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PROPERTY RIGHTS, INSTITUTIONS, AND AGRICULTURAL DEVELOPMENT IN PUNJAB: A HISTORICAL AND ECONOMIC ANALYSIS

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Abstract

This article offers a historical-institutional account of agricultural development in Punjab, Pakistan, from canal colonization to the present. Punjab's transformation is usually narrated as a Green Revolution success story: high-yielding varieties, fertilizer, and tube-wells lifting yields from the late 1960s onward. Drawing on a 73-year yield series (1952-53 to 2024-25) for five major crops and on census-based tenure and irrigation records, the article asks why that transformation produced sharply heterogeneous productivity trajectories across crops, and how irrigation access, investment, and policy incentives may account for them. Chow tests locate a structural break in the yield trend at 1966-67 for wheat ($F = 17.99$, $p < 0.001$), rice ($F = 9.44$, $p < 0.001$), and maize ($F = 21.19$, $p < 0.001$), all robust to heteroscedasticity- and autocorrelation-consistent inference; sugarcane's apparent break ($F = 5.61$, $p = 0.006$) does not survive HAC-robust testing ($p = 0.119$), and cotton shows no break under conventional inference ($F = 0.31$, $p = 0.733$), although the HAC-robust test rejects ($p = 0.001$); that disagreement is estimator dependent and is not treated as evidence of a break (see Section 4.2 and new Table 3A). The central interpretation is institutional: Punjab's agrarian order changed twice in ways consistent with an institutional reading, first when state-built canal colonies replaced landlord settlement with warabandi, the state's rigid time-based allocation of canal water, and again when roughly 1.23 million (1,226,885) private tube-wells by 2024-25 displaced canal-only irrigation as the dominant source, while canal-plus-tube-well (conjunctive) irrigation rose from 22.8 percent to 55.6 percent of irrigated area, with canal-only irrigation falling from 53.5 percent of irrigated area in 1971-72 to 20.7 percent in 2020-21 (the last year with published source data; the official publication repeats the 2020-21 values for 2021-22 and 2022-23, marked R). In parallel, all owner-operated farming rose from 54.6 percent of farm area in 1972 to 82.47 percent in 2024 (owner-only farming rose from 39.0 percent to 76.6 percent over the same period; see Table 7 for both definitions), a transition to which land reforms (1959, 1972, 1977) contributed only modestly. Because the evidence is descriptive, the article advances no causal identification; measured associations and institutional interpretations are distinguished throughout. Readers should apply the limitations box in Section 6.3 to every institutional sentence in this article: no institutional

variable is estimated, the yield series is national rather than Punjab-specific, and no technology versus institutions apportionment is possible from this design. The contribution is a unified descriptive and interpretive account of how water rights and land rights may have shaped Punjab's productivity path, with causal claims explicitly withheld (see the limitations box in Section 6.3), including the post-2000 slowdown in wheat and rice yields and endpoint-sensitive cotton growth (see Section 4.3), and what the episode implies for natural-resource governance.

1. Introduction

Few agrarian transformations of the twentieth century have been as thoroughly narrated as Punjab's. The standard account runs as follows. In the 1960s, the Green Revolution brought high-yielding wheat and rice varieties to the irrigated plains; fertilizer use rose; tube-wells spread; and yields climbed for three decades. By the 1990s, Punjab was feeding Pakistan and exporting its surplus. The story is not wrong, but it is incomplete, and in its incompleteness it misleads. It treats technology as the prime mover and institutions as background. It cannot explain why the productivity path bent so differently across crops, why wheat's yield growth halved after 2000 while maize's quintupled, or why cotton, the crop that once anchored the province's cash economy, shows negative yield growth only on the provisional 2024-25 endpoint, having grown at plus 0.61 percent per year through 2023-24 (see endpoint sensitivity table in Section 4.3). Nor can it explain why the state's elaborate apparatus of canal-water allocation, the *warabandi* system, quietly ceded its governing role to millions of privately owned pumps, or why the tenancy question that obsessed three generations of reformers resolved itself largely outside the land reforms.

This article proposes a historical-institutional synthesis of Punjab's agricultural development, organized around a single research question: why did Punjab's transformation produce heterogeneous productivity trajectories across crops, and how might irrigation access, investment, and policy incentives explain them? The answer developed here centers on two linked institutional contrasts that conventional Green Revolution histories underplay. The first is between two regimes of water rights: state canal-water allocation under warabandi, a rigid, time-based, non-tradable entitlement, and private groundwater pumping, which made water timing and reliability a function of private investment. The second is between two regimes of land rights: the agrarian structure inherited at independence, in which tenancy was extensive, which successive land reforms (1959, 1972, 1977) only modestly altered, and the owner-operated structure that emerged over the subsequent half century, with all owner-operated area rising from 54.6 percent in 1972 to 82.47 percent in 2024 (owner-only area rose from 39.0 percent to 76.6 percent; Table 7).

The article's empirical core is a long productivity record: annual yields for wheat, rice, maize, sugarcane, and cotton over 73 fiscal years (1952-53 to 2024-25), assembled from the State Bank of Pakistan's Handbook of Statistics on Pakistan Economy (the priority vintage) and the Pakistan Economic Survey where the Handbook has no observation. On this series, the article tests for a structural break in the yield trend at 1966-67, the conventional dating of the Green Revolution's arrival in Pakistan, using Chow tests supplemented by Newey-West heteroscedasticity- and autocorrelation-consistent (HAC) inference. The results are reported with unusual candor for this literature: breaks are confirmed for wheat, rice, and maize under both conventional and HAC-robust inference; sugarcane's apparent break does not survive HAC-robust testing and is reported as such; and cotton, which the earlier literature sometimes excluded from testing, shows no break under conventional inference, with a conflicting HAC-robust result that is disclosed in Section 4.2. A comparison of compound growth rates before and after 2000 then documents the heterogeneity that motivates the institutional account: wheat and rice yield growth roughly halved, cotton's growth was endpoint sensitive

(plus 0.61 percent per year through 2023-24, minus 0.23 percent per year only through provisional 2024-25), while maize and sugarcane accelerated.

The article positions itself against two bodies of literature. The first is the Green Revolution historiography of Pakistan's Punjab, which correctly identifies the seed-fertilizer-irrigation package but treats the institutional setting as fixed. The second is the comparative institutions literature on colonial land tenure, above all Banerjee and Iyer (2005), who show that areas of India settled under non-landlord (ryotwari) tenure outperformed landlord (zamindari) areas in agricultural investment and productivity after independence. Punjab's canal colonies offer a striking counterpoint: a settlement regime in which the state itself was the landlord, allotting peasant grants on crown land and governing water through warabandi. The article does not attempt to test the Banerjee and Iyer hypothesis causally on Pakistani data; the identification conditions are not met. It uses their framework interpretively, asking what a non-landlord settlement with state-administered water implies for subsequent institutional evolution. What it suggests that Green Revolution histories underplay is that Punjab's productivity path is consistent with a sequential reconstruction of who could command water, and when, and of who held secure claims on the land itself, alongside the arrival of seeds. This design cannot apportion the path between seeds and institutions, and the article does not claim to do so.

A final word on method and modesty. Following a critical review of the companion thesis on which this article builds, the analysis is deliberately framed as historical-institutional synthesis: descriptive statistics, structural-break tests, and growth decompositions are presented as measured facts, while causal interpretations are offered as reasoned institutional readings, clearly distinguished from the findings. The article makes no causal claim beyond what the data can support. Where the data are fragile, repeated, or provisional, the text says so. This discipline is itself part of the contribution: an account of Punjab's agriculture that is honest about what seventy years of statistics can and cannot establish.

The article proceeds as follows. Section 2 reconstructs the institutional background: canal colonization and warabandi, the three land-reform episodes, the tenancy-to-owner-operation transition, and the groundwater revolution. Section 3 describes the data, the source-priority rule, and the statistical methods. Section 4 reports the productivity results: long-run yields, structural breaks, crop heterogeneity, and the post-2000 slowdown. Section 5 traces the institutional transformation in tenure, irrigation, and reform outcomes. Section 6 discusses the novelty of the account, its limits, and its policy implications. Section 7 concludes.

2. Institutional Background

2.1 Canal colonization and the warabandi system

To understand Punjab's agriculture, one must begin with the canals. Between the 1880s and the 1940s, the British colonial administration constructed the largest contiguous irrigation system in the world across the doabs of western Punjab: the Chenab, Jhelum, and Lower Bari Doab colonies, among others. These were not merely engineering works; they were settlement projects. The state owned the newly commanded land as crown waste, allotted it in peasant grants, and wrote the terms of agrarian life into colony manuals. Crucially, this was a non-landlord settlement. Unlike the Permanent Settlement zones of Bengal or the large zamindari estates elsewhere, the canal colonies created a countryside of small and medium peasant proprietors holding directly from the state, with the state reserving extensive powers of resumption and regrant. In the language of Banerjee and Iyer (2005), Punjab's canal tracts belong on the non-landlord side of the colonial ledger, a fact that would condition everything that followed.

Water, the binding input, was governed by the state too. The warabandi system allocated canal water by time rather than volume: each cultivator received a fixed weekly turn, proportional to

holding size, during which the distributary's flow was theirs. The turn could not be traded, could not be banked, and could not be shifted to match the crop's moment of need; it arrived when the roster said it arrived. As a property right, warabandi was precise but rigid: a secure entitlement to a flow at a fixed time, with no market to reallocate it toward higher-value uses. For the wheat-rice rotations of the colony tracts, where canal supplies were reasonably assured, the system worked tolerably. For tail-end farmers, for drought years, and for any crop whose water demand did not respect the roster, it was a constraint. The institutional economist's observation applies with full force: the definition of the water right shaped the pattern of investment. Under warabandi, the marginal return to investing in on-farm water control was capped by the roster; reliability could not be bought at any price.

2.2 Three land reforms and their modest harvest

Independent Pakistan inherited both the canal system and a tenancy problem. At independence, a large share of Punjab's cultivated area was worked by tenants, many of them sharecroppers with insecure, often oral, contracts. Three reform episodes attempted to convert tenants into owners. The 1959 West Pakistan Land Reforms Regulation, promulgated under Ayub Khan, imposed ceilings on holdings and resumed approximately 2.5 million acres across West Pakistan, a fraction of which was redistributed. The 1972 reforms under Zulfikar Ali Bhutto lowered ceilings further and resumed 273,109 acres in Punjab; Pakistan-wide, roughly 0.9 million acres were redistributed among some 76,000 beneficiaries. The 1977 reforms resumed a further 1.8 million acres across Pakistan, though the figures remain provisional and the program was overtaken by political events. Each reform is reported in Table 1 with its geographic coverage labeled explicitly, because the literature has too often quoted Pakistan-wide figures as if they described Punjab.

The honest summary, following Herring (1983), is that South Asia's land reforms redistributed far less land than their rhetoric promised, and Pakistan's were no exception. The resumed acreages were small relative to the cultivated area; exemptions, litigation, and evasion blunted the ceilings; and the beneficiaries, while real people whose lives were changed, numbered in the tens of thousands in a province of millions of cultivators. The reforms mattered politically, signaling the state's stance toward landlordism, but as an instrument for restructuring agrarian property rights, their direct harvest was modest.

2.3 From tenancy to owner-operation

And yet the tenancy question did resolve, largely after the reforms had spent their force. In 1972, 54.6 percent of Punjab's farm area was owner-operated on the all owner-operated definition (39.0 percent on owner-only farms alone). By 2000 the all owner-operated share had reached 77.5 percent; by 2010, 77.41 percent; and by the Agricultural Census of 2024, 82.47 percent (owner-only shares: 69.3, 70.3, and 76.6 percent; Table 7). The transition toward owner-operation is among the most consequential and least theorized facts in Pakistan's agricultural history. On the operated definition, 1972 was not majority tenant-operated: tenant-operated area was 45.4 percent (sharecropped 36.8, leased 7.9, others 0.7 percent). The 'tenancy-dominated' label is therefore accurate only in the narrower sense that 61.0 percent of farm area sat on farms that were not owner-only, including mixed owner-cum-tenant farms. It was driven less by redistribution than by a slow accumulation of forces: the subdivision of large estates through inheritance, the sale of land by absentee owners, the Green Revolution's raising of the returns to direct cultivation, and state policies, from credit to mechanization subsidies, that favored the owner-cultivator. Secure tenure, in turn, reshaped investment incentives in the manner the literature predicts: owner-cultivators invest more in land improvement, soil conservation, and on-farm infrastructure than tenants with insecure contracts (Jacoby & Mansuri, 2009). The property-rights story of Punjab's land is thus not primarily a story of reform; it is a story of a half-

century transition in who holds the residual claim on the soil.

2.4 The groundwater revolution: private pumping against state allocation

The second reconstruction of Punjab's agrarian order concerned water. Beginning in the 1960s, the state's Salinity Control and Reclamation Projects (SCARP) installed public tube-wells to combat waterlogging, inadvertently demonstrating the aquifer's potential. Farmers followed, first slowly, then in a rush: private tube-wells in Punjab numbered 884,228 in 2006-07 and 1,226,885 in 2024-25 (Agricultural Statistics of Pakistan 2024-25, Table 107; Figure 2 and its data table). The institutional significance of this shift is difficult to overstate. Where warabandi had made water timing a state-administered entitlement, the private tube-well made it a function of private capital. A farmer who owned a pump could irrigate when the crop needed water, not when the roster permitted; could expand area under cultivation beyond the canal command; and could sell surplus water to neighbors, giving rise to the informal groundwater markets documented by Razzaq et al. (2022), in which sellers are typically large farmers and buyers smallholders who cannot afford their own wells.

The aggregate numbers trace the displacement. Canal-only irrigation accounted for 53.5 percent of Punjab's irrigated area in 1971-72; by 2020-21 the share had fallen to 20.7 percent, with tube-well-only irrigation rising from 15.3 percent to 20.2 percent, canal-plus-tube-well (conjunctive) irrigation rising from 22.8 percent to 55.6 percent, tube-well-involved irrigation rising from 38.1 percent to 75.8 percent, and canal-involved irrigation (canal-only plus canal-plus-tube-well) unchanged at 76.3 percent in both years (Table 5A). The story is therefore displacement of canal-only irrigation by conjunctive use, not disappearance of canal water. (2020-21 is the last year with published source data; the official publication repeats these values for 2021-22 and 2022-23, marked R, so those years are excluded.)

The state did not plan this transition and did not govern it effectively in practice: as Razzaq et al. (2022) document, there is effectively no enforced limit on groundwater extraction in Pakistan in the period they study. Later legislation (2019 and 2023, see Section 5.2) created a framework and a formal vesting of rights, but this article does not show that framework being enforced., and water tables in the irrigated plains have been falling, raising pumping costs and forcing deficit irrigation. Punjab's water institution thus appears, on the descriptive evidence, to have evolved from a rigid but secure state allocation toward an open-access (in practice, as distinct from the formal legal position after 2023) pattern in which de facto access to water timing follows the ability to drill and pump. That characterisation is interpretation, not a measured property-rights variable (see limitations box). The distributional and sustainability consequences of that evolution are the subject of Section 6.

Table 5A. Irrigated area by source, Punjab, 1971-72 and 2020-21 (thousand hectares and percent of total irrigated area)

Source	1971-72 (thousand hectares)	1971-72 (%)	2020-21 (thousand hectares)	2020-21 (%)
Canal only	4,794	53.5	3,135	20.7
Well only	331	3.7	175	1.2
Tube-well only	1,368	15.3	3,056	20.2
Canal plus well	345	3.8	231	1.5
Canal plus tube-well (conjunctive)	2,046	22.8	8,414	55.6
Other	81	0.9	123	0.8

Total irrigated area	8,965	100.0	15,134	100.0
Canal-involved total, narrow definition (canal only plus canal plus tube-well)	6,840	76.3	11,549	76.3
Canal-involved total, broad definition (canal only plus canal plus well plus canal plus tube-well)	7,185	80.1	11,780	77.8
Tube-well-involved total (tube-well only plus canal plus tube-well)	3,414	38.1	11,470	75.8
Total area sown (for reference, not the denominator)	8,965	[data not available as a share]	17,041	[data not available as a share]
Unirrigated area	[data not available]	[data not available]	1,907	[data not available as a share]

Note. Percentages use total irrigated area as the denominator and are rounded to one decimal place; component percentages may sum to 99.9 or 100.1 after rounding. The headline canal-involved figure of 76.3 percent in both years uses the narrow definition (canal only plus canal plus tube-well) and excludes canal plus well. On the broad definition that includes canal plus well, canal-involved irrigation falls from 80.1 percent to 77.8 percent. Do not quote 76.3 percent without stating which definition is used. For 1971-72 the CSV reports total area sown equal to total irrigated area (8,965 thousand hectares) and contains no unirrigated row, so unirrigated area for 1971-72 is [data not available], not zero. For 2020-21, total area sown is 17,041 thousand hectares, total irrigated area is 15,134 thousand hectares, and unirrigated area is 1,907 thousand hectares. The 2020-21 values are repeated in the official publication for 2021-22 and 2022-23, marked R, and are excluded as separate observations.

3. Data and Methods

3.1 Sources and the source-priority rule

The productivity analysis rests on annual yield series for five crops, wheat, rice, maize, sugarcane, and cotton, covering 73 fiscal years from 1952-53 to 2024-25. The geographic coverage of the underlying crop statistics is Pakistan as a whole, including West Pakistan for the years 1955 to 1970; before 1971, no separate Punjab series exists in the official statistics, and the Pakistan series is used throughout for consistency. The analysis is therefore best read as a study of the Indus basin agrarian economy centered on Punjab, which has consistently accounted for the dominant share of national output of these crops, rather than a strictly provincial series.

Two official sources supply the observations: the State Bank of Pakistan's Handbook of Statistics

on Pakistan Economy and the Pakistan Economic Survey (various years, through 2024-25). Where the two overlap for the same crop-year, vintages occasionally differ. The analysis applies an explicit source-priority rule: the SBP Handbook takes precedence for overlapping crop-years, and the Economic Survey is used only where the Handbook has no observation. This rule was adopted following a critical review of the companion thesis, which noted that the original analysis had stated no priority; it is applied consistently to every series reported here, and each table documents its vintage. The final four observations (2021-22 to 2024-25) come from the Economic Survey, since the Handbook series ends earlier; all five crops yield exactly 73 observations (69 SBP plus 4 Economic Survey).

Cotton requires a unit note. Historical cotton statistics in Pakistan were reported in bales and in maunds per acre; all cotton yields are converted to kilograms per hectare of lint (ginned cotton) at the standard conversion of 170.1 kilograms per bale, correcting the occasional mislabeling of seed cotton in official tables. Sugarcane yields are cane weight per hectare. Tenure and farm-structure figures come from the Agricultural Censuses (1972, 1980, 1990, 2000, 2010, 2024), irrigation figures from the Agricultural Statistics of Pakistan, and tube-well counts from Agricultural Statistics of Pakistan 2024-25, Table 107. Cropping intensity is reported on a net-sown-area basis.

3.2 Statistical methods

Three descriptive-statistical exercises structure the results. First, structural-break testing. For each crop, a Chow test for a break in the linear yield trend is conducted at 1966-67, the conventional dating of the Green Revolution's arrival in Pakistan's Punjab, with 15 pre-break and 58 post-break observations. The test is the standard F-test on the joint restriction that both intercept and slope are stable across the break date. Because yield series are serially correlated, the conventional test is supplemented with a heteroscedasticity- and autocorrelation-consistent Wald test using the Newey-West estimator with a Bartlett kernel and 3 lags. Both statistics are reported for every crop; where they disagree, the disagreement is reported rather than resolved by selection.

Second, area-yield decomposition. For wheat and rice, output growth between the series endpoints is decomposed by the log identity $\ln(Q1/Q0) = \ln(A1/A0) + \ln(Y1/Y0)$, expressing each term as a share of total output growth. The decomposition is an accounting identity, not a causal attribution; it is reported as descriptive evidence on whether long-run output growth was yield-led or area-led.

Third, era growth rates. Compound annual growth rates of yield are computed by the endpoint method for two eras, 1967-68 to 2000-01 and 2000-01 to 2024-25, to document the post-2000 heterogeneity across crops. The endpoint method is sensitive to endpoint conditions; it is used here for comparability with the literature, and the underlying benchmark yields are reported in full.

3.3 Reproducibility and data availability

All figures reported in this article trace to documented official sources under the vintage rule stated above. The computations were implemented in SPSS (native MATRIX routines) and independently replicated; the .sps syntax files accompany the companion thesis. The series, tables, and figure data are available from the author on request; the underlying publications, the SBP Handbook, the Pakistan Economic Survey, and the Agricultural Statistics of Pakistan, are public documents. Where official figures are repeated across years, carried forward, or provisional, the text and table notes disclose the fact. Nothing in the analysis depends on an undisclosed data choice.

4. Results

4.1 Long-run productivity: the yield record

Table 2 reports benchmark yields for the five crops at three dates: 1967-68, the eve of the Green Revolution's diffusion; 2000-01, the hinge of the post-2000 comparison; and 2024-25, the series end. The long view confirms the familiar triumph and complicates it. Wheat yields roughly tripled, from 1,072.7 kg per hectare in 1967-68 to 3,185.0 in 2024-25. Rice yields more than

doubled, from 1,055.6 to 2,494.0. Maize, the quiet performer, rose from 1,302.6 to 5,733.0, most of the gain arriving after 2000. Sugarcane yields nearly doubled, from 37,023.8 to 70,604.0 kg per hectare of cane. Cotton tells a more sensitive story: yields rose from 290.0 kg per hectare (lint) in 1967-68 to 623.5 in 2000-01, then to 717.0 in 2023-24, before falling to a provisional 590.0 in 2024-25. On the provisional endpoint the province harvests less cotton per hectare than it did a quarter century ago; through 2023-24 it harvested more. No conclusion about cotton's long-run direction should rest on the provisional final year alone (see endpoint sensitivity table).

The decomposition in Table 4 sharpens the contrast between the two cereals. For wheat, approximately 64 percent of output growth between 1952-53 and 2023-24 is attributable to yield improvement and 35 percent to area expansion: a yield-led transformation, the Green Revolution in its canonical form. Rice tells a different story. With area expanding roughly 4.3-fold alongside a 2.7-fold yield gain, only about 41 percent of rice output growth came from yield against 59 percent from area: an area-led expansion reflecting rice's spread into newly irrigated tracts. The identity cannot say why wheat intensified while rice extensified, but the institutional account of Section 5 can suggest an answer, and Section 6 takes it up. Figures 4 and 5 display the two cereal series in full. Wheat's trajectory shows the classic break: a shallow pre-1966 trend giving way to a steep, sustained climb that only flattens near the series end. Rice's break is visible but less dramatic, consistent with a crop whose growth came substantially from new area rather than rising yields on existing area. Both series carry the imprint of the 1966-67 discontinuity the tests locate; neither can be read as a smooth technological diffusion curve.

4.2 Structural breaks at 1966-67, with honest qualifications

Table 3 reports the break tests. Under conventional Chow inference, the yield trend breaks at 1966-67 for four of five crops: wheat ($F = 17.99$, $p < 0.001$), rice ($F = 9.44$, $p < 0.001$), maize ($F = 21.19$, $p < 0.001$), and sugarcane ($F = 5.61$, $p = 0.006$). Cotton shows no break under conventional Chow inference ($F = 0.31$, $p = 0.733$). Under HAC-robust inference, cotton is the exception that must be reported, not hidden: the HAC Wald test rejects (chi-square(2) = 13.34, $p = 0.001$). The two results disagree, and the article does not resolve the disagreement by selecting the convenient one. Under HAC-robust inference, the wheat, rice, and maize breaks survive comfortably (all $p < 0.001$). Sugarcane's does not: the HAC-robust p-value is 0.119, meaning the apparent break is sensitive to the error specification and cannot be asserted robustly. It is reported here as qualified, not confirmed. Cotton runs in the opposite direction: conventional inference finds no break, HAC-robust inference rejects, and the HAC result is treated as a small-sample instability, not as proof of a break, for the reasons in Table 3A.

Two features of these results deserve emphasis. First, the inclusion of cotton corrects the earlier literature's practice, repeated in the first version of the companion thesis, of excluding cotton from break testing on the mistaken claim that its usable series began only after 1966. The series in fact contains pre-1966 observations; cotton can be tested, and the conventional test finds no trend break at the Green Revolution date, although the HAC-robust test disagrees (Table 3A). This is not a null result of no interest. It is a useful comparison case: the crop most exposed to the era's institutional and technological changes that did not experience a trend break is the crop whose subsequent trajectory has been the weakest. Second, the sugarcane qualification illustrates the article's evidentiary discipline. A literature that reports only conventional tests would claim five breaks out of five, or four out of five; this article claims three robust breaks, one qualified result, and one conventional non-result with a conflicting HAC result (Table 3A). The strength of the descriptive inference is correspondingly greater for being narrower.

4.3 Crop heterogeneity and the post-2000 slowdown

Table 5 splits the post-break era at 2000-01. The heterogeneity is stark. Wheat yield growth fell from 2.37 percent per year (1967-68 to 2000-01) to 1.32 percent (2000-01 to 2024-25). Rice fell from 1.99 to 0.88 percent. Cotton's growth, 2.35 percent per year in the earlier era, was plus 0.61 percent per year through 2023-24 and minus 0.23 percent per year only when the provisional 2024-25 endpoint is used. Against this pattern, maize accelerated from 0.88 to 5.09 percent per year, and sugarcane from 0.62 to 1.86 percent. Two crops slowed, one (cotton) is endpoint sensitive (see sensitivity table), and two accelerated. No single-technology story fits all five.

Table 5B. Cotton endpoint sensitivity: post-2000 yield CAGR to alternative final years (Pakistan series, lint, kg/ha)

Final year	Yield (kg/ha)	Years from 2000-01	Post-2000 CAGR	Reading
1967-68 (context)	290.0	[data not available]	[data not available as a post-2000 CAGR]	Earlier-era base; CAGR 1967-68 to 2000-01 plus 2.35% (33 years)
2000-01 (base)	623.5	0	[data not available]	Base year
2021-22	731.0	21	plus 0.76%	Positive through 2021-22
2022-23	390.0	22	minus 2.11%	Sharp single-year fall, do not smooth or delete
2023-24	717.0	23	plus 0.61%	Positive through last non-provisional year
2024-25 (provisional)	590.0	24	minus 0.23%	Negative only on provisional endpoint, value currently used in Tables 2 and 5

Note. CAGR is the endpoint compound annual growth rate, (final yield divided by 623.5) to the power (1 divided by years) minus 1, expressed as a percent. The 2022-23 yield of 390.0 kg/ha is far below both neighbouring years (731.0 in 2021-22 and 717.0 in 2023-24) and drives the minus 2.11 percent CAGR to that year. The article therefore reports cotton's post-2000 direction only with its endpoint named, and treats the 2024-25 value as provisional.

Table 5C. Punjab cotton area, 2007-08 to 2024-25 (thousand hectares)

Year	Punjab cotton area (thousand hectares)
2007-08	2,424.8
2008-09	2,223.7
2009-10	2,435.8
2010-11	2,200.6
2011-12	2,533.7
2012-13	2,308.7
2013-14	2,199.0

2014-15	2,323.0
2015-16	2,242.7
2016-17	1,815.3
2017-18	2,052.9
2018-19	1,887.8
2019-20	1,879.7
2020-21	1,546.3
2021-22	1,279.2
2022-23	1,485.2
2023-24	1,680.2
2024-25	1,303.5

Note. Change from 2007-08 (2,424.8 thousand hectares) to 2024-25 (1,303.5 thousand hectares) is minus 46.2 percent. Punjab cotton area before 2007-08 is outside the range of this table and is not shown here; do not extend this table backwards from memory

Table 5D. Pakistan cotton area, 2000-01 to 2023-24 (thousand hectares, SBP-priority vintage)

Year	Pakistan cotton area (thousand hectares)
2000-01	2,928
2001-02	3,116
2002-03	2,794
2003-04	2,989
2004-05	3,193
2005-06	3,103
2006-07	3,075
2007-08	3,054
2008-09	2,820
2009-10	3,106
2010-11	2,835
2011-12	2,879
2012-13	2,879
2013-14	2,806
2014-15	2,961
2015-16	2,902
2016-17	2,489
2017-18	2,700
2018-19	2,373
2019-20	2,517
2020-21	2,079
2021-22	1,937
2022-23	2,144
2023-24	2,424

Note. Change from 2000-01 (2,928 thousand hectares) to 2023-24 (2,424 thousand hectares) is minus 17.2 percent. Duplicate-vintage years: for 2010-11 the SBP value used here is 2,835 thousand hectares (the Economic Survey vintage for the same year is 2,689 thousand hectares and

is not used); for 2011-12 the SBP value used here is 2,879 thousand hectares (the Economic Survey vintage is 2,835 thousand hectares and is not used). All other years in this range agree across the vintages present in the file. Pakistan cotton area for 2024-25 appears in the file only as '2024-25 (P)' (2,043 thousand hectares, provisional) and is therefore not included in this table, whose endpoint is 2023-24.

Table 6 places the crops in the present-day landscape. In Punjab's cropped area in 2021-22, wheat occupied 38.5 percent, rice 15.0 percent, cotton 7.5 percent, maize 6.9 percent, and sugarcane 5.1 percent, with other crops accounting for the remaining 27.0 percent. (An earlier version of the thesis reported wheat at 52.6 percent with other crops at zero, a denominator error corrected here: shares are computed against total cropped area including all crops.) Wheat remains the dominant crop by area, but more than a quarter of the cropped area lies outside the five majors, a reminder that Punjab's agriculture is more diversified than the wheat-rice narrative suggests.

The post-2000 pattern invites, but does not compel, institutional readings, and the article keeps the two carefully apart. Descriptively, the slowdown in wheat and rice coincides with the exhaustion of the easy margins of the Green Revolution package: fertilizer application approaching and in places overshooting agronomic optima, with diminishing marginal response; falling water tables raising pumping costs; and the plateauing of varietal gains. Maize's acceleration coincides with the diffusion of hybrid seed and the growth of feed demand from the poultry industry, a demand-side pull largely absent for the food grains. Sugarcane's acceleration coincides with a political economy of support prices and mill payments that has consistently favored the crop. Cotton's post-2000 pattern cannot be described as yield failure rather than area loss. On the provisional 2024-25 endpoint, yield growth is negative, but Punjab cotton area also fell from 2,424.8 thousand hectares in 2007-08 to 1,303.5 thousand hectares in 2024-25 (minus 46.2 percent; see area table in Section 4.3), and Pakistan cotton area fell from 2,928 thousand hectares in 2000-01 to 2,424 thousand hectares in 2023-24 (minus 17.2 percent). Both yield (on the provisional endpoint) and area moved adversely. Productivity, pest management, seed quality, and water reliability remain candidate constraints, but area loss is part of the pattern, not an alternative ruled out by the evidence. Each of these readings is offered as interpretation, clearly labeled, not as a tested causal claim.

5. Institutional Transformation: Tenure, Water, and Reform

5.1 The quiet revolution in tenure

Table 7 traces both tenure definitions across six agricultural censuses. On the all owner-operated definition the series moves in one direction for fifty years: 54.6 percent in 1972, 64.0 percent in 1980, 72.1 percent in 1990, 77.5 percent in 2000, 77.41 percent in 2010, and 82.47 percent in 2024 (owner-only shares: 39.0, 50.0, 61.0, 69.3, 70.3, and 76.6 percent). Punjab's countryside was remade toward owner-operation within two generations, and the remaking happened largely without the drama of redistribution.

The mechanism deserves more attention than it has received. The land reforms of Table 1 transferred real land to real beneficiaries, but on a scale too small to move the aggregate: tens of thousands of beneficiaries against millions of cultivators, and resumed acreages dwarfed by the cultivated area. What moved the aggregate was the slow chemistry of inheritance subdivision, land sales by absentees and distressed owners, rising returns to direct cultivation as Green Revolution technology raised the profitability of farming one's own land, and a policy environment, from agricultural credit to mechanization support, tilted toward the owner-cultivator. The result is an agrarian structure in which the residual claimant on the soil is, in three cases out of four, the person who works it. The investment literature predicts the consequences: secure, long-horizon tenure encourages spending on soil improvement, land leveling, and on-farm infrastructure such as tube-wells, exactly the investments whose diffusion the

productivity record documents (Jacoby & Mansuri, 2009).

5.2 From warabandi to the pump: the reconstruction of water rights

If the tenure transition was quiet, the water transition was loud but largely ungoverned in practice. The warabandi system had made canal water a state-administered entitlement: secure in its timing, rigid in its allocation, and non-tradable. The private tube-well inverted every one of those properties. Timing became a private choice, allocation followed investment capacity, and water, while not formally tradable in a legal market, was bought and sold through the informal contracts Razzaq et al. (2022) document across Punjab's villages.

The physical record of the transition is unambiguous. Tube-well numbers in Punjab reached approximately 1.23 million by 2024-25. Canal-only irrigation, 53.5 percent of irrigated area in 1971-72, had fallen to 20.7 percent by 2020-21, with the difference absorbed mainly by canal-plus-tube-well (conjunctive) irrigation, which rose from 22.8 percent to 55.6 percent, and by tube-well-only irrigation, which rose from 15.3 percent to 20.2 percent (Table 5A). The 2020-21 values are repeated in the official publication for 2021-22 and 2022-23, marked R, and are not treated here as new observations. Cropping intensity on a net-sown basis reached 158 percent by 2021, a level unattainable under canal supplies alone; the second and often third crop in the annual rotation is, in effect, a tube-well crop. The Green Revolution's yield gains were thus underwritten in large part by a water institution the state neither designed in advance nor effectively regulated in practice. This is the central tension the article presses: the de facto privatisation of irrigation timing through private pumping expanded largely outside effective aquifer governance. That is not the same as saying no legislation existed. The Punjab Water Act 2019 created a licensing framework, and the Punjab Irrigation, Drainage and Rivers Act 2023 formally vested groundwater rights in the government (see legislation note below). Vesting without enforcement is not governance, and this article presents no enforcement data, so the accurate claim is that the transition was largely ungoverned in practice, not that it was wholly without law.

Legislation note (Section 5.2)

Legislation note. Two later statutes qualify any claim that groundwater evolved wholly without legislation. The Punjab Water Act 2019 created a licensing framework for groundwater use. The Punjab Irrigation, Drainage and Rivers Act 2023 formally vested groundwater rights in the government. Neither statute, on its own, demonstrates effective governance. Vesting without enforcement is not governance, and this article presents no data on licensing uptake, metering, pricing enforcement, or penalties. The claim supported by the evidence in this article is therefore narrower: the tube-well transition expanded largely outside effective aquifer governance in practice, during a period when the formal framework was absent and, after 2019 and 2023, when a formal framework existed without demonstrated enforcement.

The distributional consequences follow the logic of the investment. Tube-wells require capital; large farmers drill first and deepest, and the informal water markets that emerged sell timing and reliability to smallholders at prices reflecting the sellers' market power (Razzaq et al., 2022). Razzaq and coauthors, surveying groundwater markets across Punjab's rice-wheat, cotton-wheat, and mixed cropping zones, find flat-rate contracts dominating water-scarce areas and fuel-based contracts where large farmers prevail, with buyers' bargaining power shaped by landholding and contractual history. The market fills the gap warabandi left, but on terms set by those who own the pumps. The sustainability consequences are now visible in falling water tables, rising pumping costs, and the energy burden of irrigation, documented across the Indus basin (Sajid et al., 2022). A warabandi turn, for all its rigidity, was at least a bounded claim on a managed system; a private pump is an unbounded claim on a depleting stock.

5.3 Land reforms: what they did and did not do

Table 1 assembles the three reform episodes with explicit coverage labels, a precaution against the literature's habit of quoting national figures as provincial facts. The 1959 regulation operated West Pakistan-wide and resumed on the order of 2.5 million acres. The 1972 reforms resumed 273,109 acres in Punjab specifically, while Pakistan-wide redistribution reached roughly 0.9 million acres among about 76,000 beneficiaries. The 1977 reforms resumed some 1.8 million acres across Pakistan, with figures that remain provisional. Set against a cultivated area measured in the tens of millions of acres, these are modest magnitudes, and the thesis's correction log records them as such.

The reforms' limited direct effect does not make them historically unimportant. They established the state's formal commitment to the owner-cultivator ideal, created a class of beneficiaries with secure titles, and, through the political threat they posed to large landlords, may have accelerated voluntary land sales that fed the tenure transition of Table 7. But the article's reading is that Punjab's property-rights transformation was driven more by the water transition and the market-mediated tenure transition than by the statutes. Reformers wrote the laws; tube-well owners and land markets wrote the outcome.

6. Discussion

6.1 What is new here

Three features distinguish this account from standard Green Revolution histories of Punjab. First, the water-rights contrast. Conventional histories treat irrigation as an input, tube-wells as a technology, and rising water use as a quantity. This article treats the shift from warabandi to private pumping as a change in the institution governing the single most binding input in the system: from a rigid, secure, state-administered entitlement to an open-access regime in which timing and reliability are functions of private capital. That reframing offers an interpretation of facts the input view leaves unexplained: why productivity gains appear unevenly distributed across farm sizes, why tail-end canal farmers appear to have gained less than well owners, and why the sustainability crisis is consistent with a property-rights account. None of those three links is estimated in this article., the predictable consequence of unbounded private claims on a common-pool aquifer.

Second, the tenure transition as the other half of the property-rights story. The literature on Pakistan's land reforms, following Herring (1983), correctly judges them by their redistributive shortfall. This article adds the subsequent half century: all owner-operated area rose from 54.6 to 82.47 percent of farm area through mechanisms the reforms barely touched (owner-only area rose from 39.0 to 76.6 percent). Punjab today is a countryside of owner-cultivators to a degree the reformers dreamed of but did not engineer. Any account of investment, intensification, and the post-2000 slowdown that ignores this transition mistakes the institutional setting.

Third, the heterogeneity itself as evidence. The five crops did not experience one Green Revolution; they experienced five different institutional bargains. Wheat combined a robust trend break, yield-led growth, support prices, and procurement, then slowed as the package's margins narrowed. Rice broke robustly but grew by area, spreading into new irrigated tracts. Maize showed the strongest break of all (F = 21.19) and then accelerated after 2000 on hybrid seed and feed demand. Sugarcane's break is statistically fragile, and its post-2000 acceleration tracks the political economy of cane pricing. Cotton, the comparison case, shows no trend break under conventional inference (with a conflicting HAC result, Table 3A) and endpoint-sensitive recent yield growth (plus 0.61 percent per year through 2023-24, minus 0.23 percent per year through provisional 2024-25; see Section 4.3 and the endpoint sensitivity table), making cotton the crop whose measured trajectory was weakest in the post-2000 period on the provisional endpoint (see endpoint sensitivity table). The institutional reading that follows is interpretation, not a tested causal claim. The question the article posed, why heterogeneous trajectories, thus receives an institutional interpretation, not an institutional

proof: irrigation access, investment capacity, and policy incentives differed across crops, and the differences are consistent with compounding over decades. The article does not estimate those effects.

6.2 Engagement with Banerjee and Iyer

Banerjee and Iyer (2005) demonstrate that India's non-landlord settlements outperformed landlord settlements in agricultural investment and productivity after independence, attributing the difference to the institutional legacy of colonial tenure. Punjab's canal colonies belong, in their taxonomy, firmly on the non-landlord side: peasant grants held directly from the state, without an intermediary landlord class. The subsequent history is broadly consistent with their mechanism. A countryside of small proprietors with secure, state-recognized titles proved fertile ground for the investment-intensive agriculture of the Green Revolution era: tube-wells, tractors, fertilizer, and land improvement all diffused faster where the cultivator held the residual claim. The colony settlement also prefigured the article's central contrast: the state that granted the land kept the water, administering it through warabandi long after it had surrendered direct control of cultivation. Punjab thus inherited a split property-rights regime, private in land and public in water, whose two halves then evolved on separate tracks, one toward owner-operation, the other toward unregulated private pumping. The article does not test this proposition causally; the data cannot support a district-level identification of the kind Banerjee and Iyer execute. But as an interpretive frame, it situates Punjab's experience within the comparative political economy of colonial institutions rather than leaving it as a sui generis success story. The counterpoint also runs in the other direction: where the colonial state retained the landlord's role, in canal water through warabandi, the subsequent institutional evolution, the largely unregulated expansion of private pumping is consistent with the governance problem the article describes, subject to the legislation qualification in Section 5.2 and the limitations box.

6.3 Limits

The limits of the analysis are stated plainly. The evidence is descriptive: Chow tests locate breaks, decompositions partition growth, and growth rates document heterogeneity, but none of this identifies causal effects of institutions on productivity. The institutional readings are reasoned interpretations, and the text marks them as such. The yield series splices Pakistan and West Pakistan coverages, and while the SBP-priority vintage rule disciplines the splice, pre-1971 observations describe a larger geography than post-1971 ones. The irrigation values labelled 2022-23 in the official source repeat the 2020-21 values and are disclosed as carried forward; this article therefore uses 2020-21 as the irrigation endpoint wherever an observed year is stated, and the two places that previously said 2022-23 (abstract and Section 5.2) are corrected to 2020-21. Cotton's historical yields required unit conversions across bales, maunds, and kilograms that introduce measurement error, though the post-1966 series is consistent. The decomposition is an accounting identity and cannot apportion growth among its economic causes. Finally, the article's institutional episodes, canal colonization, the reform decades, the tube-well boom, are identified narratively rather than estimated; a fuller cliometric treatment would require district-level panel data that the official statistics, in their present state, do not reliably provide. The narrative identification is nevertheless disciplined by the numbers: the episodes are dated by the break tests, the tenure transition is measured across six censuses, and the water transition is quantified in both tube-well counts and irrigated-area shares. What the article cannot do is attach standard errors to the institutional claims; it can only show that the measured facts are consistent with the institutional reading and, in the case of the crop heterogeneity, difficult to square with the main alternative.

Limitations box. What this article does not test

Box. What this article does not test. First, no institutional variable is tested in this article. The analysis contains no estimated variable for

warabandi timing or allocation, no series for groundwater depth or extraction, no variable for land reform exposure or beneficiary status, no variable for tenancy contract type, and no variable for support prices, procurement, seed variety adoption, pest incidence, or seed quality entered in any regression or test. Statements about those factors in Sections 5 and 6 are interpretations of descriptive patterns, not estimates. Second, the yield series is not Punjab-specific. It is a Pakistan series spliced with West Pakistan coverage for 1955 to 1970, used because no separate Punjab series exists in the official statistics for the early years (Section 3.1). Results therefore describe the Indus basin agrarian economy centred on Punjab, not a strictly provincial series, and district-level or Punjab-only institutional effects cannot be inferred from it. Third, the area-yield decomposition for wheat and rice is an accounting identity (Table 4). It partitions output growth into area and yield components. It does not apportion yield growth itself among seeds, water, tenure, prices, or any other cause, and no cotton decomposition is presented in this article. Fourth, technology versus institutions cannot be apportioned from this design. Chow break tests locate the timing of a trend change, compound growth rates describe change over eras, and the institutional narrative orders those facts historically. None of those steps identifies how much of any yield change was caused by seeds, by water institutions, by land institutions, or by prices. Any sentence in this article that sounds as if it apportions that total should be read subject to this box. Fifth, the institutional episodes are identified narratively and dated by break tests and census years. They are not estimated from district-level panel data, which the official statistics in their present state do not reliably provide. A fuller cliometric treatment would require that panel data, plus measured institutional variables of the kind listed above.

6.4 Implications

Three implications follow for policy and for scholarship. First, Punjab's next productivity chapter must be written in efficiency: more grain per liter of water, per kilogram of nitrogen, per unit of energy. Area expansion is exhausted, cropping intensity already stands at 158 percent, and the yield growth of the staple cereals is slowing. The binding constraints are now resource governance, varietal renewal, and input efficiency, not the extensive margin. Second, groundwater governance can no longer be deferred. The de facto privatization of irrigation timing has delivered enormous gains and is now delivering depletion; the institutional agenda is to bound the private claim, through metering, pricing, or community management, before the aquifer's decline forecloses the gains. Third, cotton's revival, if it is to come, must target both productivity and area: productivity, pest management, seed quality, and water reliability, and the retention or recovery of cotton area, which fell by 46.2 percent in Punjab between 2007-08 and 2024-25. No decomposition in this article shows that cotton's problem is yield failure alone, because the article's decomposition (Table 4) covers wheat and rice only and is an accounting identity, not a causal attribution. The break-test point must also be qualified: cotton shows no break under conventional inference, with a conflicting HAC result (Table 3A). For scholarship, the article's wager is that agricultural development is best studied as institutional history with numbers: the numbers discipline the narrative, and the narrative gives the numbers their meaning.

7. Conclusion

Punjab's agricultural transformation is best read, on the descriptive evidence presented here, alongside two reconstructions of property rights, with the causal weight of those reconstructions left unestimated. The first concerned land: a countryside in which tenancy was extensive became, over fifty years and largely outside the land reforms, a countryside of owner-cultivators, with the all owner-operated share rising from 54.6 percent in 1972 to 82.47 percent in 2024 (owner-only share: 39.0 to 76.6 percent). The second concerned water: the state's rigid warabandi allocation was displaced by roughly 1.23 million private tube-wells, converting

irrigation timing from a public entitlement into a function of private investment and leaving the aquifer, in practice, as a largely ungoverned common pool, notwithstanding the later legislation noted in Section 5.2. On the productivity record, the Green Revolution's arrival registers as a robust structural break in the yield trend at 1966-67 for wheat, rice, and maize; sugarcane's apparent break does not survive autocorrelation-robust inference; and cotton, the comparison case, shows no break under conventional inference, with a conflicting HAC result disclosed in Section 4.2. Wheat's long-run growth was yield-led (about 64 percent of output growth from yield), rice's was area-led (about 59 percent from area), and after 2000 the crops diverged sharply: wheat and rice slowed, cotton was endpoint sensitive (plus 0.61 percent per year through 2023-24, minus 0.23 percent per year through provisional 2024-25), while maize and sugarcane accelerated. The article has advanced these findings as measured facts and the institutional account as interpretation, keeping the two distinct. What Punjab's experience suggests that Green Revolution histories underplay is that the definition of rights, to water timing and to the soil's residual, may have shaped the productivity path alongside the seeds. How decisively, relative to seeds, cannot be determined from this design, and that the next chapter of growth will be decided not in the laboratory but in the governance of the aquifer and the efficiency of the farm.

Tables

Table 1. Land reforms affecting Punjab: scale and geographic coverage

Reform	Coverage	Scale	Note
1959 West Pakistan Land Reforms Regulation	West Pakistan-wide	~2.5 million acres resumed	Ceilings on holdings; limited redistribution
1972 land reforms	Punjab: 273,109 acres resumed; Pakistan-wide: ~0.9 million acres redistributed	~76,000 beneficiaries (Pakistan-wide)	Lowered ceilings; resumed acreage is Punjab-specific, redistribution Pakistan-wide
1977 land reforms	Pakistan-wide	~1.8 million acres resumed	Figures provisional; program overtaken by political events

Note. Coverage labels are explicit because the literature often quotes Pakistan-wide figures as provincial facts. Sources: official reform notifications and secondary compilations; see Herring (1983) for the comparative context.

Table 2. Yield benchmarks by crop, Pakistan series, 1967-68 to 2024-25 (kg per hectare)

Crop	1967-68	2000-01	2024-25
Wheat	1,072.7	2,325.4	3,185.0
Rice	1,055.6	2,020.6	2,494.0
Maize	1,302.6	1,740.5	5,733.0
Sugarcane	37,023.8	45,375.7	70,604.0
Cotton (lint)	290.0	623.5	590.0 (provisional)

Note. SBP Handbook of Statistics on Pakistan Economy (priority vintage); Pakistan Economic Survey 2024-25 for 2021-22 to 2024-25. Cotton in lint weight (ginned cotton), converted at 170.1

kg per bale. Sugarcane in cane weight. Coverage: Pakistan, including West Pakistan 1955-1970. Cotton 2024-25 (590.0) is provisional; cotton 2023-24 was 717.0. See the endpoint sensitivity table in Section 4.3.

Table 3. Chow tests for a structural break in the linear yield trend at 1966-67 (15 pre-break, 58 post-break observations)

Crop	Chow F (2, 69)	Conventional p	HAC-robust p (Newey-West, 3 lags)	Finding
Wheat	17.99	< 0.001	< 0.001	Break confirmed (robust)
Rice	9.44	< 0.001	< 0.001	Break confirmed (robust)
Maize	21.19	< 0.001	< 0.001	Break confirmed (robust)
Sugarcane	5.61	0.006	0.119	Break not robust to HAC; qualified
Cotton	0.31	0.733	0.001	No break under conventional test; HAC result sensitive to error specification

Note. HAC-robust inference uses the Newey-West estimator with Bartlett kernel and 3 lags. For cotton the two specifications disagree: the conventional test does not support a 1966-67 trend break (p = 0.733), while the HAC-robust test rejects (p = 0.001). The article does not claim a cotton break on the HAC result alone, because the HAC estimate rests on only 15 pre-break observations and on the residual variance pattern in Table 3A. Cotton's inclusion corrects the earlier claim that it could not be tested.

Table 3A. Cotton break test at 1966-67: why the conventional and HAC-robust results disagree

Item	Value
Pre-break observations	15 (1952-53 to 1966-67)
Post-break observations	58 (1967-68 to 2024-25)
Total observations	73
Conventional Chow test	F(2, 69) = 0.31, p = 0.733 (exact: F = 0.3121, p = 0.732907)
HAC-robust Wald test (Newey-West, Bartlett kernel, 3 lags, no small-sample correction)	Chi-square(2) = 13.3389, p = 0.001269 (article rounding: p = 0.001)
Pre-break residual sum of squares, unrestricted segmented trend	3,813.02
Post-break residual sum of squares	599,586.80
Total unrestricted residual sum of squares	603,399.82
Restricted residual sum of squares	608,859.11
Pre-break residual variance, SSR/(n minus 2)	293.31 (residual standard deviation 17.13 kg/ha)
Post-break residual variance	10,706.91 (residual standard deviation 103.47 kg/ha)

Post-break to pre-break residual variance ratio	36.5
Pre-break slope minus post-break slope	Minus 4.44 kg/ha per year
Standard error of that slope contrast, OLS	5.64
Standard error of that slope contrast, HAC	1.72

Note. The HAC standard error for the pre-break slope contrast (1.72) is far smaller than the OLS standard error (5.64), so the HAC test rejects while the conventional test does not. With only 15 pre-break observations and a post-break residual variance about 36.5 times the pre-break variance, the HAC long-run variance estimate is unstable in this small pre-break sample. The honest reporting is therefore: no break under conventional inference, a conflicting HAC result that is disclosed, and no claim of a cotton break on either result alone. Source: author's calculations from the 73-observation cotton series; HAC values as verified in data_verification.md, Section 6, and data_verification.json, task6.

Table 4. Area-yield decomposition of output growth, 1952-53 to 2023-24 (log decomposition)

Crop	Yield contribution (%)	Area contribution (%)	Reading
Wheat	63.8	36.2	Yield-led transformation
Rice	40.7	59.3	Area-led expansion

Note. ln(Q1/Q0) = ln(A1/A0) + ln(Y1/Y0); shares are each term as a percentage of total output growth. SBP vintage (SBP Handbook priority; final Pakistan wheat year in the source file is 2023-24). Rice figures from the companion thesis Table 6.3, same dataset and vintage rule; rice area expanded roughly 4.3-fold against a 2.7-fold yield gain. The decomposition is an accounting identity, not a causal attribution.

Table 5. Post-2000 heterogeneity: compound annual growth rates of yield by era (percent per year)

Crop	Yield 1967-68 (kg/ha)	Yield 2000-01 (kg/ha)	Yield 2024-25 (kg/ha)	CAGR 1967-68 to 2000-01	CAGR 2000-01 to 2024-25	Direction
Wheat	1,072.7	2,325.4	3,185.0	2.37	1.32	Slowed
Rice	1,055.6	2,020.6	2,494.0	1.99	0.88	Slowed
Maize	1,302.6	1,740.5	5,733.0	0.88	5.09	Accelerated
Sugarcane	37,023.8	45,375.7	70,604.0	0.62	1.86	Accelerated
Cotton	290.0	623.5	590.0 (provisional)	2.35	-0.23	Endpoint sensitive (see note)

Note. Endpoint CAGR on the 73-observation series: 1967-68 to 2000-01 (33 years), 2000-01 to 2024-25 (24 years). Source: author's calculations from Table 2 series. The 2024-25 endpoint is provisional, and cotton is endpoint sensitive: cotton CAGR from 2000-01 is plus 0.76 percent per year to 2021-22, minus 2.11 percent per year to 2022-23, plus 0.61 percent per year to 2023-24, and minus 0.23 percent per year to provisional 2024-25 (see endpoint sensitivity table in Section 4.3). The sign of cotton's post-2000 growth therefore depends on which final year is chosen, and must not be stated without naming the endpoint.

Table 6. Cropping pattern in Punjab, 2021-22 (share of total cropped area)

Crop	Share (%)
Wheat	38.5
Rice	15.0
Cotton	7.5
Maize	6.9
Sugarcane	5.1
Other crops	27.0

Note. Shares computed against total cropped area of 17,058 thousand hectares (all crops); the five-crop sum is 12,449 thousand hectares, leaving other crops at 4,609 thousand hectares (27.0 percent). Source: crop area statistics, Punjab 2021-22.

Table 7. Tenure evolution, Punjab, 1972-2024: owner-only share and all owner-operated share (percent of farm area)

Census year	Owner-only share (%)	All owner-operated share (%)	Basis
1972	39.0	54.6	ILO InFocus WP25 (2004), Appendix Tables 5-6, citing the censuses (secondary tabulation)
1980	50.0	64.0	same ILO secondary tabulation
1990	61.0	72.1	same ILO secondary tabulation
2000	69.3	77.5	owner-only computed from tenure areas, all owner-operated from ILO operated-area percent
2010	70.3	77.41	owner-only computed from census acres, all owner-operated computed from operated areas (see Table 7A)
2024	76.6	82.47	owner-only computed from census acres, all owner-operated computed from operated areas (see Table 7A)

Note. Two definitions are shown and must not be confused. Owner-only share is farm area on owner-only farms as a share of total farm area. All owner-operated share is owned area on owner-only plus owner-cum-tenant farms as a share of total farm area (in census terms, operated area classified as owner-operated). The early years (1972, 1980, 1990) rest on the secondary ILO

tabulation cited in the Basis column; primary census definitions for those years should be checked before journal submission. The 2000 owner-only share is computed as 7,789.8 of 11,235.2 thousand hectares (69.33 percent, shown as 69.3); the ILO tabulation reports 69 percent. The 2010 and 2024 shares are computed from the acre figures in Table 7A. Sources: farm_structure.csv indicators tenure_area_pct, operated_area_pct, tenure_area, and operated_area; Agricultural Censuses of Pakistan, Punjab tables; ILO InFocus WP25 (2004) for the early-year percentages.

Table 7A. Tenure accounting in acres: owner-only, owner-cum-tenant, and tenant area

Item	2024 (acres)	2010 (acres)	How obtained
Area on owner-only farms	23,789,796	20,602,398	direct census row, tenure_area, category owner
Total area on owner-cum-tenant farms	4,867,664	5,368,440	direct census row, tenure_area, category owner_cum_tenant
Owned portion on owner-cum-tenant farms	1,808,903	2,098,333	derived residual: all owner-operated area minus area on owner-only farms, not a separate published row
Rented portion on owner-cum-tenant farms	3,058,761	3,270,107	derived residual: total owner-cum-tenant area minus owned portion
All owner-operated area	25,598,699	22,700,731	direct census row, operated_area, category owner_operated, equals owner-only area plus owned portion on owner-cum-tenant farms
Area on tenant-only farms	2,382,512	3,355,608	direct census row, tenure_area, category tenant
Tenant-operated area	5,441,273	6,625,705	direct census row, operated_area, category tenant_operated
Total farm area	31,039,972	29,326,436 (operated total); 29,326,446 (tenure total)	sum of tenure rows and sum of operated rows, see 10-acre note
Owner-only share (%)	76.64	70.25	owner-only area divided by total farm area, shown as 76.6 and 70.3 in Table 7
All owner-operated share (%)	82.47	77.41	all owner-operated area divided by operated total

Note. For 2024 the tenure total and the operated total agree exactly (31,039,972 acres), so the derived owned and rented portions on owner-cum-tenant farms reconcile exactly. For 2010 they do not agree by 10 acres: the tenure rows sum to 29,326,446 acres while the operated rows sum to 29,326,436 acres, so the tenure-implied tenant-operated area (6,625,715 acres) exceeds the published operated tenant-operated area (6,625,705 acres) by 10 acres. That 10-acre difference is retained in this note and is not forced to balance. For 1972, 1980, and 1990, absolute acre figures for these items are [data not available] in farm_structure.csv; only the percentage shares in Table 7 are available for those years.

Figures

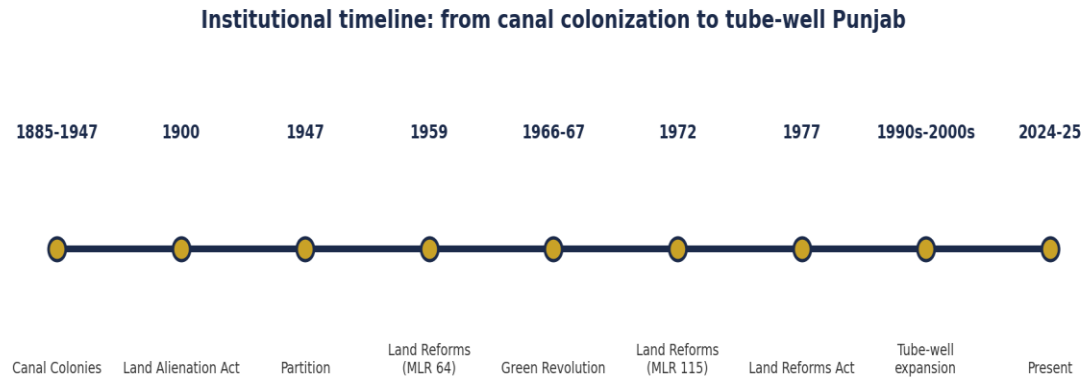


Figure 1. Institutional timeline: from canal colonization to tube-well Punjab. ()

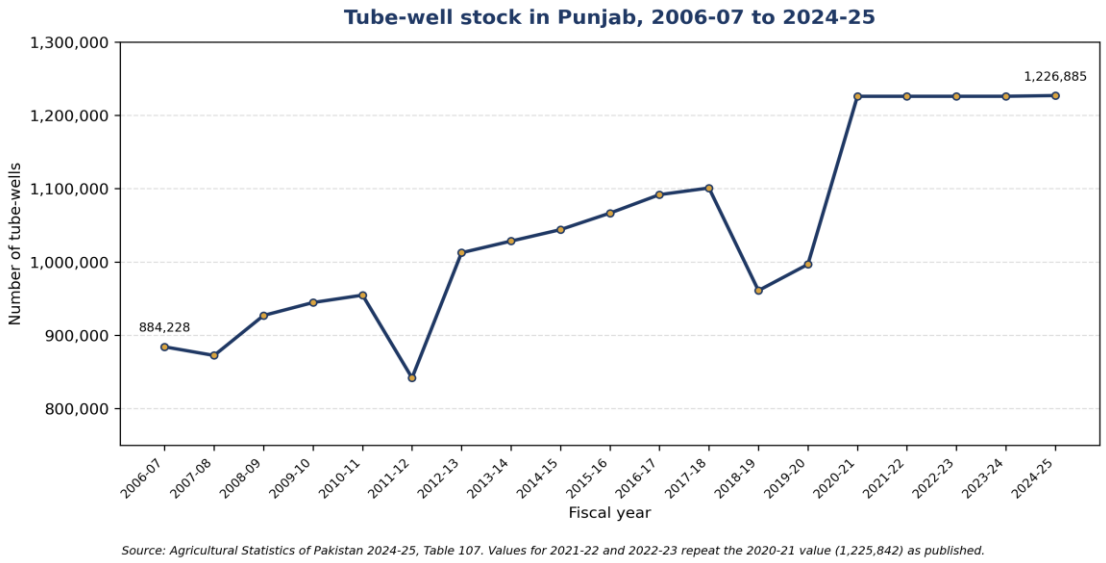


Figure 2. The groundwater revolution: tube-well stock in Punjab, 2006-07 to 2024-25. Source: Agricultural Statistics of Pakistan 2024-25, Table 107. Data table under the figure.

Figure 2 data. Tube-well stock in Punjab, 2006-07 to 2024-25 (number)

Year	Tube-well stock (number)
2006-07	884,228
2007-08	872,444
2008-09	927,006
2009-10	944,649
2010-11	954,706
2011-12	841,819
2012-13	1,012,541
2013-14	1,028,424
2014-15	1,044,044
2015-16	1,066,600
2016-17	1,091,734
2017-18	1,100,841
2018-19	960,967
2019-20	996,739
2020-21	1,225,842
2021-22	1,225,842
2022-23	1,225,842
2023-24	1,225,870
2024-25	1,226,885

Note. Annual stock series only, 2006-07 to 2024-25. The values for 2021-22 and 2022-23 repeat the 2020-21 value of 1,225,842, the same repeated-source pattern disclosed for irrigation in Section 2.4; they are shown as published and are not independent observations. No stock value for 2005-06 is available in this source, so the series starts at 2006-07 and no value is interpolated. The 2004 Machinery Census stock benchmark (837,904, stock in use) is not part of this annual fiscal series and, if shown at all, must be plotted as a separate benchmark point with a break in the line, not as an annual observation.

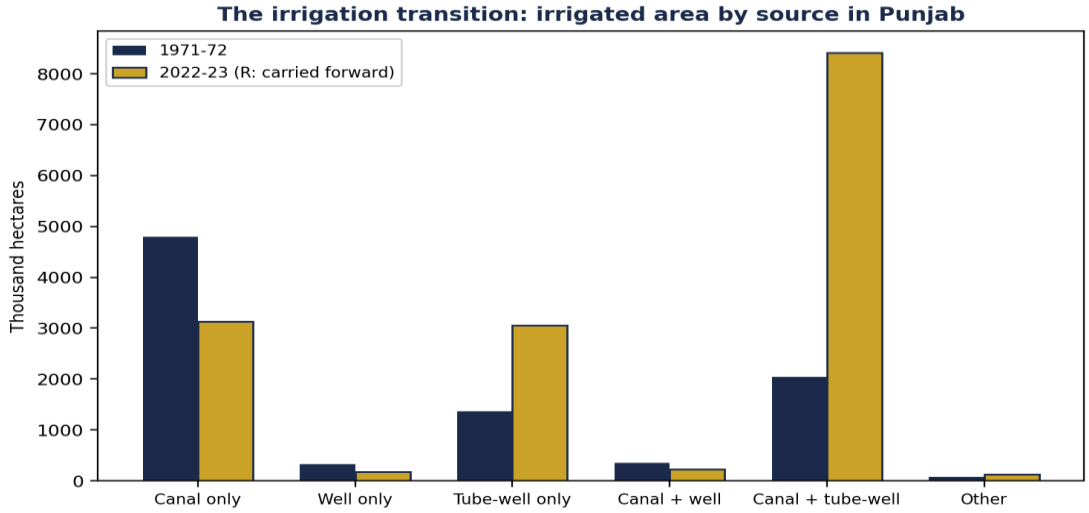


Figure 3. The irrigation transition: irrigated area by source in Punjab, 1971-72 versus 2020-21. ()

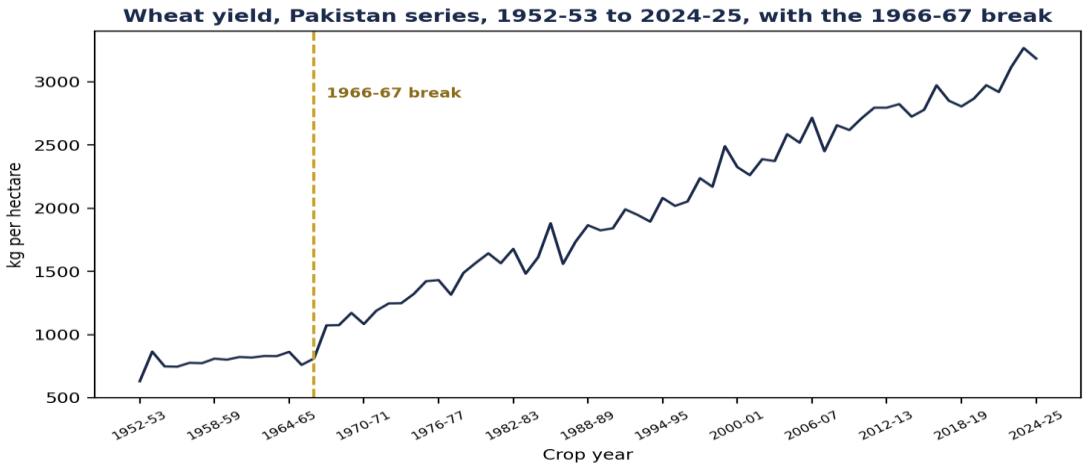


Figure 4. Wheat yield, Pakistan series, 1952-53 to 2024-25, with the 1966-67 break. ()

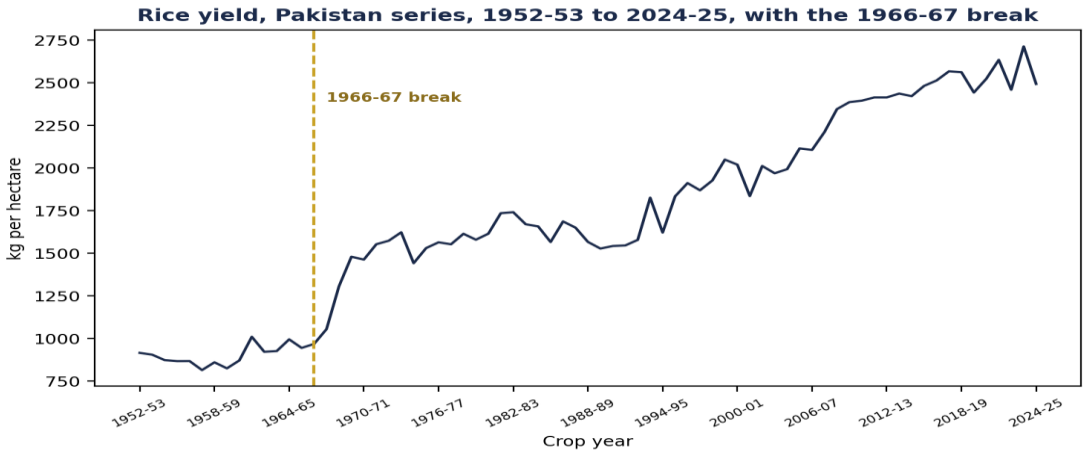


Figure 5. Rice yield, Pakistan series, 1952-53 to 2024-25, with the 1966-67 break. ()

Note on figures: Figure 3 uses 2020-21 as the endpoint, the last year with published source data (the official publication repeats these values for 2021-22 and 2022-23, marked R).

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