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National wheat intensification and rapid scaling of a registered dry-seed conditioning programme in Uzbekistan

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Abstract

Low-cost seed innovations can help resource-constrained farming systems translate knowledge into field performance. We analysed 1,953 wheat records from 13 regions of Uzbekistan during 2016–2026 and 260 field-monitoring records from 154 districts in 2026. Cultivated area declined by 16.4%, while area-weighted yield increased by 73.4% and production by 45.0%. A registered dry-seed conditioning programme expanded from 973 ha in 2025 to 685,065 ha in 2026. Across 2026 specifications, the programme-associated yield difference ranged from 0.78 to 0.94 t ha − 1; the exact-matched estimate was 0.90 t ha − 1 (95% confidence interval, 0.78–1.02). In 106 mixed-adoption districts, programme fields reached 75% emergence 2.59 days earlier, recorded 39.1% higher early stand density and reached full maturity 3.64 days earlier. National harvest records and independent field monitoring support a scalable intensification pathway for arid farming systems.

Introduction

Wheat is central to global food security, and productivity growth is especially important in arid irrigated systems exposed to heat, water limitation and land constraints [1–3]. National yield records characterise realised production trajectories across heterogeneous farms [4–6], although aggregate series alone do not identify site-specific yield potential, yield gaps or causal effects. When combined with matched comparisons and independently collected field monitoring, such records can assess whether agronomic innovations retain practical value beyond controlled experimental conditions. Yield gains observed under researcher-managed conditions may not translate directly to routine farming, where operational demands interact with resources, technical knowledge, infrastructure and farmer decisions [7, 8]. Evidence from routine farming therefore complements experimental efficacy by characterising ecosystem-specific operational performance.

Integrated agronomy can increase realised wheat yield by aligning cultivar choice, crop establishment, nutrient and water management and timely field operations [9, 10]. Improved management can also reduce production carbon footprints [11], while digital systems can strengthen programme delivery and measurement [12]. In resource-constrained farming systems, practical innovation often depends on adapting established methods into low-cost, operationally simple practices whose benefits can be observed directly by farmers. Uzbekistan combined coordinated wheat management and farmer-support reforms with a dry-seed cold-conditioning programme piloted in 2025 and expanded nationally in 2026. The registered regulation uses the operational term ‘vernalization’; here we describe the specified physical exposure as dry-seed cold conditioning.

The longevity and field performance of dry seed depend on initial seed quality, moisture, storage temperature and duration. Seed vigour governs the speed and uniformity of crop establishment, and storage conditions influence how long this performance is retained [13, 14]. Wheat studies show that dry-storage dormancy and germination responses depend on seed moisture, genotype and physiological age [15–17]. Genetic control of wheat dormancy and germination is supported by studies of PM19, MFT

and MKK genes [18–20], whereas hydrated cold stratification represents a distinct low-temperature treatment [21]. Genetic, hormonal, metabolic and epigenetic regulation of seed state is also well established [18–24]. The Uzbekistan programme originated within a broader epigenetically informed agricultural framework, but the present study evaluates the operational programme package rather than a specific molecular mechanism. DNA methylation, chromatin state, regulatory RNA and other molecular-level impacts were outside its scope.

We integrated 11 years of national wheat records with matched variety-by-region comparisons and district field monitoring. We asked whether rapid programme scaling coincided with national intensification, whether the same varieties grown within the same regions showed consistent yield differences, and whether field establishment and phenology formed a coherent agronomic pathway. This multiscale design evaluates performance under routine commercial farming and its relevance to climate-exposed wheat systems in Central Asia and the wider Global South.

Results

National intensification with declining cultivated area

The national dataset comprised 1,953 variety-by-region observations from 13 regions, 40 named varieties and 11 completed harvest seasons. It provides a continuous nationwide view of wheat area, productivity, varietal deployment and seed-treatment uptake. Annual coverage and regional yield trajectories are shown in Fig. 1 and Supplementary Fig. S1.

National wheat area declined from 1,132,630 ha in 2016 to 947,110 ha in 2026 (− 16.4%). Over the same interval, area-weighted yield increased from 5.641 to 9.781 t ha − 1 (+ 73.4%), and derived production increased from 6.389 to 9.264 million tonnes (+ 45.0%) (Fig. 1 and Table 1). Symmetric decomposition assigned + 4.305 million tonnes to improved yield and − 1.431 million tonnes to area contraction, showing that productivity growth more than compensated for the smaller cultivated area.

Table 1
National wheat area, area-weighted yield and derived production, 2016–2026.

Year	Reported observations	Area (ha)	Yield (t ha − 1)	Derived production (t)
2016	168	1,132,630	5.641	6,388,996
2017	178	1,122,630	5.866	6,584,886
2018	184	1,107,130	5.531	6,123,969
2019	174	1,091,630	6.530	7,127,988
2020	177	1,077,569	5.755	6,201,559
2021	154	1,038,104	6.412	6,656,571
2022	149	1,030,464	6.981	7,193,313
2023	165	1,010,833	7.047	7,123,584
2024	191	1,012,776	8.512	8,620,464
2025	165	996,900	8.436	8,410,345
2026	248	947,110	9.781	9,263,777

Notes: Yield is weighted by cultivated area. Production was calculated as the sum of record-level area × yield and rounded to the nearest tonne for display; analyses used the unrounded values in Data File 1.

Across 2016–2024, national yield increased by 0.297 t ha − 1 yr − 1 (R^2 = 0.733); the Theil–Sen slope was 0.295 t ha − 1 yr − 1 (95% confidence interval, 0.129–0.497). The 2026 yield was 1.525 t ha − 1 above the pre-implementation point forecast of 8.256 t ha − 1 and only 0.098 t ha − 1 below the upper 95% prediction limit, placing it near the upper boundary of the range expected from the 2016–2024 trajectory (Supplementary Table S1). The 2023–2024 increase of 1.464 t ha − 1 was the largest annual rise in the series, whereas yield declined by 0.075 t ha − 1 in 2025. The sequence therefore shows a strong upward national trajectory with meaningful seasonal variation; continued monitoring will determine whether the 2026 performance persists in upcoming seasons.

Regional yields also changed over time (Friedman χ^2 = 110.60, 10 d.f., P = 4.04 × 10 − 19). All 13 regions had higher area-weighted yield in 2026 than in 2016; the mean paired increase was 4.254 t ha − 1, and the exact Wilcoxon signed-rank P value was 0.00024. Region-specific ordinary least-squares and Theil–Sen slopes are reported in Supplementary Table S2.

Scale-up and treatment-associated yield differences

The programme covered 973 ha in the 2025 pilot (0.10% of national wheat area) and 685,065 ha in 2026 (72.3%). The registered exposure comprised prepared, treated and packaged seed at controlled moisture together with refrigerated storage; estimates therefore apply to this programme package, not to storage

temperature alone. National treatment-specific area-weighted yields in 2026 were 9.997 t ha − 1 for programme records and 9.218 t ha − 1 for traditionally stored records (Supplementary Table S3).

In a record-level restricted maximum-likelihood mixed model, harvest year was associated with yield (Wald χ^2 = 396.62, 10 d.f., P = 4.92 × 10 − 79). After adjustment for harvest year and variety class, programme records averaged 0.762 t ha − 1 higher than traditionally stored records (95% confidence interval, 0.675–0.849). Location-by-year environment accounted for 79.6% of the estimated random-plus-residual variance, named variety for 1.7% and residual variation for 18.7%. A 2026-only refit with location and variety random intercepts estimated 0.857 t ha − 1 (0.782–0.933). An area-precision sensitivity model, which allowed larger aggregated records to contribute greater precision, estimated 0.908 t ha − 1 (0.850–0.965) (Supplementary Table S4).

The primary paired analysis compared programme and traditionally stored records for the same harvest year, named variety, variety class and region. Exact matching retained 92 paired variety-by-region combinations from ten regions, representing 446,746 ha of programme wheat, or 65.2% of the national programme area (Supplementary Table S5d). Every matched yield difference was positive (Fig. 2). The unweighted mean difference was 0.90 t ha − 1 (region-cluster bootstrap 95% confidence interval, 0.78–1.02), and the programme-area-weighted difference was 0.94 t ha − 1 (0.81–1.05) (Table 2 and Supplementary Table S5a). Cluster-robust t intervals were 0.76–1.04 and 0.79–1.09 t ha − 1, respectively. Exact enumeration of all 1,024 Rademacher sign patterns gave two-sided wild-cluster bootstrap-t P = 0.002 for both estimands, the minimum attainable two-sided value under exact enumeration with ten clusters. Across analytical approaches differing in covariate adjustment, exact matching and area weighting, the estimated programme-associated yield contrast ranged from 0.779 to 0.939 t ha − 1 (Supplementary Table S5b,f).

Table 2
Paired within-year, variety, variety-class and region yield contrasts.

Year	Pairs (regions)	Programme area (ha)	Mean difference (95% CI), t ha − 1	Weighted difference (95% CI), t ha − 1	Positive	Programme area represented
2025	13 (13)	973	0.37 (0.24–0.50)	0.39 (0.25–0.52)	13/13	100% of pilot area
2026	92 (10)	446,746	0.90 (0.78–1.02)	0.94 (0.81–1.05)	92/92	65.2%

Notes: Differences are programme minus traditionally stored yield. CIs are 95% percentile confidence intervals from 20,000 bootstrap samples, with regions resampled as clusters.

The 2025 pilot contained 13 paired observations, one in each region and 973 ha in total, and every difference was positive. Its mean difference was 0.370 t ha − 1, providing directional feasibility evidence before national scale-up. Because the 2025 and 2026 comparisons differed greatly in coverage, cultivar

deployment and seasonal context, their magnitudes were not interpreted as a temporal treatment-effect increase (Supplementary Fig. S2 and Supplementary Table S5).

Regional robustness and cultivar deployment

In 2026, the regional programme-area share ranged from 45.6% in Samarkand to 100% in Andijan, Bukhara and Khorezm (Fig. 3a,b). The three fully converted regions demonstrate the programme's operational reach, while the direct within-region comparison used the ten mixed-adoption regions. Within those regions, programme-area-weighted differences ranged from 0.54 t ha − 1 in Karakalpakstan to 1.13 t ha − 1 in Jizzakh (Supplementary Table S6).

Leave-one-region-out estimates remained positive, ranging from 0.879 to 0.957 t ha − 1 for the unweighted mean and from 0.898 to 0.985 t ha − 1 for the programme-area-weighted mean (Fig. 3c and Supplementary Fig. S3). Regional programme-area share had weak rank associations with 2026 yield (Spearman $\rho = 0.13$, $P = 0.67$) and the regional 2016–2026 yield increase ($\rho = -0.03$, $P = 0.91$; Fig. 3d). The ecological slope for 2026 yield was 0.241 t ha − 1 per 100-percentage-point increase in adoption (95% confidence interval, − 0.575 to 1.057; $P = 0.53$). This regional analysis had limited discrimination because every region was exposed and adoption already ranged from 45.6% to 100%; it does not alter the consistently positive within-variety comparisons (Supplementary Table S6).

A deployment-context cultivar analysis included 26 varieties represented by at least 20 observations, five years and five regions. Yield was centred on the area-weighted mean within each region-year-treatment environment. Vassa, Alekseich and Asr had positive mean environment-adjusted differences whose bootstrap intervals excluded zero, whereas Bobur, Pervitsa, Xisorak, Brigada and Yesaul had negative differences whose intervals excluded zero (Supplementary Fig. S4 and Supplementary Table S7). These patterns identify cultivars for targeted multi-environment validation and show how varietal deployment contributed to the wider intensification system. Variety-class and sensitivity results are reported in Supplementary Tables S8 and S9.

Field establishment and phenology under routine farming

The field-monitoring dataset contained 260 district-treatment records from 154 districts, covering 35,875 farms and the complete 947,110 ha represented in Data File 1. Of these districts, 106 in ten regions contained both seed treatments, 46 used programme seed exclusively, and two used traditional seed exclusively. Each district supplied one recorded sowing date, indicating a common district-level sowing window by design but not independently verifying treatment-specific timing within every field. District averages integrated observations from multiple farms and fields and therefore captured the operational diversity of routine wheat production (Supplementary Tables S10 and S11).

Across the 106 paired districts, programme fields reached 75% emergence 2.59 days earlier (province-cluster t 95% confidence interval, 2.01–3.18 days earlier) and recorded 180.25 more plants m − 2 at the

early density assessment (39.1%; 95% confidence interval, 162.56–197.94). Tillering, jointing, heading and full maturity occurred 3.68, 3.24, 3.10 and 3.64 days earlier, respectively. Plant height was 6.47 cm greater, while productive-stem density was 54.33 stems m − 2, or 9.6%, higher. Thus, the large early stand difference was substantially attenuated by the productive-stem stage, consistent with stand attrition and density-dependent tillering compensation. All 106 paired districts favoured earlier emergence and greater early stand density; 104 reached full maturity earlier, one on the same day and one later (Fig. 2c,d, Supplementary Fig. S5 and Supplementary Table S10).

A regulated practice embedded in food-system reform

The registered programme package specifies treated and packaged seed at no more than 14% moisture, storage at + 1 to + 5°C (permitted deviation ± 0.5°C) for 45–60 days, and documented facility and seed-quality checks [25] (Fig. 4a). National scale-up occurred within an enabling policy environment that included market-based wheat sales, agricultural risk insurance, preferential wheat credit and support for water-saving irrigation [26–29]. These instruments aimed to strengthen farmer incentives, reduce production risk and support continued investment. Measures introduced after establishment of the 2026 crop provide prospective support for sustaining productivity in future seasons (Fig. 4b).

Discussion

Uzbekistan's national wheat yield increased by 4.140 t ha − 1 between 2016 and 2026 while cultivated area declined, providing a national example of productivity-led intensification. The pre-implementation increase of 297 kg ha − 1 yr − 1 provides agronomic context alongside the 65 kg ha − 1 yr − 1 genetic gain measured in controlled CIMMYT spring-wheat trials [30], but the estimates are not directly comparable because the national trajectory also integrates varietal turnover, management, climate and institutions. The central inference is therefore that coordinated genetic, agronomic and institutional change increased realised farm productivity. Dry-seed conditioning entered this broader pathway as a scalable establishment practice rather than as an isolated input.

Seasonal variation around the upward trajectory was substantial: the largest annual increase occurred in 2024, followed by a slight decline in 2025. Wheat is highly sensitive to rising temperature [2], and the 3.64-day advancement of full maturity in 2026 may provide a useful heat-avoidance and harvest-coordination window in arid production systems. Because daily field-level weather was not linked to the present records, this interpretation remains a testable agronomic hypothesis for future monitoring rather than an attribution of annual yield variation.

The 2026 paired yield association, 9.8% using the unweighted relative difference and 10.3% when weighted by programme area, was of similar order to the 7–14% gains projected for efficient agronomic packages in a 22-site Chinese wheat study [10]. The field observations provide agronomic coherence without establishing a mediated causal chain. Programme fields reached emergence earlier and recorded 39.1% higher early stand density, but the difference attenuated to 9.6% at the productive-stem

stage. This pattern is consistent with stand attrition and density-dependent tillering compensation in wheat [31]. Because optimum density varies markedly with yield environment and tillering potential, the larger early stand should not be interpreted as a proportional yield mechanism; earlier and more uniform establishment remains a plausible complementary pathway. Earlier phenological progression and full maturity were nevertheless directionally consistent across nearly all districts. Preserving seed vigour during storage offers a biologically plausible explanation for faster, more uniform establishment [13, 14], while treatment-specific seed-quality and seeding-rate measurements are needed to test that explanation directly.

Routine commercial farming is a major strength of this evidence. Controlled experiments establish efficacy and mechanisms under defined conditions, whereas real-world implementation reveals whether an innovation remains usable and agronomically valuable when soils, water access, management capacity, resources and farmer decisions vary [7, 8, 32, 33]. This distinction is especially relevant to arid and resource-constrained farming systems in the Global South, where practical value depends on compatibility with infrastructure, finance, extension capacity and farmer knowledge. The registered practice was implemented through routine farming without researcher allocation or standardisation of surrounding crop management, yet programme records showed consistent establishment, phenology and yield associations. These ecosystem-specific estimates characterise Uzbekistan's 2026 irrigated wheat system, in which cultivars, climate, farm practice, cold-storage infrastructure, extension, finance, markets and public coordination operated together. For other Global South systems, the transferable element is not the same numerical yield gain but the implementation principle: simplify a scientifically grounded practice, align it with local resources, demonstrate field value and support adoption through trusted extension and enabling institutions. Expansion from 973 ha to 685,065 ha within one season demonstrates operational scalability within Uzbekistan.

The programme was conceived within an epigenetically informed agricultural framework, but the observed associations do not establish an epigenetic mechanism. Dry seed at low moisture is metabolically quiescent, and the literature more directly supports storage effects on seed longevity and vigour13,14. Wheat germination and dormancy responses to temperature depend strongly on seed moisture, genotype and physiological state15–17,21, while molecular studies establish that seed state is genetically, hormonally, metabolically and epigenetically regulated [18–24]. The present agronomic evidence therefore supports a biologically informed operational practice. Controlled germination, vigour and seed-lot studies, followed by nested molecular analyses, can determine which physiological and regulatory processes underlie the field response.

An integrated production system enabled rapid scaling. Market-based wheat sales were designed to strengthen the relationship between productivity and farm income, while preferential credit, agricultural insurance and support for water-saving irrigation aimed to reduce financial and production barriers [26–29]. Digital harvest monitoring strengthened coordination and measurement [34, 35]. This integrated framing also aligns with evidence that improved spring-wheat management can reduce production carbon footprints [11]. Instruments adopted after establishment of the 2026 crop are most relevant to

future sustainability, but together these reforms show why agronomic innovation must be aligned with farmer incentives, extension capacity and reliable implementation. This combination of simple technology and enabling institutions is transferable to other Global South farming ecosystems, with local adaptation to cultivars, climate, storage infrastructure and farmer practice.

This nationwide implementation study was observational. Treatment was not randomly allocated, and matching could not eliminate differences among farms, fields, soils, irrigation, weather or other inputs. The estimand is the complete registered programme package: prepared, treated and packaged seed at controlled moisture followed by cold storage. Seed-lot germination, purity, thousand-kernel weight, seed class and fungicide treatment, as well as district-specific seeding rates, were unavailable; storage temperature cannot therefore be separated from pre-existing or programme-related seed quality, and recorded stand density cannot be converted to establishment percentage. The field observers knew treatment status, creating potential expectation and measurement bias. Sowing date was available only as a district-level value, administrative yield was aggregated by variety and region, and field traits were district means without cultivar identity or underlying field-level variance. The Ministry series covers irrigated harvested area and uses the final grain-reception weight recorded through its administrative workflow. Over the common 2016–2024 period, Ministry area-weighted yield increased by 50.9%, compared with 12.6% in FAOSTAT [36] (Supplementary Table S12); the 73.4% headline increase reported here spans 2016–2026. FAO recommends clean, dry grain as the cereal-production reporting basis [37], and a recent peer-reviewed assessment using FAOSTAT provides complementary long-term context for Uzbekistan's wheat trajectory and yield gaps [38]. Because the series differ in coverage, grain-weight basis and estimation or revision status, they cannot be decomposed as nested irrigated and residual national components. FAOSTAT provides the harmonised basis for international comparisons, whereas the Ministry series provides the internally consistent basis for the within-system temporal and matched treatment analyses conducted here. Formal reconciliation of their absolute levels would require record-level comparison of harvested-area coverage, grain moisture, foreign material and reception-weight adjustments. Only one fully scaled season is available. These constraints limit causal partitioning, but do not alter the documented national trajectory, the positive direction of all 92 matched yield differences or the highly consistent field-stage differences. Randomised multi-location trials, treatment-specific seed-quality measurements, linked weather data and nested physiological and molecular studies can test causality, durability and mechanism while building on this real-world evidence.

Together, these records document substantial national wheat intensification, rapid scaling of a registered seed-conditioning programme and a coherent field pattern spanning earlier emergence, higher early stand density, accelerated development, greater productive-stem density and higher matched yield. Uzbekistan's experience illustrates how an operationally simple, biologically informed adaptation of classical seed management can be integrated with crop management, extension, farmer support, market incentives and digital monitoring to reach national scale. For arid farming systems across Central Asia and the wider Global South, the transferable lesson is not an expectation of identical yield gains, but an implementation logic: adapt scientifically grounded knowledge to local resource constraints, use available infrastructure, make field value visible to farmers, and align extension, finance, markets and

public institutions around sustained delivery. Real-world agronomic evidence thereby complements proof-of-concept science by showing whether an innovation can function within the farming ecosystem that must sustain its continued use.

Methods

Study design and national agricultural reporting

We conducted a retrospective nationwide observational analysis of wheat harvest records for 2016–2026. Farm organisations and local administrations compiled harvested-area and yield data. District and regional coordination groups verified these records, which were endorsed by the relevant local authorities, submitted to the Ministry of Agriculture, reviewed within its institutional process and archived annually. Beginning in 2025, harvest receipt and monitoring were progressively digitised using Agroplatforma and the Hosil-qabuli information system [34, 35]. This reporting structure provided the national administrative series used for programme monitoring, operational decision-making and the present analysis. The study did not assign seed treatments or standardise surrounding crop management; treatment use and field management proceeded through routine programme delivery, extension support and farm-level decision-making.

Yield was recorded as final grain-reception weight, with harvested irrigated wheat area as the denominator; rainfed production was outside the reporting frame. The system covered 35,875 farms together with agricultural cluster companies operating on irrigated land. Reception and storage personnel recorded harvest weight according to the national workflow, and programme status, variety and region were retained in the aggregated records. The same reporting definitions were applied to comparisons across years, regions and treatment groups.

The 1,953-record national agricultural dataset is supplied as Supplementary Data File 1. Variables include harvest year, province, variety class, named variety, seed-storage treatment, cultivated area, yield and derived production, together with province-year adoption summaries. The 2026 records are final harvested records. No personal farmer identifiers are included.

District field monitoring

Supplementary Data File 2 contains 260 district-treatment averages from 154 districts in 13 provinces for the 2026 harvest, covering 35,875 farms. Farm agronomists and trained district agricultural specialists in the Agriculture Knowledge and Innovation System, working with farmers, used the same written protocol and standardised phenological notebooks. Observers knew which fields received programme seed. Agricultural contours were individual fields. Field observations were combined as simple arithmetic farm means and then as simple arithmetic district means; they were not weighted by field area. The national sowing-rate value of 250 kg ha − 1 is a programme average, not a uniform district-level exposure.

Farm agronomists monitored crop emergence and recorded the date on which approximately 75% of seedlings were visible above the soil surface. Seedling density was measured 3–4 days after this emergence threshold had been reached. Measurements were taken along the field diagonal using four to ten 1-m² quadrats per field, and counts were averaged to obtain field-level density. Tillering, jointing and heading dates represent the day on which approximately 75% of plants had reached the full stage. Full maturity was identified by yellow, dry plants and hard grain; the approximate 14–17% grain-moisture range was inferred from grain hardness and field inspection rather than measured with a moisture meter. Plant height and productive stem density were recorded in the same standardised field monitoring notebooks.

Emergence, phenology and stand traits were monitored independently in the field, whereas district yield values were derived from the corresponding 2026 administrative harvest records in Data File 1.

Data preparation and national summaries

Records were eligible when harvested area and yield were present and positive. Observed records were analysed as submitted; missing information remained missing, and no values were imputed. Production was calculated as area × yield. National and regional yield was:

$$\Sigma(\text{area} \times \text{yield})/\Sigma\text{area}, \quad (1)$$

Treatment-area share was the treatment area divided by the total area in the corresponding year or region. The symmetric two-factor decomposition partitioned the 2016–2026 production change as:

$$\Delta P_{area} = \Delta A \times (Y0 + Y1)/2 \text{ and } \Delta P_{yield} = \Delta Y \times (A0 + A1)/2. \quad (2)$$

For external context, Ministry area, yield and production values for 2016–2024 were compared descriptively with the corresponding FAOSTAT Crops and livestock products wheat series [36], the FAO clean, dry grain reporting recommendation [37] and a recent peer-reviewed assessment of Uzbekistan's wheat yield gaps and agronomic pathways [38]. The series were treated as independently defined reporting systems rather than as nested irrigated and residual national components. Because the Ministry records did not retain the lot- or year-specific grain-quality information required for conversion to a common moisture and impurity basis, no post hoc mass adjustment was applied (Supplementary Table S12).

Historical and regional trend analyses

Ordinary least squares was fitted to the nine national annual area-weighted yields from 2016–2024, and 2025–2026 predictions used two-sided 95% prediction intervals for new annual observations. Given the two post-implementation harvests, this pre-period regression was used for descriptive forecasting rather than estimation of a segmented level or slope change [39]. Durbin–Watson and Ljung–Box statistics assessed residual serial correlation. Theil–Sen slope and its 95% confidence interval provided a rank-based sensitivity estimate [40]. Regional repeated measures were assessed with Friedman's test, and the 2016–2026 regional change with paired t, exact Wilcoxon signed-rank and exact sign tests.

Spearman correlations and ordinary least-squares ecological models related regional programme-area share to 2026 yield and to the 2016–2026 regional yield change.

Record-level mixed model and cultivar summaries

A Gaussian linear mixed model was fitted by restricted maximum likelihood to record-level yield. Harvest year, programme status and variety class were fixed effects; region-by-year environment and named variety were crossed random intercepts. Fixed-effect blocks were evaluated with Wald χ^2 tests, and coefficient intervals were based on asymptotic normal approximations. Sensitivity analyses refitted the model to 2026 with region and named variety as crossed random intercepts, first with equal record weights and then with residual precision proportional to cultivated area. The area-precision analysis tests sensitivity to record scale; it does not treat hectares as independent field replicates. These structures accommodate unbalanced commercial and on-farm records [41, 42]. For the cultivar comparison, each record was centred on the area-weighted mean of its region-year-treatment environment. Eligible cultivars had at least 20 records, five years and five regions; mean environment-adjusted differences used 20,000 percentile bootstrap resamples.

Paired treatment contrasts

Within each harvest year, we matched named-variety, variety-class and region combinations containing one record for each seed-treatment group [43]. The contrast was programme minus traditionally stored yield. We reported the unweighted mean, median, range, programme-area-weighted mean, exact sign test, Wilcoxon signed-rank test and paired t test. Principal uncertainty intervals used 20,000 percentile bootstrap samples in which regions, with all matched observations, were resampled as clusters [44]. Cluster-robust variance estimation with a finite-sample correction (CR1) and *t* intervals with nine degrees of freedom accounted for clustering across the ten contributing regions. As an additional small-cluster sensitivity, wild-cluster bootstrap-t P values were calculated by exact enumeration of all 2^{10} Rademacher sign patterns for the region-level score contributions [45]. For weights w_i, differences d_i and G regions, variance was

$$[G/(G-1)](\Sigma_i w_i)^{-2}\Sigma g\,[\Sigma i\in g w_i(d_i-\bar{d}w)]^2. \quad (3)$$

Leave-one-region-out and square-root-area-weighted estimates evaluated robustness to regional influence and large area weights.

District field comparisons

Within-district field contrasts used the 106 mixed-adoption districts. The single sowing date recorded for each district defined a common district-level sowing window; it was not interpreted as field-level proof of identical treatment timing. Districts were the observational units, and each contrast was programme minus traditional. Means and two-sided 95% confidence intervals used CR1 cluster-robust standard errors with province as the cluster and t inference with 9 degrees of freedom. Holm adjustment controlled the family-wise error rate across eight prespecified phenology and stand traits. Paired

Wilcoxon tests and leave-one-province-out means were sensitivity analyses. Complete district pairs were used for each trait, while single-treatment districts contributed to descriptive adoption summaries.

Registered dry-seed conditioning programme

Protocol parameters were taken from Ministerial Order No. 35 of 7 August 2025, registered by the Ministry of Justice as No. 3675 on 9 September 2025 [25]. The registered exposure was a programme package comprising treated and packaged seed at ≤ 14% moisture, storage at + 1 to + 5°C (± 0.5°C) for 45–60 days and documented quality control. The analysis does not isolate refrigerated storage from other components of seed preparation and handling. Primary legal instruments described the market, finance, insurance and irrigation-support environment. Instruments introduced after establishment of the 2026 crop were treated as measures supporting future production seasons.

Analysis

We performed analyses in Python using pandas, NumPy, SciPy and matplotlib. All analyses are reproducible from Supplementary Data Files 1 and 2. Two-sided P values are reported.

Declarations

Data availability

The complete analysis datasets used for all analyses are provided as Supplementary Data Files 1 and 2. Data File 1 contains the 2016–2026 national wheat variety-by-province records; Data File 2 contains the 2026 district-by-treatment field-monitoring averages. No personal farmer identifiers are included.

Code availability

The corresponding author can provide the Python scripts used for statistical analyses upon reasonable request.

Competing Interests

The authors declare the following non-financial competing interests: I.Y.A. is Minister of Agriculture of the Republic of Uzbekistan, and several co-authors are employed by institutions involved in programme implementation and monitoring. The authors declare no financial competing interests.

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Author Contribution

I.Y.A. contributed conceptualisation, methodology, formal analysis, supervision and writing of the original draft. S.I.O. and A.E.E. contributed protocol development, regulatory documentation and field-method interpretation. S.S.E., S.S.K., N.O.E. and B.M.A. contributed data curation and validation. A.A.T., A.A.M., Z.F.Z., Z.M.Z., D.U.U., R.X.K. and A.A.K. contributed programme implementation, field monitoring, farmer engagement and interpretation. All authors reviewed and edited the manuscript, approved the submitted version and accept accountability for their contributions.

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Figures

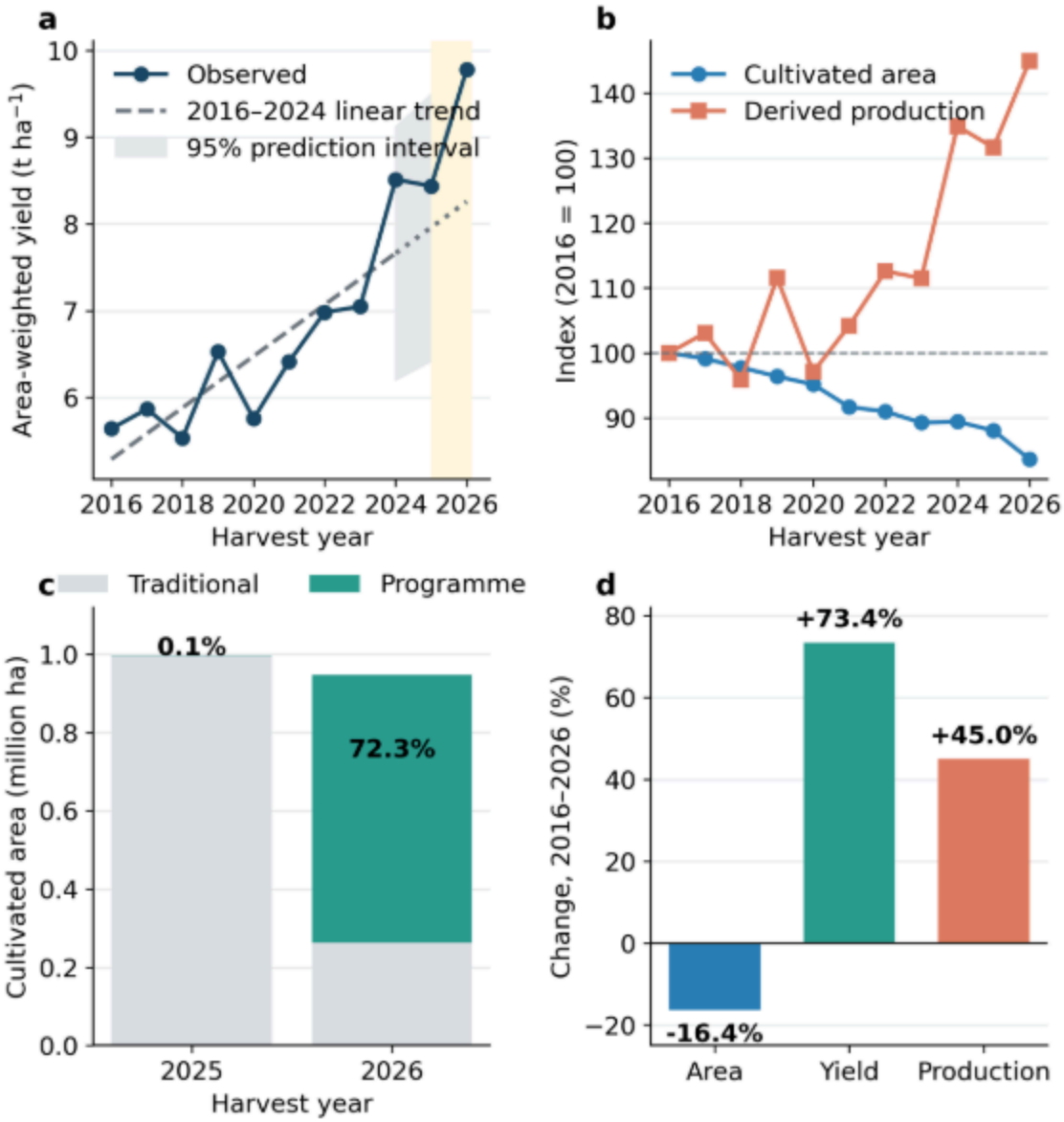


Figure 1

National wheat trajectory and programme diffusion. a, Area-weighted yield during 2016–2026. The dashed line is an ordinary least-squares fit to 2016–2024; the grey band is the two-sided 95% prediction interval for a new annual observation, and shading marks 2025–2026. b, Cultivated area and derived production indexed to 2016. c, Cultivated area by recorded seed-storage treatment in 2025 and 2026. d, Percentage changes in area, yield and derived production from 2016 to 2026.

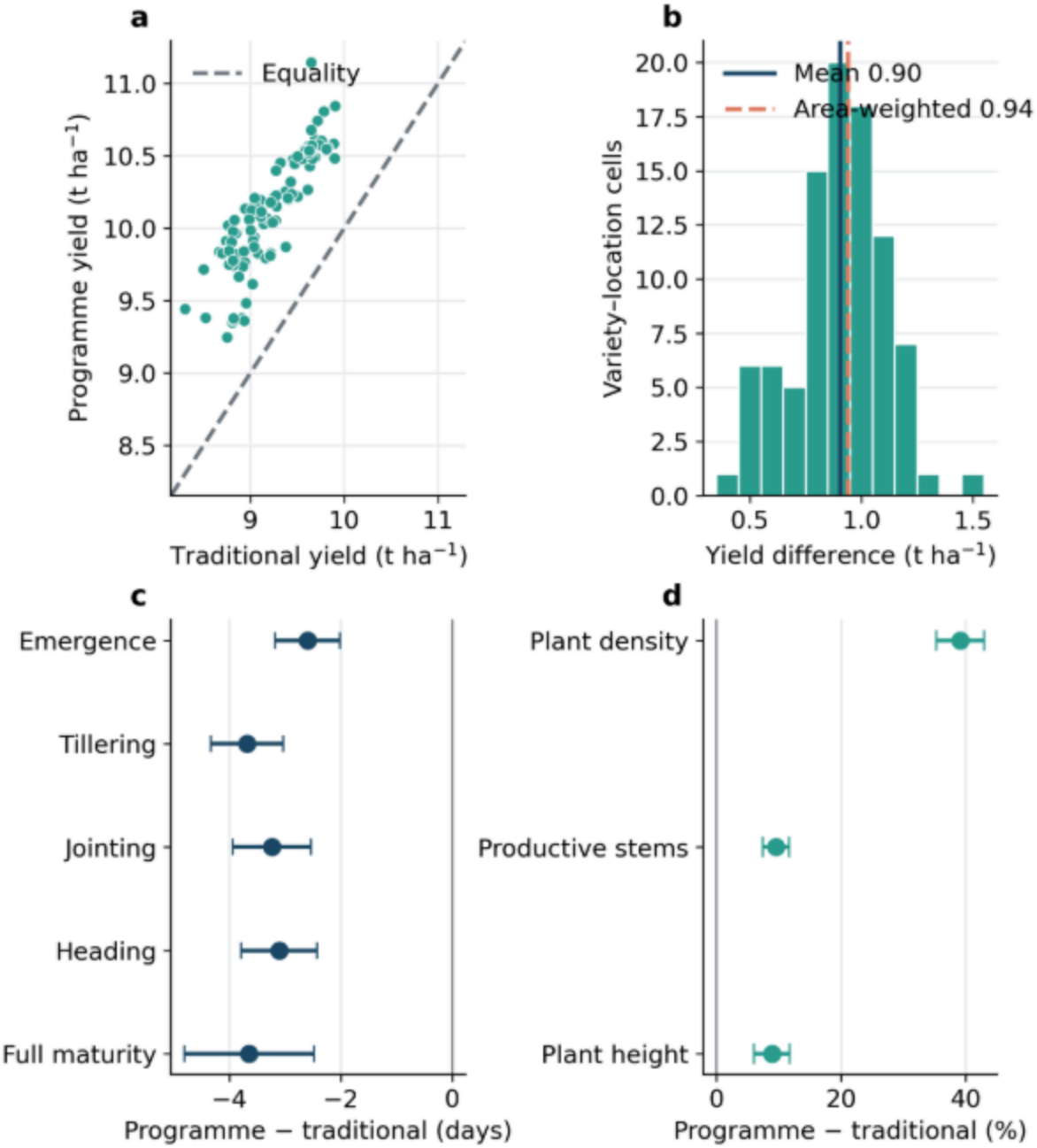


Figure 2

Matched programme and traditional wheat outcomes in 2026. a, Traditional versus programme yield for 92 matched variety-by-region observations; the diagonal denotes equality. b, Distribution of administrative yield differences; vertical lines show the unweighted and programme-area-weighted means. c, Mean programme minus traditional differences in days from sowing to the 75% phenological threshold across 106 paired districts. d, Relative differences in stand traits across the same paired districts (plant height, n = 105). Error bars in c and d are two-sided 95% cluster-robust t intervals with province as the cluster (10 provinces; 9 d.f.). Panels a and b use administrative variety-by-region aggregates; panels c and d use district field-monitoring averages.

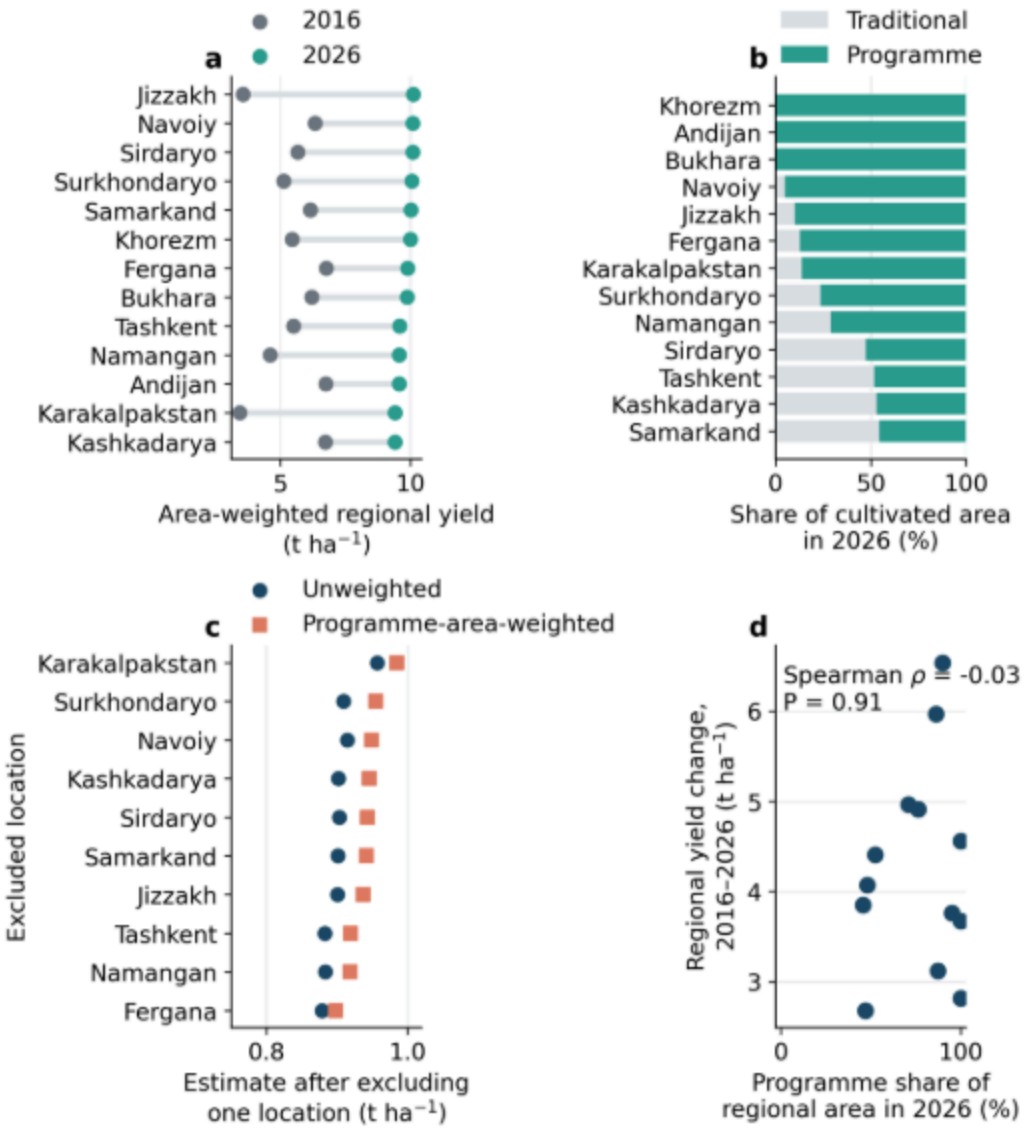


Figure 3

Regional yield change, programme adoption and robustness. a, Area-weighted regional yield in 2016 and 2026. b, Regional share of recorded cultivated area by seed-storage treatment in 2026. c, Leave-one-region-out paired estimates. d, Regional programme-area share in 2026 versus the regional yield change from 2016 to 2026. Spearman's rank correlation is two-sided; each point represents one region.

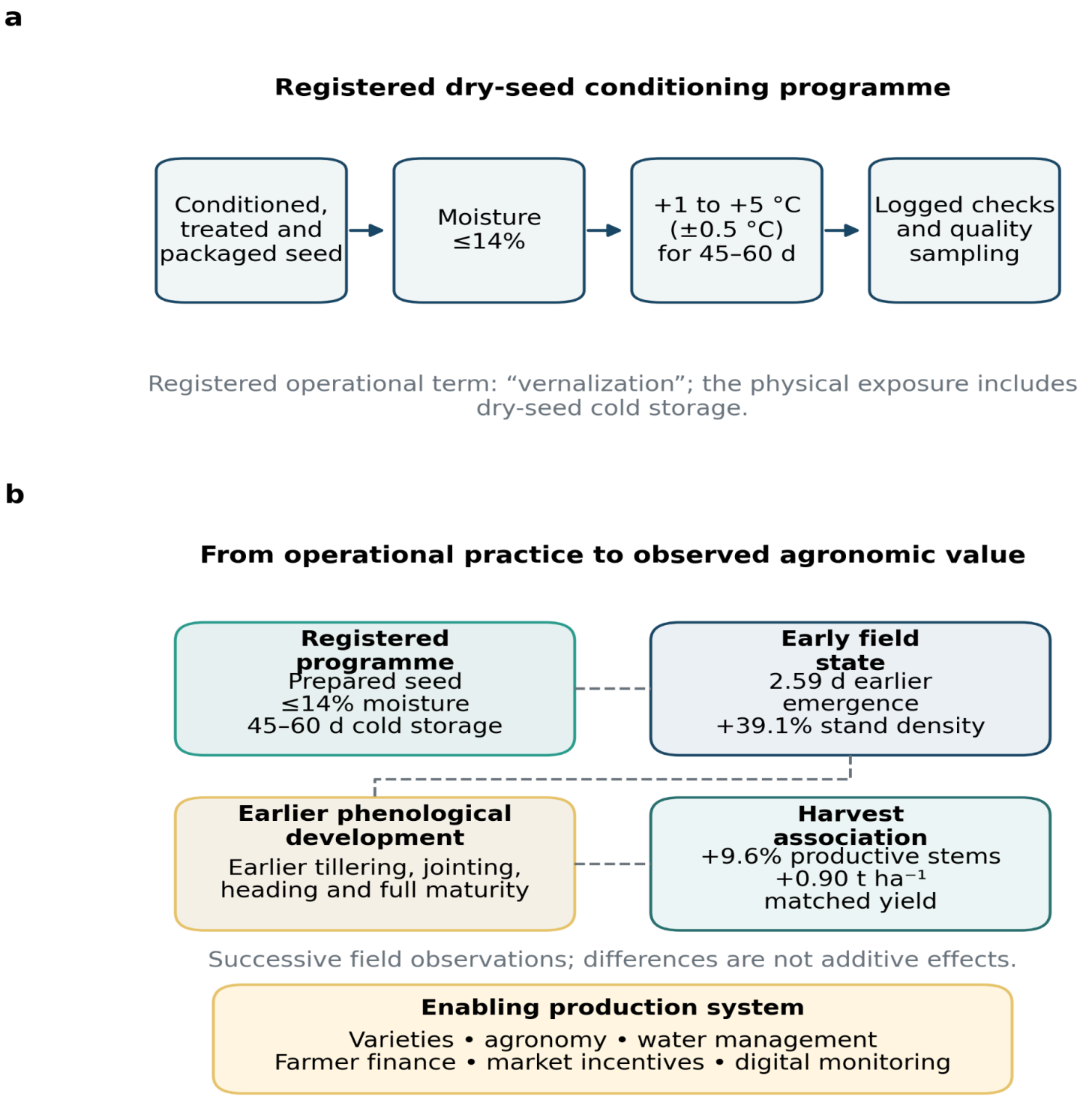


Figure 4

Registered dry-seed conditioning programme and the integrated implementation pathway. a, Operational elements of the programme package registered by the Ministry of Justice of Uzbekistan. b, Field differences observed at successive crop stages: earlier emergence and higher early stand density were followed by earlier phenological development, attenuation of the density difference to a 9.6% productive-stem difference and a positive matched-yield association. The dashed connectors indicate

temporal ordering, not additive mediation or proof of causality. The enabling production system combines varieties, agronomy, water management, farmer finance, market incentives and digital monitoring. Values summarise 106 paired districts and 92 matched variety-by-region yield comparisons.

Supplementary Files

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