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Nature-based solutions with ecosystem

services gains for managing saline waterlogged landscapes in semi-arid regions

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Soil salinity and waterlogging are major land degradation challenges, particularly in arid and semi-arid regions, severely impacting agricultural productivity and ecological stability. In India, approximately 8.5 million hectares are affected, largely due to poorly managed irrigation systems lacking proper drainage. Bio-drainage, using deep-rooted trees to remove excess water through transpiration emerges as a sustainable, low-cost, and eco-friendly alternative to traditional drainage methods. Tree-based bio-remediation models, particularly those involving Eucalyptus tereticornis, Prosopis juliflora, Acacia nilotica, and Tamarix aphylla, have been successfully implemented across varying degrees of salinity and waterlogging. These models provide multiple ecosystem services: provisioning (fuelwood, timber, fodder), regulating (carbon sequestration, groundwater control, climate moderation), supporting (biodiversity enhancement, soil health), and cultural (aesthetic and recreational value). Eucalyptus-based models in moderately affected areas demonstrated the highest biomass yield, carbon sequestration, and microclimate regulation. Despite these benefits, cultural services and social values remain under-researched. For broader adoption, future strategies should emphasize ecosystem service valuation, community participation, and location-specific species selection to ensure long-term sustainability and resilience of saline waterlogged landscapes.

Keywords: Agroforestry, Ecological restoration, Groundwater management, Soil salinity, Waterlogging

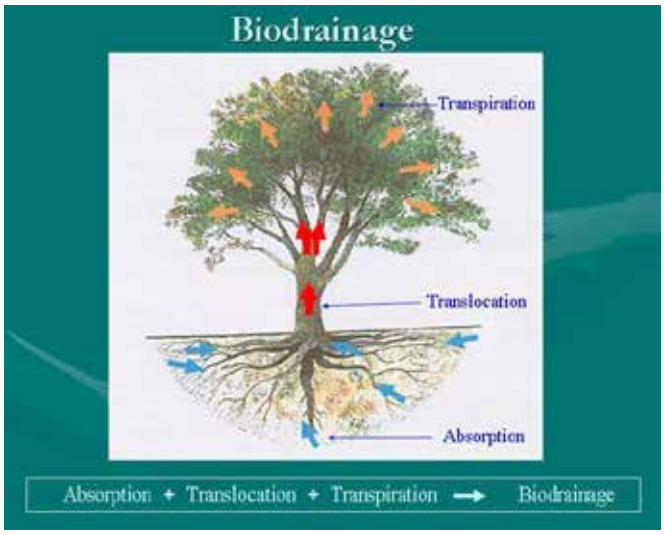
SOIL salinity and waterlogging are major forms of land degradation that threaten agricultural productivity and ecological stability, particularly in arid and semi-arid regions. Globally, about 33% of irrigated land, nearly 1.0 billion hectares is affected by these twin issues. In India, around 8.5 million hectares of lands are impacted, including 5.5 million ha with combined salinity and waterlogging problems, approximately 2.3 million ha each within and outside canal command areas. Primary cause is the introduction of irrigation systems without proper drainage. States such as Haryana, Maharashtra, Gujarat, Odisha, Uttar Pradesh, Punjab, West Bengal, Bihar, Andhra Pradesh, Tamil Nadu, Rajasthan, and Kerala are significantly affected. Waterlogging severity is defined by groundwater depth potentially waterlogged (≤3 m), waterlogged (≤1.5 m), and severely waterlogged (0–30 cm). Traditional drainage methods, though effective, are capital-intensive and raise environmental concerns. In contrast, bio-drainage offers a cost-effective, low-input, and eco-friendly solution. Nature-based bio-remediation strategies, including agroforestry, have shown promise in managing saline waterlogged areas by providing both reclamation and a range of ecosystem services.

Bio-drainage as a solution for saline waterlogged areas

Bio-drainage is the process by which deep-rooted plants use their bio-energy to absorb excess soil water and release it into the atmosphere through transpiration. While primarily explored for water table control, bio-drainage also offers both curative and preventive applications. However, its economic viability and the broader benefits, including tangible and ecosystem services, remain largely unexamined in current literature.

Tree based bio-remediation models

Tree-based models using *Eucalyptus tereticornis, Prosopis juliflora, Acacia nilotica,* and *Tamarix aphylla* were adopted across saline waterlogged areas, with species distribution varying by salinity severity. *Eucalyptus* thrived in less to moderately affected areas, while *Prosopis, Acacia,* and *Tamarix* were suited to severely impacted




Eucalyptus in block model

areas. In less affected regions, boundary plantations (1.5–2.0 m spacing) were common, transitioning to block plantations (1.0 × 3.0 m) in moderately affected areas. Severely affected zones lacked structured planting geometry. Block and boundary models were widely used in such conditions. Block plantations followed spacings of 1.5 × 3.0 m, 1.5 × 4.0 m, or 1.5 × 6.0 m, while boundary models employed single-row planting at 1.5 m spacing and strip plantations with 1.5 × 2.0 m (parallel rows) or 1.5 × 1.5 m (staggered rows).

Ecosystem services associated with bio-drainage models in saline waterlogged areas

There is no universally accepted typology of ecosystem services, but they are broadly understood as the benefits humans derive from ecosystems. These services are categorized into four types: provisioning, regulating, supporting, and cultural. Tree-based bio-remediation models on waterlogged saline soils offer multiple benefits, including food, fodder, fuelwood, and income. Through leaf litter and root decomposition, they improve soil health, sequester carbon, moderate the local climate, and enhance landscape aesthetics. These are part of a broader range of ecosystem services delivered by tree-based land uses.

Provisioning services: Plantations in saline waterlogged areas provide vital services such as food, fodder, fuel, fibre, and timber. *Eucalyptus tereticornis* based bio-drainage model yielded up to 28.65 Mg/ha of timber and 1.84 Mg/ha of fuelwood.Total biomass (above and below ground) ranged from 102 to 186 Mg/ha, outperforming other species. *Eucalyptus* based models on moderately saline and waterlogged sites produced 30 Mg/ha of biomass which was 62.3% and 84.5% higher than those on less and severely affected areas in Haryana, respectively.

Regulating services: Trees planted for bio-drainage play a significant role in climate change mitigation through carbon sequestration and groundwater regulation. *Eucalyptus globulus* has been reported to sequester 3.3 to 11.5 Mg C/ha/yr over 10 years, while *Eucalyptus tereticornis* on saline waterlogged soils accumulated 15.5 Mg C/ha in 5 years. It was found that agroforestry systems on waterlogged soils sequestered 15.82 Mg C/ha and 58.03 Mg CO_2/ha, and bio-saline systems captured 6 Mg CO_2 eq./ha. Groundwater drawdown of up to 15.7 m was recorded under plantations, with *Acacia mangium* and *Casuarina* systems lowering water levels by 3.2 m. Additionally, tree canopies moderate microclimates, reducing


Eucalyptus in boundary model


Sporadic trees in waterlogged saline soil

summer temperatures by 2–4°C and slightly raising them in winter. Species like *Dalbergia sissoo* and *Casuarina equisetifolia* enhance soil nutrient availability (NPK) through improved litter decomposition. Bio-remediation models in these areas can help in reduction of greenhouse gas emissions. *Eucalyptus* based bio-remediation models in moderately saline waterlogged areas showed superior regulating services, including higher carbon stock, carbon sequestration, and better regulation of air and soil temperatures. The greenhouse gas (GHG) emissions were reduced under tree canopies, with the lowest CO_2 flux observed in *Eucalyptus* models at moderately affected sites, lowest N_2O flux in isolated tree models at severely affected sites, and lowest CH_4 flux in *Eucalyptus* models at less affected sites. Soil properties were comparatively better in less affected sites, declining with increasing salinity and waterlogging. Higher ECe values were observed under isolated tree based models, particularly in the topsoil (0–15 cm). Soil organic carbon (SOC) was highest under *Eucalyptus* (boundary) models in less affected areas (0.33%) and block models in moderately affected areas. Available nitrogen and potassium were generally low, while phosphorus remained in the medium range. *Eucalyptus* based models in moderately affected site gave higher soil microbial count (MBC) values than *Eucalyptus* based models in less and isolated tree based models in severely affected sites.

Supporting services: Biodiversity studies in saline waterlogged areas are limited, but it is well established that tree plantations in such regions support key ecosystem services. *Eucalyptus* based models on moderately affected sites showed higher site stability (Shannon-Wiener index) and plant diversity (Simpson's index). *Eucalyptus* emerged as the dominant species across all less, moderately and severely affected sites, contributing 93%, 67%, and 82% of the total basal area, respectively.

Cultural services: Cultural ecosystem services, non-material benefits such as spiritual, cognitive, recreational, and aesthetic experiences are often difficult to quantify despite being well recognized. A pilot study in saline waterlogged areas of Haryana found that tree-based land use systems (LUS) offered the highest cultural services (aesthetics and social recreation), while fallow lands recorded the lowest. Cultural services were found to be more prominent in Eucalyptusbased models on less affected sites, and comparatively lower in isolated trees on severely affected sites. Despite these insights, cultural services remain underrepresented in the available literature and merit further research.

SUMMARY

Saline and waterlogged soils threaten agricultural sustainability, especially in poorly drained in-land irrigated areas. Bio-drainage, using deep-rooted tree species to remove excess water through transpiration, offers a costeffective and eco-friendly solution. Tree based bio-drainage models support land reclamation while delivering a range of ecosystem services viz. provisioning, regulating, supporting, and cultural. *Eucalyptus* based models particularly in moderately affected areas have shown high biomass yields and ecosystem benefits. However, cultural and social values of such systems remain underexplored. Future efforts should prioritize holistic ecosystem valuation, community involvement, and site-specific species selection to enhance the sustainability and acceptance of these models in managing saline waterlogged landscapes.

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