Climatic distance to cultivar origin predicts Deglet Noor date quality across two continents

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HIGHLIGHTS

- A single-optimum, climatic-distance-to-origin framework describes commercial Deglet Noor quality across a controlled-cultivar Maghreb–Jerid panel (n = 13): a four-dimensional distance to the cultivar's historical origin (Tolga, Algeria) explains 57% of cross-site quality variance in-sample and 33% under leakage-free nested leave-one-out cross-validation (permutation $p = 0.005$).
- A floating-optimum analysis — testing every panel site as the candidate optimum — identifies Tolga (tied with neighbouring Biskra, the same Zibans basin) as the best-

fitting optimum, providing support that the cultivar's quality optimum coincides with its documented origin. Because Tolga's top grade is itself assigned partly on its origin status, this reduces rather than fully removes circularity; the informative content is that climatic distance from the Tolga–Biskra core orders quality better than distance from any other candidate site.

- A trans-Atlantic diaspora site (Coachella Valley, USA), held out entirely from model fitting and standardisation, is predicted at grade 2.5 from its climatic distance to Tolga alone; its independently market-anchored observed grade is 2.
- Three climatically opposite regimes converge on the same marginal grade by departing from Tolga along different dimensions — El Menia by dryness, Gabes by humidity, Coachella by heat — empirical evidence of a non-monotonic (Goldilocks) reaction norm.
- An AR6 regional delta-method projection indicates that Tolga itself drifts about 1.3–2.1 grade points from its own historical optimum by 2050 (n=13 calibration), with the geographical optimum migrating toward the Tunisian Jerid–Gafsa corridor; under SSP5-8.5, 12 of the 13 Maghreb panel sites fall below grade 3.
- We hypothesise that the distance-to-origin framework transfers to other quasi-clonally propagated terroir cultivars (grapevine, olive, coffee, tea) where origin is documented and consistent quality grading exists, and we provide an open, replicable workflow to test it.

PLAIN LANGUAGE SUMMARY

For seven centuries the oases of the northern Algerian Sahara have produced Deglet Noor — "the date of light" — a premium variety whose finest fruits turn slightly translucent when ripe. Carried from Tolga to Tunisia around 1600 and to California's Coachella Valley around 1900, this single cultivar now lives across two continents. Across thirteen North-African production sites, fruit quality declines as the local climate drifts from Tolga's conditions. Three very different climates — Saharan dryness (El Menia), Mediterranean humidity (Gabes) and Californian desert heat (Coachella) — converge on the same lower grade, but each for a different climatic reason, showing the cultivar carries a narrow climatic memory of its origin. A model trained only on North Africa predicts the Californian grade correctly without ever seeing it. By 2050 the optimum migrates northeast toward the Tunisian Jerid–Gafsa region. The framework is offered as a quantitative, openly replicable basis for adaptation planning that may extend to other heritage cultivars — grapevine, olive, coffee, tea.

ABSTRACT

Background. Premium-grade cultivars of terroir-controlled crops are tied to specific climatic origins, yet the quantitative relationships linking climate, soil and quality remain poorly resolved across whole production landscapes. Deglet Noor date palm — the historically dominant premium cultivar of North African oases, named for the optical translucency of its top-grade fruits — exemplifies this knowledge gap and is increasingly threatened by climate change.

Methods. Using 35 years of ERA5 reanalysis (1990–2024) on a controlled-cultivar panel of thirteen Deglet Noor sites spanning the Algerian Septentrional Sahara and the Tunisian Jerid–Nefzaoua, we tested two hypotheses: (i) at the event scale, that orographic basin topography amplifies thermal extremes and depresses diurnal temperature range during fruit maturation; and (ii) at the site scale, that quality declines non-linearly with a four-dimensional climatic distance to the cultivar's historical origin (Tolga, Algeria). Out-of-sample skill was assessed by leakage-free nested leave-one-out cross-validation and a permutation test; the location of the optimum was tested by a floating-optimum analysis. A long-established trans-Atlantic diaspora site (Coachella Valley, California) was held out entirely from fitting and standardisation and used as an independent out-of-sample prediction, with a quality grade anchored on commercial market positioning independently of climate.

Results. The Biskra–Saida iso-latitudinal contrast confirmed seven independent topoclimatic signatures of basin-amphitheatre warming (all seven contrasts $p < 1e\text{-}6$; range 3.6×10^{-7} to 2.7×10^{-38}). The four-dimensional climatic distance to Tolga — combining cumulative GDD, mean September–October diurnal temperature range, relative humidity and total precipitation — explained 57% of cross-site quality variance in-sample and 33% under nested leave-one-out cross-validation (standardised slope = -0.59, slope $p = 0.003$; permutation $p = 0.005$, 0.011 after correcting for the five-subset selection, $n = 13$), and was the most generalisable of five candidate parameter subsets. A floating-optimum analysis ranked Tolga (tied with neighbouring Biskra) first of thirteen candidate optima, and a competing four-predictor linear regression returned nested LOO R^2 = -0.36, together supporting a single-optimum (Goldilocks) interpretation centred on the origin. The held-

out Coachella site was predicted at grade 2.5 from distance alone against an independent observed grade of 2. An AR6 regional delta-method projection indicates that Tolga itself drifts about 1.3–2.1 grade points by 2050 (n = 13 calibration), with the geographical optimum migrating toward the Tunisian Jerid–Gafsa corridor.

Implications. A climatic-optimum framework anchored on a cultivar's origin parsimoniously captures terroir–quality relationships within a controlled-cultivar panel and yields a verifiable cross-continental prediction. We hypothesise transferability to other quasi-clonal terroir cultivars (wine, coffee, tea, olive) and provide an open workflow to test it, together with a quantitative basis for projecting the climate-change vulnerability of premium cultivars.

Keywords: Phoenix dactylifera; Deglet Noor (Deglet Nour in French); date palm; terroir; cultivar origin; climatic distance; fruit quality; climate-change adaptation; climatic optimum; reaction norm; ERA5 reanalysis; AR6 projection; Sahara; Coachella; diurnal temperature range; cultivar quality; agro-heritage.

1. INTRODUCTION

1.1 The terroir concept and its extension beyond viticulture

The terroir concept defines the operational interaction of climate, soil, cultivar and cultural practices. Originating in French viticulture, it has been extended successively to coffee, tea, cocoa and olive oil. Despite the conceptual maturity, rigorous quantification of climate–quality relationships outside viticulture remains scarce.

1.2 The Deglet Noor date palm as a model

Deglet Noor is the historically dominant premium date-palm cultivar in North Africa (Algeria, Tunisia), with a documented commercial diaspora in California (Coachella Valley). Its origin is traced to Tolga, Algeria (Munier, 1973). The cultivar name itself — Deglet Noor, "date of light" — refers to the diagnostic optical translucency of premium fruits. Global production: Algeria ~1.19 million t and Tunisia ~345,000 t of dates of all cultivars (FAOSTAT, 2021 official figures, accessed 2026; 2023 imputed estimates ~1.32 and ~0.39 million t respectively). Deglet Noor, the premium export cultivar, is the single largest category in both countries: ~53% of Algerian production (Office National des Statistiques, 2020/2021 campaign — a national census of 11.9 million quintaux that matches the FAOSTAT total) and ~63% of Tunisian output. Tunisia is the leading exporter by value, Algeria the leading producer; the Coachella Valley diaspora produces ~20,000 t/year. The cultivar propagates quasi-clonally by offshoots (Battesti et al., 2018; Zarkouna et al., 2025), has been cultivated for ~700 years in the Algero-Tunisian Saharan basin, was introduced to Tunisia around 1600 by Sidi Touati, and reached the Coachella Valley around 1900. Documented sensitivity to irrigation-water salinity is non-trivial (Tremblay et al., 2011).

1.3 Methodological bottlenecks

Fine-resolution climatic data have historically been difficult to obtain in Saharan regions because of sparse weather-station networks. Multi-site comparisons are confounded by cultivar–climate interaction. Quality metrics are subjective or proprietary. To date, no quantitative study has compared diaspora production (Americas, Levant) to the historical core of the cultivar's range.

1.4 Proposed conceptual framework: the cultivar climatic optimum

Our central hypothesis is that a terroir-dependent cultivar expresses maximum quality in its historical terroir, where it has adapted over centuries, and that climatic displacement away from this optimum degrades quality non-monotonically, regardless of the direction of the deviation (a Goldilocks pattern). This hypothesis contrasts with (i) multivariate linear modelling (susceptible to overfitting and multicollinearity with small panels) and (ii) species-level niche envelopes (which ignore cultivar specificity). A long-established diaspora site (Coachella, California), held out entirely from model fitting, provides an independent trans-Atlantic test: if diaspora quality is predictable from climatic distance to Tolga alone, the framework generalises beyond the Maghreb. The same distance-to-origin metric is being extended to wild Saharan paleoendemic species surviving in mountain refugia (Selkh, in preparation).

1.5 Objectives and structure

We test the hypothesis at two scales: event-level (Biskra–Saida iso-latitudinal contrast) and inter-site (controlled-cultivar Maghreb panel, n = 13). We assess generalisation beyond the Maghreb via a held-out commercial diaspora location, and demonstrate methodological transferability through a publicly replicable workflow (Open-Meteo, public Python scripts). We discuss edaphic co-determinations (irrigation-water salinity) that modulate the climatic expression of quality.

2. MATERIALS AND METHODS

2.1 Site selection

The main panel comprises 13 commercial Deglet Noor production sites distributed across the northern Saharan margin (Table 1). A long-established diaspora location external to the Maghreb (Coachella Valley) is treated separately as a held-out external validation (Section 3.3) and is NOT part of the fitting panel.

Table 1. Controlled-cultivar Maghreb–Jerid fitting panel (n = 13). Coachella (last row, starred) is a held-out trans-Atlantic diaspora site used for independent out-of-sample validation; it is excluded from model fitting and from the standardisation of the distance metric.

Site	Country	Lat (°N)	Lon (°E)	Grade	Status / source of grade
Tolga	DZ	34.72	5.38	5	Absolute reference — visible pit translucency (cultivar origin); Selkh expertise
Biskra	DZ	34.85	5.73	4	Excellent (translucency < Tolga); Selkh expertise
Touggourt	DZ	33.10	6.07	4	Very good (Souf / Oued Righ)
Ouargla	DZ	31.95	5.32	4	Good — *tifizouine* caveat (§2.1.1); S. Bissati field obs. 2024–2026

Site	Country	Lat (°N)	Lon (°E)	Grade	Status / source of grade
Nefta	TN	33.87	7.88	4	Tunisian premium (Jerid); Munier 1973
Tozeur	TN	33.92	8.13	4	Tunisian premium (Jerid); TN introduction point (~1600)
El Oued	DZ	33.37	6.86	3	DN coexists with Ghars; commercial value > Ghars
Ghardaïa	DZ	32.49	3.67	3	Acceptable; A. Chehma field obs. 2024–2026
Kebili	TN	33.70	8.97	3	Good (Nefzaoua); commercial literature
Douz	TN	33.46	9.02	3	Chott periphery (Nefzaoua)
Gafsa	TN	34.42	8.78	3	Northern; variable quality
El Menia	DZ	30.57	2.88	2	Acclimated; sweet but degraded flavour (Selkh field obs.)
Gabès	TN	33.88	10.10	2	Coastal; Mediterranean humidity degrades aroma
Coachella*	US	33.72	−116.22	2	Held-out diaspora; grade anchored on market positioning (see text)

Quality grade refers to commercial premium Deglet Noor classification on an ordinal scale from 1 (marginal limit) to 5 (premium reference, Tolga). Sites where the cultivar produces fruits with deviating organoleptic profiles (e.g. higher sugar but flatter aromatic complexity at El Menia) are classified as marginal regardless of crude productivity. Grades for Algerian sites were assigned by C. Selkh from direct field expertise of regional markets and producer interviews (Adrar regional markets, 2024–2026), with complementary observations by S. Bissati (Ouargla) and A. Chehma (Ghardaia); grades for Tunisian sites were assigned from the published commercial and agronomic literature (Munier 1973; Brousse & Fils 2022).

Coachella as a held-out validation site. The diaspora site (Coachella Valley, Indio area, California, USA; 33.72 N, -116.22 W; Salton Trough, elevation -12 m) is not included in model fitting or in the standardisation of the climatic-distance metric; it is held out entirely and treated as an independent out-of-sample prediction (Section 3.3). Its climatic parameters were re-extracted from Open-Meteo using strictly the same procedure as the Maghreb sites, to ensure they reflect the site's own data (maturation DTR = 12.83 C). Its quality grade was assigned independently of climate, on the basis of commercial market positioning: across the international date trade, premium fresh Deglet Noor is benchmarked to Maghreb (Tunisian/Algerian) production — marketed on-branch as a premium gifting product — whereas Coachella Deglet Noor occupies a commodity/ ingredient tier (loose, pitted, baking, date paste), with premium fresh Deglet Noor frequently imported from Tunisia by Coachella packers (trade sources; Krueger, 2015). USDA date grades (A/Fancy, B/Choice, C/Standard) are defect- and uniformity-based and are orthogonal to this varietal-premium scale. On this independent basis Coachella was assigned a commercial grade of 2 (marginal end of the commercial range), blind to the model prediction.

2.1.1 Sites excluded from the panel and climatic controls

Climate data were also extracted for two additional Saharan sites — Adrar (27.87 N, 0.29 W) and Beni Abbes (30.13 N, 2.17 W) — but these were excluded from the quality-regression panel because commercial Deglet Noor production is not established there; local production relies on other cultivars (Tinaicir, Takerboucht, Aghamou) and the Deglet Noor available locally is imported from Biskra and El Menia. They are retained as arid-environment climatic controls. Other arid date-producing regions where Deglet Noor is cultivated as a minor cultivar — Saudi Arabia (Medina, Qassim), Iran (Bam, Kerman), Pakistan (Sindh, Balochistan) — were excluded from the principal panel because no defensible commercial-grade quality scoring of the cultivar was identifiable in the accessible literature; the dominant commercial cultivars there are local (Sukkari, Khalas, Ajwa; Mazafati, Piarom; Aseel). Extending the framework to these regions would require primary field-based quality scoring or calibration of an alternative scoring system, reserved for future studies. The climate of Medina is retained as an extreme-aridity datum in Supplementary Information S5. At Ouargla, the morphologically similar local cultivar 'Deglat Ouargla' (tifizouine; Munier 1973) is occasionally commercialised under the Deglet Noor denomination; quality scores attributed to Ouargla here should be interpreted as the commercial 'Deglet Noor' grade reaching consumers in regional markets.

2.2 Climatic data

Daily climatological data were retrieved from the Open-Meteo Historical Weather API (Zippenfenig 2023), which redistributes the ERA5 reanalysis product (Hersbach et al. 2020) of ECMWF. For each panel site (and Coachella, and the two climatic controls) we extracted daily maximum, minimum and mean 2-m air temperature, mean 2-m relative humidity, and total precipitation, over 1 January 1990 – 31 December 2024 (12,784 days, 5 variables, 35 annual cycles). The diaspora site (Coachella) was extracted with strictly the same procedure (extract_diaspora_2026.py in the replication pack). ERA5 has documented biases over arid regions, notably (i) underestimation of fine-scale diurnal temperature range due to spatial smoothing at the 0.25 deg native grid (Tarek et al. 2020) and (ii) overestimation of rare precipitation events from convection schemes (Lavers et al. 2022). To partially mitigate these biases, comparative analyses are conducted on multi-decadal means and on between-site differences (robust to systematic ERA5 offsets). Validation against OGIMET station data is reported as supplementary analysis (S1).

2.3 Computation of climatic parameters

Four parameters were retained for their documented physiological relevance to the date palm. P1 — annual growing-degree-days (GDD): sum of mean daily temperatures above 7 C over the full calendar year, averaged across the 35 cycles. P2 — maturation diurnal temperature range (DTR): mean daily thermal amplitude (Tmax - Tmin) over the September–October window, the Khalal -> Rutab -> Tamr transition and final sugar-concentration period. P3 — maturation relative humidity (RH): mean RH over September–October. P4 — maturation precipitation: total mean precipitation over September–October. The September–October window was fixed a priori on physiological grounds (final ripening); its sensitivity is examined in Section 4.5 and S2.

2.4 Topoclimatic signature analysis (event scale)

To test whether the orographic basin geometry of Biskra produces detectable thermal signatures relative to the iso-latitudinal continental site of Saida, we computed seven climatological indices over 1990–2024: annual frequency of days with Tmax > 40, > 42 and > 45 C; mean July–August nocturnal minimum (Tmin); summer DTR (June–August); annual frost-day frequency (Tmin < 0 C); and absolute minimum winter Tmin. Differences were tested with two-sample Welch t-tests on annual values (n = 35 per site), reporting effect sizes (Delta) and p-values.

2.5 Climatic distance to cultivar origin (inter-site scale)

Following the climatic-optimum hypothesis, we defined the climatic distance of each panel site to Tolga (the cultivar's documented origin and the highest-graded site) as a Euclidean distance in standardised parameter space: d_Tolga(s) = sqrt(SUM_i [(X_i(s) - X_i(Tolga)) / sigma_i]^2), where sigma_i is the panel standard deviation of parameter i. The distance is non-negative, zero at Tolga by construction, and invariant to the absolute scale of each parameter. Parameters are not weighted a priori: each standardised dimension contributes equally, avoiding free parameters. Quality grade was regressed on d_Tolga by ordinary least squares. Predictive performance was assessed by leakage-free nested leave-one-out cross-validation (nested LOO): for each held-out site, the standardisation (sigma_i) and the Tolga reference were recomputed on the n-1 training fold only, so that the held-out site never influences the feature engineering. Five parameter subsets were tested (three 2D combinations, the 3D set P1–P3, and the full 4D set) to identify the most generalisable model. The statistical significance of the out-of-sample skill was assessed by a permutation test (grades shuffled, nested LOO recomputed, with a fixed random seed). We additionally tested whether the optimum is empirically located at Tolga by a floating-optimum analysis, in which every panel site was used in turn as the reference and the site minimising out-of-sample error was identified. Held-out diaspora prediction. Coachella was excluded from both fitting and standardisation. Its grade was predicted by projecting its climatic parameters onto the n = 13 panel standardisation, computing its distance to Tolga, and applying the n = 13-calibrated regression; the prediction was then compared with the independently assigned observed grade (Section 2.1).

2.6 Reproducibility and open data

All Python scripts (data extraction, parameter computation, regression, nested cross-validation, permutation and floating-optimum analyses, distance computation, figure generation), the panel CSV files and the figure code are publicly archived on GitHub (https://github.com/Selkh-arch/biskra_paper) and on Zenodo with a citable DOI. The Open-Meteo API requires no authentication and serves the same ERA5 product as the Copernicus Climate Data Store; replication of the dataset takes ~2 minutes on a standard internet-connected computer.

3. RESULTS

3.1 Topoclimatic signatures of the orographic amphitheatre (Biskra–Saida)

Figure 1. Topographic context of the Biskra orographic amphitheatre. SRTM 1-arcsec (~30 m) hillshade of the Aurès massif and the northern Saharan platform, with a north–

south elevation cross-section A–A′ (≈ 200 km, along ~5.7 °E) descending from the Aurès crest to the Saharan platform through Biskra, showing the basin geometry that shields the Zibans (Tolga–Biskra) from Mediterranean cold-air invasions.

(Figure regenerated from SRTM 1-arcsec tiles N34–N35 / E005–E006; supplied separately.)

The seven topoclimatic indices computed over 1990–2024 confirm every signature predicted by the basin-amphitheatre hypothesis; all contrasts go in the predicted direction, with overwhelming p-values (Table 2).

Table 2. Topoclimatic signatures of Biskra (Aurès basin, 87 m) versus Saïda (open plateau, 750 m), 1990–2024. Two-sample Welch t-test on annual values (n = 35).

Signature	Biskra	Saïda	Δ	p-value
Days/year Tmax > 40 °C	47.5	2.9	+44.6 (×17)	1.9×10^{-20}
Days/year Tmax > 42 °C	24.5	0.06	+24.4	8.8×10^{-15}
Days/year Tmax > 45 °C	6.5	0.0	+6.5	8.6×10^{-8}
Mean July–August Tmin (°C)	28.5	21.6	+6.9	2.7×10^{-38}
Summer DTR (°C)	12.1	13.9	−1.8	5.4×10^{-19}
Frost days/year (Tmin < 0 °C)	0.03	4.0	−4 days	3.6×10^{-7}
Absolute winter Tmin (°C)	+1.8	−1.5	+3.4	5.0×10^{-16}

Three counter-intuitive signatures deserve emphasis. The nocturnal thermal retention (July–August Tmin +6.9 C) is statistically the most overwhelming (p = 2.7e-38), reflecting daytime heat persistence through stable nocturnal stratification — the metaphorical “parabolic oven” effect. The reduced summer DTR (Biskra 12.1 C < Saida 13.9 C, p = 5.4e-19) despite Biskra’s much lower altitude is the thermodynamic signature of basin trapping, and runs counter to the naive intuition “lower elevation = larger DTR”. The near-absence of winter frost at Biskra (0.03 vs 4 days/year) reflects the blocking of Mediterranean cold-air invasions by the Aures. This pattern is qualitatively reproduced by other low-altitude Saharan sites (Touggourt 87 m, El Oued, Ouargla), while higher-altitude sites (Batna 1040 m, Tlemcen 850 m) follow the classical continental pattern, confirming the signature is the general regime of low-altitude Saharan basins rather than a local anomaly. Crucially, Saida lies at the same latitude (~34.8 °N) but on the high plateau (750 m) and supports no date-palm cultivation, isolating fine-scale topoclimate — not latitude — as the determinant of cultivar suitability.

Independent OGIMET station observations at Biskra (2019–2024) corroborate the ERA5 diurnal temperature range. The maturation-window DTR that enters the climatic-distance metric matches almost exactly — station 10.82 °C versus ERA5 10.87 °C over 207 September–October days — confirming that the diurnal-range predictor is not a reanalysis artefact. The same station record confirms — and amplifies — the summer-DTR contrast: basin Biskra averages 13.1 °C (n = 227 station-days, 2019–2024) against 17.5 °C at the iso-latitudinal open-plateau Saïda (n = 541), a station contrast of +4.4 °C versus +1.8 °C in ERA5. The station–reanalysis offset is itself site-dependent (≈ +1 °C at Biskra, ≈ +3.6 °C at Saïda), consistent with ERA5’s documented smoothing of fine-scale DTR over open terrain (Tarek et al. 2020); ERA5 therefore conservatively understates the basin-compression signal, and we base the contrast on its sign and station-confirmed magnitude rather than on absolute reanalysis values. Station data likewise corroborate the primary nocturnal-retention signature: mean July–August minimum temperature is +9.2 °C higher at Biskra than at Saïda in station observations (29.5 vs 20.3 °C), against +6.9 °C in ERA5.

3.2 Climatic distance to Tolga on the Maghreb panel (n = 13)

A multivariate linear regression of quality grade on the four standardised parameters yields R^2 = 0.685 but nested LOO R^2 = -0.36 — the classical overfitting signature with N = 13 and k = 4 predictors. The dominant coefficient (beta = +0.99 for P4, p = 0.011) is biologically aberrant: it predicts that increasing rainfall improves quality, contradicting date-palm phytopathology in arid conditions. Diagnostics: (i) the latitudes of the main sites span only ~3 deg, reducing linear discriminating power; (ii) the four predictors are moderately to strongly co-linear (VIF 2.48, 6.29, 6.82, 2.27; maximum pairwise |r| = 0.892 between DTR and RH), and the first two principal components capture 91.1% of the variance — an effective dimensionality near two; (iii) the lowest-quality sites (El Menia, Gabes) occupy opposite corners of the climatic space, violating the linear assumption. We report this failure as such: it is science working — we test, we falsify, we reformulate.
Univariate regression of quality grade on the multidimensional climatic distance to Tolga yields, for the 4D variant: R^2 = 0.568, nested LOO R^2 = 0.333 (slope p = 0.003), standardised slope = -0.587. The negative slope means quality decreases with climatic distance from Tolga, consistent with the Goldilocks hypothesis, and the nested LOO of 0.333 — against -0.36 for the over-parameterised linear model — reflects the robustness gained by parsimony (a one-parameter model has 11 degrees of freedom at N = 13). The 4D distance is the most generalisable of the five variants tested (Table 3).

Table 3. Predictive performance of five variants of the climatic-distance-to-Tolga model (Maghreb panel, n = 13). Leave-one-out values are leakage-free (nested): standardisation and reference recomputed on each training fold. The 4D variant is the most generalisable.

Variant	R^2	R^2adj	Nested LOO R^2	Slope	p (slope)
2D: DTR + RH	0.559	0.519	−0.005	−0.642	0.003
2D: GDD + RH	0.400	0.345	+0.175	−0.639	0.020
2D: GDD + DTR	0.321	0.259	+0.024	−0.511	0.044
3D: GDD + DTR + RH	0.458	0.409	+0.084	−0.522	0.011
4D: GDD + DTR + RH + precip	**0.568**	**0.529**	**+0.333**	**−0.587**	**0.003**

A crucial observation: the two minimum-quality sites (El Menia, Gabes, grade 2) occupy diametrically opposed positions in climatic space (Table 4). El Menia presents the highest DTR and lowest RH of the panel (hyper-aridity); Gabes the lowest DTR and highest RH (coastal hyper-humidity). That two opposite climatic regimes produce the same degraded class is strong evidence for the non-linear (Goldilocks) character of the climate–quality relationship.

Table 4. The El Menia–Gabès paradox: two grade-2 sites at opposite climatic extremes.

Site	Grade	DTR Sep–Oct	RH Sep–Oct	Precip	Regime
El Menia	2	12.87 °C	32.5% (min)	4.6 mm	Extreme desert: DTR ↑, RH

Site	Grade	DTR Sep–Oct	RH Sep–Oct	Precip	Regime
		(max)			↓
Tolga (ref)	5	11.13 °C	44.8%	27.3 mm	Cultivar optimum
Gabès	2	7.28 °C (min)	64.5% (max)	33.6 mm	Coastal humid: DTR ↓, RH ↑

3.3 Trans-Atlantic validation by held-out prediction, and tests of the optimum location

Floating-optimum test. To test whether the cultivar's quality optimum coincides with its documented origin rather than being merely assumed there, every panel site was used in turn as the reference of the distance metric and the resulting nested-LOO skill was recorded. Tolga ranked first of thirteen candidate optima (nested LOO $R^2 = 0.333$), tied with neighbouring Biskra (0.333) — the same Zibans basin, ~35 km away — followed by the other premium sites (Tozeur 0.20, Nefta 0.16), while the marginal sites as reference (El Menia, Gabes) gave strongly negative skill. The optimum therefore lands empirically on the Tolga–Zibans core, providing support for the origin-as-optimum hypothesis (this reduces, but does not fully remove, circularity, since Tolga's top grade is itself partly assigned on origin status; the non-circular content is that distance from the Tolga–Biskra core out-predicts distance from any other anchor). Significance of the predictive skill. A permutation test (grades shuffled, nested LOO recomputed) placed the observed nested LOO R^2 of 0.333 well into the tail of the null distribution (null median -0.35), giving $p = 0.005$ (rising to 0.011 once the model-selection step is folded into the permutation — the choice among the five candidate distance subsets is re-run within every shuffle, so the null distribution is that of the best-of-five statistic; 5000 permutations), confirming the signal is not an artefact of selecting the best-performing subset. The predictive signal is thus unlikely to arise by chance at this sample size. Resolution within the panel. The model strongly separates the optimum (Tolga) from climatically distant, low-grade sites; its quantitative resolution among the non-optimal sites is more modest: a leave-Tolga-out analysis (Tolga removed from the regression points while retained as the distance anchor) returns nested LOO $R^2 = 0.21$ on the twelve remaining sites. The framework is therefore best read as a single-optimum descriptor — "distance from the optimum degrades quality" — with moderate quantitative precision between intermediate sites, rather than a high-resolution quality predictor. Held-out trans-Atlantic prediction (Coachella). Coachella was excluded from both fitting and standardisation. Projected onto the $n = 13$ panel standardisation, it lies at a four-dimensional climatic distance to Tolga of 3.48; the $n = 13$-calibrated regression ($grade = -0.587 * d_{Tolga} + 4.54$) therefore predicts a grade of 2.5. Its independently market-anchored observed grade is 2 (prediction error +0.4). A model trained only on North-African sites thus places a Californian site at the marginal end of the commercial range without ever having seen it — an out-of-sample prediction consistent with the independently assigned grade on a separate continent (a single corroborating point, not a statistical validation). Competing-optimum and linear controls. A competitive regression on the distance to Coachella returned $R^2 = 0.015$ and nested LOO $R^2 = -0.76$ (slope $p = 0.68$), i.e. Coachella's climatic position carries essentially no predictive information for cross-panel quality — by contrast with d_{Tolga}. The concurrent four-predictor linear model, already falsified at n = 13 (nested LOO R^2 = -0.36), is the diagnostic signature of an over-fit linear specification applied to a non-linear, single-optimum surface. We retain the climatic-distance specification as the operative model. The fair comparison is to parsimonious alternatives (the 2D/3D distance variants and single-predictor models), among which the 4D distance is the most generalisable (Table 3).

Table 5. Summary of the corrected climatic-distance analysis (Maghreb fitting panel, n = 13), Coachella treated as an independent held-out prediction. All cross-validation is leakage-free (nested).

Metric (Maghreb panel, n = 13)	Value
R^2 in-sample (4D distance)	0.568
Nested (leakage-free) LOO R^2 (4D distance)	0.333
Permutation p (predictive skill)	0.005
Slope p (OLS)	0.003
Floating-optimum rank of Tolga	1 of 13 (tied with Biskra)
Nested LOO R^2 on non-anchor sites (Tolga removed)	0.21
Concurrent 4-predictor linear model, nested LOO R^2 (falsified)	−0.36
Held-out Coachella: predicted vs observed grade	2.5 vs 2

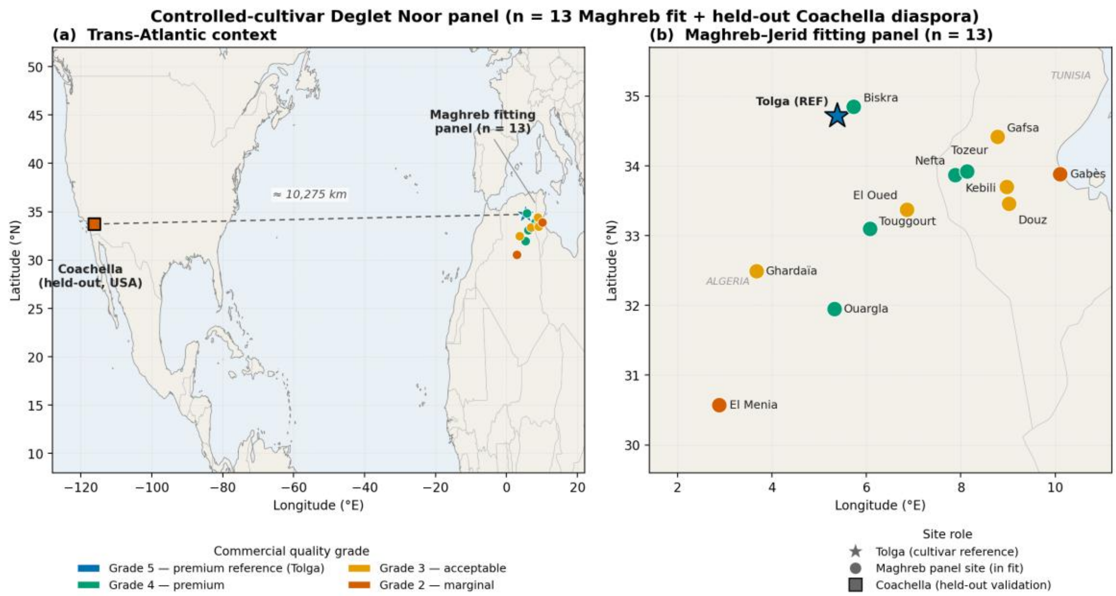

Figure 2. Geographical distribution of the controlled-cultivar Deglet Noor panel. (a) Trans-Atlantic context: the n = 13 Maghreb–Jerid fitting panel and the held-out Coachella Valley diaspora site (USA), ≈ 10,275 km from the cultivar origin at Tolga. (b) Maghreb–Jerid fitting panel. Marker colour encodes commercial quality grade (5 = premium reference at Tolga, to 2 = marginal; colour-blind-safe Okabe–Ito palette); marker shape encodes site role (star = Tolga reference; circle = Maghreb panel site used in fitting; square = Coachella, held out of both fitting and standardisation). Coordinates and grades as in Table 1. Basemap: Natural Earth (public domain).

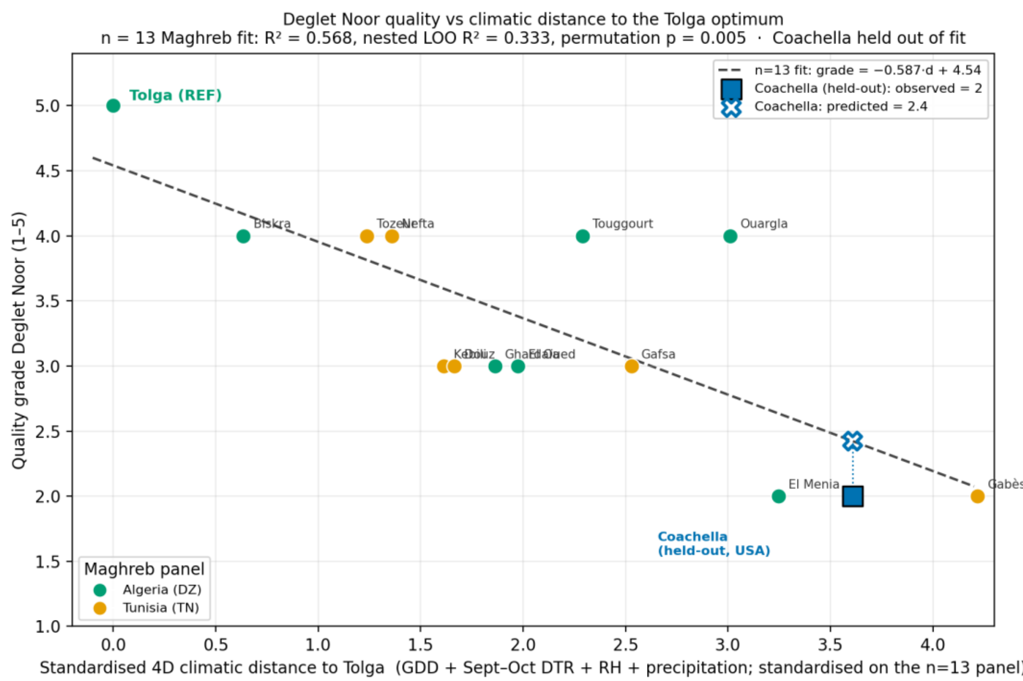

Figure 3. Quality grade versus standardised four-dimensional climatic distance to Tolga. Dashed line: regression fitted on the Maghreb panel only (n = 13; grade = −0.587·d + 4.54; R^2 = 0.568; nested LOO R^2 = 0.333; permutation p = 0.005). Coachella is held out of fitting and standardisation; its observed grade (square) and the n = 13 model prediction (×, 2.5) are shown. Tolga annotated REF at d = 0.

3.4 Empirical test of a climatological intuition (Tolga vs Tozeur)

The grade 5 assigned to Tolga (vs grade 4 to Tozeur) rests in part on field expertise (visible pit translucency through the pulp at Tolga, less common at Tozeur). A candidate climatological explanation is the higher residual atmospheric humidity of Mediterranean origin at Tozeur, owing to its proximity to the Gulf of Gabes (~150 km) and the Chott el Jerid. The Welch test on the 35 years of daily September–October data confirms this: Tozeur RH = 47.1% vs Tolga 44.8% (Delta = +2.3%, t = +5.84, p = 5.6e-9), while DTR is statistically identical (~11.1 C, $p = 0.42$) — the difference is not thermal. A modest humidity deviation (~2 percentage points) is thus consistent with the perceptible organoleptic difference, suggesting that small humidity deviations may suffice to degrade premium organoleptic fineness.

4. DISCUSSION

4.1 Translucency as the organoleptic anchor of the optimum

The cultivar name Deglet Noor ("date of light") refers to the optical translucency of premium-grade fruits, in which the pit becomes faintly visible through the flesh. This signature emerges only when sugar accumulation reaches its maximum while cellular maturation remains slow — a combination requiring substantial thermal accumulation and a wide diurnal temperature range during the maturation window, with controlled atmospheric moisture. The translucency criterion thus provides an organoleptic anchor for the climatic hypothesis: sites where the cultivar fails to develop translucency are predicted to lie at significant climatic distance from Tolga, bridging a millennial vernacular vocabulary of fruit quality with a quantitative biophysical framework.

4.2 The El Menia–Gabes–Coachella convergence and the Goldilocks non-linearity

At El Menia, where Deglet Noor was introduced from Tolga via Saharan trade routes, fruits retain identical morphology and reach higher sugar content but exhibit a flatter aromatic profile that disqualifies them from the premium grade. This dissociation of sugar accumulation and aromatic complexity is mirrored at Gabes, where coastal Mediterranean humidity produces softer, less concentrated fruit. The convergence of two diametrically opposite climatic regimes onto the same low grade — extreme aridity (El Menia) and coastal humidity (Gabes) — is direct empirical evidence for a non-linear, Goldilocks-type response, and is the strongest single test of the hypothesis on the Maghreb panel. Decomposing each site's climatic distance to Tolga by dimension (Supplementary Figure S7) shows that the marginal sites depart from the optimum along DIFFERENT axes: El Menia chiefly by dryness (precipitation), Gabes by humidity (RH and low DTR), and the held-out Coachella site by heat (GDD). The three marginal sites therefore converge on grade 2 not because they resemble one another, but because each lies far from Tolga along a different dominant axis (El Menia by dryness, Coachella by heat, Gabes by humidity); the genuinely opposite poles are aridity (El Menia and the held-out Coachella, which share low RH, low precipitation and high DTR) versus coastal humidity (Gabes) — a stronger demonstration of multidimensional non-monotonicity than a single pair. The decomposition also explains the limited within-panel resolution noted in Section 3.3: two dry but high-quality Algerian sites, Touggourt and Ouargla, are pushed far from Tolga mainly along the precipitation axis while remaining grade 4, which is why precipitation is the weakest predictor (see Section 4.5).

Because the four-dimensional climatic distance is non-negative, the cultivar origin necessarily lies at the boundary (d = 0) of the predictor range, so the quality–distance relationship can be observed only as a one-sided monotone decline; the two-sided structure of the underlying reaction norm is instead evidenced along individual axes, where climatically opposite extremes — arid El Menia and humid Gabes — flank the intermediate origin. Consistent with this, fitting explicit peaked forms to the quality–distance data gives no advantage over the linear model: an unconstrained quadratic, free to place its extremum anywhere, locates its maximum at the origin ($d^* \sim 0$) and does not improve out-of-sample skill (nested LOO $R^2 = 0.24$ versus 0.33 for the line), while origin-forced and Gaussian forms fit no better and lower predictive skill. The data therefore neither require nor support an interior optimum: quality is maximal at the origin and declines monotonically with distance, and the location of that optimum is established by the floating-optimum analysis rather than by the curvature of the fit.

4.3 Salinity as a contextual co-determinant

Adding ordinal irrigation-water salinity as an additive predictor to the climatic-distance model gave SCHEME-DEPENDENT and non-significant results on the $n = 13$ panel under leakage-free cross-validation. Relative to the climate-only baseline (nested LOO $R^2 = 0.333$): under the "passation" classification (Touggourt and Ouargla as moderate salinity) the combined model rose to nested LOO $R^2 = 0.478$, but the salinity term itself was not individually significant (residual–salinity slope -0.26, $p = 0.24$; Spearman rho = -0.45, $p = 0.12$); under the alternative Wadi Rhir classification (those two sites as high salinity, following Belghemmaz et al., 2018) the combined model FELL to nested LOO $R^2 = 0.193$, with a non-significant, sign-reversed salinity term (slope +0.02, $p = 0.91$; rho = -0.11, $p = 0.73$). Because the apparent contribution of salinity both depends on the hydrogeological classification chosen and never reaches individual significance at this sample size, we treat salinity as an unresolved contextual co-determinant rather than a robust additive predictor, and retain the climatic-distance model as the parsimonious operative specification. The held-out Coachella site offers a consistent line of evidence: under Colorado River water (moderate salinity) it reaches the same independently assessed grade 2 as El Menia (high-salinity continental aquifer) and Gabes (high-salinity coastal aquifer), arguing against a simple additive salinity effect. The Northern Sahara Aquifer System supplies the Maghreb panel oases through the Continental Intercalaire and the Complexe Terminal (Castany, 1982; Belghemmaz et al., 2018); total dissolved solids vary by an order of magnitude, from ~1–2 g/L in the Tolga–Biskra Zibans to >7 g/L in the Wadi Rhir region. Tremblay et al. (2011) found that even moderate increases in irrigation-water electrical conductivity (1.8 vs 4 dS/m) reduced fruit yield by 35–50% over six years; field observations at El Menia describe a sweeter taste with a flattened aromatic profile, consistent with the literature that high-salinity irrigation enhances sugar concentration while degrading organoleptic complexity. We interpret salinity as depressing quality only when compounded with a major climatic deviation from the Tolga optimum.

4.4 A reaction-norm interpretation and implications for production zones

The single-optimum framework is best understood as a quantitative operationalisation of the reaction-norm concept of evolutionary ecology (Schlichting & Pigliucci, 1998; Pigliucci, 2001): the phenotypic response of a fixed genotype to a continuous environmental gradient. In a quasi-clonally propagated cultivar (Battesti et al., 2018; Zarkouna et al., 2025) the genotype is invariant by construction, only the environment varies, and the realised phenotype (commercial grade) is the reaction norm. The documented response — a non-monotonic Goldilocks curve with a single optimum anchored on the origin — corresponds to a narrow, peaked reaction norm, contrasting with the broad-plateau norms of locally adapted wild species (Kawecki & Ebert, 2004; Savolainen et al., 2007; Aitken et al., 2008), and is consistent with ~700 years of essentially asexual propagation under stabilising selection in the Tolga–Zibans climate. Documented somaclonal variation (Devanand & Chao, 2003) is small relative to this fixed-genotype baseline and does not relocate the optimum. The held-out Coachella site provides a first quantitative test of whether the topoclimatic determinants identified on a Maghreb panel generalise across continents. Coachella lies at substantial four-dimensional climatic distance from Tolga (+812 C.d in cumulative GDD, +1.17 C in maturation DTR, -12.9 percentage points in maturation RH, -11.2 mm in September–October precipitation), reflecting the dry-continental Salton Trough regime, and departs from the optimum chiefly along the heat (GDD) axis. Its independently assessed grade of 2 matches the model prediction (2.5) from distance alone, supporting a single, narrow climatic optimum rather than a broad plateau. The diaspora site does not refute the framework; it constrains it.

4.5 Study limitations

The principal limitation concerns the response variable itself. The quality grade was assigned by expert judgement — the corresponding author for the Algerian sites, and the published commercial and agronomic literature for the Tunisian sites — rather than by blind sensory panels or instrumental measurement, and the grader was not blind to the origin-as-optimum hypothesis. Four features bound this risk: (a) every grade was fixed before, and independently of, the computed climatic distances, so the distance–quality regression cannot be circular by construction; (b) the central result is reported on rank statistics (Spearman rho = -0.68, Kendall tau = -0.59) that do not depend on the cardinal spacing of the ordinal scale; (c) the floating-optimum test is anchored on climatic distance rather than on Tolga's identity, and the climatically near-identical but separately graded Biskra (~35 km) ties Tolga for first while climatically distant premium sites do not — a pattern that an origin-labelling artefact could not produce; and (d) the held-out Coachella grade was assigned on independent commercial-market criteria, blind to the model prediction. Nonetheless, single-grader, non-blind scoring remains the principal potential bias at this sample size; instrumental anchoring of the scale — in particular quantitative measurement of mesocarp translucency, the cultivar's defining trait, together with total soluble solids on a subset of sites — and blind multi-evaluator grading are the priority robustness checks for future work.

(i) The fitting panel ($n = 13$) is modest, so the power of sensitivity analyses (salinity, climate x edaphic interaction) is intrinsically limited, and the out-of-sample LOO point estimate carries non-trivial uncertainty (permutation $p = 0.005$ nonetheless indicates a real signal). (ii) Most of the predictive skill derives from contrasting the optimum against distant low-grade sites; the leave-Tolga-out resolution among non-optimal sites is more modest (nested LOO $R^2 = 0.21$), so quantitative grade predictions between intermediate sites should be treated cautiously. (iii) Out-of-sample skill is sensitive to the maturation-window definition — nested LOO R^2 falls from 0.333 for September–October to 0.05 when August is included; the September–October window is justified a priori on physiological grounds (final Khalal -> Rutab -> Tamr ripening, August still being developmental), and its sensitivity is reported transparently (S2). (iv) The maturation-precipitation dimension is the weakest predictor: it conflates physically distinct rain regimes (a

North-American monsoon contribution at Coachella, Mediterranean frontal rain, and sparse Saharan rain) and pushes dry but high-quality Algerian sites far from Tolga; the framework is robust to its removal (Table 3). (v) The Coachella grade is anchored on commercial market positioning and trade literature rather than direct sensory grading, with possible commercial-optimism bias. (vi) ERA5 biases on RH and precipitation in arid climates (Tarek et al. 2020; Lavers et al. 2022) are mitigated by 35-year means, and an independent cross-check against MERRA-2 reanalysis reproduces the cross-site maturation-RH pattern used by the distance metric (Pearson r = 0.95, Spearman rho = 0.88 across the thirteen sites), with a systematic ~7-percentage-point dry offset that largely cancels under the standardisation of the distance (Supplementary S1). (vii) The assumption of perfect cultivar identity is an approximation given documented somaclonal variation (Devanand & Chao 2003). (viii) The 2050 projection (Section 4.7.1) is a first-order delta-method: it applies AR6-assessed sub-regional changes uniformly within the domain (rather than a model-resolved spatial field) and linearly extrapolates the regression beyond its calibration range (d_Tolga > 4 for several sites); the projection is therefore most reliable as the DIRECTION and ORDERING of change rather than as precise grade values for distant sites.

4.6 A framework offered as transferable to other terroir cultures

The climatic-optimum framework demonstrated here for Deglet Noor is, we hypothesise, transferable to other terroir-controlled cultivars where (i) the cultivar's geographical origin is documented; (ii) the cultivar is commercially produced across a climatic gradient;

and (iii) quality grading exists at a coarse but consistent scale. Candidate applications include viticulture cepages, coffee landraces in Ethiopian and Yemeni terroir systems, tea provenances of Darjeeling and Yunnan, and olive cultivars of the Mediterranean basin. Demonstrating transferability will require a proof-of-concept on at least one additional cultivar; we provide the open Open-Meteo / ERA5 workflow precisely so that such tests can be run on any internet-connected computer, removing a significant barrier to applied terroir science in regions with sparse meteorological networks. The held-out trans-Atlantic prediction reported here (Section 3.3) shows that the framework is at least not regionally idiosyncratic. The same distance-to-origin metric is being extended by our group to wild Saharan paleoendemic refugia — Cupressus dupreziana (Tassili) and Olea europaea subsp. laperrinei (Hoggar) (Selkh, in preparation).

4.7 Climate-change vulnerability

If the cultivar's optimum lies near Tolga's late-twentieth-century climate, the projected warming of the Saharan basin (intensifying summer maxima and possible compression of the diurnal temperature range as nights warm faster than days; IPCC AR6) implies a progressive drift away from this optimum. Premium production may then require cultural adaptation (shaded micro-irrigation, shifts in maturation-window management), cultivar substitution toward more thermally tolerant sub-clones, or geographical migration of premium production to higher-altitude or coastal-shielded oases. The held-out Coachella site already sits at the marginal grade despite established infrastructure, suggesting limited room for adaptive expansion further from the optimum without a quality penalty.

4.7.1 2050 projection: AR6 regional delta-method

To illustrate the projected drift of the optimum, we applied a regional delta-method based on the IPCC AR6 WGI assessed mid-century changes. For each of the thirteen Maghreb panel sites the 1990–2024 ERA5 baseline of each predictor was perturbed by the AR6-assessed sub-regional change under two scenarios: a uniform maturation warming, propagated to the growing-degree-day accumulation as $\Delta GDD = \Delta T \times 340$ growing days, together with the assessed Mediterranean–Saharan reductions in maturation relative humidity and precipitation and a slight compression of the diurnal range (SSP2-4.5: ΔT +1.9 °C, ΔRH -2.5 points, Δprecip -8 %, ΔDTR -0.2 °C; SSP5-8.5: ΔT +3.1 °C, ΔRH -4.0 points, Δprecip -15 %, ΔDTR -0.4 °C). The four-dimensional distance to Tolga was recomputed under each scenario, holding the present-day panel Tolga values as the immutable cultivar anchor, and the predicted grade was obtained from the recalibrated $n = 13$ regression ($grade = -0.587 * d_{Tolga} + 4.54$). The trans-Atlantic Coachella site, used here only as an independent validation, is not projected.

Figure 4. Projected mid-century (2050) commercial quality grade for the thirteen Maghreb panel sites (IPCC AR6 WGI assessed regional delta-method). Site-level grades are obtained by recomputing the four-dimensional climatic distance to Tolga under the AR6-assessed SSP2-4.5 and SSP5-8.5 changes (keeping the panel Tolga values as the immutable cultivar anchor) and applying the recalibrated $n = 13$ regression; the assessed deltas are uniform within the sub-region, so no spatial interpolation is implied. See §4.7.1.

(Figure regenerated as the AR6 delta-method site-level projection, $n = 13$ calibration, grade $= -0.587 \cdot d + 4.54$, colour-blind-safe palette; supplied separately.)

The projection points to three outcomes. (i) Tolga drifts away from its own historical optimum — by about -1.3 grade points under SSP2-4.5 and about -2.1 under SSP5-8.5: the site that anchored Deglet Noor for seven centuries is no longer climatically optimal by mid-century, its SSP5-8.5 climate approximating the present-day climate of Ouargla. (ii) A geographical migration of the optimum is implied: only Gafsa (currently sub-optimal at grade 3, displaced from Tolga chiefly along the humidity axis — its September–October relative humidity, 54.2%, sits 9.4 points above Tolga and is the panel's second-highest after Gabes) shows positive drift as Mediterranean moisture declines toward the Tolga optimum, so the Tunisian Jerid–Gafsa corridor emerges as the most likely 2050 host of premium-grade production; Gabes retains essentially marginal grade under both scenarios. (iii) Collapse of the commercial landscape under high warming: nine of the thirteen Maghreb sites drop below grade 3 under SSP2-4.5, and twelve of thirteen under SSP5-8.5. The qualitative direction of this drift is robust — it follows directly from the AR6-assessed Saharan summer warming and Mediterranean drying (IPCC AR6, Chapters 11–12), independently of the precise delta magnitudes — so the adaptive responses identified in Section 4.7 appear urgent rather than optional under high-emissions trajectories. These projections carry the residual limitations listed in Section 4.5(viii).

5. CONCLUSIONS

1. The Biskra–Saida iso-latitudinal contrast reveals a topoclimatic signature of the orographic basin-amphitheatre: seven independent indices confirm the hypothesis with each $p < 1e\text{-}6$ (the strongest at 2.7×10^{-38}) over 35 years of ERA5 data. The most diagnostic signature is the nocturnal thermal retention (July–August Tmin +6.9 °C, $p = 2.7 \times 10^{-38}$); the reduced summer DTR, counter-intuitive given the elevation contrast, points the same way.
2. On a controlled-cultivar Maghreb panel ($n = 13$), Deglet Noor quality follows a single-optimum pattern, declining monotonically with four-dimensional climatic distance from the cultivar's origin (Tolga). The 4D distance captures 33% of out-of-sample variance under leakage-free nested cross-validation (permutation $p = 0.005$) and is the most generalisable of five candidate models.
3. A floating-optimum analysis places Tolga (tied with neighbouring Biskra) first of thirteen candidate optima, providing evidence that the cultivar's quality optimum coincides with its documented origin — support that reduces, though does not fully remove, circularity, since Tolga's top grade is itself partly assigned on origin status.
4. A trans-Atlantic diaspora site (Coachella), held out from fitting and standardisation, is predicted at grade 2.5 from distance alone against an independent observed grade

of 2 — an out-of-sample prediction consistent with the independently assigned grade across continents (a single corroborating point rather than a validation). “The cultivar travelled; the optimum did not.”

5. Three grade-2 sites occupying very different climatic positions — El Menia (dryness), Gabes (humidity), Coachella (heat) — converge on the same marginal grade by departing from the optimum along different dimensions, the most direct evidence of the non-linear character of the response. Field observation of translucency as a premium marker, with the “sweet but degraded flavour” phenotype at El Menia, converges with the salinity literature to suggest a climate–edaphic co-determination, without a simple additive salinity effect.
6. An AR6 regional delta-method projection implies that Tolga itself drifts about 1.3–2.1 grade points from its own historical optimum by 2050 (n = 13 calibration), with the geographical optimum migrating toward the Tunisian Jerid–Gafsa corridor; under SSP5-8.5, 12 of the 13 Maghreb panel sites fall below grade 3.

The methodology is openly replicable (Open-Meteo / ERA5 / public scripts), removing a major barrier for terroir science in regions with sparse meteorological networks, and is offered as a transferable hypothesis for other terroir-controlled cultivars where cultivar origin is documented.

CREDIT AUTHOR STATEMENT

Chouaib Selkh: Conceptualization, Methodology, Software, Formal analysis, Data curation, Investigation, Visualization, Writing — original draft. Samia Bissati: Investigation (field observation of Deglet Noor commercial quality at Ouargla, 2024–2026), Supervision, Validation, Writing — review & editing. Abdelmadjid Chehma: Investigation (field observation at Ghardaia, 2024–2026), Supervision, Validation, Writing — review & editing. All authors have read and approved the final manuscript.

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DATA AND CODE AVAILABILITY

All Python scripts, the panel CSV dataset, and computed climatic parameters are archived on Zenodo (DOI: 10.5281/zenodo.21399151) under a CC-BY-4.0 license. The repository includes the controlled-cultivar panel data, the daily ERA5 extracts (1990–2024) for the panel sites, the held-out Coachella extract and the two climatic controls, and all Python scripts — including the leakage-free nested cross-validation, permutation and floating-optimum analyses, the bi-optimum control, the held-out diaspora prediction, the AR6 delta-method projection and figure generation — together with a README describing how to reproduce all figures and results. ERA5 reanalysis data are freely available from the Copernicus Climate Change Service (C3S) Climate Data Store (https://cds.climate.copernicus.eu) and via the Open-Meteo API. SRTM 1-arcsec (~30 m) elevation data are available via the AWS Terrain Tiles open dataset and via OpenTopography; Natural Earth vector data are in the public domain. Production statistics were obtained from FAOSTAT (https://www.fao.org/faostat) and the Office National des Statistiques (Algeria). Complete replication runs in ~2 minutes on standard hardware.

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COMPETING INTERESTS

The authors declare no competing interests.

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SUPPLEMENTARY INFORMATION (planned for final submission)

- S1. OGIMET station validation for Biskra (maturation diurnal-temperature-range 10.82 vs ERA5 10.87 °C, n = 207 station-days) and Saïda, tabulated in Table S1; and an independent MERRA-2-vs-ERA5 validation of the September–October relative-humidity baseline (site-by-site comparison; mean bias -7.1 points, RMSE 7.5 points, Pearson r = 0.95, Spearman rho = 0.88), confirming the cross-site RH ordering used by the climatic-distance metric. The same station validation extends to the summer topoclimatic indices: the iso-latitudinal Biskra–Saïda diurnal-temperature-range contrast (station +4.4 °C; Biskra 13.1 °C, n = 227 station-days, versus Saïda 17.5 °C, n

= 541) and the July–August nocturnal-minimum contrast (station +9.2 °C; 29.5 vs 20.3 °C) both confirm and exceed their ERA5 counterparts (+1.8 °C and +6.9 °C), indicating that ERA5 conservatively understates the basin-amphitheatre signal (Biskra WMO 60525; Saïda WMO 60536; OGIMET, 2019–2024).

- S2. Sensitivity to the maturation window: an August–October window versus the adopted September–October window (in-sample R^2 stable; nested LOO R^2 = 0.05 vs 0.33), confirming the September–October window.
- S3. Climatic-regression residuals against ordinal salinity classification — two variants (passation, Wadi Rhir).
- S4. Full table of the seven topoclimatic indices for the seven main Algerian stations.
- S5. "Naive" 4-parameter aggregate scoring rejected — heatmap, radar and bar-ranking on 22 global stations.
- S6. Permutation-test null distribution and floating-optimum ranking of all 13 candidate optima.
- S7. Per-dimension decomposition of the climatic distance to Tolga (file: figS_distance_decomposition.png). The three marginal sites depart from the optimum along different axes — Coachella by heat (GDD), El Menia by dryness (precipitation), Gabes by humidity (RH/DTR).