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Rehabilitation of Barren Sodic Land in North India

Bajrang S*

National Botanical Research Institute (NBRI), Lucknow, India

***Corresponding author:** Bajrang S, National Botanical Research Institute (NBRI), ENV DAS (I) PVT. Ltd., D -2247 Indira Nagar, Lucknow, 226016, India, Tel-+919889098179; E-mail: bsingh471@rediffmail.com

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Abstract

Sodic lands, commonly found in north India in sporadic patches, do not support any significant vegetation cover and are difficult for rehabilitation in agriculture and forestry sectors due to various soil constraints. Several efforts have been made in past few decades to reclaim and utilize this hostile land for agriculture and forest production through chemical and biological methods, respectively. Although soil amelioration is relatively slow through biological, it is stable and eco-friendly. Uttar Pradesh Land Development Corporation has developed a rice-wheat cropping system on these lands to some extent through World Bank assistance. Some alternative models developed by National Botanical Research Institute, (NBRI) have been proposed for rehabilitation in horticulture and forestry sectors. Forest ecosystem developed on sodic land besides generating the additional resources and soil reclamation, provides several intangible benefits (ecosystems services) essential for vital life. Reclamation, restoration, ecosystem management and soil amelioration have been described and future guidelines were suggested for efficient reclamation and utilization of sodic land. It would be better to develop such barren land in integrated land use system involving herbs, shrubs and trees to maximize the land use efficiency. Initially native salt tolerant species are established applying proven silvicultural technology. In due course of time other semi-tolerant species are introduced to form understory and ground layer. Reclamation and rehabilitation of sodic land in agriculture and forestry sectors was emphasized as both are equally important acting as complimentary and supplementary to each other.

Keywords: Sodic soil; Afforestation; Agriculture; Forestry

Abbreviations: FRI: Forest Research Institute; CSAU: Chandra Shekhar Azad University; UPFD: Uttar Pradesh Forest Department; UPSLRP: Uttarpradesh Sodic Land Reclamation Project; NDAU: Narendra Deo Agriculture University; MB: microbial biomass; PFLA: Phospholipids Fatty Acid; AFLP: Analysis Amplified Fragment Length Polymorphism; SSR: Simple Sequence Repeats; RAPD: Random Amplification of Polymorphic DNA; OC: Organic Carbon; GIS: Global Information Systems; LUS: Land Use Systems.

Introduction

Sodic soils are commonly found in both, developing and developed countries. Approximately 581 million (M) ha of sodic lands are found worldwide in arid and semi-arid regions, and occurring disproportionately throughout Australasia (340 M ha), North and Central Asia (120.1 M ha), South America (59.6 M ha), Africa (27 M ha), Europe (22.9 M ha), North America (9.6 M ha), and South Asia (1.8 M ha) [1]. The major constraints against the establishment and growth of plants in these soils are attributed to structural, chemical, nutritional, hydrological, and microbial deterioration of soils [2-4]. In India, these soils are centuries old without any vegetation cover, and are largely distributed in the Indo-Gangetic plain region having properties of high pH (9-10.5) and exchangeable sodium percent (up to 90%) with low fertility and water permeability due to the severe electrochemical bonding of sodium and clays. The soil particles are highly dispersed and interspaces are filled with the precipitated calcite ($CaCO_3$). Such conditions adversely affect the water permeability causing a very low infiltration rate and hydraulic conductivity. Sodic soils of Indo-Gangetic alluvium were formed by periodic submergence and evaporation caused by both natural and anthropogenic influences. The geological deposition of clay minerals (sedimentation) in undulating topography formed the sodic soils in depressions during recurrent submergence and evaporation. The construction of roads, canals, dams, and railway lines have further compounded the problem by impeding natural drainage. In addition, the lateral movements of soil water from the sodic patches to the cultivated fields have contributed to the extension of sodic lands in India.

The widespread degradation of alluvial soil in the Gangetic plains of Uttar Pradesh (UP) state that are affected by varying degrees of sodicity or salinity have received priority attention for reclamation during the past few decades. Primarily these soils are utilized in the agriculture and forestry sectors. Soil is treated with gypsum ($CaSO_4$) for quick reclamation and cultivation of field crops for agricultural production. Alternatively, afforestation with salt tolerant trees develops new forests and ameliorates soil gradually with the growth and development of trees. Both of these land use systems are interdependent on each other for food security, forest products, maintaining the ecological balance, environmental stability, restoration of biodiversity and several other ecosystem services. This issue has been well addressed in Indian Agriculture and Forest Policies for wide implementation throughout the country.

Since land is a finite natural resource necessary and vital for the sustenance of life on the earth, we must take care of it properly to keep it in a healthy state. Restoration of degraded lands in productive land use systems (LUS) has been a major R& D program of National Botanical Research Institute (NBRI), Lucknow, India since the establishment of a Banthra Research Station in 1953 on 200ha barren sodic land. Forest Research Institute (FRI), UP forest department (UPFD) and state agricultural universities *viz* Chandra Shekhar Azad University (CSAU) and Narendra Deo Agriculture University (NDAU) have also initiated the sodic land reclamation program at Sultanpur (FRI), Kanpur (CSAU), Faizabad (NDAU), Aligarh (UPFD), Unnao (UPFD), and Lucknow (UPFD). However large scale impacts were only observed in the past 20 years when UP sodic land reclamation project (UPSLRP) was conceived by UP Bhumi Sudhar Nigam (UPBSN) in 1993 through World Bank assistance (IDA). The first phase of this project was successfully completed in 2001 with the reclamation of 68,414 ha sodic land in agriculture sector. In the second phase of UPSLRP (1999-2007) 126,780 ha have been reclaimed and cultivated and in the third phase (2009-2018), which is currently being conducted, has a target of reclaiming 130,000 ha.

After reclamation of sodic soil, cultivation of field crops should not be interrupted; otherwise resodification occurs on fallow land due to upward movement of salts from subsoil, which remains submerged under crops. In perennial land use systems stable reclamation is observed, as a consequence alternative R & D models developed by NBRI (energy plantations, bamboo culture, man-made forest, agro-forestry); FRI (Plantation forest) and NDAU (fruit orchards) have been advocated. NBRI has developed several leads in restoration of sodic lands in potential land use systems. Many of these are good productive and ameliorated the soil substantially during 10 years [5]. Among them, prominent ones are biomass based fuel wood forestry program, energy plantations including a biofuel plant *Jatropha curcas*, cultivation of German Chamomile (*Matricaria chamomilla*), bamboo culture, agro-forestry with poplar and turmeric. These developments indicate that degraded lands may be restored in productive land use systems if scientifically managed with proper sprit otherwise many trials made elsewhere could not succeed in proper rehabilitation due to lack of proven technology, proper financial support and dedication [6,7]. Economically viable and adaptable eco-technology for afforestation on such land was suggested [8,9] and that was further updated [10].

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Eco-Restoration Approaches

The eco-restoration of sodic lands has been studied over the past 10 years in the major land use systems (agriculture and forestry) with the objectives of restoring soil properties, productivity and diversity of the developing ecosystems at spatial and temporal scales. Agro-technology standards for the management of these soils still need an improved protocol to optimize the normal yield for healthy ecosystem structure and function. Lands are considered as degraded when their edaphic conditions and/or biotic richness including, soil organic matter, soil nutrients, seed pools and biomass (ecosystem's storage), have been reduced to the point that natural inputs cannot replenish them to their original state [11], and therefore sodic lands are described as degraded due to low capacity for plant production its least response for plant production [12]. Sodic soils contain an excess of exchangeable Na^+ on soil colloids and have soluble carbonates in the form of Na_2CO_3 and $NaHCO_3$. This causes a high soil pH, clay dispersion, soil swelling and overall poor soil physical properties [2]. Agriculture is particularly challenged to develop appropriate strategies for sustainable crop productivity on sodic soils. Soil degradation is a serious problem in India, where, 57% of the land is affected with some type of land degradation [13]. Optimizing the biological productivity of these soils through management requires a clear understanding of the simultaneous transport of water and solute within the soil profile and how to restore fertility and soil microbial activity.

Soil microbial biomass measurements are useful in determining the degree of disturbance and the subsequent system recovery. Soil microorganism have been recognized as the driving force behind nutrient transformation in soils and therefore have a major role in soil fertility and ecosystem functioning. Without microbes and their functions no other organism could be supported by the soil [14]. Studies on the effect of soil management practices on the size of soil microbial biomass can help to quantify their role in soil fertility and agricultural production [15]. It is now important to understand the mechanisms and processes of soil restoration for greater resilience and ultimately to make a better strategy for land use management. In order to achieve the efficient restoration, crop productivity or phyto-diversity and soil characteristics are monitored periodically in degraded, semi-reclaimed and standard crop fields. Site and seasonal variations are correlated with the vegetation dynamics particularly during the transition state (semi-reclaimed crop fields) of the degraded soils being restored under agro-ecosystem. Periodic biodiversity and crop yield assessment and the associated changes occurring in the structural, chemical, nutritional, hydrological and microbiological properties of the soils were determined to evolve an appropriate agricultural land use system to augment the declining food production in India. Thus, the vegetation and soil interactions are monitored periodically in order to develop efficient wasteland management strategies to alleviate the sodicity problem in the state.

There is now limited scope to increase the productivity of crops/trees per unit area on arable lands, as a consequence degraded lands must be rehabilitated in productive ecosystems (mainly in agriculture and forestry sectors) to cater the needs of the ever increasing Indian population. Do we understand how plants grow in stressed condition on degraded lands and do we have appropriate agro-technology to ensure climate based optimum yields? Sites not suitable for agriculture may be rehabilitated with forest ecosystems or agro-forestry systems, if appropriate plant species are selected and established through proven silvicultural methods. NBRI has been a premier institution to address all these issues and acquired a good deal of proficiency in development of several practical models of eco-restoration on degraded sodic land in north India.

Since the forest cover on Indian land surface is dwindling to the extent of 19-23% during past ten years, many kinds of degraded lands unfit for agriculture should be afforested to accomplish the minimum recommended level of 33% forest cover for ecological balance. Tropical forests are being exploited at an alarming rate such that they are unable to recover naturally [16,17]. Indian forests are being exploited to significant extent by anthropogenic activities [18,19]. Therefore planting new forest and protection of natural forests becomes today's need because they are important in environmental conservation, ecological balance, supplying the goods and ecosystem services.

The development of forest structure is influenced by several factors including soil. Soil physical properties play an important role to anchoring plants through roots proliferation [20], whereas chemical and biological properties mediate for soil fertility and nutrient availability to the plants [21]. The correlation between tree species association and soil variables has been successfully demonstrated in numerous studies of tropical forests world-wide [22-24]. Understanding these relationships helps knowing how to best manipulate the ecosystem for better soil resilience [25]. Soils, along with competitive abilities and climate, play a leading role in

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determining species [26]. Therefore, knowing the soil characteristics may be helpful in restoring and maintaining the sustainable land use systems.

Restoration And Ecosystem Management

Brown and Lugo [11] have illustrated several concepts of ecosystem rehabilitation for developing and managing degraded/derelict land. Even monoculture plantations, if established on degraded lands, improve the soil condition and enrich the species diversity. Sodic wastelands of north India are degraded to such an extent that natural succession is arrested. Few native species have been established initially and subsequently other species invaded and colonized forming a niche. The knowledge obtained from the performance of species and processes involved in enhancing natural succession is indispensable for eco-restoration of barren lands. Restoration and management of degraded lands with multiple species are thought to improve degraded soil more efficiently [27].

Unless direct economic or indirect incentives (including any environmental and social services are provided to the local communities through afforestation programs, their involvement is not likely to be sustained and, consequently, the viability of many afforestation programs become questionable. This implies that trade-off exists between social welfare considerations and complete restoration of native biodiversity and ecological functions. The relative importance given to these concerns will depend on the larger context in which the project is undertaken for reconstruction of habitat to deliver the following goods and services to mankind:

- Production of ecosystem goods
- Generation and maintenance of biodiversity
- Life supporting climate
- Mitigation of floods and droughts
- Pollination
- Natural pest control services
- Seed dispersal
- Aesthetic beauty, intellectual and spiritual stimulation

There will be two broad objectives for rehabilitation of degraded land in forestry sector, first, to generate biomass (fuel-wood/timber) in production forestry program and second, reconstruction of entire forest ecosystem in protection forestry program, which provides most of the aforesaid ecosystem services. Among them nutrient cycling, soil porosity & fertility, hydrology and atmospheric temperature primarily facilitate the restoration by accelerating its resilience. Ecosystem approaches do not focus on a single commodity but recognize that land must be managed for multiple goods and services to meet the needs of diverse stakeholders. A mass awareness program to educate the people with the benefits of ecosystem services should be included in restoration of degraded ecosystems. We have classified ecosystem services into four categories: provisional, supportive, regulatory and cultural. These services may account for trillions of dollars annually; but their costs are generally hidden from traditional economic accounting. Ecosystem services operate on such a grand scale and in such intricate and little explored ways that most could not be replaced by technology. Human activities are already impairing the flow of ecosystem services on a large scale, modifying or destroying the natural ecosystem leading to deterioration of ecological services.

Afforestation, especially with exotic monocultures, can pose a threat to indigenous biodiversity as plantations of *Prosopis juliflora* and *Leucaena leucocephalla* have not been observed to support the existence of any other species with their association [28]. This may be possible due to some allelopathy effect. The fauna and flora associated with grasslands, scrub and other early serial vegetation will often be lost. Even-aged monocultures will support far less biodiversity than a natural mixed-species forest [29]. But there are many ways in which the biodiversity of planted monocultures can be enhanced. The afforestation program must include the natural vegetation of the particular region to maintain almost identical or compatible landscape. Leguminous trees are more suitable for a good forest establishment as well as soil amelioration [30]. If the sodic land is given to industry, an appropriate portion of green belt must be developed with the industrial tree plantations. According to regulatory guidelines issued by the Ministry of Environment, Forest and Climate Change, Government of India for environment clearance of developmental projects, one-third of the land allocated to the industrial enterprise is mandatory to be rehabilitated or retained under natural forest as a reserve. However, this law has not been uniformly observed, nevertheless, there are a number of examples in Indonesia and Sumatra where large-scale pulp plantations have been established with a reasonable portion of their land as natural forest reserve.

Soil Amelioration

When the forest plantation is established on barren land, degraded soil is gradually improved with the growth and development of trees. There are large areas in the world where soils suffer with the excess sodium in the exchangeable cations. Unlike their saline counterparts which are more extensive, management of sodic soils has

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received less attention. Reclamation of sodic soils primarily require the removal of part or most of the exchangeable sodium from the soil exchange complex and its replacement by a more favorable divalent calcium ions in the rhizosphere. This can be accomplished in many ways, depending on local conditions, available resources, and kinds of crops/plants/trees to be grown. Treatment of soil with gypsum (Ca_2SO_4) followed by cultivation is a common practice to utilize sodic soils in agriculture sector [2]. Addition of gypsum reduces exchangeable Na and increases exchangeable Ca simultaneously. Amelioration in sodic soils through tree plantations have been observed in many studies from young to old stages [5,31-34]; which are primarily influenced by litter and fine root inputs. The contribution of fine roots was apparently greater in the reclamation of soil structure, pH and water permeability, whereas forest litter contributes much in soil fertility and moisture retention. A rehabilitated forest accumulated soil carbon 13 times and total nitrogen twice during 40 yr through the regular inputs of litter and fine roots [32,35].

Prospects and Suggestions for Future Work

Management of sodic lands for crop production or afforestation maintains a quality environment around us. There is need to find out the appropriate land use system for a particular site depending on its degradation status. Thereafter a standard biotechnology is required to rehabilitate it properly. Increasing soil sodicity has become a major issue in natural resource management worldwide and several efforts are underway for the sodic land reclamation programs in various countries like India, Pakistan, and Australia. The purpose of afforestation must be defined clearly as the different sectors need variable strategies to rehabilitate such land for effective uses. It is suggested to focus further attention on the following points for developing a more efficient and sustainable soil restoration model to optimize the biological productivity of such sterile land:

- Several land use models need to be certified through multi-location trials and if they deserve should be adapted on large scale.
- The effect of sodicity on soil carbon dynamics has not been observed for the fast carbon sequestration in the soil. Any attempt for reclaiming sodic soils affects soil carbon dynamics, recovery of microbial populations and their diversity. It is therefore imperative to determine microbial population size and diversity, particularly nitrogen-fixing bacteria, plant growth–promoting rhizobacteria (PGPR), symbiotic mycorrhizal fungi and bacteria. This could be possible through phospholipids fatty acid analysis (PFLA) and other molecular markers, such as amplified fragment length polymorphism (AFLP), random amplification of polymorphic DNA (RAPD), and simple sequence repeats (SSR).
- Periodical monitoring of many restoration programs are not done for a long period to collect data for both ecological and socio-economic developments [36]. Initially these programs are started with a great enthusiasm but later on dull follow-up actions do not complete the projects successfully. The environmental and social problems associated with large-scale reforestation schemes should be carefully attended otherwise many conflicts generate [37-39].
- Carbon sequestration in soil depends on several factors—mainly texture, mineralogy and environmental conditions. Substrate quality and humus fractions need to be explored well for less emission of CO_2 from soil surface.
- Different land-use systems can sequester organic carbon (OC) in sodic soils in the range of 0.17–0.77 Mg C ha^{-1} yr^{-1} [40]. It would be better to consider multilayer cropping system/vegetation developments (trees, shrubs and herbs integrated) for efficient utilization of solar energy and nutrients from different areal and sub areal strata to maximize carbon sequestration per unit area.
- Methanotrophs (methane–oxidizing bacteria) are known to be a potential biological sink to curb the CH_4 emissions [41]. These are unique and ubiquitous bacteria that use CH_4 as the sole source of carbon and energy. Since rice is the most successful crop during reclamation of sodic soil and waterlogged rice fields are supposed to generate substantial methane, these bacteria may be quite useful in soil reclamation process as well as alleviation of methane emissions. Application of farm yard manure and pyrite singly or in combination significantly enhanced the soil methanotroph number, as well as rice yield, in saline paddy fields [42]. However, information regarding soil methanotroph population in sodic fields is still not available. Soil meta-genomics may identify and record activity of such metahnotrophic communities at different sodicity stress.
- Cyanobacteria (blue-green-algae)-photosynthetic oxygen–releasing prokaryotes are considerably tolerant to salt stress and their some strains are used as algal biofertilizer amendment in reclaiming saline

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and sodic lands. Efficient strains and their mechanisms in soil reclamation need to be understood.

- Plant growth–promoting rhizobacteria can be used for the efficient restoration of sodic soil. Presently, the scope of PGPR application is limited because it colonizes the rhizosphere only in certain plants and cannot survive in harsh environments, such as high concentrations of heavy metals and salts. Therefore, suitable strains must be isolated from the identical sites to overcome PGPR mortality in rehabilitation of degraded soils.
- The efficacy of endocellular enzymes, such as dehydrogenase, and exocellular enzymes involved in the transformations of carbon (amylase, cellulase, invertase), nitrogen (protease, nitrogenase, denitrogenase), and phosphorus (phosphatase) in soil systems in response to phyto-restoration has not been examined so far, which needs to be investigated.
- Rhizosphere ecology is poorly known in reclamation and restoration of sodic soil. It is required to analyze the chemical traits that mediate interactions between rhizospheric microbes and plant roots. An integrated approach with microbial ecology, root biology, physiology and soil meta-genomics would be useful to develop efficient reclamation protocol.
- Soil microbial biomass (MB) and enzyme activities catalyze the nutrient availability in the soils therefore right prescriptions should be identified for efficient reclamation and restoration of sodic wastelands. Periodical monitoring and modeling of MB and soil enzymes will provide a better understanding of complex sodicity effects.
- Maximum structural complexity must be created for the recovery of sustainable ecosystem services. Development policies must be reoriented to maintain a balance between ecosystem services and economic development through rational utilization of natural resources.
- Use of geostatistical methods (a part of spatial statistics) and global information systems (GIS) should be extended in land mapping for delineation of sodic lands, rehabilitated and restored sites.
- Bio-reclamation is an effective, low-cost, and viable solution for sodic soil rehabilitation. New modules should be developed for wide spread afforestation from the small sample plots to reduce the cost of rehabilitation.
- Consequent upon the increasing demand of timber, fuel-wood and medicinal herbs as well as good ecosystem services, it is imperative to create and develop new forest on degraded lands. Forest area in UP state is lowest (7%) among all the states of India and it is insufficient to provide essential goods and services to the most thickly populated state of the country. It is therefore important to create and develop new forests on barren sodic lands for multiple uses to the society. Besides, it is also observed that when medicinal herbs, which are in great demand presently with enormous export potential, are cultivated in farming system or out of their natural habitat, the active ingredients/secondary metabolites which are useful in particular ailment, are not synthesized. So the cultivated produce even after having its maximum purity is of no use (ineffective) to cure the particular disorder for which it is known. Thus their cultivation in the new forests (similar habitat) developed on sodic land would be of quite useful to synthesize the particular active ingredients which may be further screened-out for an enhanced levels of the desired compound by introducing & evaluating different accessions of the particular herb in associations with diverse groups of tree species.

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