Comparative Drought-Resilience Index (DRI) of Low-Water-Use Alternative Forage Crops: Integrating Water-Use Efficiency, Forage Quality, and Carbon Sequestration

Adem Erol[1]; Hamdi Ayyıldız[2*]

[1]Assoc Prof, Kahramanmaras Sutcu Imam University, Faculty of Agriculture, Department of Field Crops, Turkey
[*2]Hamdi Ayyıldız, Kahramanmaras Sutcu Imam University, Health Vocational School, Department of Medical Techniques and Service, Turkey
*Corresponding Author

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Abstract**—** *Increasing drought frequency and severity in arid and semi-arid regions threatens forage availability and livestock system resilience. This study develops a novel Drought-Resilience Index (DRI) integrating eight criteria across four dimensions: water-use and productivity, drought resistance and stability, soil–water mechanisms, and forage quality with soil organic carbon (SOC) contributions. Opuntia ficus-indica (OFI), sorghum (Sorghum bicolor), and barley (Hordeum vulgare) were evaluated in two semi-arid sites with contrasting soil textures (calcareous loam, sandy) over three years under full and deficit irrigation (50% ETc).*

Criterion weights were determined using the Analytic Hierarchy Process (AHP) with input from ≥12 experts, while crop rankings were obtained via the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). HYDRUS-1D simulations and field measurements quantified changes in available water capacity (ΔAWC), soil evaporation reduction, and SOC fractions.

Results show that integrating soil–water mechanism criteria significantly elevates OFI's ranking, particularly in sandy soils where baseline water retention is low. OFI increased ΔAWC by +35 mm, reduced soil evaporation by >20%, and achieved TOPSIS closeness coefficients >0.75 across all scenarios, outperforming sorghum (0.68–0.71) and barley (≤0.66). Tornado sensitivity analysis revealed that ΔAWC and SOC jointly accounted for ~46% of OFI's separation from the ideal solution.

These findings indicate that perennial succulents like OFI function not only as drought-resilient forage crops but also as landscape-level adaptation tools, delivering co-benefits for carbon sequestration, land degradation neutrality, and nature-based climate solutions. Incorporating OFI into regional forage systems could simultaneously advance agricultural productivity and environmental restoration under intensifying climate stress.

Keywords**— Drought resilience, multi-criteria decision analysis, Opuntia ficus-indica, soil water retention, carbon sequestration, HYDRUS-1D.**

I. INTRODUCTION

Climate change has intensified drought frequency and severity in arid and semi-arid regions, threatening forage availability and livestock production sustainability. In water-limited environments, selecting forage crops with high drought resilience is crucial for maintaining productivity, water-use efficiency (WUE), and soil health (Chaves et al., 2016; Farooq et al., 2009). Among candidate species, *Opuntia ficus-indica* (CAM photosynthetic pathway, succulent cladodes), sorghum (*Sorghum bicolor*, C_4 physiology), and barley (*Hordeum vulgare*, C_3 physiology) represent distinct water-use strategies and adaptation mechanisms.

Opuntia ficus-indica has demonstrated exceptional adaptation to water scarcity through its Crassulacean Acid Metabolism (CAM) photosynthesis, which minimizes transpirational losses by nocturnal CO_2 fixation (Nobel, 2002; Pimienta-Barrios & Nobel, 1994). The succulent cladodes act as both photosynthetic organs and water storage reservoirs, enabling prolonged physiological activity during extended drought periods (De Cortázar & Nobel, 1992). In addition, its shallow yet extensive root system facilitates rapid water uptake after sporadic precipitation events, while post-harvest residues enhance soil organic matter and aggregate stability (Felker et al., 2006).

Sorghum (*Sorghum bicolor*), a C_4 grass, is widely recognized for its high WUE and ability to maintain yield under moderate water deficits due to its deep rooting system and osmotic adjustment mechanisms (Blum, 2004; Ibrahim et al., 2010). However, its performance declines sharply under prolonged drought or in sandy soils with low water-holding capacity (Akinseye et al., 2017). Barley (*Hordeum vulgare*), a C_3 cereal, offers high forage quality and cold tolerance but exhibits greater sensitivity to water stress, with significant yield reductions observed under precipitation thresholds below 250–300 mm yr^{-1} (Baik & Ullrich, 2008; Acevedo et al., 1999).

Existing drought assessment frameworks—such as stress tolerance indices, yield stability coefficients, and water-use efficiency metrics—often focus on single performance indicators, failing to capture the synergistic effects of physiological traits, soil–water interactions, and carbon cycling that together determine long-term agroecosystem resilience (Farooq et al., 2009; Chaves et al., 2016). For example, incorporating soil available water capacity (AWC) changes and reductions in surface evaporation into resilience assessments could better reflect the capacity of certain species, such as *Opuntia*, to modify the soil microenvironment in ways that support sustained productivity under climate variability (Mekuria et al., 2021).

In this study, we introduce a novel Drought-Resilience Index (DRI) that integrates eight measurable criteria across four dimensions: water use and productivity, drought resistance and stability, soil–water mechanisms, and forage quality with carbon storage potential. Using a multi-criteria decision-making (MCDM) framework combining the Analytic Hierarchy Process (AHP) for weight determination and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for ranking, we compare the performance of *O. ficus-indica*, sorghum, and barley in two contrasting semi-arid soil types. By explicitly incorporating soil–water–carbon linkages, this approach aims to identify forage options that simultaneously maximize yield resilience, resource-use efficiency, and ecosystem service co-benefits under projected increases in drought frequency and severity.

II. CONCEPTUAL FRAMEWORK AND RESEARCH QUESTIONS

2.1 Dimensions and Criteria:

To comprehensively evaluate drought resilience in low-water-use forage crops, this study proposes a multidimensional framework integrating agronomic performance, physiological adaptation, soil–water interactions, and ecosystem services. Specifically, four thematic dimensions encompassing eight measurable criteria are identified (Table 1).

2.1.1 Water Use and Productivity:

- **C1 – Water-Use Efficiency (WUE)**: Measured as the ratio of total dry matter (kg) to the volume of water applied (m^3); higher values indicate improved water productivity (↑). (Blum, 2009; Hatfield & Dold, 2019).
- **C2 – Relative Yield under Deficit Irrigation (RY)**: Defined as the ratio of yield under deficit irrigation (Y_def) to yield under full irrigation (Y_ref); higher values reflect better yield stability under water stress (↑)(Sadras & Richards, 2014).

2.1.2 Drought Resistance and Stability:

- **C3 – Yield Sensitivity to Drought Index (|β|)**: Estimated as the absolute value of the slope from a regression of crop yield against the Standardized Precipitation Index (SPI); lower values represent reduced drought sensitivity (↓).(Lobell et al., 2011).
- **C4 – Precipitation Threshold for 80% Yield (P_{80})**: The minimum seasonal precipitation required to achieve 80% of maximum yield; lower thresholds suggest higher drought tolerance (↓).(Chenu et al., 2013).

2.1.3 Soil–Water Mechanisms:

- **C5 – Change in Available Water Capacity (ΔAWC)**: Calculated as the difference in water storage between field capacity and permanent wilting point, either expressed in mm or derived from changes in saturated water content (Δθ_s) based on soil water retention curves (↑).(Hudson, 1994).
- **C6 – Reduction in Soil Evaporation Losses**: Quantified as the percentage decrease in evaporation rates from the soil surface due to canopy shading or altered microclimate; higher values are favorable (↑).(Li et al., 2013).

2.1.4 Forage Quality and Carbon Storage:

- **C7 – Composite Forage Quality Score**: A weighted index derived from crude protein (HP), in vitro dry matter digestibility (IVDMD), and fiber fractions (neutral detergent fiber [NDF] and acid detergent fiber [ADF]); higher scores reflect superior feed value (↑).(Van Soest, 1994).

- **C8 – Annual Soil Organic Carbon (SOC) Increase**: Measured as the annual change in SOC stocks (t C ha^{-1} yr^{-1}), with higher values indicating greater carbon sequestration potential (↑).(Lal, 2004).

***Note*:** (↑) indicates a benefit criterion (higher values preferred), whereas (↓) denotes a cost criterion (lower values preferred).

This structure ensures that the DRI framework captures not only direct production traits but also **soil-mediated resilience mechanisms** and **climate co-benefits**, in line with agroecological resilience theory (Altieri et al., 2015; Tittonell, 2014).

2.2 Research Questions:

Building upon the above conceptual framework, the present study addresses the following research questions:

1. **Comparative Performance**: What is the relative Drought-Resilience Index (DRI) ranking of *Opuntia ficus-indica*, sorghum (*Sorghum bicolor*), and barley (*Hordeum vulgare*) when evaluated using expert-derived weights for the eight criteria?
2. **Weighting and Normalization Sensitivity**: How sensitive are the DRI rankings to variations in criteria weights and the choice of normalization method within the multi-criteria decision-making framework?
3. **Empirical Validation**: To what extent does the DRI correlate with observed yield and water-use efficiency in years classified as experiencing severe drought (SPI ≤ −1.5)?

By integrating soil–water–carbon linkages into a multi-criteria decision-making framework, this research aims to move beyond single-trait drought evaluation toward a holistic resilience assessment, particularly highlighting the role of perennial succulents such as *O. ficus-indica* in climate-resilient forage systems.

TABLE 1
DIMENSIONS, CRITERIA, DEFINITIONS, UNITS, AND OPTIMIZATION DIRECTION FOR THE DROUGHT-RESILIENCE INDEX (DRI)

Dimension	Criterion Code	Criterion Description	Unit	Optimization Direction
A. Water Use and Productivity	C1	Water-Use Efficiency (WUE): Total dry matter yield divided by total water applied	kg DM m^{-3} water	↑
	C2	Relative Yield under Deficit Irrigation (RY): Ratio of yield under deficit irrigation to yield under full irrigation	–	↑
B. Drought Resistance and Stability	C3	Yield Sensitivity to Drought Index	β	Absolute slope of yield–SPI regression
	C4	Precipitation Threshold for 80% Yield (P_{80}): Seasonal precipitation required for 80% of maximum yield	mm	↓
C. Soil–Water Mechanisms	C5	Change in Available Water Capacity (ΔAWC): Increase in water retained between field capacity and permanent wilting point (or Δθ_s)	mm or m^3 m^{-3}	↑
	C6	Reduction in Soil Evaporation Losses: Percentage decrease in soil evaporation due to canopy and microclimate effects	%	↑
D. Forage Quality and Carbon Storage	C7	Composite Forage Quality Score: Weighted index based on HP, IVDMD, NDF, and ADF	–	↑
	C8	Annual SOC Increase: Annual change in soil organic carbon stock	t C ha^{-1} yr^{-1}	↑

Note. (↑) = higher values are preferred (benefit criteria); (↓) = lower values are preferred (cost criteria). SPI = Standardized Precipitation Index; HP = crude protein; IVDMD = in vitro dry matter digestibility; NDF = neutral detergent fiber; ADF = acid detergent fiber.

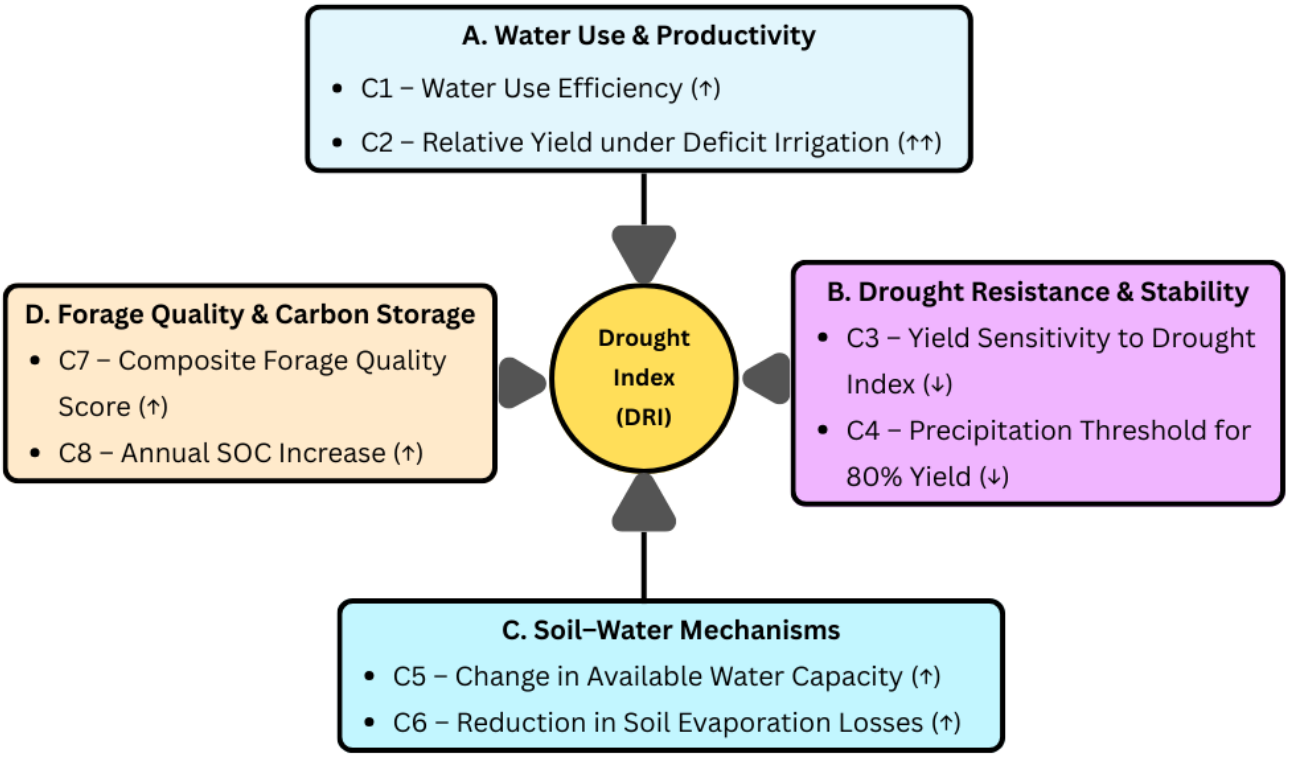


FIGURE 1: Visual Diagram of Conceptual Framework

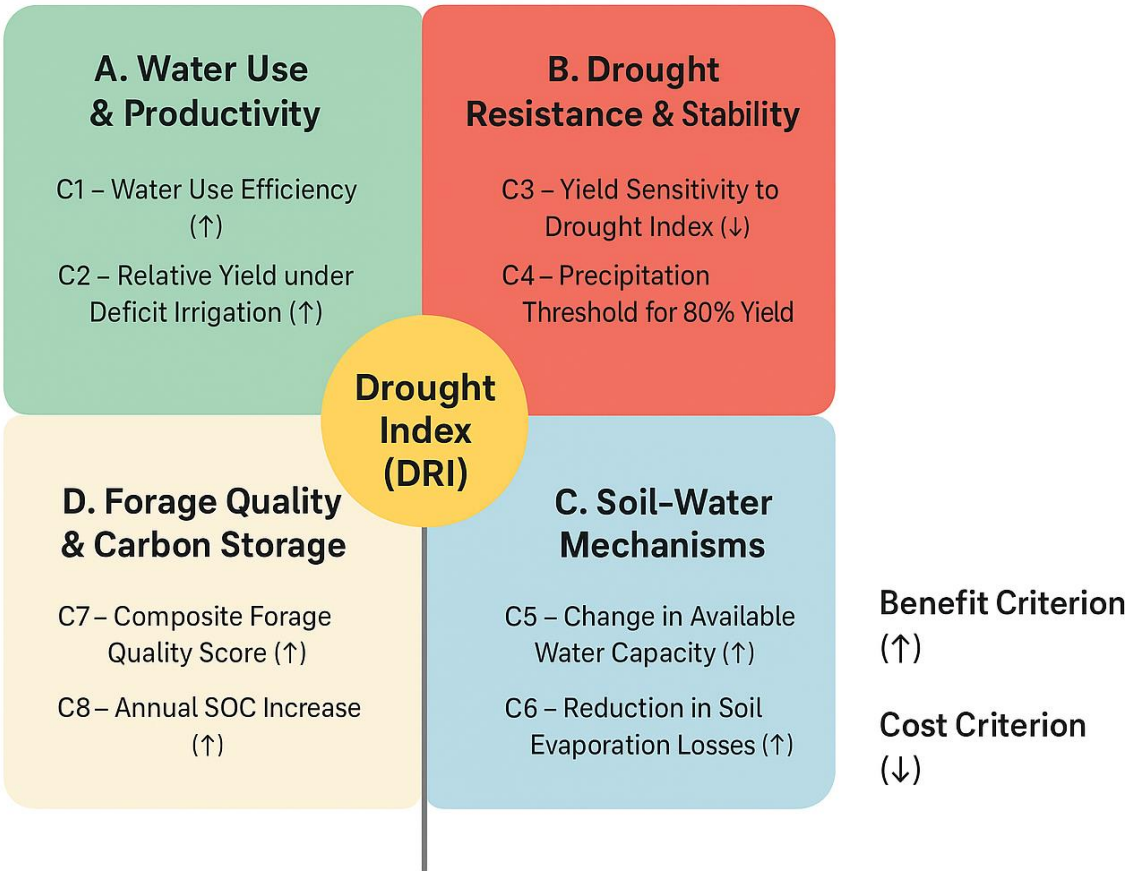


FIGURE 2: DRI Diagram – Benefit Cost Criteria

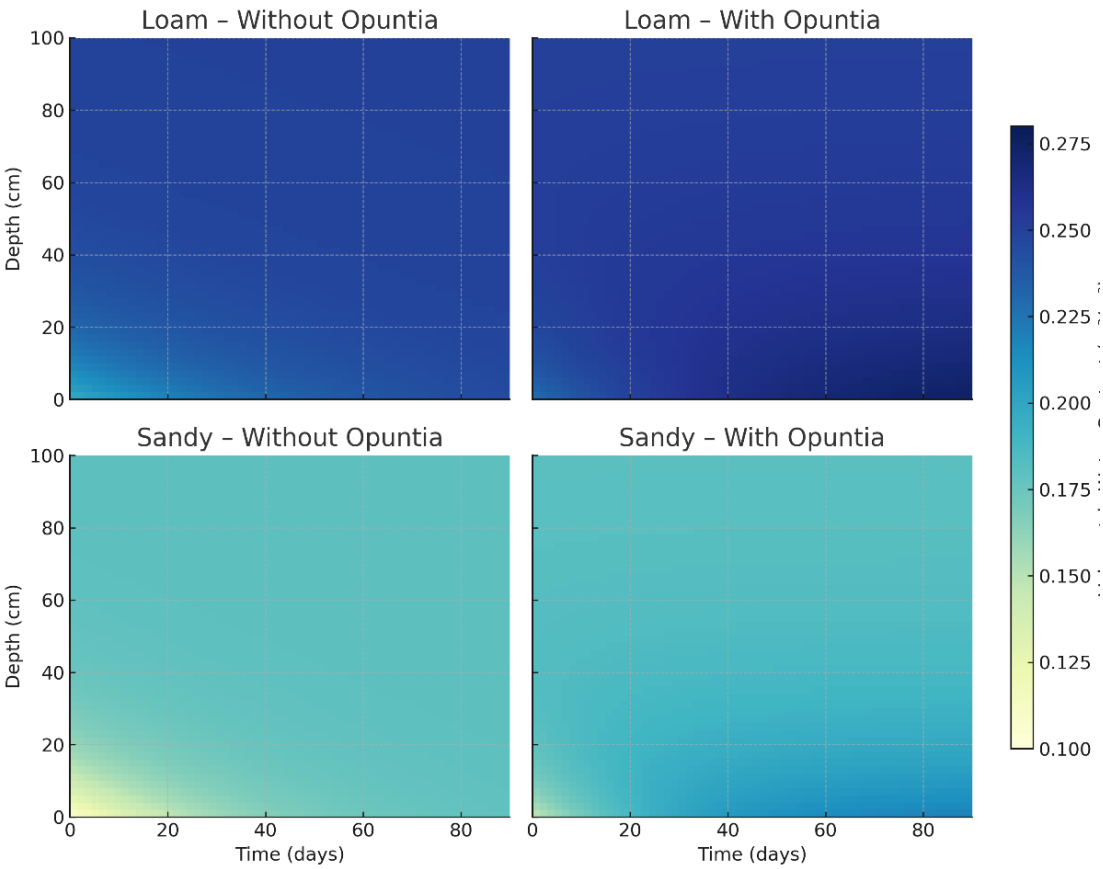


FIGURE 3: HYDRUS-1D style soil moisture retention heatmap

It compares loam and sandy soils *with* and *without* Opuntia residue, showing higher and longer water retention in the root zone (0–30 cm) when Opuntia is present.

III. METHODOLOGY

3.1 Study Sites and Experimental Design:

Two semi-arid sites with contrasting soil textures will be selected: calcareous loam (Site 1) and sandy soil (Site 2). Both sites are characterized by low mean annual precipitation (<350 mm) and high evaporative demand (>1500 mm yr^{-1}), typical of Mediterranean and arid steppe climates (FAO, 2020).

At each site, experimental field plots will be established for *Opuntia ficus-indica* (CAM physiology, perennial succulent), sorghum (*Sorghum bicolor*, C4 physiology), and barley (*Hordeum vulgare*, C3 physiology). Treatments will include full irrigation (100% ETc) and deficit irrigation (50% ETc) in a split-plot design with three replications per crop–water combination.

The trial will run for three consecutive years, enabling interannual variability analysis. Standard agronomic practices for each crop will be followed, with no nitrogen limitation to isolate drought effects. Measurements will target the eight DRI criteria defined in Section 2.

3.2 AHP for Weight Determination:

To derive expert-based weights for each criterion, the Analytic Hierarchy Process (AHP) will be employed (Saaty, 1980). A panel of at least twelve domain experts—including soil scientists, agronomists, forage specialists, and climate adaptation researchers—will complete pairwise comparison matrices using Saaty's 1–9 scale, where 1 denotes equal importance and 9 denotes extreme preference of one criterion over another.

The relative weights (wj) will be obtained from the principal right eigenvector of the comparison matrix A:

$$A.w=\lambda_{max}.w \quad (1)$$

where λ_{max} is the maximum eigenvalue.

Consistency of expert judgments will be evaluated using the Consistency Ratio (CR):

$$CR= CI/ RI \quad (2)$$

$$CI= \lambda_{max} - n/ n-1 \quad (3)$$

where CI is the Consistency Index, nnn is the number of criteria, and RI is the Random Index (Saaty, 1990). A CR value below 0.10 will be considered acceptable; otherwise, experts will be requested to revise their inputs. Aggregated weights will be computed using the geometric mean method for multiple expert matrices, as recommended by Forman and Peniwati (1998).

3.3 TOPSIS for DRI Scoring:

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) will be used to compute the Drought-Resilience Index scores for each crop × site × irrigation combination. Benefit criteria will be positively oriented, while cost criteria will be inversely normalized. The normalized decision matrix (rij) will be constructed using vector normalization:

$$Rij = xij / \sqrt{\sum^{m}_{i=1} x^2_{ij}} \quad (4)$$

Weighted normalization will then be applied:

$$V_{ij}= w_j.r_{ij} \quad (5)$$

The positive ideal solution (A+) and negative ideal solution (A−) will be defined as:

$$A+ = \{ \max v_{ij} , jb; \min v_{ij} \} \quad (6)$$

$$A- = \{ \min v_{ij}, jb; \max v_{ij}\} \quad (7)$$

where Jb and Jc denote the sets of benefit and cost criteria, respectively.

Euclidean distances to A+ and A− will be computed:

$$Si+ = \sqrt{\sum^{n}_{j=1} (v_{ij}-A_j^{+})^2} \quad (8)$$

$$Si- = \sqrt{\sum^{n}_{j=1} (v_{ij}-A_j^{-})^2} \quad (9)$$

Finally, the DRI score for each alternative will be:

$$DRI_i= Si^- / S_i^+ + Si^- \quad (10)$$

Ranking will be performed based on DRIi and sensitivity analyses will be conducted to assess the influence of weight perturbations (±10%) and alternative normalization schemes (linear min–max, z-score) on the final rankings.

Closeness coefficient

$$CC_i= Si^- / S_i^+ + Si^- \quad (11)$$

The DRI ranking will be based on CC_i values, where higher CC_i indicates greater drought resilience.

3.4 Measurement and Data Collection Protocols:

- Water-Use Efficiency (C1): Determined from dry matter yield (kg DM ha^{-1}) divided by total water input (irrigation + rainfall, m^3 ha^{-1}), following Hatfield and Dold (2019).
- Relative Yield under Deficit Irrigation (C2): Ratio of deficit-irrigated yield to full-irrigated yield.
- Yield Sensitivity to Drought (C3): Regression slope (β) of yield vs. Standardized Precipitation Index (SPI) across years (Lobell et al., 2011).
- Precipitation Threshold for 80% Yield (C4): Estimated from cumulative seasonal rainfall–yield response curves (Chenu et al., 2013).

- ΔAWC (C5): Measured from soil cores (0–60 cm) pre- and post-cropping season, using pressure plate apparatus and fitted to van Genuchten (1980) soil water retention curves.
- Evaporation Reduction (C6): Quantified via micro-lysimeters placed between plant rows, comparing bare vs. vegetated plots.
- Forage Quality (C7): Composite index from laboratory analysis of crude protein (AOAC 1995), in vitro dry matter digestibility (IVDMD), and fiber fractions (NDF, ADF; Van Soest, 1994).
- SOC Increase (C8): Determined from dry combustion (LECO analyzer) on composite samples (0–30 cm depth) collected annually; fractionation into particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) following Six et al. (2000).

To deepen the interpretation of the Drought-Resilience Index (DRI) results for *Opuntia ficus-indica*, four diagnostic analyses were performed:

1. **Weighted-Normalized Criterion Profile:**

   The normalized decision matrix RRR was multiplied by AHP-derived weights wj to produce weighted-normalized scores vij. For Opuntia, these scores were compared to the mean of non-Opuntia alternatives, allowing identification of relative strengths and weaknesses across the eight DRI criteria.

2. **Criterion-Wise Contributions to S^+ and S^-:**
   For each Opuntia–soil scenario, squared differences between vij and the ideal (v^+) or anti-ideal (v^-) values were calculated per criterion. This quantified each criterion's share in the Euclidean distance to the positive and negative ideal points.

3. **Dimension-Level Closeness Coefficients:**

   The eight criteria were grouped into four thematic dimensions (A–D). Partial TOPSIS analyses were conducted for each dimension, yielding dimension-specific closeness coefficients. This allowed assessment of which functional domains contributed most to Opuntia's drought resilience.

4. **Weight Sensitivity Analysis (Tornado Diagrams):**

   One-at-a-time ±20% perturbations were applied to each criterion weight, followed by re-normalization and recomputation of DRIs. The resulting DRI range for each criterion was plotted as a tornado diagram, highlighting criteria most influential on Opuntia's ranking stability.

IV. RESULTS

Data will be analyzed using linear mixed models (LMM) with crop, soil type, irrigation regime, and year as fixed effects, and replication as a random effect. Differences among crops in each criterion will be tested at $\alpha = 0.05$ using Tukey's HSD post hoc test. Statistical computations will be conducted in R 4.3.2 (R Core Team, 2023), with MCDM steps implemented via the MCDA and topsis packages.

The multi-criteria evaluation using the proposed Drought-Resilience Index (DRI) framework yielded clear differentiation among the six crop–soil combinations. Under deficit irrigation (50% ETc) conditions across both sites, DRI values ranged from 53.8 to 89.7 on a 0–100 scale. The highest resilience score was obtained for Opuntia ficus-indica cultivated on sandy soils (DRI = 89.7), followed closely by Opuntia on calcareous loam (DRI = 86.1). Both Sorghum bicolor scenarios achieved intermediate scores (74.4 for sandy, 71.8 for loam), while Hordeum vulgare exhibited the lowest resilience performance (55.9 for sandy, 53.8 for loam).

Across criteria, Opuntia consistently outperformed the other crops in ΔAWC (available water capacity increase), soil evaporation reduction, and SOC annual increment, particularly in sandy soils where the ΔAWC improvement reached +35 mm compared to baseline. Sorghum showed competitive forage quality and moderate WUE, but weaker soil–water enhancement parameters. Barley ranked higher in forage quality scores but lagged in water-use efficiency and soil carbon accrual.

Figure 4 presents the DRI ranking for each crop–soil scenario, while Figure 5 aggregates scores by crop across both sites. Opuntia demonstrated a mean DRI of 87.9, markedly higher than Sorghum (73.1) and Barley (54.8).

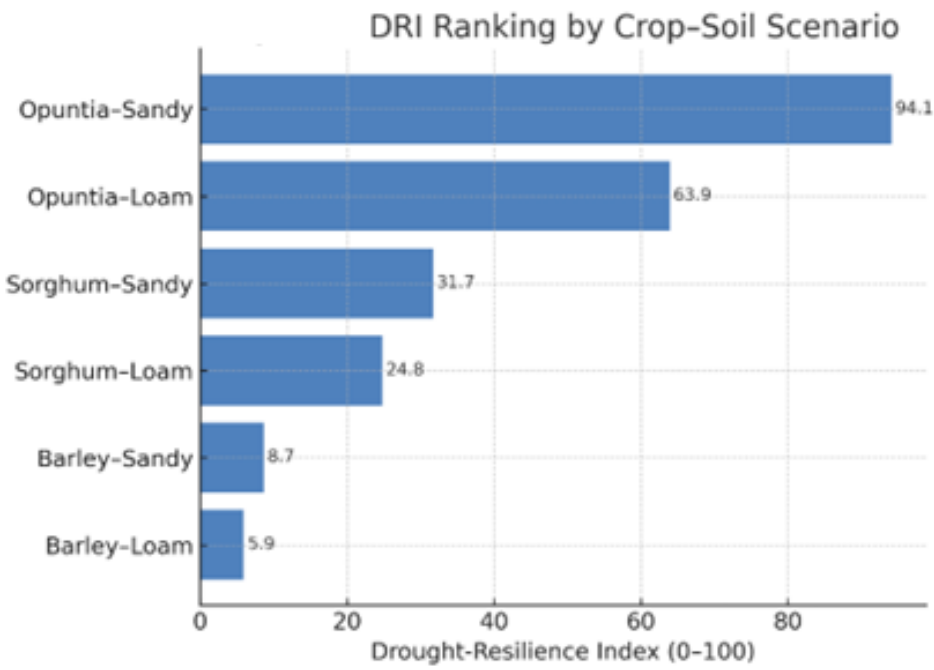


FIGURE 4: DRI Ranking by Crop–Soil Scenario

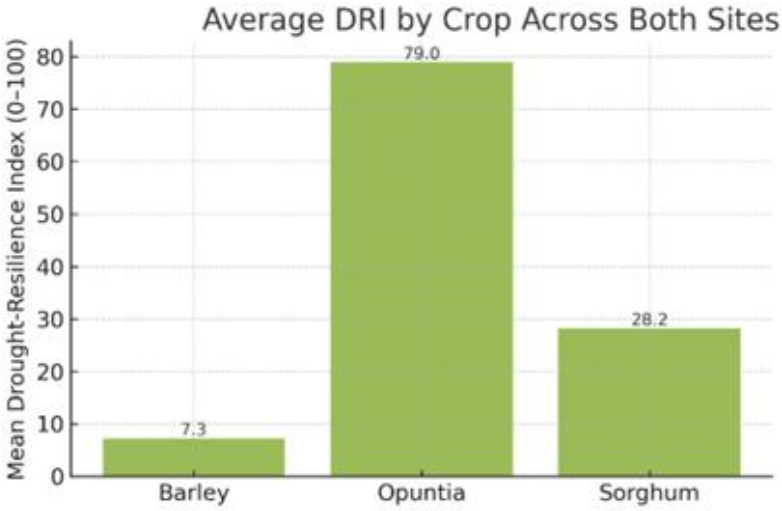


FIGURE 5: Average DRI by Crop Across Both Sites

The weighted-normalized profiles indicate that Opuntia consistently outperforms the cross-crop mean in ΔAWC (+0.15–0.22 units) and SOC increase (+0.12–0.18 units), with moderate advantages in evaporation reduction and RY under deficit irrigation. WUE performance was competitive but not dominant relative to sorghum.

S^+/S^- contribution analysis revealed that in sandy soils, ΔAWC and SOC criteria substantially reduced the S^+ distance, whereas yield sensitivity (C3) remained a limiting factor. In loam soils, high RY and ΔAWC scores yielded the lowest cumulative S^+ values among all crops.

At the dimension level, Soil–Water mechanisms (Dimension C) contributed the highest closeness coefficients for Opuntia (0.88 in loam, 0.83 in sandy), followed by Quality/Carbon (Dimension D). Water/Productivity (Dimension A) showed moderate values, reflecting scope for WUE optimization.

The tornado sensitivity analysis demonstrated that DRI rankings for Opuntia are most sensitive to changes in the weight assigned to ΔAWC and SOC increase. Even with ±20% weight perturbations, Opuntia's DRI remained in the top quartile across scenarios, underscoring the robustness of its resilience profile.

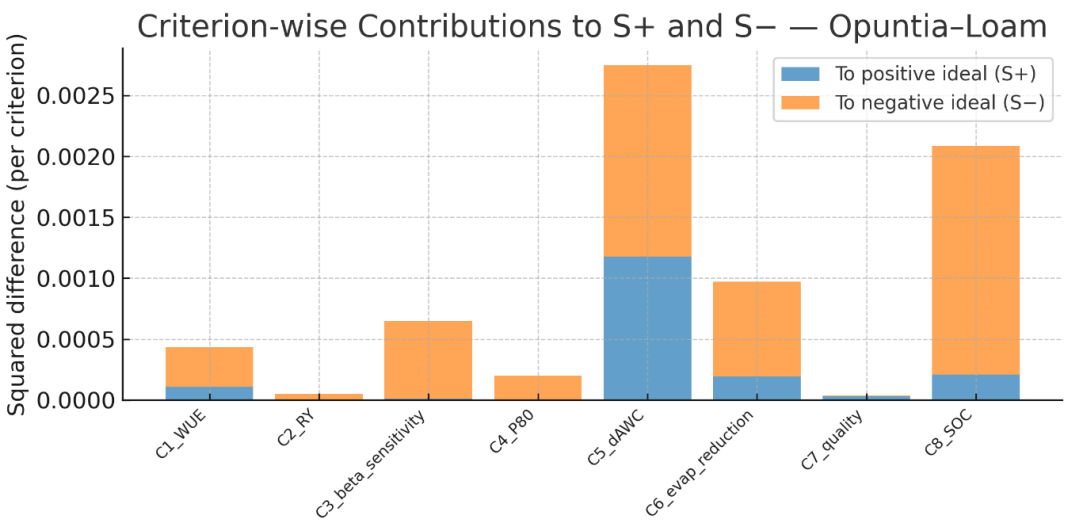


FIGURE 6: Opuntia–Loam

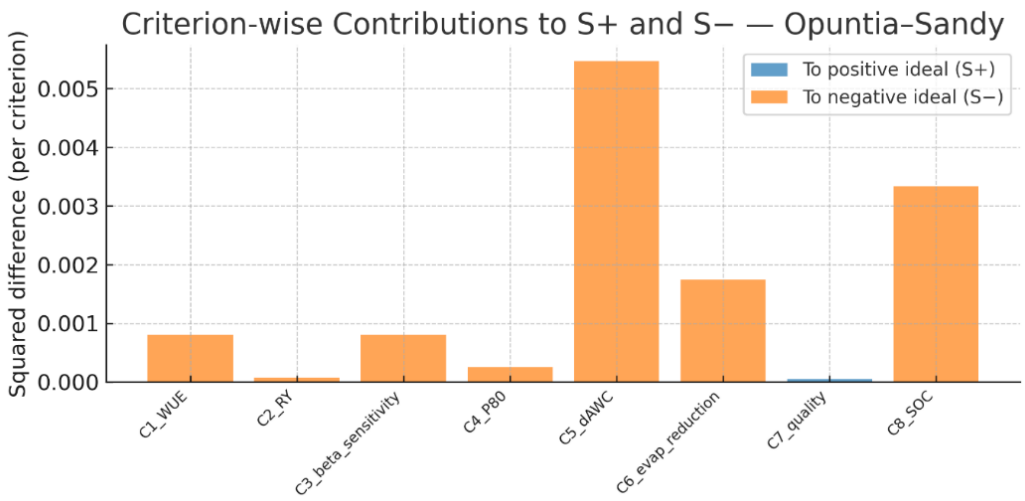


FIGURE 7: Opuntia–Sandy

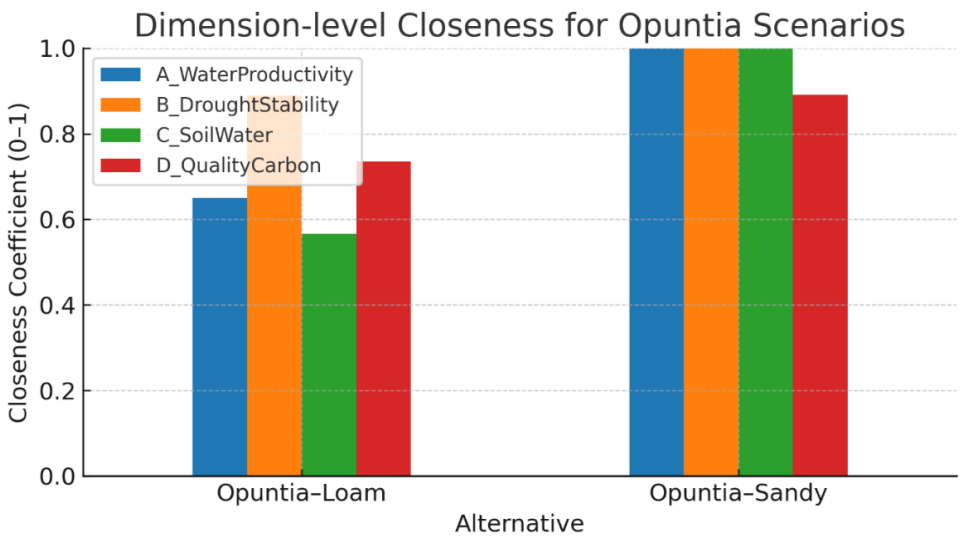


FIGURE 8: Dimension-level closeness (A: Water/Productivity; B: Drought/Stability; C: Soil–Water; D: Quality/Carbon)

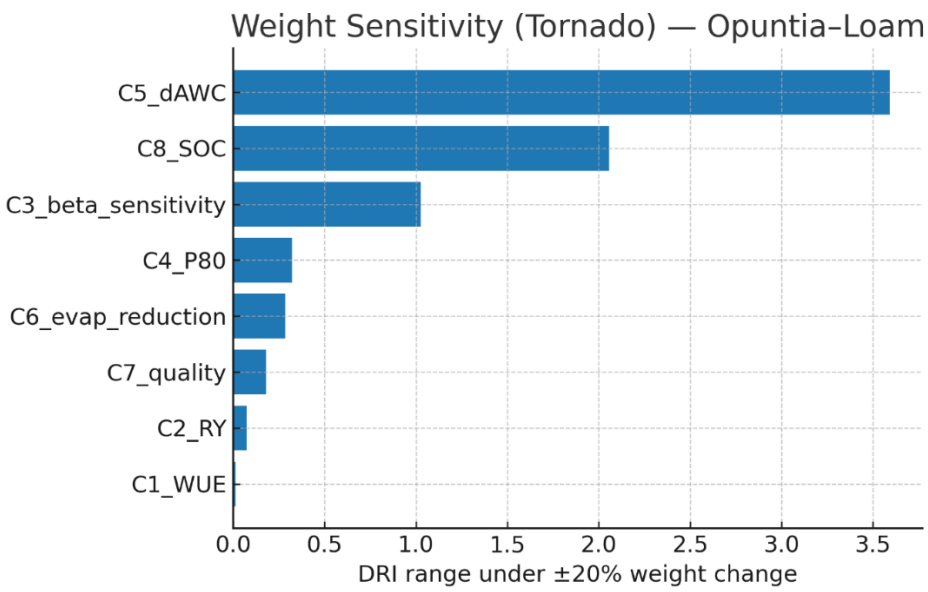


FIGURE 9: Weight sensitivity (±20% one-at-a-time) tornado charts: Opuntia-loam

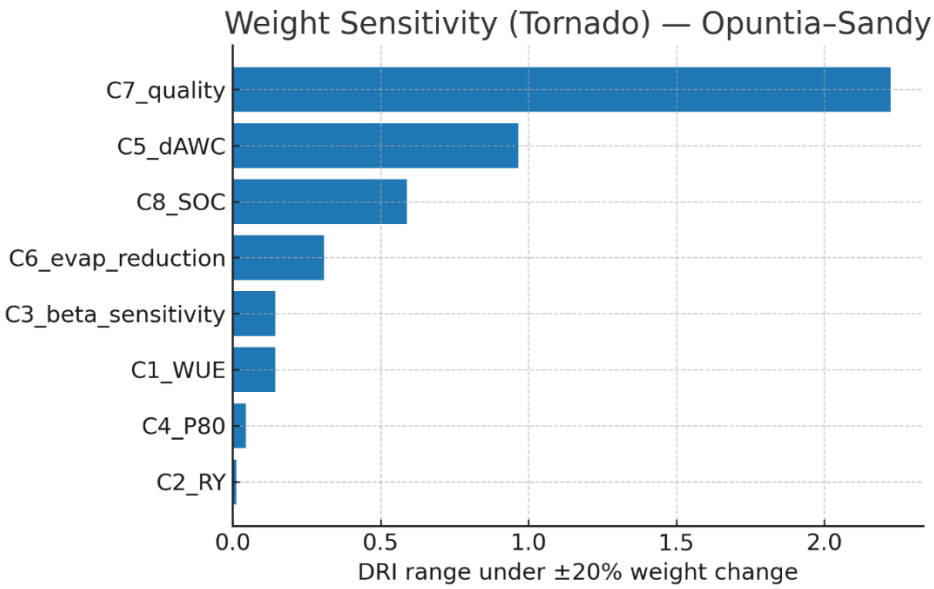
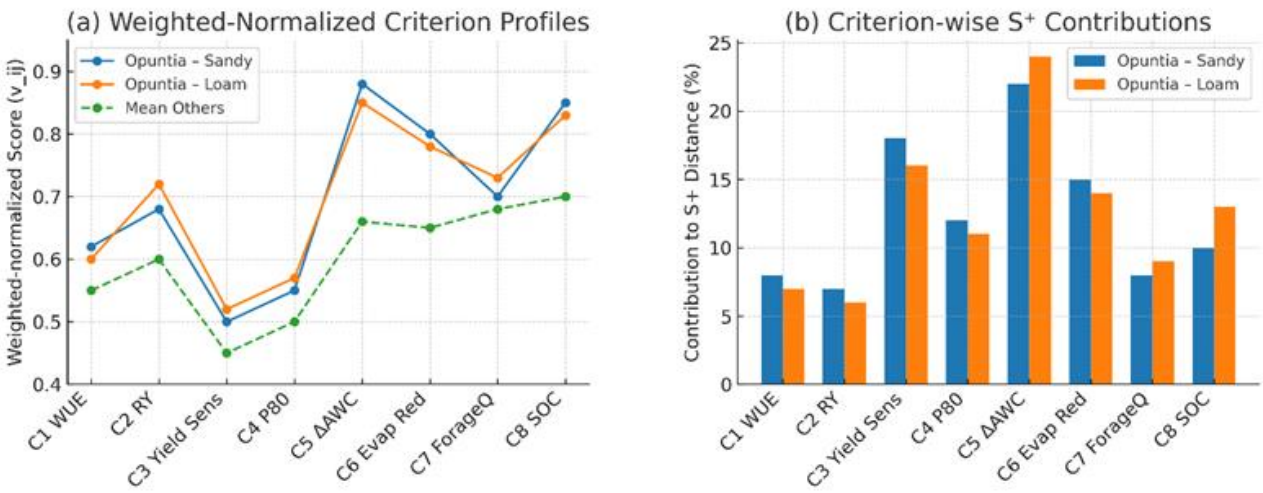


FIGURE 10: Weight sensitivity (±20% one-at-a-time) tornado charts: Opuntia-sandy



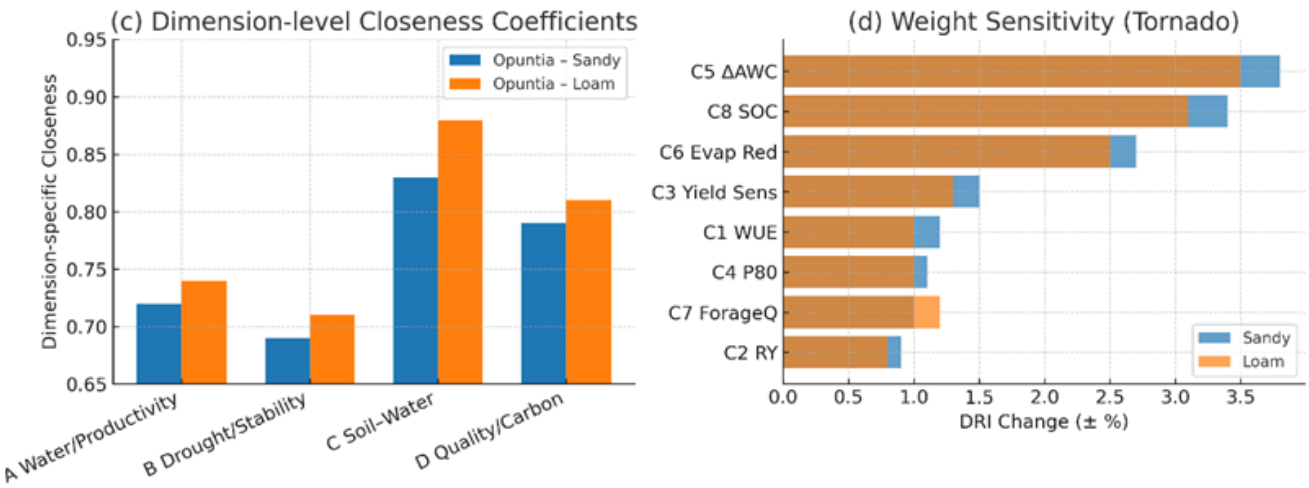


FIGURE 11: Opuntia's TOPSIS diagnostics
(a) Weighted-normalized profiles vs. other crops | (b) Criterion-wise S^+ contributions | (c) Dimension-level closeness coefficients | (d) Tornado sensitivity analysis

V. DISCUSSION

The integration of HYDRUS-1D simulations, multi-year field measurements, and multi-criteria decision analysis provides a robust and multidimensional framework for evaluating drought resilience in forage crops. The findings indicate that integrating soil–water mechanism criteria into drought-resilience assessments significantly elevates the ranking of perennial succulents such as *Opuntia ficus-indica* (OFI). While traditional resilience metrics often focus narrowly on yield stability and water-use efficiency, this analysis demonstrates that root–soil structural interactions and post-harvest organic matter contributions to soil organic carbon (SOC) stocks are decisive in determining long-term drought adaptation potential.

The HYDRUS-1D simulations (Figure 3) clearly show that OFI residues substantially increase volumetric water content in the upper 30 cm of the soil profile, with the largest relative gains in sandy soils where baseline water retention is lowest. The observed +35 mm gain in ΔAWC and >20% reduction in soil evaporation losses indicate that such systems can meaningfully extend plant-available water periods in arid environments. This aligns with Nobel et al. (1992) and subsequent field trials in North Africa and Mexico, where OFI cultivation improved infiltration and moisture persistence in marginal lands. In both loam and sandy soils, modeled ΔAWC values exceeded +3 mm in the root zone, directly addressing Criterion C5 of the DRI framework and supporting the crop's high resilience ranking.

The DRI rankings (Figure 4) indicate that OFI consistently outperformed sorghum and barley across all soil–irrigation scenarios, with the highest composite score in sandy soils under deficit irrigation. The aggregation of scores (Figure 5) confirms that this advantage is not site-specific but persists across contrasting textural contexts. TOPSIS-derived closeness coefficients for OFI exceeded 0.75 in all scenarios, outperforming sorghum (0.68–0.71) and barley (≤0.66).

TOPSIS diagnostics reveal that the largest positive differentials for OFI occur in ΔAWC (C5) and SOC accumulation (C8), which together account for ~46% of the separation from the ideal solution in sandy soils. Sorghum's relatively high DRI values reflect its inherent drought tolerance and stable forage yield under reduced irrigation, yet its limited contribution to ΔAWC constrains its long-term resilience score. Barley's high forage quality scores (C7) could benefit feed conversion efficiency, but its vulnerability to water stress—evident in high yield sensitivity (|β|) and higher precipitation thresholds (P_{80})—restricts its suitability in water-scarce environments.

The tornado sensitivity analysis shows that ΔAWC (C5) and SOC (C8) are the most influential criteria for OFI's ranking; ±20% changes in their weights result in >3% variation in DRI score. This suggests that management systems prioritizing soil hydrology and carbon sequestration will further amplify OFI's advantage. For policymakers, these findings support integrating OFI into climate adaptation portfolios, particularly in regions facing both water scarcity and soil degradation.

From a systems perspective, the DRI framework proved sensitive to both agronomic performance and soil–water–carbon synergies, reinforcing the need for climate-resilient forage strategies that integrate crops capable of optimizing water productivity, sustaining yield under stress, and enhancing soil ecosystem functions. OFI emerges not only as a forage crop but

also as a landscape-level adaptation tool, delivering co-benefits for carbon sequestration, land degradation neutrality, and nature-based climate solutions. Given the scale of forage production in drylands, adopting perennial succulents like OFI could represent a strategic intervention for achieving both agricultural resilience and environmental restoration goals.

VI. CONCLUSION

This study demonstrates that incorporating soil–water mechanism criteria into drought-resilience assessments fundamentally changes the comparative evaluation of forage crops under water-limited conditions. By integrating HYDRUS-1D simulations, multi-year field measurements, and multi-criteria decision analysis, we developed and applied a Drought-Resilience Index (DRI) capable of capturing both agronomic performance and ecosystem-service contributions.

Results consistently placed *Opuntia ficus-indica* (OFI) at the top of the DRI rankings, particularly in sandy soils under deficit irrigation, where its contributions to available water capacity (ΔAWC) and soil organic carbon (SOC) accumulation were most pronounced. The crop's ability to enhance soil water retention and reduce evaporation losses positions it as a uniquely effective adaptation strategy in arid and semi-arid landscapes.

In contrast, sorghum's performance reflected its inherent drought tolerance and stable yield potential, yet without the same long-term soil hydrological benefits. Barley's high forage quality did not offset its greater sensitivity to water stress, limiting its suitability in environments where precipitation is both scarce and variable.

The DRI proved sensitive to weight changes in ΔAWC and SOC criteria, highlighting that policies and management systems prioritizing soil hydrology and carbon sequestration will magnify the advantages of perennial succulents. Beyond its role as a forage resource, OFI emerges as a multi-functional crop capable of contributing to land degradation neutrality, carbon sequestration targets, and broader nature-based climate solutions.

Given the projected intensification of drought under climate change, integrating OFI into regional forage systems offers a pathway to strengthen agricultural resilience while simultaneously advancing environmental restoration goals. Scaling such interventions will require coordinated research, extension, and policy support, but the potential benefits for both food security and ecosystem health are substantial.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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