Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 04 (JULY-AUG, 2026)
Available online at http://www.agriarticles.com

Restoring Degraded Saline Vertisols for Carbon Credit Generation through Scientific Interventions

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In India, Vertisols occupy around 26.6 million hectares of area of which nearly 3.7% face severe salinity/sodicity stress. Maharashtra holds the largest share of salt affected Vertisols with approximately 0.54 million hectares followed by Gujarat with about 0.12 million hectares. In Gujarat, Bhal, Bara tract, Ukai and Kakrapara canal command area dominate with salt affected vertisols. These soils are prominent in coastal and inland canal zones driven by sea-water ingress and marine influences. From crop production point of view, these salt affected Vertisols have several constraints *viz.* reduced infiltration and internal drainage, higher evaporation of water through cracks, non-uniform wetting of soil profile, deep percolation of water below crop root zone, secondary salinity developed due to irrigation under canal command areas, narrow optimum moisture range for tillage and seeding operations, poor seed germination and difficulties associated with rapid drying of granular surfaces and scaling and crusting, yield losses due to salinity hazards associated with rising groundwater table and use of poor quality irrigation water, loss of nutrients below root zone as well as poor aeration of wet soils and root development.

All these constraints can directly or indirectly be addressed through the improvement of soil organic carbon content as it influences the soil physical, chemical and biological properties. The presence of 2:1 type expanding clays e.g. montmorillonite causes swelling and shrinking in Vertisols creating cracks which are sometimes as deep as 50 cm and more. Due to pedoturbation, the organic carbon rich top soil, moves to the deeper soil layers and get sequestered with higher mean residence time. Higher smectite clay content in vertisols increases the clay-humus stability which enhances the soil C sequestration potential of these soils. Thus, the land use system(s) showing promising attributes in terms of higher TOC stock, plant and root biomass can not only address the associated challenges but also show potential in C credit generation and may therefore be advocated in the less productive or unproductive saline Vertisols for restoration and bringing them under cultivation in the long run. This may not only lead to enhanced farmers' income through farm produce and carbon credit generation from the otherwise unproductive land but at the same time aid to soil and environmental sustainability.

Calculation of Carbon credit in tree-based systems and estimation of its economic value

A carbon credit is a standardized, tradeable permit that represents the legal right to emit one metric ton of carbon dioxide or an equivalent amount of other greenhouse gases. In academic and environmental economics, carbon credits function as a market-based instrument designed to quantify, commodify, and reduce global greenhouse gas emissions. Trees with a diameter at breast height (DBH) of 10 cm and more are generally selected for studying the carbon credit generation. DBH of each tree is measured using a tape measure, height by an

Altimeter. The CO_2 equivalent (eq.) in a particular system is then calculated based on the protocol as depicted in the Fig.1.

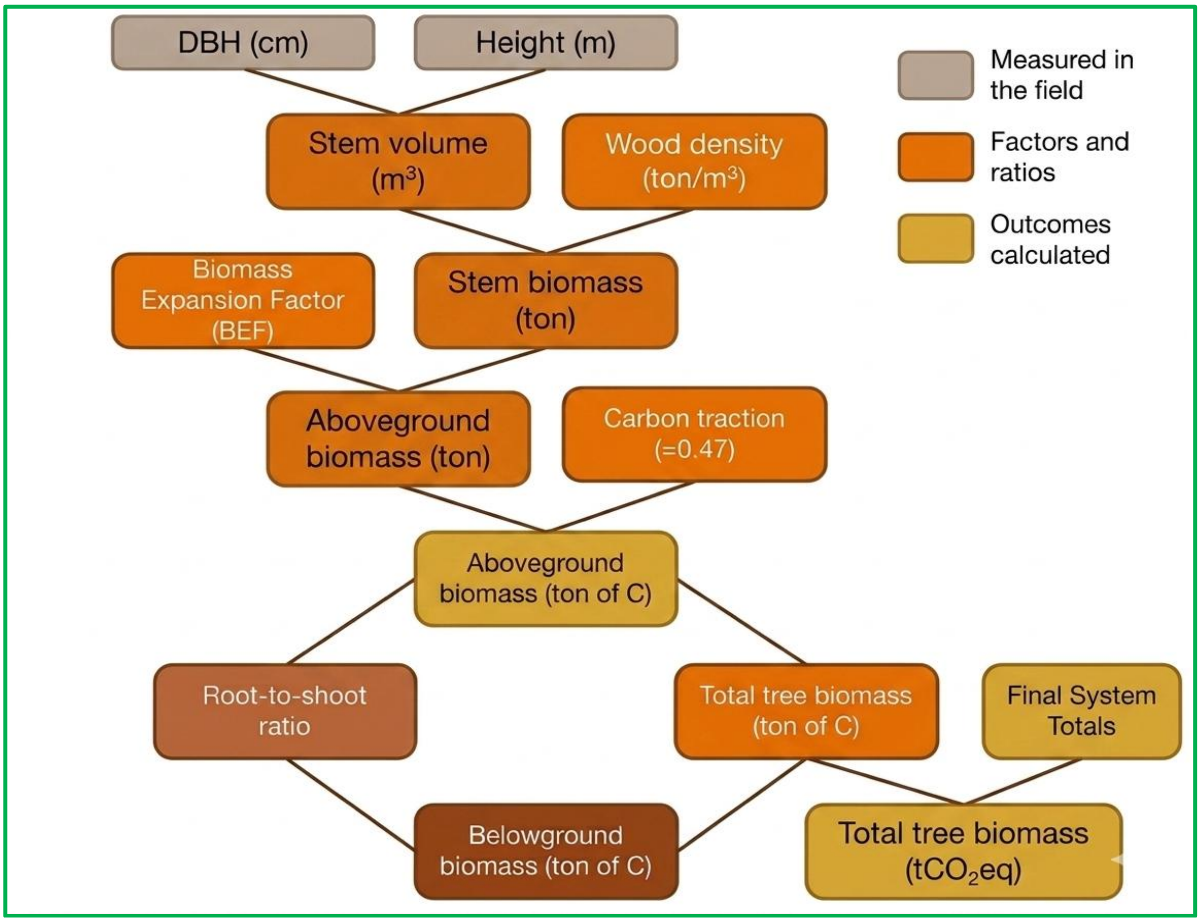

Fig.1 Methodology used in calculating C credit in tree-based systems

The calculation of CO_2eq from sequestered carbon in tree biomass is calculated using a stoichiometric factor of 3.67, which converts carbon atoms into CO_2 molecules. The overall carbon sequestration of a specific land use is quantifed by aggregating the biomass of both above- and belowground tree biomass, along with litterfall, shrubs, herbs and SOC. Each metric ton of CO_2 sequestered or mitigated through plant biomass and SOC in a land use system corresponds to one carbon credit. One C credit, on an average is valued at $6.97-10. (Ecosystem Marketplace,2023) and is expected to increase to $25 to $30 by 2030 due to increased demand for higher-quality credits and potential scarcity.

Agro-engineering practices to increase C credit generation in saline vertisols

1.**Integrated Salinity Management:** Technologies like sub-surface drainage coupled with regenerative agricultural practices like green manuring, crop rotation with legumes etc. can wash out salts, transforming previously waterlogged, carbon-emitting saline Vertisols into viable crop lands. Integrated Salinity Management (ISM) improves carbon credit generation in saline Vertisols by reversing osmotic and physical barriers to increase biomass production, which accelerates the accumulation of mineral-associated organic carbon (MAOC). Prior to reclamation, saline Vertisols act as net carbon sources because high water tables and sodium toxicity trigger anaerobic conditions, which release methane (CH_4) and nitrous oxide (N_2O) while suppressing plant growth. ISM disrupts this cycle, turning degraded soil into a high-capacity carbon sink.

2.**Amendment-Driven Sequestration:** In saline Vertisols, application of soil amendments alters the physical and chemical matrix of the soil to dramatically accelerate the soil's natural capacity to capture and hold atmospheric carbon. The use of gypsum, biochar, farmyard manure (FYM) and microbial fertilizers help build soil organic matter in challenging environments (Tab.1).

Table.1 Different amendments and their mode of carbon sequestration in saline Vertisols

Amendments	Mode of action in soil	Carbon Sequestration	Permanence Horizon
Gypsum / Phosphogypsum	Replaces exchangeable (Na^+) with (Ca^{2+}); remediates structural collapse	**Indirect:** Rebuilds soil macro-aggregates that physically shield new root-derived organic matter from oxidation.	Medium (Decadal)
Biochar (Pyrolyzed Biomass)	Increases Cation Exchange Capacity (CEC); retains moisture; reduces osmotic stress.	**Direct & Indirect:** Adds recalcitrant elemental carbon while providing a highly stable home for beneficial microbial communities.	Very High (Centuries)
Pressmud / Sugar Factory Waste	Rich in calcium and organic acids; neutralizes high pH; feeds native soil microbes.	**Synergistic:** Rapidly converts labile organic matter into stable Mineral-Associated Organic Carbon (MAOC) by binding with smectite clay	Medium to High

3.Halophytic Agroforestry: Halophytic agroforestry species survive salt stress through exclusion or accumulation of soluble ions and bio-amelioration. The different species in halophytic agroforestry may be classified into the following categories:

i.Phyto-Desalination Species (Excluders/Accumulators): These plants actively absorb soluble sodium (Na^+) and chlorine (Cl^-) through their deep root networks and store them safely within their vacuoles or drop them via leaf litter.

- *Key Species: Prosopis juliflora*, *Salvadora persica*, and *Suaeda maritima*.

ii.Bio-Ameliorating Leguminous Trees: These trees are highly salt-tolerant and they naturally fix nitrogen, which speeds up the breakdown of organic matter and improves humification and overall soil fertility.

- *Key Species: Acacia nilotica* and *Casuarina equisetifolia*.

These species accelerate carbon capture in heavy smectite clay (Vertisol) matrices through three distinct ways (Fig.2):

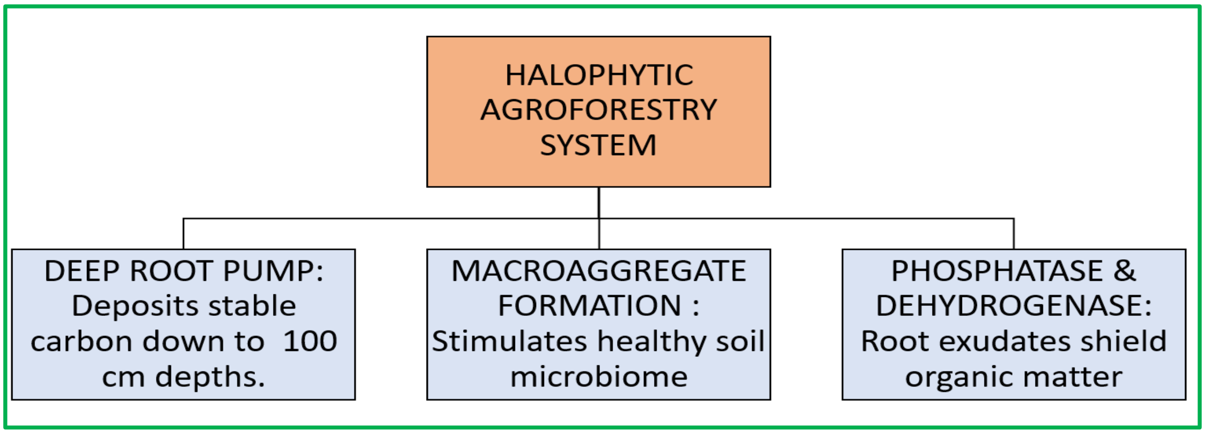

Fig.2 Biogeochemical C Sequestration Pathway in halophytic agroforestry systems

a. Deep-Profile Carbon Protection

Standard field crops rarely penetrate the top 15–30 cm of soil, especially in impervious clayey soils. Halophytic trees like *Casuarina equisetifolia* physically break through these dense sub-surface layers. They deposit highly stable, root-derived organic matter deep down into the profile (60 to 100 cm and more). At these depths, the carbon is physically shielded from the air and remains safe from oxidation during the heavy seasonal drying and cracking typical of surface Vertisols.

b. Activating the Rhizosphere Microbiome

The extreme osmotic pressure in saline soils essentially sterilizes the ground, halting the biological processes that turn plant derived organic matter into long-term soil carbon *i.e.* humus. The roots of halophytes naturally exude organic acids and other rhizodepositions that lower the surrounding soil pH and electrical conductivity (ECe). This micro-environment stimulates critical soil enzymes (such as dehydrogenase and alkaline phosphatase), promoting microbial growth. The resulting dead microbial cells (necromass) bind tightly with the fine clay particles to create highly resilient Mineral-Associated Organic Carbon (MAOC).

c. Rebuilding Structural Macroaggregates

As halophyte roots grow and decay, they release complex sugars and mucilage that act as a natural glue for the soil. These compounds bind dispersed clay particles together into stable macroaggregates. These aggregates physically trap and lock away organic carbon, preventing it from being broken down by microbes and escaping back into the atmosphere.

Conclusion

Transforming the salt-affected Vertisols into high-yielding carbon sinks through sub-surface drainage, soil amendments, and agroforestry offers a critical pathway for agricultural sustainability and climate change mitigation. By restoring soil structure to sequester stable mineral-associated organic carbon and monetizing this via carbon credits, these formerly barren or less productive tracts can become productive, tradeable assets that bridge rural development with global environmental goals.

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