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Central Asian Winter Cold Desert Rangelands (CACDR): Climate-smart approaches towards restoration and conservation

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Abstract:
The cold winter rangelands of the Aral Sea basin are among the world's biodiversity hotspots, providing unique habitats, breeding grounds, migration corridors, and flyways for rare and endangered species of plants, animals, and birds. Situated along the historic "Silk Road," the Central Asian Cold Desert Rangelands (CACDR) are also the origin of many cultivated crops, including wheat, rye, barley, legumes, roots, tubers, and fruit trees. However, the increasing frequency of droughts due to climate and human affected changes is expected to exacerbate and further reduce the productivity of already degraded rangelands. Additionally, soil salinization, one of the major issues affecting agriculture, significantly decreases vegetation cover, botanical diversity, and the palatability of key species.

This study introduces a novel assessment of isotope screening for salinity and drought tolerance in key C_3 and C_4 halophytes. These halophytes, cultivated on various arid and semi-arid rangelands, are evaluated based on their life forms, root depths, and biomass yield production. The Circular Halophytic Mixed Farming (CHMF) system is explored as a strategy to improve the productivity of rangelands impacted by

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salinization and drought. This system involves intercropping halophytes with salt-tolerant non-conventional crops (NCCs) such as wild succulents, amaranthus, foxtail, pearl millet, licorice, artichoke, sesame, and sorghum. Within a single growing season, the CHMF system can remove approximately 1.8 kg of NaCl equivalent per kilogram of dry soil.The harvested biomass from halophytes serves as a bioenergy source and as livestock feed when mixed with traditional crops in specific proportions. Re-seeding and 'seed isles' techniques—utilizing species such as *Haloxylon ammodendron, Xylosalsola paletzkiana, X. richteri, Halothamnus subaphyllus, Artemisia halophylla, Caroxylon orientale*, and *Bassia prostrata*—are employed to establish pastoral agrophytocenoses, shelters, windbreaks, and to enhance the productivity of salt-affected pasturelands. These innovative rangeland restoration technologies aim to address the ongoing degradation of indigenous knowledge systems and promote sustainable management of arid and semi-arid ecosystems.

Introduction

The deserts of Central Asia represent the northernmost and coldest edge of native C_4 plant growth, showcasing a globally unique taxonomic composition alongside diverse and unusual biochemical, physiological, and structural features (Gintzburger et al., 2003; Matsuo et al., 2013). However, the ongoing desiccation of the Aral Sea has caused detrimental changes in the vegetation composition of rangelands with perennial valuable forage species being replaced by less palatable and invasive annual plants. Severe soil salinization in the Aralkum desert rangelands (former seabed of the Aral Sea) is a major driver of land degradation, threatening the crop-livestock ecosystem services essential for food security and rural livelihoods in the region. Recurrent cycles of drought and high soil salinity further exacerbate these challenges, limiting food and fodder production and necessitating large-scale imports of both. Overcoming the winter feed bottleneck remains one of the most pressing challenges for livestock development across Central Asia. Halophytes have shown promising potential in rangeland restoration programs (Toderich et al., 2024) under limited water availability and land salinization. Despite extensive evidence of the benefits desert rangelands offer for livestock grazing and ecosystem services, there is an urgent need to incorporate native forage halophytes and underutilized crops into rangeland restoration schemes. Currently, the salinity and drought tolerance indices, as well as water use characteristics of wild halophytes in the Central Asian Cold Desert Rangelands, remain poorly documented, along with road map cultivation techniques for these species. This study aims to evaluate the adaptation potential of halophytes and the benefits of their domestication to enhance the productivity and economic value of CACDR rangelands degraded by salinization.

Methods

Plant material for stable isotope analysis had been gathered at natural halophytic vegetation of typical desert plant communities. The carbon and oxygen isotope ratios were expressed in standard delta notation (&) relative to the VPDB (Vienna Pee Dee belemnite) and VSMOW (Vienna Standard Mean Ocean Water) standards, respectively: d 13C or d 18O = (R_{sample} / $R_{standard}$) – 1, where R_{sample} and $R_{standard}$ represent the $^{13}C/^{12}C$ or $^{18}O/^{16}O$ of the samples and the standard, respectively. The d ^{18}O in the stem water were analysed using an isotope ratio mass spectrometer (MAT252; Thermo Fisher Scientific, Rockford, IL, USA) at the Mie University, Japan. R v.3.6.1 software was used for principal component analysis (PCA) with multiple factors. The package "factoextra" was used for multiple correlations between parameters.

Research target area

Uzbekistan, a double-landlocked country in central Eurasia within the Aral Sea basin, is particularly vulnerable to environmental degradation and drought. The majority of its land cover consists of herbaceous vegetation in deserts and semi-deserts, along with piedmont mountainous regions (Fig. 1). The total desert

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area in the region is estimated at approximately 150 million hectares, accounting for 37% of the total land area. Rangeland soils in these areas have lost 30–50% of their soil organic carbon pool, leading to a significant decline in soil quality due to widespread salinization. The region's climate variability, characterized by an aridity index of 0.065–0.18 and low annual precipitation (80–150 mm), drives successive droughts and extreme temperatures, further exacerbating rangeland degradation. Additionally, changes in land use—such as the conversion of desert and steppe vegetation into new croplands—are accelerating desertification. Agricultural expansion and concentrated livestock grazing near settlements have become the primary drivers of these new land-use practices, intensifying pressure on already fragile ecosystems.

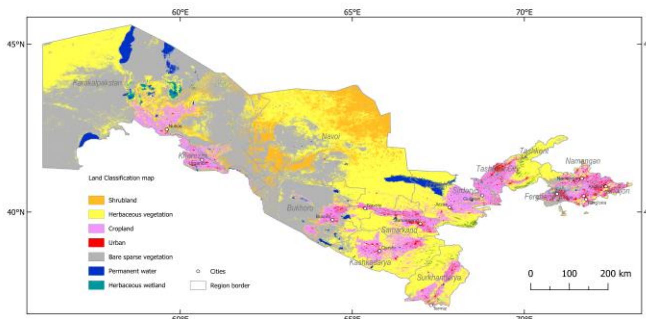

Fig. 1. Land cover of Uzbekistan adapted from Buchhorn et al. 2020 (modified by Timur

Results

Screening of Halophytes and Non-Conventional Crops. The analysis of stable isotope ratios (d^{13}C and d^{18}O) in 53 wild rangeland halophytes across diverse pasture types, characterized by varying climatic conditions (precipitation, elevation), groundwater levels, reproduction strategies, and biomass yield, highlighted the dominance of C_4 species within the *Amaranthaceae* family (>53.2%). Among ten neglected non-conventional, but already naturalized crops, C_4 species (*Amaranthus*, *Setaria*, *Sorghum*, and *Pennisetum*) and C_3 species (licorice, artichoke, sesame, rhubarb, safflower, and alfalfa) were nearly equally represented. Notably, C_4 halophytes and neglected crops exhibited significantly higher δ^{13}C values in their leaves compared to C_3 plants, indicating higher water-use efficiency under arid conditions. Perennial C_4 plants further displayed elevated d^{18}O values, suggesting deeper root systems and enhanced drought tolerance (Fig. 2a). When categorized by plant types—annual herbs, perennial herbs, and woody species—significant differences in d^{13}C were observed, while perennial herbs had notably lower d^{18}O values in leaves. Additionally, a strong positive correlation was established between d^{18}O and root system depth among the studied species, underlining the adaptive strategies of deeper-rooted plants in accessing water under saline and arid conditions (Fig. 2b).

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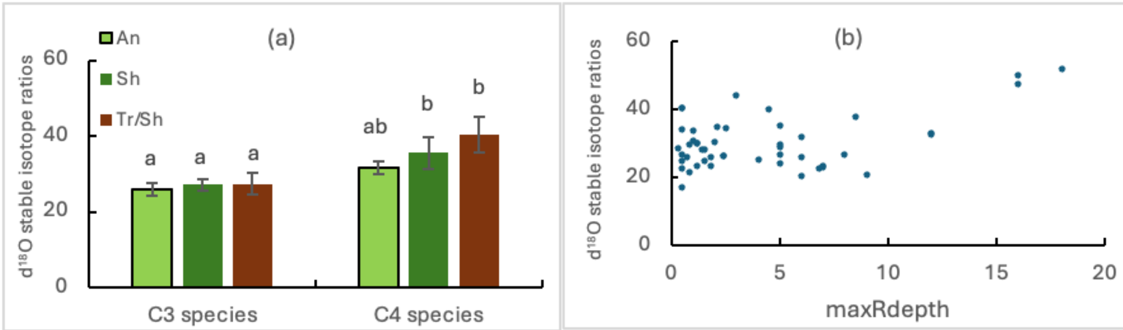

Fig. 2 The oxygen isotope ratio (d ^{18}O) in leaves of annual plants (An), shrubs (Sh) and tree-like shrubs (Tr/Sh) of C_3 and C_4 species (Fig. 2a) in relation to its maximum root depth (Fig. 2b).

Agroforestry and Afforestation technologies for Rangeland Restoration. These techniques revealed significant potential for restoring desert rangelands, severely affected by salinity and drought. Deeply transplanted seedlings of C_3 and C_4 trees, shrubs, and plants during early spring or late fall performed well on both loamy and sandy soils with shallow to moderately saline groundwater. Species such as *Elaeagnus angustifolia*, *Robinia pseudoacacia*, *Populus*, *Tamarix* and *Ulmus*, when intercropped with annual succulent halophytes, legumes, and annual grasses, demonstrated the fastest growth rates and highest water-use efficiency. Optimal agroforestry systems designed for traditional farming practices included 12% tree cover, 20% wild succulents' halophytes, 30% alfalfa, and 38% annual forage crops. This configuration effectively reduced salt accumulation in the root zone, enhanced soil drainage, and provided year-round feed resources for livestock. In addition, these systems contributed by reducing wind erosion and stabilizing soils mitigating the effects of climate variability (Yamanaka et al., 2020).

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Circular Halophytic Mixed Farming (CHMF) Technology. The CHMF system was developed by utilizing over 45 economically valuable halophyte species selected from the 760 identified in Central Asia. Following 3.5 to 6 years of continuous cultivation, severely degraded saline rangelands were converted into fertile soils capable of supporting diverse crops, including saltbush, *Karelinia, Suaeda, Amaranthus, Bassia*, cereals (*Agropyron*, foxtail millet, sorghum, pearl millet), sesame, sunflower, and melon (Fig. 3). This system achieved a 1.5–1.8-fold reduction in soil salinity due to the efficient salt uptake and removal by halophytes and reduction of using irrigation water, main source of salts. Additionally, the harvested biomass served as a dual-purpose resource, providing high-quality animal feed and raw materials for bioenergy production. The implementation of CHMF also yielded broader ecological and socioeconomic benefits. Improved soil organic carbon stocks, soil health, and vegetation cover contributed to ecosystem restoration, while promoting biodiversity by supporting rare, endangered, and climate-vulnerable species. The system's capacity for year-round biomass production stabilized fodder availability for livestock through the production of organic products such as honey and high-value fodder. Moreover, CHMF facilitated community engagement, sustainable land-use practices, and integrating indigenous knowledge systems required for rangeland management and conservation.

Fig. 3 Multi-stage salts remediation effect of CHMF technology (Karabuga Site),

Community-based Landscape Restoration actions. Community engagement played a critical role in restoring degraded rangelands through the implementation of "seed isles technique." Pastoral communities were trained to utilize this low-cost approach, which involves spreading mixed seeds of halophytes in uncovered areas. This technique relies on anemochory (wind dispersal) to propagate seeds, achieving significant rehabilitation of degraded *Artemisia* foothill rangelands within three to five years. Without disturbing the topsoil, such approach facilitated vegetation cover and self-regeneration of native species, drastically reducing labour and costs associated with traditional restoration methods.

The results demonstrated remarkable success: in the first year, shrubs yielded approximately 150 kg of dry mass per hectare, increasing to 220 kg/ha of dry mass and 40 kg/ha of seeds in the second year. By the third year, dry yield reached 800 kg/ha, with 100 kg/ha of seeds. Once established, these mixed perennial shrub plantations can sustain grazing forage production for over 20 years. The CHMF approach highlights the importance of integrating indigenous knowledge and community participation work in achieving long-term sustainability for rangeland restoration.

Synergies Between Technologies. The integration of agroforestry and CHMF technologies offers a synergistic approach to combating rangelands degradation in Central Asia. While agroforestry systems provide immediate benefits in soil stabilization, microclimate regulation and resource diversification, CHMF contributes long-term soil recovery and sustainable biomass production. Together, these technologies hold immense potential for reversing land degradation trends, enhancing rural livelihoods, and building climate resilience in arid and semi-arid regions. Although, it is important to address policy regulations and overgrazing practices that are widely spread across the area.

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Fig. 4. Foothill improved pastures (seed island techniques) by seeding mixed *Ceratoides*, *Camphorosma*, and *Bassia* (C4 forage halophytes), better known as desert "alfalfa", a high-calorie, year-round small ruminant feed. (Mugol village (Jizzakh region,2022).

Discussion and conclusion

Our study highlights the critical role of abiotic factors (temperature, precipitation, and groundwater) variations in shaping the distribution and abundance of C_3 and C_4 plants in the halophytic flora of desert and semi-desert rangelands, while biotic interactions play a secondary role. As shown in Fig. 5, the distribution of C_3 succulent halophytes is largely influenced by life form and root depth, with a higher prevalence of succulents among perennial species than annuals.

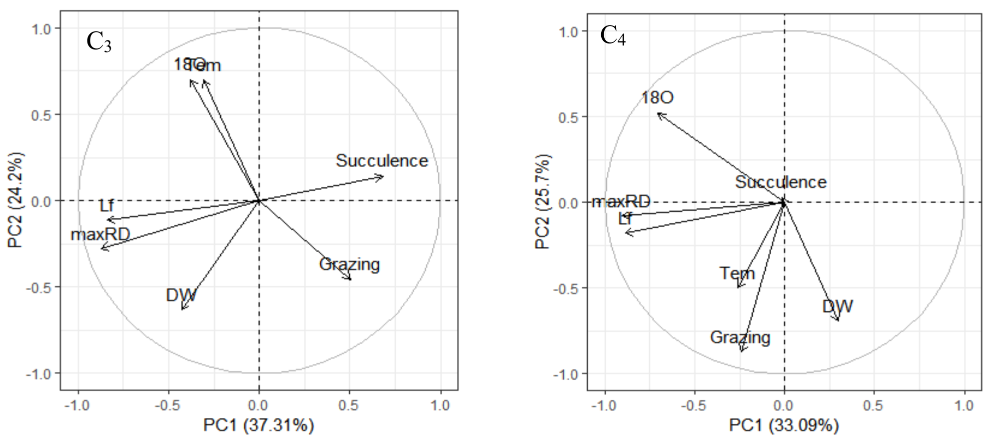

Fig. 5 The multiple correlations between life form (Lf), root depth (maxRD), dry biomass (DW), succulence (Succulence), type of grazing (Grazing), $d^{18}O$ (18O) in leaves of C_3 and C_4 species and mean temperature (Tem).

These findings align with previous studies emphasizing the adaptive strategies of perennial halophytes, which utilize deep root systems to access water from subsurface aquifers. Groundwater-dependent C_3/ C_4 rangeland ecosystems, as noted by Ronde et al. (2024), provide essential drought protection. In cold winter desert rangelands, shallow groundwater aquifers act as "water savings accounts," sustaining ecosystems during periods of low or absent precipitations, particularly during hot summer months. This dependency is evident for C_3 species, where oxygen isotope discrimination ($d^{18}O$) is positively correlated with temperature, reflecting the role of groundwater in supporting physiological functions under temperature stress. Conversely, no such relationship exists for C_4 species, which are more reliant on their inherent water-use efficiency and less dependent on groundwater availability.

Biomass production in these ecosystems is influenced by both abiotic and physiological factors. For C_3 species, biomass is strongly correlated with life form, while for C_4 species, other factors such as water-use efficiency and salinity tolerance appear to play a more prominent role. The study also revealed that the optimal spatial combination of C_3 and C_4 halophytes—considering life form, aridity index, physiological traits, water uptake depth, and adaptation mechanisms to soil salinization—can maximize biomass yield on rangelands. This highlights the potential for leveraging complementary ecological strategies of C_3 and C_4 plants to improve rangeland productivity in short-and long-term use.

A particularly promising approach is the integration of wild native and naturalized rangeland fodder species into the Circular Halophytic Mixed Farming system. Our results suggest that combining C_3 halophytes in open grazing areas with non-conventional crops (NCCs) in cultivated grazing systems creates a synergistic effect, enhancing biomass yield and improving the resilience of rangelands to climate stress. Annual precipitation and grazing type were positively correlated with fodder biomass yield, underscoring the importance of tailoring rangeland restoration strategies to specific climatic conditions and animal grazing schemes. Furthermore, this study reaffirms the ecological niches occupied by C_3 and C_4 halophytes in degraded rangelands. C_3 species tend to colonize nutrient-rich microsites, where their physiological adaptations allow them to thrive, while C4 species are better suited to nutrient-poor microsites due to their efficiency in photosynthesis and resilience to arid conditions (Shuyskaya et al., 2012). By strategically utilizing these species, restoration efforts can optimize both spatial and functional diversity, contributing to sustainable rangeland management and conservation.

In conclusion, the integration of wild native halophytes, naturalized species, and non-conventional crops within the CHMF framework offers a scalable solution for addressing rehabilitation of rangelands affected by soil salinity. The coexistence of C_3/C_4 species under a wide range of soil salinities is essential for developing optimal rangelands rehabilitation technique. This approach not only reduces salinization and enhances climate resilience but also supports biodiversity conservation and the sustainable use of ecosystem services. The findings of this study provide valuable insights for the design and implementation of rangeland restoration programs in arid and semi-arid regions globally.

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