. The baseline treatment equals one once any county or district within a city is covered by the mechanization subsidy pilot. Column (2) uses an indicator for at least half of counties/districts treated; Column (3) uses an indicator for at least two-thirds treated; Column (4) uses the treated share of counties or districts within a city. Standard errors are clustered at the city level.

B4. Other Robustness Checks

We also conduct three additional robustness checks: estimating a Poisson pseudo-maximum-likelihood specification, controlling for baseline-characteristic trends, and excluding the earliest 2004 pilot cohort. Table A.5 reports these estimates.

Table A.5: Other Robustness Checks

	(1) PPML	(2) Excluding 2004 cohort	(3) City trends
$Pilot_{ct}$	0.299*	0.106**	0.103**
	(0.160)	(0.053)	(0.0444)
Household controls	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	96,971	105,037	125,985

Notes: Column (1) estimates a Poisson pseudo-maximum-likelihood specification using land-rental expenditure in levels. Column (2) excludes cities first treated in 2004. Column (3) controls for city-specific linear time trends. Household controls include household size, education, and skill level. Standard errors are clustered at the city level.

B5. City-Year Mechanization Regressions

The main text reports machinery-composition estimates using city-year machinery outcomes merged to the household panel. That specification is useful because it weights local mechanization changes by the household observations used in the land-rental regressions. Table A.6 reports the

corresponding collapsed city-year regressions. The estimates are very similar in substance: pilot exposure raises the number and share of large and medium tractors, while the coefficient on small tractors remains small and statistically insignificant. The city-year results therefore confirm that the mechanism evidence is not generated by household-level weighting or by the mechanics of merging city-level machinery data to the household panel.

Table A.6: Mechanization and the Composition of Agricultural Machinery (City-Year Panel)

	(1) All tractors	(2) Share	(3) Large & medium	(4) Small
$Pilot_{ct}$	0.108***	0.0350***	0.317***	0.0503
	(0.0347)	(0.00617)	(0.0564)	(0.0355)
City fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
R^2	0.967	0.883	0.955	0.962
Observations	1,427	1,427	1,427	1,427

Notes: This table reports regressions estimated on the collapsed city-year panel. Column (1) uses the log number of all tractors; Column (2) uses the share of large and medium tractors in the local tractor stock; Column (3) uses the log number of large and medium tractors; and Column (4) uses the log number of small tractors. No household-level controls are included because the unit of observation is a city-year. Standard errors clustered at the city level are reported in parentheses.