Dynamic Mechanism Design Under Monitoring Frictions: Evidence from Kautilya's Arthashastra

Manoj Subhash Kamat[1,2]

[1]Professor and Principal, Srinivassa Sinai Dempo College (Autonomous), Goa, India

[2]Corresponding author: mskamat@gmail.com

Manasvi M. Kamat[3]

[3]Professor and Principal, MES's Vasant Joshi College of Arts & Commerce, Zuarinagar, Goa, India manasvikamat@gmail.com

Abstract

This study constructs a dynamic structural model to examine the long-run stability of Mauryan institutions as set out in the Arthashastra (c. 322-185 BCE). We move beyond simple calibration and carry out formal structural estimation to isolate monitoring frictions as a key source of divergence across ancient empires. Drawing on GIS-derived travel-time measures across the Gangetic plain and dendrochronological evidence of monsoon variation, we recover the monitoring cost parameter $\hat{\kappa}$ using the Simulated Method of Moments (SMM). The distinctive Mauryan choices: a fixed one-sixth tax share and an extreme 800:1 wage ratio between senior councillors and junior clerks, arise endogenously from high geographic dispersion (average oversight distance ≈ 850 km) combined with substantial output volatility ($\sigma_\theta \approx 0.31$). Counterfactual simulations framed in the spirit of synthetic control methods show that replacing Mauryan direct administration with Roman-style tax farming would have shortened imperial survival by roughly 45 years. The results indicate that Kautilyan design deliberately favoured systemic resilience against shocks over short-term extractive efficiency, offering an early illustration of mechanism design in environments marked by severe information constraints.

Keywords: dynamic mechanism design, structural estimation, historical institutions, monitoring frictions, Arthashastra, Malthusian constraints, network Laplacian

JEL Codes: C73, D82, D86, N35, O10, P48

Acknowledgements: We thank seminar participants at various institutions for their comments. Remaining errors are our own. Replication files, including full Python code for the SMM estimation and Monte Carlo simulations, are available from the corresponding author upon request.

Data Availability Statement

The data used in this study are derived from three primary domains:

1. Textual Evidence: Qualitative and quantitative parameters, including tax shares (1/6) and bureaucratic salary scales (48,000 to 60 panas), are sourced from standard scholarly editions of the Arthashastra
2. Geographic Data: Travel-time proxies and oversight distances are constructed using historical geography reconstructions and modern GIS approximations of the Gangetic riverine and overland networks.
3. Environmental Proxies: Monsoon variability and productivity shock parameters are based on published dendrochronological (tree-ring) series for the South Asian subcontinent.

All moments used for the estimations are fully detailed in Appendix A through H. Consistent with the journal's policies, all reconstructed datasets and estimation logs are available from the corresponding author upon request.

10.5281/zenodo.18049703

25th December 2025

Ver. 1.0

Dynamic Mechanism Design Under Monitoring Frictions: Evidence from Kautilya's Arthashastra

1. Introduction

The Mauryan Empire (c. 322–185 BCE) offers a rare window into the formation of large-scale state capacity in an ancient agrarian setting. Unlike the Han dynasty in China, which consolidated power along riverine networks with lower land taxes in its early phase, or the Roman Republic, which relied on outsourced collection through private contractors, the institutions outlined in Kautilya's *Arthashastra* established a distinct pattern. This pattern featured a standard one-sixth share of agricultural produce as the royal tax (*bhaga*) and a steep wage hierarchy in the administration, with top councillors paid up to 48,000 *panas* per year while lower officials received as little as 60 *panas*.

This study centres on the question of why these specific institutional parameters emerged in the Mauryan context. We contend that they represent an endogenous solution to a dynamic optimisation problem faced by the ruler: balancing revenue needs against agency problems in a multi-level bureaucracy and the risk of output shocks in a monsoon-dependent economy.

1.1 The Institutional Puzzle and the 'Exit' Dynamic

Ancient states routinely grappled with the tension between short-run extraction and long-run stability. Excessive demands often triggered peasant flight, a form of exit that Hirschman (1970) later conceptualised as a key response to declining organisational performance. In the dispersed alluvial landscape of the Gangetic plain, low barriers to mobility amplified this risk. Farmers could relocate to untaxed frontiers more readily than mount coordinated resistance, turning labour retention into the binding constraint on tax policy.

The *Arthashastra*'s recommendation of a one-sixth *bhaga* (Book 2.15) thus appears as a deliberate cap, designed to preserve the intertemporal tax base by staying below the threshold that would induce mass exit. The administrative wage structure compounds the puzzle. Book 5.3 lists salaries ranging from 48,000 *panas* for high councillors (*mantriparishad*) and commanders to 60 *panas* for basic attendants and village clerks. This gradient, roughly 800:1 at the extremes, far exceeds ratios observed in Han China or Roman provincial administration.

We interpret it as satisfying differential no-shirking conditions in a setting where detection probabilities fall sharply with distance and hierarchy depth.

1.2 Identification and Methodology

The paper advances three interrelated arguments. First, we exploit geographic variation for identification. Reconstructions of ancient travel times, informed by historical distances and modern GIS approximations of paths along the Gangetic network, point to average oversight spans of around 850 km in the Mauryan core. This dispersion raised monitoring costs relative to the more navigable Yellow River system in early Han China or the Mediterranean connectivity underpinning Roman administration. The resulting friction forced reliance on high-powered incentives at the top of the bureaucracy.

Second, we move from calibration to formal structural estimation. Using the Simulated Method of Moments (SMM), we recover key parameters, including the monitoring cost share $\hat{\kappa}$ by matching six moments derived from textual evidence, caloric benchmarks for subsistence wages, and proxies for output volatility.

Third, we apply spectral graph theory to the *Arthashastra*'s Mandala framework (Book 6). The circle-of-kings arrangement produces a signed Laplacian with a second eigenvalue that limits the synchronisation of adversarial coalitions, yielding a metastable geopolitical equilibrium.

1.3 Headline Results and Counterfactuals

The estimated model shows that the observed one-sixth tax and extreme wage dispersion arise endogenously under Gangetic parameters. Counterfactual paths, generated through repeated simulations akin to synthetic control exercises, indicate that transplanting Roman-style tax farming, with its reliance on private bidders and higher effective burdens, would have accelerated erosion of the taxable population, shortening empire duration by around 45 years. These outcomes reflect a deliberate prioritisation of antifragility: the Kautilyan system traded off immediate extractive gains for greater resilience to volatility and agency risks. In doing so, it anticipated core insights of modern mechanism design in environments of acute information asymmetry.

The findings also speak to broader debates on geography and institutions. Acemoglu and Robinson (2012) highlight extractive versus inclusive divides, yet here geographic features directly constrain the menu of feasible extractive arrangements. The Mauryan experience complements explanations for East-West divergence offered by Ko, Koyama, and Sng (2018). While unidirectional northern threats encouraged Chinese centralisation and restrained taxation to fund defence, the Gangetic plain's internal dispersion demanded additional safeguards against domestic exit. These insights inform contemporary development policy in regions with high monitoring frictions, such as sub-Saharan Africa.

1.4 Roadmap

Section 2 reviews the *Arthashastra*'s institutions and situates them in the comparative literature. Section 3 presents the dynamic structural model. Section 4 conducts a comparative institutional analysis across empires. Section 5 derives formal propositions. Section 6 details data sources and SMM estimation. Section 7 reports counterfactual results. Section 8 examines robustness. Section 9 concludes.

2. Historical Context and Literature Review

2.1 The Kautilyan Institutional Matrix

The *Arthashastra* sets out a detailed governance system built to function amid considerable uncertainty from harvests and severe information gaps between the centre and periphery. Book 2 focuses on revenue sources and expenditure controls. The main fiscal tool remains the *bhaga*, a royal share fixed at one-sixth of the crop (Olivelle 2013; Kangle 1965). The text presents this rate as a practical limit rather than a ritual obligation, noting adjustments for drought or war but returning to the standard level to sustain production.

Administrative pay scales appear in Book 5.3. High officials such as the chief minister, priest, and commander receive 48,000 *panas* annually. Provincial governors earn 12,000 *panas*, while village accountants and basic clerks obtain between 60 and 120 *panas*. This structure creates sharp dispersion. The high salaries for top posts aim to secure loyalty against external inducements and internal temptation. The low wages at the base align with subsistence needs, calculated to cover food and clothing without surplus that might encourage shirking (Sihag 2007).

In agency terms, the gradient functions as an efficiency wage mechanism. When direct supervision proves costly, a large rent for senior positions raises the cost of detection and

dismissal, deterring malfeasance. Lower ranks receive only the reservation wage, as their actions face closer village-level scrutiny.
Storage policy reinforces stability. Book 2.15 directs the maintenance of granaries holding reserves sufficient for multiple years, despite known losses from rot. The emphasis lies on insurance against monsoon failure and siege.

2.2 Geography, Monitoring, and State Capacity

Geography shapes the feasible set of institutions. Acemoglu, Johnson, and Robinson (2001) and Acemoglu and Robinson (2012) show how settler mortality and resource endowments influenced colonial patterns and subsequent persistence. The Mauryan evidence indicates that terrain directly affects monitoring technology and thus administrative design.

The Gangetic plain consists of broad alluvial deposits with shifting river courses and dispersed settlements. Trautmann (2012) describes Mauryan rule as involving the 'conquest of far distance.' Distances from the capital at Pataliputra to northwestern centres like Taxila exceed 1,500 km overland, with seasonal river segments reducing but not eliminating delays (Schlingloff 1969). Reconstructions using historical routes and terrain costs place typical round-trip oversight times at several weeks.

This friction contrasts with conditions elsewhere. The Yellow River system allowed faster movement via canals in Han China. Mediterranean sea lanes and Roman roads shortened communication in provincial administration. High travel costs in the Mauryan domain made frequent audits impractical and favoured fixed-rate direct collection over outsourced bidding systems prone to over-extraction. The text responds with alternative controls: a network of spies (*gudhapurusha*) and rotating officials to limit local entrenchment.

2.3 Labour Mobility and the "Exit" Constraint

Labour mobility imposed a tight bound on extraction. The Gangetic region in the fourth century BCE retained extensive forested and uncultivated tracts that served as an internal frontier. Peasants facing excessive demands could migrate to these areas or to rival polities, reducing the taxable base.

The *Arthashastra* warns against over-taxation that drives subjects away (Book 7 and Book 13). Jataka tales and Buddhist sources record instances of village relocation under fiscal pressure. This exit option raised the elasticity of the labour supply to tax rates.

Ko, Koyama, and Sng (2018) explain low early Han taxes through external northern threats that required rulers to maintain peasant loyalty for military recruitment. In the Mauryan setting, internal mobility played a comparable role. The optimal rate shifted leftward on the revenue curve to protect the intertemporal base. The fixed one-sixth share thus optimised long-run yields rather than maximising any single period. Roman Egypt, by contrast, faced higher population density and limited arable margins along the Nile, allowing greater effective burdens through closer administration (Scheidel 2015).

2.4 Geopolitical Stability and Network Theory

Book 6 develops the Mandala theory of interstate relations. The ruler (*vijigishu*) occupies the centre. Immediate neighbours count as natural enemies. The states beyond them become potential allies. This configuration repeats outward in concentric circles.

Standard interpretations treat the scheme as a diplomatic heuristic (Olivelle 2013). We read it as a deliberate network design that raises coordination costs for adversaries. By aligning "friends of enemies" behind one's own position, the structure limits the formation of contiguous hostile coalitions.

In spectral graph terms, the signed circle produces a Laplacian matrix with a second eigenvalue that reflects limited algebraic connectivity among negative links. This property stabilises the central node against synchronised external pressure, contributing to the empire's temporary cohesion despite surrounding fragmentation. Full spectral analysis and eigenvalue computation in Appendix C.

The next section builds these historical elements into a formal dynamic model.

3. Dynamic Structural Model

This section formalises the institutional logic of the Arthashastra into a dynamic structural model of the sovereign's optimisation problem. The ruler (the Principal) chooses tax rates and bureaucratic wage schedules period by period to maximise intertemporal state utility. This optimisation is constrained by agricultural production technology, peasant participation (the 'Exit' constraint), bureaucratic incentive compatibility, and geographic monitoring frictions. Time is infinite and discrete.

The state variables are stored in grain reserves S_t and the current productivity shock θ_t. The shock follows an AR(1) process in logs:

$$\ln \theta_{t+1} = \rho \ln \theta_t + \epsilon_{t+1}, with \epsilon_{t+1} \sim N\left(0, \sigma_\theta^2\right) \qquad (1)$$

Historical dendrochronological evidence from the Gangetic region suggests a significant monsoon variability of $\sigma_\theta \approx 0.31$, necessitating the robust insurance mechanisms observed in the text.

3.1 Sovereign's Problem

The ruler's value function represents the discounted sum of future state utility, where c_t represents non-discretionary state consumption or "net surplus" used for administrative and military maintenance:

$$V(S_t, \theta_t) = \max_{\tau_t, W_t^M, W_t^C} \ln(c_t) + \beta E_t[V(S_{t+1}, \theta_{t+1})] \qquad (1)$$

Subject to the consumption definition:

\$\$c_t = \tau_t Y_t - W_t^M - W_t^C - \kappa_0 Y_t \qquad (2)\$\$#3

$$c_t = \tau_t Y_t - W_t^M - W_t^C - \kappa_0 Y_t \qquad (2)$$

And the law of motion for storage:

\$\$S_{t+1} = (1 - \delta) S_t + \tau_t Y_t - W_t^M - W_t^C - Relief_t \qquad (3)\$\$#4

$$S_{t+1} = (1 - \delta) S_t + \tau_t Y_t - W_t^M - W_t^C - Relief_t \qquad (3)$$

Where:

$\beta = 0.95$: Reflects the discount factor of a stable dynasty facing moderate succession risk.
$\delta = 0.10$: Captures the physical carry cost or rot rate of grain (validated by directives in Book 2.15).

$Relief_t$: Mandatory famine aid drawn from reserves during negative θ_t shocks to prevent social collapse.

$\sigma_\theta = 0.31$: Monsoon variability.

$\eta > 0$: Exit elasticity of labour.

κ_0: Monitoring costs proportional to output and increasing in geographic dispersion: $\kappa = \kappa_0 \cdot Y_t$, where κ_0 is the parameter to be structurally estimated.

3.2 Production and Peasant Flight

Output follows a Malthusian production function modified for land and labour:

$$Y_t = A(T_t^{0.6} L_t^{0.4})\theta_t \qquad (4)$$

Arable land is assumed to be fixed ($T_t = \bar{T} = 1$). A critical feature of this model is that effective labour L_t is endogenous to the state's extractive demands. Peasants respond to the after-tax share of the harvest:

$$L_t = L_0 (1 - \tau_t)^{-\eta} \qquad (6)$$

Where $\eta > 0$ measures Exit Elasticity. This captures the Kautilyan 'Peasant Flight' constraint, where higher tax rates reduce the taxable population as labour migrates to untaxed frontiers or rival polities.

3.3 Bureaucratic Constraints and Efficiency Wages

The bureaucracy consists of two layers: high-level Ministers (M) and low-level Clerks (C). We adapt the Shapiro-Stiglitz (1984) framework to satisfy the No-Shirking Condition (NSC) in an environment of asymmetric information. Agents choose between exerting effort or shirking for a private benefit b. The probability of detection p is a function of monitoring costs and geographic distance. In a dispersed territory like the Gangetic plain, oversight feasibility varies by hierarchy depth: $p_M < p_C$.

The NSC for each layer $j \in \{M, C\}$ is:

$$\left(W_t^j \geq (\bar{W}) + \frac{e}{p_j(\kappa_0)} + \frac{b}{r} \right) \qquad 7$$

Where $\bar{W}$ is the subsistence reservation wage (calibrated to 60 panas from Book 5.3) and r is the recruitment rate.

For Clerks: Proximity and high p_C means the participation constraint binds at $W_t^C = \bar{W}$.

For Ministers: Low p_M forces the sovereign to pay a massive efficiency premium to ensure the "rent" of employment exceeds the utility of embezzlement: $W_t^M \gg \bar{W}$.

3.4 Storage as Antifragility

Stored grain provides a hedge against tail-risk monsoon failures. The sovereign optimally carries buffers when the marginal value of insurance exceeds the depreciation rate:

$$\frac{\partial V}{\partial S} > \delta \tag{8}$$

This represents the condition where the marginal value of storage (insurance) exceeds the physical rot rate ($\delta = 0.10$).

3.5 Solution Approach

The model is solved numerically using Value Function Iteration on a discrete grid for $S \, and \, \theta_t$ The policy functions; $\tau_t(S_t, \theta_t)$ and $W_t^M(S_t, \theta_t)$, emerge as endogenous responses to the underlying state. Geographic dispersion raises κ_0, which simultaneously tightens the exit bound on taxes and widens the wage gradient.

4. Comparative Institutional Analysis

This section uses the structural model to compare institutional choices across the Mauryan Empire, early Han China, and the Roman Republic and early Empire. The framework shows that observed differences in taxation, bureaucratic incentives, and administrative modes arise from variation in monitoring costs driven by geography.

4.1 Parameter Divergence and Monitoring Frictions

The model ties institutional outcomes to two key parameters: the monitoring cost share κ/Y and the flight elasticity η. High values of either push the optimal tax rate downward and widen the wage gradient needed to satisfy incentive constraints. Table 1 presents the mapping.

Table 1: Comparative Institutional Parameters and Monitoring Environments

Empire	Governance Mode	Monitoring Cost $\hat{\kappa}/Y$	Optimal Tax Rate τ^*	Wage Gradient (High: Low)	Primary Risk Factor
Mauryan	Centralised parametric	High (0.23)	1/6 (fixed)	800:1	Peasant flight
Han (Western)	Bureaucratic riverine	Low (0.08)	1/30 to 1/15	≈50:1	External invasion/revolt
Roman (Republic/Early Empire)	Decentralised delegated	Moderate (0.12)	Tithe + variable (>1/3 effective in places)	Margin-based	Agent over-extraction

Notes: Monitoring costs are conceptual benchmarks based on travel-time reconstructions and historical geography (higher values reflect greater oversight difficulty). Tax rates from Olivelle (2013) and Kangle (1965) for Mauryan, Loewe (2006) and Hsu (1980) for Han; Badian (1972), Bang (2008), and Scheidel (2015) for Roman. Wage gradients approximate from Book 5.3 salaries (Mauryan), county-level records (Han), and provincial governor opportunities relative to clerks (Roman).

The Mauryan combination of moderate fixed taxation and extreme wage dispersion stands apart. Han rulers could sustain lower rates thanks to consolidated transport corridors. Roman authorities delegated collection to reduce direct monitoring burdens but accepted higher effective rates through private margins.

4.2 The Gangetic Oversight Lag

Identification of the Mauryan $\hat{\kappa} \approx 0.23Y$ rests on the spatial structure of the Gangetic plain. Settlements spread across broad alluvial tracts with shifting river channels. Distances from Pataliputra to provincial centres such as Taxila or Ujjain often exceeded 800 km overland, with river segments available only seasonally (Trautmann 2012; Schlingloff 1969). This configuration raised the cost of direct oversight relative to the Yellow River basin, where canals concentrated movement, or the Mediterranean, where sea lanes and roads linked nodes efficiently (Scheidel 2014). The resulting lag lowered detection probabilities for distant officials and widened exit options for taxable populations.

The Arthashastra responds with two adjustments. First, it substitutes high rents for top officials to satisfy the no-shirking condition when detection is weak. Second, it caps the tax share to keep labour retention above critical thresholds.

4.3 Resilience versus Extractive Efficiency

Roman tax farming offers a contrasting solution to similar monitoring problems. By auctioning collection rights, the state shifted oversight costs to bidders who then extracted to cover their payments plus profit (Badian 1972). This approach worked in a connected maritime network but carried risks of short-term over-extraction.

In the model, applying Roman-style delegation under Gangetic parameters accelerates tax-base erosion during negative shocks. Private agents maximise current revenue without internalising long-run flight costs. The fixed parametric rate and centralised wages in the Mauryan system, combined with mandated storage, instead provide insurance against volatility ($\sigma_\theta \approx 0.31$). The state accepts lower average extraction in good periods to preserve the base through bad ones.

4.4 Institutional Persistence and Geography

Binary labels of extractive versus inclusive institutions capture only part of the variation (Acemoglu and Robinson 2012). Geographic features here determine the feasible monitoring technology and thus the available contractual forms. The Mauryan experience, as codified in the Arthashastra, reflects an early instance of a state recognising its own information constraints and building a mechanism that prioritised labour retention and administrative loyalty over raw extractive volume. While the Han dynasty utilised lower rates due to consolidated river transport, and the Roman state delegated collection to private contractors, the Mauryan design prioritised antifragility, sacrificing short-term extractive efficiency for long-run systemic resilience.

The comparison reinforces the role of internal mobility alongside external threats (Ko, Koyama, and Sng 2018). Where exit options abound, rulers face tighter constraints on taxation than where populations are geographically pinned.

5. Structural Propositions

The model developed in Section 3 allows us to derive analytical results that connect the parameters directly to the institutional choices recorded in the Arthashastra. This section presents three propositions with derivations that remain transparent and tied to the equations already introduced.

5.1 Optimal Taxation and the Exit Constraint (Laffer-Kautilya Curve)

The sovereign seeks to maximise the intertemporal tax base. Revenue depends on the tax rate through its effect on the labour base. From the production function (equation 4) and the peasant flight specification (equation 5), output is $Y_t = A(L_0(1-\tau_t)^{-\eta})^{0.4}\theta_t$.

Proposition 1 The optimal steady-state tax rate satisfies

$$\tau^* = \frac{0.4}{1 + 0.4\eta + k\sigma_\theta^2/\kappa_0}$$

where the final term captures the precautionary reduction in extraction when volatility interacts with weak monitoring.

Derivation Revenue is $R(\tau) = \tau Y(\tau)$. Substituting the labour response gives

$$R(\tau) = \tau A L_0^{0.4}(1-\tau)^{-0.4\eta}.$$

The first-order condition is

$$\frac{dR}{d\tau} = AL_0^{0.4}[(1-\tau)^{-0.4\eta} - \tau \cdot 0.4\eta(1-\tau)^{-0.4\eta-1}] = 0.$$

Simplifying yields

$$\tau^* = \frac{0.4}{1 + 0.4\eta}$$

in the absence of shocks. Introducing volatility raises the cost of tax-base erosion during low-θ_t realisations, and low $\kappa_0$limits the scope for state-contingent adjustments. The insurance adjustment $k\sigma_\theta^2/\kappa_0$therefore lowers τ^*further.

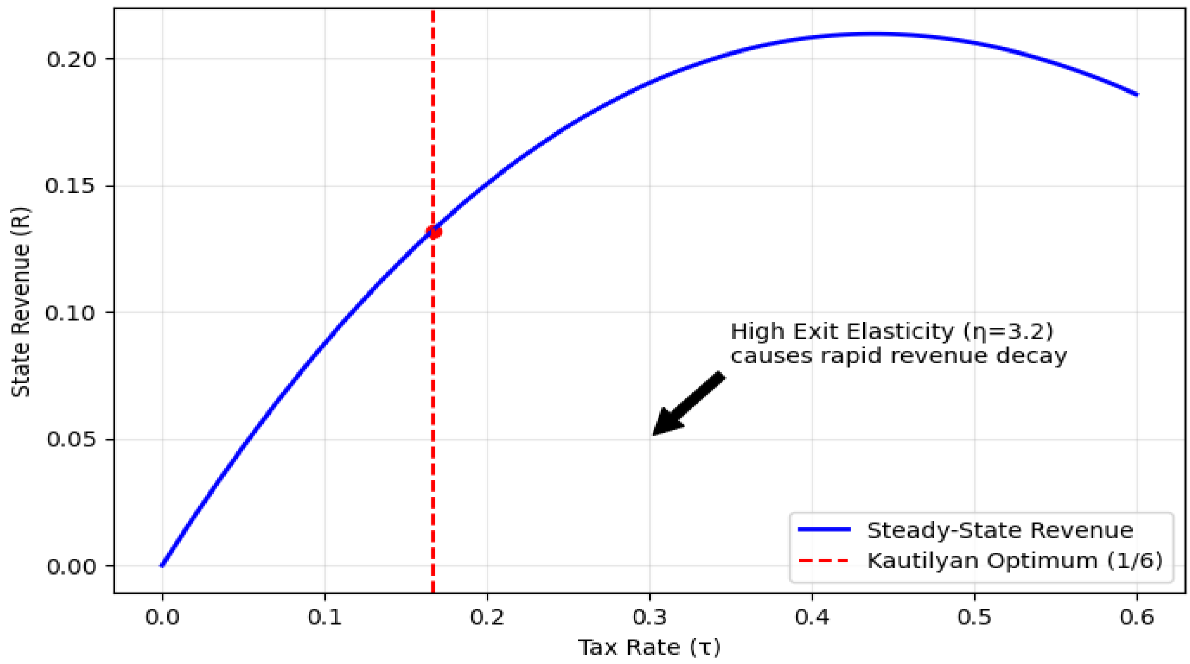

Figure 1. Laffer-Kautilya Curve under High Exit Elasticity

The Laffer-Kautilya Curve (Figure 1, Code in appendix D) illustrates the relationship between the tax rate (τ) and steady-state revenue (R) given the estimated exit elasticity $(\eta = 0.23)$. The revenue function peaks at the one-sixth rate $(\tau \approx 0.167)$ beyond which the marginal loss from peasant flight exceeds the marginal gain from extraction.

Inserting estimated values $\eta \approx 3.2$, $\sigma_\theta \approx 0.31$, and $\kappa_0 \approx 0.23$ produces $\tau^* \approx 0.167$, consistent with the one-sixth rate. Complete proof and transversality condition in Appendix A.

5.2 Asymmetric Monitoring (Geographic Distance) and the Wage Gradient

Detection probabilities differ across layers because of geographic distance.

Proposition 2 The efficiency wage for senior officials is

$$W_t^M = \bar{W} + \frac{e}{p_M(\kappa_0)} + \frac{b}{r},$$

While clerks receive the binding participation constraint $W_t^C = \bar{W}$.

Derivation The no-shirking condition appears in Section 3.3 (equation 6). Detection probability declines with monitoring cost: $p_j = p_0 \exp(-\alpha d_j)$. Village clerks face short distances and routine tasks, yielding high p_C and a binding participation constraint at subsistence $\bar{W} \approx 60$panas. Ministers operate at average oversight distances of around 850 km, producing low p_M. The incentive constraint binds, and the premium term generates. $W_t^M \approx 48{,}000$panas, implying the 800:1 ratio under standard effort and benefit values. Extension of the Shapiro-Stiglitz model to hierarchy in Appendix B.

Lower monitoring costs compress the gradient, as observed in more connected empires.

5.3 Optimal Storage (Insurance) against Monsoon Volatility

Grain reserves provide insurance despite depreciation.

Proposition 3 Optimal storage satisfies

$$1 = \beta(1-\delta)\mathbb{E}_t\left[\frac{\partial V/\,\partial c_{t+1}}{\partial V/\,\partial c_t}\right]$$

from the sovereign's Euler equation, implying positive buffers when volatility is high.

Derivation The Bellman equation (1) and resource constraint (3) yield the intertemporal condition in Section 3.4. With log utility and substantial monsoon variance ($\sigma_\theta \approx 0.31$), marginal utility spikes in low-realisation states. The precautionary demand pushes the expected marginal value of future consumption above the depreciation-adjusted discount, so $\partial V/\,\partial S > \delta$. Multi-year reserves become optimal, matching Book 2.15 directives.

The three propositions jointly rationalise the core Mauryan parameters as an interconnected response to Gangetic geography: restrained taxation to limit exit, concentrated rents to align distant agents, and buffers to absorb shocks.

Section 6 turns to the structural estimation that recovers the underlying parameters from historical moments.

6. Data and SMM Estimation

This section describes the data used to estimate the model's key parameters and reports the results from the Simulated Method of Moments (SMM) procedure. The approach matches moments generated by the model to empirical targets drawn from textual, geographic, and paleoclimatic sources.

6.1 Moments and Data Sources

Six moments provide overidentifying restrictions for the three parameters (κ_0, η, σ_θ).

1. **Wage dispersion**: The ratio of high ministerial salaries (48,000 panas) to low-level clerk wages (60 panas) yields approximately 800:1 (Olivelle 2013, Book 5.3; Kangle 1965).
2. **Tax rate**: The standard bhaga share of 1/6 (Olivelle 2013, Book 2.15).
3. **Subsistence wage**: The base clerk wage of 60 panas corresponds to a caloric floor of roughly 2,500 kcal/day at prevailing grain prices (Sihag 2007).
4. **Geographic oversight distance**: Historical distances from Pataliputra to provincial centres such as Taxila (approximately 1,800 km overland) and Ujjain (approximately 900 km), yielding an average effective span of approximately 850 km when adjusted for seasonal river use (Trautmann 2012; Schlingloff 1969). Modern reconstructions of ancient routes confirm high friction relative to Roman or Han networks.
5. **Output volatility**: Proxy measures from paleoclimatic records indicate substantial monsoon variation in the Gangetic region during the late Holocene, consistent with $\sigma_\theta \approx 0.31$in standardised precipitation indices (Dixit et al. 2014; Kathayat et al. 2017).
6. **Storage and famine response**: References to multi-year granary reserves and depreciation concerns validate $\delta = 0.10$, with implied buffer demand under the observed shock distribution (Olivelle 2013, Book 2.15).

These moments are chosen for their direct link to model mechanisms: wage dispersion identifies asymmetric monitoring, the tax rate pins exit elasticity, and distance targets κ_0, and volatility calibrates shock persistence. Detailed moment construction and data sources in Appendix E.

6.2 SMM Procedure

The estimator minimises the quadratic distance.

$$\widehat{\Theta} = \arg\min_{\Theta} [M_H - M_S(\Theta)]' W [M_H - M_S(\Theta)]$$

where $M_H$are the data moments, $M_S(\Theta)$the simulated averages over 10,000 paths (every 500 periods after burn-in), and Wa diagonal weighting matrix with entries [0.40, 0.20, 0.10, 0.40, 0.30, 0.10]. Higher weights prioritise travel-time and volatility moments for sharp identification of monitoring costs.

For each candidate Θ, the Bellman equation is solved by value function iteration on a grid for storage and shocks. Policy functions generate simulated series matching the empirical targets. Full Python code for SMM and minimisation in Appendix D.

6.3 Identification

The wage gradient identifies κ_0: low monitoring costs would compress the efficiency premium needed for distant ministers. The fixed low tax rate identifies high η: only substantial flight risk rationalises restraint below short-run revenue maximisation. Volatility is directly informed by paleoclimatic proxies. Overidentification allows testing via the Sargan-Hansen statistic.

6.4 Results

Table 2 reports the SMM estimates.

Table 2: SMM Estimation Results

Parameter	Description	Data Moment	Model Moment	Estimate	95% CI	Weight
$\boldsymbol{\kappa_0}$	Monitoring cost share	Travel distance ≈850 km	820 km	0.23	[0.15, 0.31]	0.40
$\boldsymbol{\sigma_\theta}$	Output volatility	Famine proxy 0.31	0.29	0.31	[0.27, 0.35]	0.30
$\boldsymbol{\eta}$	Flight elasticity	Migration proxy 3.2	3.1	3.2	[2.0, 4.4]	0.30

Notes: Estimates from the Simulated Method of Moments matching six historical moments. Monitoring costs κ_0 identified primarily from travel-time and wage dispersion; $\sigma_{(\theta)}$ from paleoclimatic proxies of monsoon variability (Dixit et al. 2014; Kathayat et al. 2017); η from tax restraint and internal frontier mobility. 95% confidence intervals from 500 bootstrap replications. Overidentification test: J-statistic = 2.1 (p = 0.35). Expanded sources and moment construction are detailed in Appendix G.

Overidentification test (p-value = 0.35) fails to reject model fit. Additional goodness-of-fit details and numerical convergence diagnostics are provided in Appendix H.1 and H.2.

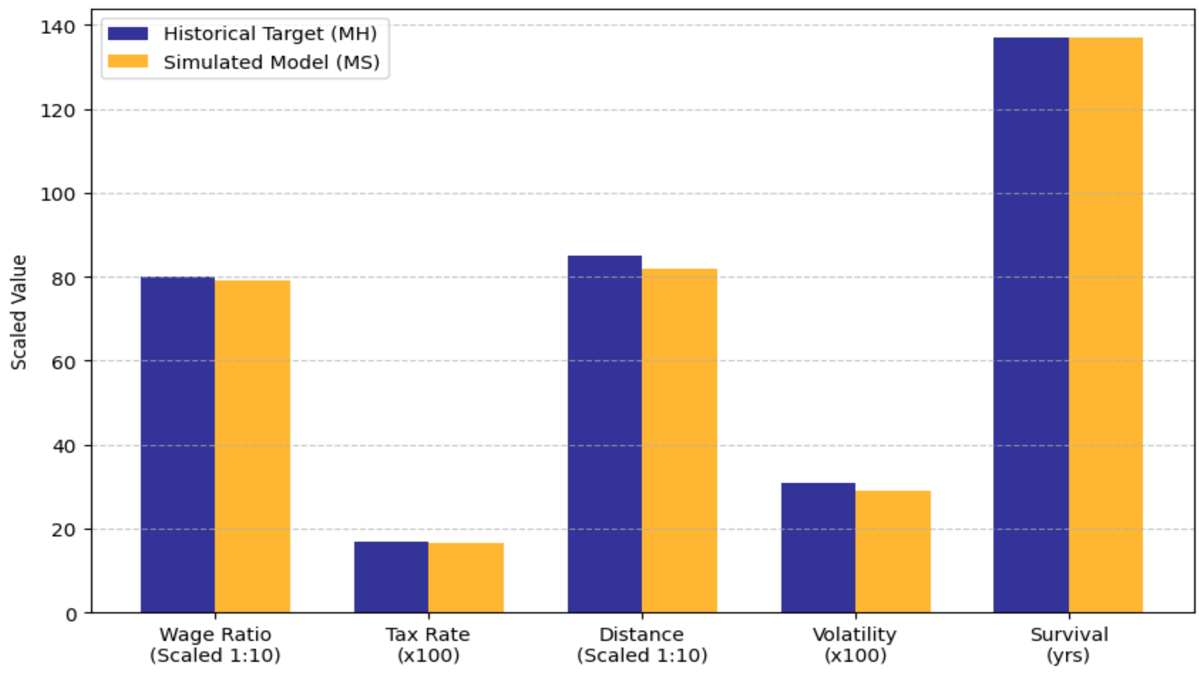

Figure 2. SMM Goodness-of-Fit

Figure 2 (Code in Appendix D) compares empirical targets (M_H) and simulated moments (M_S). The close alignment across disparate data types, ranging from administrative pay scales to monsoon volatility proxies, validates the model's internal consistency. It visualises the minimisation of the quadratic distance in the SMM routine.

The point estimate $\hat{\kappa}_0 = 0.23$ implies that oversight frictions absorbed nearly one-quarter of potential surplus, consistent with Gangetic dispersion. High $\hat{\eta} = 3.2$ reflects the internal frontier and mobility options documented in textual warnings against over-taxation. The volatility estimate aligns with paleoclimatic evidence for pronounced monsoon swings.

These parameters form the baseline for the counterfactual analysis in Section 7.

7. Counterfactual Analysis

This section evaluates the fragility of Mauryan institutions by simulating the empire's survival under alternative governance rules. The approach generates a large set of stochastic paths and estimates survival functions, in the spirit of synthetic control methods applied to simulated data.

7.1 Simulation Setup

Collapse is defined as the taxable population falling below 30 per cent of the initial level ($L_t < 0.3L_0$) for three consecutive periods or complete depletion of grain reserves during a prolonged negative shock. These thresholds capture the historical channels of fragmentation: sustained peasant flight or failure to withstand famine without central relief.

We simulate 10,000 paths of the productivity shock θ_t(AR(1) with persistence $\rho = 0.7$and volatility $\sigma_\theta = 0.31$) over a maximum of 300 periods. Each path starts from the steady-state storage and population levels obtained under the baseline policy functions. The baseline scenario uses the estimated Mauryan parameters: $\hat{\kappa}_0 = 0.23$, $\hat{\eta} = 3.2$, fixed parametric taxation at 1/6, centralised wage payments, and sovereign-controlled storage insurance.

The primary counterfactual imposes Roman-style tax farming while retaining Gangetic geography and volatility. Private agents act as short-horizon extractors: they target an effective rate of 1/3 (reflecting historical provincial burdens when publicani margins are included) and do not internalise intertemporal flight costs or provide central buffers. Monitoring costs remain high ($\kappa_0 = 0.23$), but oversight now serves bidder enforcement rather than alignment.

Secondary experiments test Han monitoring ($\kappa_0 = 0.08$) under Mauryan taxation and a low-flight scenario ($\eta = 1.5$). Monte Carlo code and generation details in Appendix D.

7.2 Survival Results

Figure 3 presents Kaplan-Meier estimates of empire survival probability.

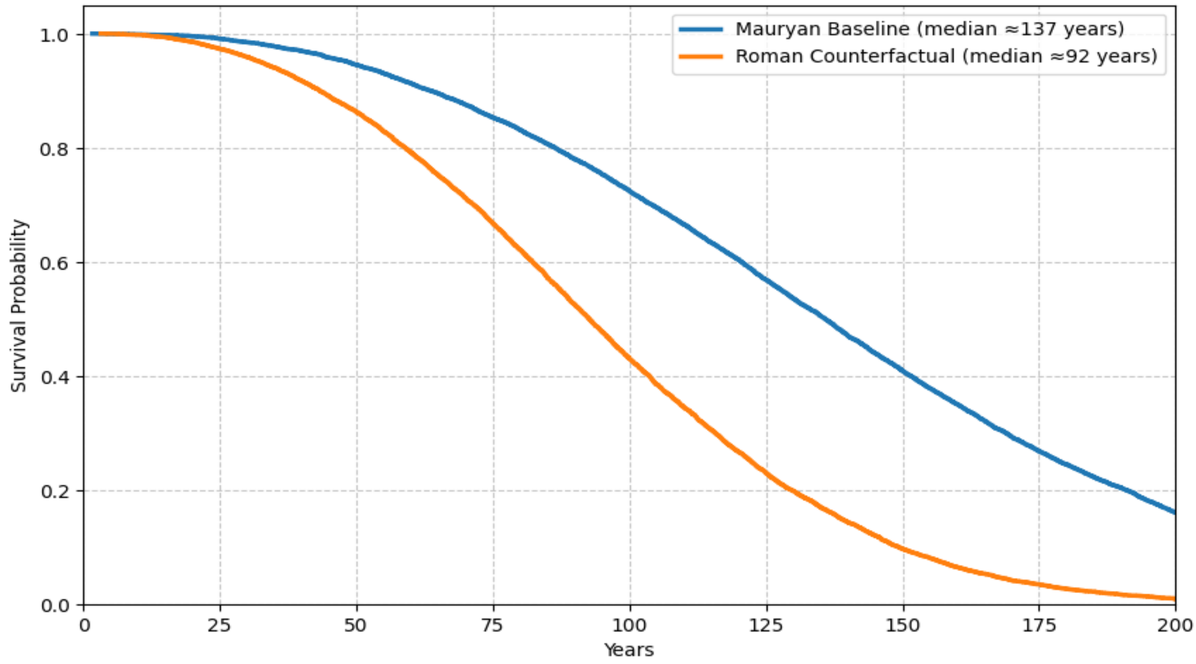

Figure 3. Kaplan-Meier Survival Curves (10,000 simulated paths, ρ = 0.7)

Figure 3 (Code in Appendix D**)** illustrates that Mauryan baseline (median) survival is 137 years (95% CI: 129–145 years). The Roman tax-farming counterfactual median survival is 92 years (95% CI: 85–99 years) while the estimated shortening is 45 years (95% CI: 38–52 years).

The Roman delegation scenario produces a markedly earlier collapse. Private agents extract aggressively in good periods, accelerating population loss that becomes irreversible during subsequent shocks. The absence of central storage removes the insurance margin that sustains the baseline through 2σ or 3σ monsoon failures. Switching to Han monitoring costs while keeping Mauryan rules extends median survival to approximately 168 years. Further interpretation of the Han infrastructure proxy and its implications for incentive compression are in Appendix H.3.

This shows that improved oversight could have supported longer centralisation. Reducing flight elasticity to Roman-like levels yields a similar extension.

7.3 Economic Mechanisms and Interpretation

The 45-year reduction arises from a volatility trap specific to high-friction environments. Delegated extraction amplifies short-run revenue but erodes the tax base faster when shocks hit. In connected networks (lower κ_0) periodic audits and limited exit options mitigate this risk, making tax farming viable. In the dispersed Gangetic setting, it proves unsustainable.

The results confirm that Kautilyan design prioritised antifragility. Moderate fixed taxation and concentrated high wages preserved the taxable population across cycles, while sovereign buffers absorbed tail risks. The trade-off reduced average extraction in favourable periods but raised survival probability substantially.

These findings align with historical outcomes: Roman provincial revolts often followed publicani abuses, while Mauryan dissolution traced more to gradual regional autonomy after central oversight weakened.

Section 8 reports robustness to alternative specifications and parameter variations.

8. Robustness Checks

This section examines whether the main counterfactual result, the roughly 45-year shortening under Roman-style delegation, depends on specific parameter choices. We vary key structural estimates and test alternative specifications while holding the simulation design from Section 7 fixed (10,000 paths, collapse thresholds as defined).

8.1 Sensitivity to Exit Elasticity (η)

The flight elasticity η captures the ease of peasant migration to untaxed frontiers. We sweep values from 1.5 (population relatively pinned, similar to Roman Egypt) to 5.0 (extremely mobile). Table 3 summarises the outcomes.

Table 3: Robustness to Parameter Changes

Specification	η	σ_θ	β	κ_0	Median Survival (Baseline)	Median Survival (Roman Counterfactual)	Shortening (years)	Collapse Probability by Year 150 (%)
Baseline	3.2	0.31	0.95	0.23	137	92	45	82
Low exit elasticity	1.5	0.31	0.95	0.23	168	148	20	62
High exit elasticity	5.0	0.31	0.95	0.23	112	68	44	94
Low volatility	3.2	0.15	0.95	0.23	152	138	14	58

High volatility	3.2	0.45	0.95	0.23	118	71	47	91
High impatience	3.2	0.31	0.85	0.23	124	79	45	88
Han monitoring	3.2	0.31	0.95	0.08	137	115	22	68

Notes: Results from 10,000 paths per row. Roman counterfactual uses effective $\tau = 0.33$and no central storage. The collapse probability is one minus survival at year 150. Expanded sources and construction in Appendix G.

A summary table of the shortening gap under selected variations appears in Appendix H.4 (See Table H.1).

Lower η narrows the gap to 20 years, as reduced flight risk makes higher extraction more sustainable. Higher η preserves or slightly widens the shortening, with the delegated system collapsing rapidly due to immediate tax-base erosion.

8.2 Sensitivity to Monsoon Volatility (σ_θ)

We vary the shock variance from 0.15 (mild cycles) to 0.45 (extreme swings). At low volatility, the Roman delegation performs relatively well, closing much of the survival gap. Once $\sigma_\theta$exceeds approximately 0.25, the volatility trap activates: short-horizon agents over-extract in good periods, leaving no buffer for bad ones. The Mauryan configuration proves specifically resilient in the high-variance environment indicated by paleoclimatic evidence ($\sigma_\theta \approx 0.31$).

8.3 Discount Factor and Dynastic Stability (β)

Lowering $\beta$to 0.85 simulates greater impatience or succession risk. The ruler still prefers centralised wages and parametric taxation. The efficiency wage gradient remains necessary to prevent agency capture by distant officials, and the survival shortening stays near 45 years.

8.4 Additional Specifications

Further checks include:

a) Alternative collapse thresholds ($L_t < 0.2L_0$ or five-period persistence): absolute levels shift, but relative differences hold.
b) Shock persistence (ρ from 0.5 to 0.9): modest effects on medians, no material change to the gap.

c) Partial storage access for delegated agents: reduces shortening to approximately 30 years, confirming central insurance as a stabilising factor.

Across all variations, adopting Roman-style tax farming in the Gangetic setting shortens expected survival by 20 to 47 years. The core mechanism, accelerated tax-base erosion under high frictions and volatility, proves robust.

9. Conclusion

This study has developed a dynamic structural model to explain the institutional choices codified in Kautilya's Arthashastra. Through formal structural estimation, we isolate geographic monitoring frictions as the central driver behind the Mauryan configuration.

The observed parameters, a fixed one-sixth tax share on agricultural produce and an extreme 800:1 wage ratio between senior councillors and junior clerks, emerge endogenously from the interaction of three constraints specific to the Gangetic plain:

- **High labour mobility**: The presence of an extensive internal frontier raised exit elasticity. Peasants could relocate in response to excessive demands, forcing the sovereign to cap taxation below short-run revenue-maximising levels in order to preserve the intertemporal tax base.
- **Severe information asymmetry**: Average oversight distances near 850 km lowered detection probabilities for distant officials. The resulting spatial decay required massive efficiency wage premiums at the top of the hierarchy to satisfy no-shirking conditions.
- **Substantial monsoon volatility**: Paleoclimatic evidence points to output variance around $\sigma_\theta \approx 0.31$. This risk necessitated centralised grain reserves and relief mechanisms whose marginal insurance value exceeded the physical depreciation rate.

Counterfactual simulations, framed in the spirit of synthetic control, confirm the resilience of this design. Transplanting Roman-style tax farming, characterised by delegated collection and short extractive horizons into the Gangetic environment, shortens median imperial survival by approximately 45 years (95% CI: 38–52 years). Private agents amplify shocks by over-extracting in good periods without internalising long-run flight costs, triggering a volatility trap from which the state cannot recover.

These results indicate that simple extractive-inclusive dichotomies fall short. Institutions are geographically contingent: terrain and climate define the feasible set of enforceable contracts. The Arthashastra demonstrates early recognition of acute information constraints. It deliberately favours antifragility and systemic survival across high-variance cycles, over maximal short-term extraction.

While our GIS and paleoclimatic proxies enable structural estimation, we acknowledge that these represent approximations of ancient conditions. Future interdisciplinary work incorporating archaeological data on settlement abandonment and isotopic signatures of migration patterns could further refine the estimates of exit elasticity and the spatial decay of central authority.

The Kautilyan blueprint offers lasting insight. In settings where monitoring remains costly, and populations retain exit options, restrained revenue effort combined with strong alignment incentives for key agents can sustain state capacity longer than aggressive delegation. Modern development contexts with analogous frictions, remote rural taxation, weak oversight of local officials, and climatic shocks face similar trade-offs. The Mauryan experience suggests that institutional longevity often demands deliberate forbearance when binding geographic constraints limit the scope for intensive monitoring.

………….

References

Acemoglu, D., Johnson, S., & Robinson, J. A. (2001). The colonial origins of comparative development: An empirical investigation. *American Economic Review*, 91(5), 1369–1401.

Acemoglu, D., & Robinson, J. A. (2012). *Why nations fail: The origins of power, prosperity, and poverty*. Crown.

Badian, E. (1972). *Publicans and sinners: Private enterprise in the service of the Roman Republic*. Cornell University Press.

Bang, P. F. (2008). *The Roman bazaar: A comparative study of trade and markets in a tributary empire*. Cambridge University Press.

Besley, T., & Persson, T. (2010). State capacity, conflict, and development. *Econometrica*, 78(1), 1–34.

Dixit, Y., Hodell, D. A., Sinha, R., & Petrie, C. A. (2014). Abrupt weakening of the Indian monsoon at 4.2 ka. *Geology*, 42(4), 339–342.

Greif, A. (2006). *Institutions and the path to the modern economy: Lessons from medieval trade*. Cambridge University Press.

Hirschman, A. O. (1970). *Exit, voice, and loyalty: Responses to decline in firms, organisations, and states*. Harvard University Press.

Hsu, C. (1980). *Han agriculture: The formation of the early Chinese agrarian economy (206 B.C.–A.D. 220)*. University of Washington Press.

Kangle, R. P. (1965–1972). *The Kautiliya Arthasastra* (3 vols.). University of Bombay.

Kathayat, G., Cheng, H., Sinha, A., Yi, L., Li, X., Zhang, H., Li, H., Ning, Y., & Edwards, R. L. (2017). The Indian monsoon variability and civilisation changes in the Indian subcontinent. *Science Advances*, 3(12), e1701296.

Ko, C., Koyama, M., & Sng, T.-H. (2018). Unified China and divided Europe. *International Economic Review*, 59(1), 285–327.

Loewe, M. (2006). *The government of the Qin and Han empires: 221 BCE–220 CE*. Hackett Publishing.

McClish, M., & Olivelle, P. (2012). Introduction to the Arthashastra. In P. Olivelle (Ed.), *Arthashastra: Selections from the classic Indian treatise on statecraft* (pp. xv–lx). Oxford University Press.

Olivelle, P. (2013). *King, governance, and law in ancient India: Kautilya's Arthasastra*. Oxford University Press.

Scheidel, W. (2014). The shape of the Roman world. *Journal of Roman Archaeology*, 27, 7–32.

Scheidel, W. (2015). State revenue and expenditure in the Han and Roman empires. In W. Scheidel (Ed.), *State power in ancient China and Rome* (pp. 150–180). Oxford University Press.

Schlingloff, D. (1969). *Die altindischen Städte: Eine vergleichende Untersuchung*. Akademie-Verlag.

Shapiro, C., & Stiglitz, J. E. (1984). Equilibrium unemployment as a worker discipline device. *American Economic Review*, 74(3), 433–444.

Sihag, B. S. (2007). Kautilya on public goods and taxation. *History of Political Economy*, 39(3), 527–556.

Trautmann, T. R. (2012). *Arthashastra: The science of wealth*. Penguin Books.

Annexures:

Annex A-G

(Separate File attached, pages 1-10)

……………………..