COMPENDIUM OF



SUSTAINABLE LAND MANAGEMENT

PRACTICES

CENTRE OF EXCELLENCE ON SUSTAINABLE LAND MANAGEMENT
INDIAN COUNCIL OF FORESTRY RESEARCH AND EDUCATION
DEHRADUN, INDIA



Editors:

Krishna Giri

Gaurav Mishra

Sanjay Singh

Manoj Kumar

Rajesh Sharma

Kanchan Devi

A.S. Rawat

COMPENDIUM OF SLM PRACTICES

SUSTAINABLE LAND MANAGEMENT



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Editors:
Krishna Giri, Gaurav Mishra, Sanjay Singh, Manoj Kumar, Rajesh Sharma, Kanchan Devi and A.S. Rawat

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मंत्री
पर्यावरण, वन एवं जलवायु परिवर्तन
और
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MINISTER
ENVIRONMENT, FOREST AND CLIMATE CHANGE
AND
LABOUR AND EMPLOYMENT
GOVERNMENT OF INDIA

भूपेन्द्र यादव
BHUPENDER YADAV



MESSAGE

Land resources facilitate various physical, social, economic, and infrastructure activities. For example, the land is used for agriculture, watershed management, afforestation, mining, transportation, and development. It is, therefore, important to protect and maintain land resources to ensure the sustained provision of vital services by terrestrial ecosystems. However, human activities such as extensive agriculture, overgrazing, and deforestation can degrade the land by reducing its productivity and quality. Additionally, various natural factors, such as earthquakes, heavy rainfall, landslides, cloud bursts, and volcanic eruptions, contribute to land degradation. Land degradation affects people, ecosystems, and climate across the world. The impact of climate change aggravates the ongoing land degradation processes and introduces new degradation patterns. Land degradation and climate change adversely affect the livelihoods of societies dependent on natural resources—the decline in soil quality and agricultural productivity due to land degradation cause significant harm to rural communities.

Land degradation can be avoided, reduced, or reversed through Sustainable Land Management practices that yield multiple co-benefits, including climate change adaptation and mitigation. Merely restoring land is also insufficient; stewardship is essential for continuous and ongoing conservation while addressing community needs. An ideal restoration scenario involves a repaired ecosystem, community governance of land, and establishing mutually beneficial relationships between people and resources for sustainable livelihoods. This strategy empowers local communities, encourages them to take ownership of the protection of their land, and engages them in decision-making, planning, and implementation. Sustainable Land Management is the comprehensive approach comprising technologies combined with social, economic, and political enabling conditions.

The Government of India has extended its support for the Bonn Challenge pledge at Paris COP 2015 to restore deforested and degraded land, becoming one of the first Asian countries to join the global commitment, and has targeted to restore 26 million hectares of degraded lands to achieve Land Degradation Neutrality (LDN) by 2030. Indian Council of Forestry Research and Education, Dehradun, has set up a Centre of Excellence on Sustainable Land Management (CoE-SLM) under its umbrella for the creation of a national-level database on degraded lands, develop state-of-the-art scientific approaches and facilitate induction of cutting-edge technologies for restoration of degraded land in the country.

CoE-SLM has compiled "**Compendium of Sustainable Land Management Practices**" which includes contributions from eminent Researchers and Academicians from various Research and Development organizations. The compendium provides a comprehensive compilation of articles on sustainable land management practices and case studies in agriculture, forestry, and other land use sectors. The proposed interventions and allied conservation measures can act as a roadmap for restoring degraded lands.

I congratulate the CoE-SLM, ICFRE, officials for the remarkable work and especially commend DG, ICFRE, for his leadership in this endeavor. I am confident that the document will be immensely useful for planners and other stakeholders.

Date: 7 .04.2023

(Bhupender Yadav)

पर्यावरण भवन, जोर बाग रोड़, नई दिल्ली–110003, फोन: 011–20819275, 20819225, फैक्स: 011–20819299
Paryavaran Bhawan, Jor Bagh Road, New Delhi-110003 Tel.: 011-20819275, 20819225, Fax: 011-20819299
ई–मेल/E-mail: mefcc@gov.in

Preface

Land is a finite natural resource that provides the base for the survival of living beings on Earth. Land resources encompass soil, water, and biodiversity which serve as the foundation of the world's socioeconomies. Nearly 44 trillion US $ economic outputs (more than half of the global GDP) are moderately or highly resilient on natural capital. The increasing global population has aggravated food grain demand and exerts huge pressure on land resources. Consequently, the land resources have undergone degradation and suffered loss due to huge anthropogenic pressure in recent decades. Land degradation is the persistent reduction of the capacity of the land to support biodiversity, ecosystem services, and human needs which hampers food production, water storage, biodiversity, and carbon sequestration in the soil–plant system. However, land degradation in arid, semi-arid and dry sub-humid areas is termed as desertification. About 25% area degraded globally has affected 3.2 billion people around the world.

India is the 7th largest country covering 2.4% of the world's geographical area and supporting about 18% each of the human and cattle population of the world. About 228.3 million hectares (i.e. 69.6%) of the total geographical area of the country is estimated as dry lands (arid, semi-arid, and dry sub-humid regions). According to the recent estimates of the Space Applications Centre published in Desertification and Land Degradation Atlas of India, 2021, the current extent of land degradation has been estimated at 97.85 million hectares covering 29.77% of the geographic area of the country.

Restoration of degraded lands need concerted global efforts and has been acknowledged in the 2030 Agenda for Sustainable Development with the adoption of SDG 15, which urges countries to "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably managing forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss". The UN Decade on Ecosystem Restoration (2021-2030) is a rallying call for the protection and revival of ecosystems all around the world, for the benefit of people and nature. The SDG target 15.3 championed by the United Nations Convention to Combat Desertification (UNCCD) states "by 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world."

Achieving land degradation neutrality by preventing land degradation and rehabilitating already degraded land, scaling up sustainable land management, and accelerating restoration initiatives is a pathway to greater resilience and security for all. Restoring the soils of degraded ecosystems has the potential to store up to 3 billion tonnes of carbon annually. To achieve India's ambitious targets of restoring 26 Mha degraded lands and creating an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030, it is essential to realize the current state of institutional and policy arrangements.

Realizing the need for a strong institutional and policy framework the Hon'ble Prime Minister of India while addressing the High-Level Segment of the Fourteenth Session of the Conference of Parties to United Nations Convention to Combat Desertification (UNCCD) made an announcement in 2019 to set up a Centre of Excellence on Sustainable Land Management at Indian Council of Forestry Research and Education (ICFRE) in order to further develop scientific approach and facilitate induction of technology on land degradation issues.

Accordingly, the Centre of Excellence on Sustainable Land Management (CoE-SLM) has been established at ICFRE Dehradun with the aim to facilitate the restoration of degraded lands, achieving land degradation neutrality and promoting South-South cooperation. Capacity building and technical support in setting priorities and LDN target setting, capacity building for developing transformative projects, networking of national and international institutions working on sustainable land and ecosystem management for knowledge sharing and exchange, awareness and technical support for the implementation of sustainable land and ecosystem management programmes/ projects are the key objectives of CoE-SLM.

Preface

CoE-SLM has made an attempt to compile Sustainable Land Management Practices from the domain experts in Agriculture, Forestry, and allied sectors. The compendium consists of thirteen chapters covering soil and water conservation measures, sustainable land management practices, strategies to combat desertification, farming practices in dry lands, mangrove restoration and management, precision farming systems for land restoration and livelihood sustenance of marginalized and smallholder farmers, and sustainable land management practices evolved through indigenous knowledge of the farming communities.

Compilation of this compendium could not have been possible without the valuable contributions made by eminent experts from various organizations. The editors are sincerely grateful to all authors for making valuable contributions and cooperation during various stages of the publication process. We hope that the publication will serve as resource material for the successful implementation of land restoration measures in the country.

Editors

List of Abbreviations

ADWCB	Acidified Dicer Wood Chips Biochar
AFRI	Arid Forest Research Institute
ARSB	Acidified Rice Straw Biochar
BAC	Bacterial and Archeal Communities
BBF	Broad Bed and Furrow
BNF	Biological Nitrogen Fixation
BSC	Bio Solids Co-compost
BT	Box Trenches
BWCD	Brush Wood Check Dam
CAZRI	Central Arid Zone Research Institute
CBT	Conservation Bench Terrace
CCA	Culturable Command Area
CCT	Continuous Contour Trenches
CDA	Chilika Development Authority
CEC	Cation Exchange Capacity
CIL	Coal India Limited
COP	Conference of the Parties
CRIDA	Central Research Institute for Dryland Agriculture
CRZ	Coastal Regulation Zone
CT	Contour Trenches
DAP	Di-amonium Hydrogen Phosphate
DHA	Dehydrogenase
DLD	Desertification and Land Degradation
DLTs	Drainage Line Treatment
EC	Electrical Conductivity
EGS	Ecosystem Goods and Services
EMP	Exchangeable Magnesium Percent
FAO	Food and Agriculture Organization

Abbreviations

FGDG	Flue Gas Desulfurization Gypsum
FYM	Farm Yard Manure
GD	Gradoin Ditches
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GIS	Geographical Information System
GWC	Green Waste Compost
HDPE	High Density Polyethlyene
HLRDC	Haryana Land Reclamation and Development Corporation
ICFRE	Indian Council of Forestry Research and Education
IGNP	Indira Gandhi Nahar Pariyojana
IISWC	Indaian Institute of Soil and Water Conservation
IMD	India Meteorological Department
IMSQI	Integrated Mine Soil Quality Index
IPCC	Intergovernmental Panel on Climate Change
IPZ	Island Protection Zone
IRS-AWiFS	Indian Remote Sensing-Advanced Wide Field Sensor
ISFR	India State of Forest Report
ISRO	Indian Space Research Organization
ITPS	Inter-Governmental Technical Panel on Soils
IWSM	Integrated Watershed Management
JMM	Joint Mangrove Management
LBCD	Loose Boulder Check Dam
LDN	Land Degradation Neutrality
LMU	Land Management Units
LRI	Land Resource Inventory
LULC	Land Use Land Cover
MBC	Microbial Biomass Carbon
MBN	Microbial Biomass Nitrogen
MBP	Microbial Biomass Phosphorus

Abbreviations

MDS	Minimum Data Set
METT	Management Effectiveness Tracking Tool
MG	Marine Gypsum
Mha	Million hectares
MOP	Muriate of Potash
MSSRF	M.S. Swaminathan Research Foundation
MSW	Municipal Solid Waste
Mt	Metric ton
NAAS	National Academy of Agricultural Sciences
NATP	National Agricultural Technology Project
NCL	Northern Coalfields Limited
NDVI	Normalized Difference Vegetation Index
NHM	National Horticultural Mission
NIA	Net Irrigated Area
NPCA	National Plan for Conservation of Aquatic Ecosystems
NPP	Net Primary Productivity
NRAA	National Rainfed Area Authority
NSA	Net Sown Area
OB	Overburden
OCP	Open Cast Project
PAFS	Pineapple Agroforestry Systems
PAME	Protected Area Management Evaluation
PAWC	Plant Available Water Capacity
PCA	Principal Component Analysis
PME	Post Mining Ecosystem
PRA	Participatory Rural Appriasal
RKVY	Rashtriya Krishi Vikas Yojana
R-METT	Ramsar Management Effectiveness Tracking Tool
RMS	Restored Mine Sites
RWH	Rain Water Harvesting

Abbreviations

SAC	Space Applications Centre
SAG	Sulfurous Acid Generator
SAGY	Sansad Adarsh Gram Yojana
SALT	Slopping Agricultural Land Technology
SAR	Sodium Adsorption Ratio
SDGs	Sustianable Development Goals
SER	Society for Ecological Restoration
SH	Soil Health
SLM	Sustainable Land Management
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SQUs	Soil Quality Units
SSP	Single Super Phosphate
STCR	Soil Test Crop Response
SWA	State Wetlands Authorities
SWC	Soil and Water Conservation
TDS	Total Data Set
TGA	Toatal Geographic Area
TN	Total Nitrogen
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UPBSN	Uttar Pradesh Bhumi Sudhar Nigam
USDA	United State Department of Agriculture
VD	V-ditch
VDMC	Village Development and Mangrove Consrvation Council
VGCTR	Vegetally Guarded Conservation Trenches and Ridges
WBC	Wood Chip Biochar
WFPS	Water Filled Pore Space

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ONE

P.C. Moharana, P. Santra and J.P. Singh
ICAR-Central Arid Zone Research Institute, Jodhpur, Rajasthan-342003



Sand Dune Stabilization, Jaisalmer, Longewala

1.1 Introduction

Land degradation is one of the important Global Issues. The UN defines desertification as a process of land degradation in dryland areas due to various factors, including climatic variations and/or human activities (United Nations Convention to Combat Desertification or UNCCD). Land degradation and climate change, both individually and in combination, have profound implications for natural resource-based livelihood systems. It is a fact that the world is looking at drylands for many of these above problems. About 2/3 of the world is affected by desertification and 3.2 billion people are affected. Though degraded, such lands are now the centre of attraction as there is an alarming increase in the demand for food, fodder/feed and fuel at global, regional and national level. Considering the limitation in the extent of arable land, its production capability and productivity, the attention is now focused on cropland expansion towards degraded or marginal lands. The high value or challenged ecosystems (hilly, arid lands & coastal), are now suggested as a solution to issues of land scarcity and as an ideal way to meet mounting demands for agricultural goods. The conceptual framework for land degradation assessment has undergone significant changes. The UNCCD and its CoP (Conference of the Parties) countries have come out with pledge to restore degraded lands meaning that desertification is reversible in many ways and thus activities under the umbrella of SLM/LDN/SDG, needs to be carried out by each of the member countries to address the issue of land restoration. About 136 out of 196 CoP countries of UNCCD have committed to work within objectives of LDN framework for the land restoration. India was also the host country for organizing CoP-14 meeting at the capital city New Delhi during September, 2019. The deliberations confirmed that desertification has still remained one of the major environmental problems especially in the drylands.

1.2 How big is the problem of desertification in India?

India has a large land mass (total geographical area of 328.72 Mha) and huge human population (1.21 billion), thus it is most likely that desertification or land degradation would certainly affect life in its drylands. To quote

Monique Barbut, the Executive Secretary of UNCCD, "India is one of the countries affected by desertification, and is facing new challenges, among which are recurrent droughts, dust, and sand storms. The country has tremendous potential to turn these challenges into opportunities through improved land use and management, and to provide the leadership the world needs to take bold actions." Whether we need to say "desertification" is a big problem in India, there is a need to look at the database at various scales.

India has a fragile physical environment of 31.7 Mha classified as a hot arid zone which can be termed as a challenged ecosystem. The northwestern part of India is home to a major part of this hot arid zone and is also known for the occurrence of the Thar Desert region. The state of Rajasthan has the maximum area under hot arid region (19.60 Mha) and the country's cold arid regions are confined to mountainous Himalayan terrain in Leh and Ladakh regions distributed over 7.0 Mha land. State-wise distribution of hot and cold arid regions is presented in Figure1.1 and Table 1.1

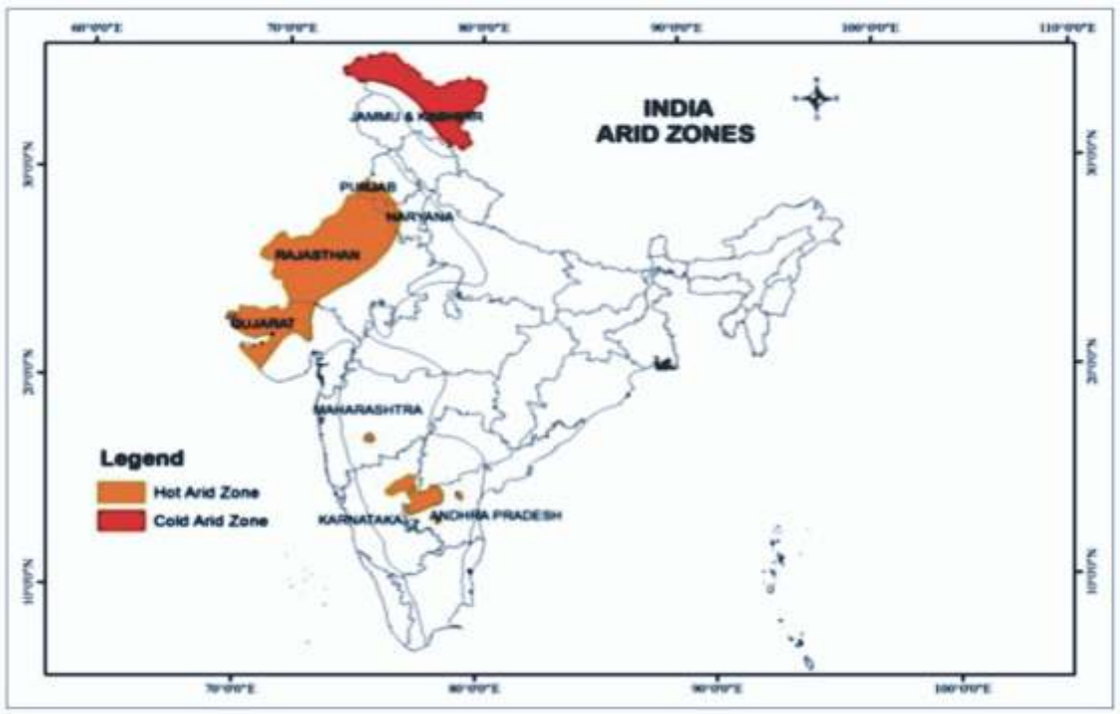


Figure 1.1: Map depicting the hot and cold arid zones in India

Hot arid zone in India: 317090 km^2		
State	**Area (km^2)**	**Percentage of the total Hot Arid Regions of the country**
Rajasthan	196150	61.9
Gujarat	62180	19.6
Punjab	14510	4.6
Haryana	12840	4.0
Maharashtra	1290	0.4
Karnataka	8570	2.7
Andhra Pradesh	21550	6.8
Cold arid zone in India: 70300 km^2		
Jammu & Kashmir, Leh–Ladakh, Himachal Pradesh		

Table 1.1: Distribution of arid regions in India

Within the drylands of the country (arid, semi-arid, and dry sub-humid regions), 83.69 Mha area is observed as undergoing desertification as reported during 2018-19. If India's total geographical area is considered, the total degraded land is about 97.85 Mha or about 29.77% area, affected by various processes of land degradation. The major processes of degradation in the country are water erosion (11.01% area), vegetation degradation (9.15% area), wind erosion (5.46% area), salinity/alkalinity (1.11% area), manmade/ settlement (0.69% area) and others (water logging, frost shattering, mass movement, barren and rocky land types) in 2.07% area (SAC, 2021). There is a cumulative increase of 1.45 Mha area under desertification from 2011-13 to 2018-19.

The desertification database analyzed for all the arid states of India revealed that eight out of nine, have reported increased area under land degradation during 2018-19, except Rajasthan, where the degraded area has declined by 1.13% or in 387939 ha area (Table1.2).

States	2003-05	2018-19	Change (2018-19)-(2003-05)
	Area (%)	Area (%)	Area (ha)
Rajasthan	63.19	62.06	-387939
Gujarat	51.35	52.22	+170602
Haryana	7.12	8.24	+49571
Punjab	1.85	3.34	+74874
Andhra Pradesh	14.16	14.84	+110314
Karnataka	36.19	36.29	+18904
Maharashtra	43.38	46.49	+957425

Table 1.2: Change in spatial extent of degraded lands in the arid states of India

Source: *SAC, 2021*

As described earlier, western Rajasthan shares the maximum area of India's hot arid region. Salient environmental characteristics are described to understand the region's vulnerability to various processes of land degradation.

The Northwestern part of the country contains the Indian segment of the Thar Desert and climate-wise, this region represents the country's hot arid zone. Situated between the western scarps of the Aravalli mountain ranges in the east and the Indus River in the west, the Thar Desert is bounded by aridity indexes of -66.6% in the east to a maximum -93.7% in the west. Aravalli hills, the Indus River system, and the saline environment of Greater/Little ranns in the south which represent the geomorphic units, influence regional climate, landform formation, and hydrology of the desert environment. The Aravallis are one of the oldest hill ranges in the world, were formed more than 2500 million years ago and had undergone at least three cycles of orogenesis and plantation since the Proterozoic. The climatic variations and prolonged interplay of wet and dry periods have created a dominant aeolian province (in > 80% area) having sand dunes, alluvial and sandy plains. The seasonal and annual temperature range is high, in summer the temperature may rise up to 50°C, while in winter it dips as low as -4°C. The annual average rainfall is very low, varying from 100 mm in the west to 500 mm in the eastern part a year, but pan evaporation is too high (1800 mm) making the desert water limiting. Wind speed occasionally is very high (40-60 km hr^{-1}), particularly in the summer season which together with low humidity makes the environment inhospitable. The aeolian or sand-covered terrain spread over ~ 80% area. Among the landforms, the maximum area is covered by sand dunes and interdune plains in about 48% area. Demographically, western Rajasthan has a large population of ~28 million (Census, 2011) distributed over 12 districts that fall on four agro-climatic zones and dominant agrarian land use.

1.2.1 Geomorphic Scenario

The western Rajasthan region is endowed with a variety of landform types; aeolian or wind driven, fluvial or due to water action, lacustrine (lake related) and tectonic (denudation types). Thus many researchers term Thar landforms as polygenic in nature. Sand dunes, sand sheets, deflation plains, interdune plains, desert

pavements and playas (inland Ranns) are landforms of aeolian origin. Sand dunes are the major landforms of the desert region. Higher concentrations of dune fields occur in districts of Jaisalmer (in 21684 sq. km or 56.79%), Bikaner (20950.94 sq. km or 77.1%), Barmer (15791.42 sq. km or 55.82%). The extent of dune-fields has been restricted in the canal irrigated districts of SriGanganagar and Hanumangarh where sand dune area occurs in 42.69% and 46.98% respectively. Based upon, morphological characteristics and genesis, dunes are of parabolic, linear, transverse, barchans and obstacle types. It has been possible to map the extent and morphology of 09 major and 21 sub types sand dunes using remote sensing satellite images. Even though this region receives very less rainfall, much of the fluvial forms were created during a geologically wetter period. The present day fluvial landforms cover 13.3% area of western Rajasthan. The major sites are the northern part of SriGanganagar and Hanumangarh districts, where the Ghaggar River is the major factor and in the districts of Nagaur, Jodhpur, Pali, Jalore and Sirohi, where several floods (1979, 2003 and 2007) by Luni River and its tributaries are known to carry lots of sediments or cause soil loss. The alluvial plains of the Luni river and its tributaries thus contribute to the region's agricultural activities. Besides, playa lakes or saline depression surfaces (lacustrine origin) occur in almost all districts of western Rajasthan. These lands are considered culturable wastes which have the potential to be utilized either for commercial use or to be utilized as grazing lands. The variability in the landscape is explained through agro-climatic classification. Western Rajasthan (divided into 12 administrative districts) falls under two agro-climatic regions; western Dry region and Trans-Gangetic plain region and four agro-climatic zones: (1) Arid western Plain, (2) Transitional plain of inland drainage, (3) Transitional plain of Luni basin, and (4) Rajasthan irrigated north-western plain. Jaisalmer, Barmer, Bikaner, Churu and Jodhpur in Arid western plain zone (133073.6 sq. km), SriGanganager and Hanumangarh (Rajasthan NW canal irrigated plain, 20556.6 sq km), Nagaur, Jhunjhunun and Sikar (Transitional plain of Inland drainage, 31329.3 sq. km) and Pali and Jalor (Transitional plain of Luni basin, 22951.1 sq. km) are the districts.

1.2.2 Vegetation

Vegetation in hot arid regions is very sparse having a few thorny trees, shrubs and in large open areas of sprawling annual and perennial herbs, forbs and grasses. The surveys in western Rajasthan over the past 60 years revealed two major trends in its vegetation: 1) It follows a typical gradient from 400 mm to 150 mm annual rainfall from mesophytic to xerophytic, and 2) within each rainfall zone, it has a typical habitat-plant cover relationship. These trends are further compounded by variable landforms, soil types, groundwater depth and quality. Types, severity and intensity of anthropogenic factors further compound the occurrence, density and vigour of vegetation. Accordingly, sand dunes, hummocks and sandy plains have a predominance of psammophytes such as *Calligonum polygonoides, Acacia jacquemontii*, *Lasiurus sindicus*, and *Panicum turgidum;* hills and rocky areas have lithophytes such as *Acacia senegal*, *Euphorbia caducifolia*, *Trphrosia uniflora*; and saline habitats have predominance of halophytes such as *Haloxylon recurvum*, *Salsola baryosma*, *Suaeda fruticosa*, *Sporobolus* spp. Yet in the overall scenario, distinct plant communities occur in different habitats whereas varyingly degraded vegetation in these habitats is found in their successional stages.

1.2.3 Vegetation cover change

Grazing is a prominent land use throughout western Rajasthan and it has substantial effects on vegetation composition and diversity in different ways, depending on the type of grazing animals and intensity of grazing. Therefore, increased livestock pressure changed the composition of vegetation, particularly in grazing lands from high to less palatable species accompanied by decreased herbage production. For example, under excessive grazing and particularly under drought and scarcity periods the *Lasiurus sindicus* grasslands deteriorate to the bare ground with a few annuals like *Aristida adscensionis, A. funiculate* and *Indigofera linifolia* etc. Moreover, changes in land use patterns/ conversion of grasslands into croplands due to irrigation critically affected the high valued *Lasiurus sindicus* and also *Panicum turgidum* grasslands particularly in Jaisalmer district. Further, due to over exploitation of the woody perennials i.e. very high browsing pressure, cutting and digging the roots of key arid shrubs like *Calligonum polygonoides* have seriously affected

the vegetation composition and plant diversity as well.

1.3 Vulnerability vs. Reduced Desertification in western Rajasthan

The Thar region is one of the most fragile and vulnerable area prone to various processes of desertification, especially the process of wind erosion/depositional hazards. The wind erosion map prepared by the ICAR-CAZRI during the year 2000, indicates, 5800 km^2 area under very severely degraded, 25540 km^2 area severely affected, 73740 km^2 area, moderately affected and 52690 km^2 area is slightly affected. The impact of wind erosion is assessed through soil loss due to windblown activity and removal of nutrient rich topsoil, crop loss by sandblasting or abrasion actions on tender stems and leaves, and burial of the short height crops through saltation particles. A series of maps on the desertification status of the region have been prepared by CAZRI scientists since 1992 till recent. An assessment using IRS-AWiFS sensor and GIS-based mapping at a scale of 1:500,000, has found 62.06% (21.23 Mha) of the total geographical area in the state is undergoing Desertification/Land Degradation (D/LD) during the timeframe 2018-19. During the period 2011-13, the affected area was 62.90% (21.52 Mha). Thus, a decrease of 288847 ha area undergoing DLD is observed between 2011-13 and 2018-19. The most significant process of desertification/ land degradation in the state is wind erosion (43.37% in 2018-19, 44.41% in 2011-13) followed by vegetation degradation (7.64% in 2018-19, 7.62% in 2011-13) and water erosion (6.21% in 2018-19, 6.18% in both 2011-13). Details of the database are given in the following table (Table 1.3).

Process of Desertification/ Land Degradation	2018-19		2011-13		Change (ha)
	Area (ha)	Area (%)	Area (ha)	Area (%)	(2018-19) (2011-13)
Vegetation degradation	2614640	7.64	2606221	7.62	8418
Water erosion	2124456	6.21	2116314	6.18	8141
Wind erosion	14843215	43.37	15197874	44.41	-354659
Salinity	365834	1.07	363768	1.06	2066
Water logging	18425	0.05	18421	0.05	4
Manmade	81796	0.24	53058	0.16	28738
Barren/Rocky	1050236	3.07	1052374	3.07	-2138
Settlement	139064	0.41	118482	0.35	20582
Total Area under Desertification	21237665	62.06	21526512	62.90	-288847
No Apparent Degradation	12821672	37.46	12546925	36.66	274747
Total Geographical Area (ha)	34223900				

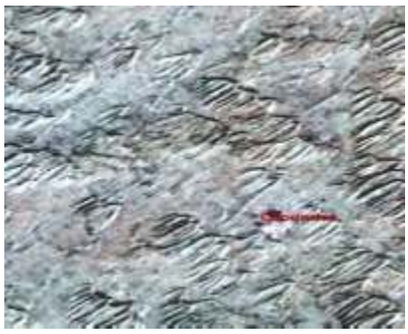
Table 1.3: Land degradation status database for Rajasthan

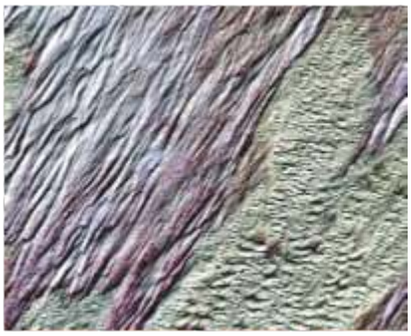
The above mapping has come out with some important findings; (1) wind erosion affected area in Rajasthan has reduced by 3.54 lakh ha since 2011-13, (2) the area classified as severe to very severe category, has decreased in 4% area and (3) degraded area due to manmade processes has increased by 28738 ha. The perpetual problem of hot waves, dust storms and sand movement is reported to be reduced. Water logging and secondary salinity have remained problems within the IGNP canal irrigated region and occur in a smaller area (~1%). Groundwater irrigation is causing deterioration of the land quality in the easternmost districts. Vegetation degradation has increased mainly due to unrestricted grazing and mismanagement of village common grazing lands. Mining of rocks and minerals being an important economic activity, area under such activities is increasing.

1.4 The changing faces of wind erosion /deposition

Wind erosion is the dominant process of desertification, mainly in the western part of

Rajasthan. Five districts of western Rajasthan (Jaisalmer, Bikaner, Barmer, part of Jodhpur and Churu) falls under the arid western plain (agro-climatic zone), where wind erosion index values are >120. This representative region is more vulnerable to wind erosion. The causes for such vulnerability have been explained by many researchers through studies on dynamics of wind erosion; wind speed, low and erratic distribution of rainfall, a vast desert terrain, area under sand dunes, scattered vegetation cover and land use. The wind dynamics have determined the scale of features or Aeolian bed forms that varies from closely spaced stabilized sand dunes to the formation of barchans, mega barchans, nebkhas, and other smaller features like sand streaks, and also fence line ridges (Figure 1.2).


A parabolic dune field in Barmer


Mega-barchanoids in Jaisalmer


Star-network dunes in Hanumangarh


Sand accumulation over a parabolic dune


Sand encroachment in roads


Sand encroachment in croplands


Water erosion and gully formation


Salinity/alkalinity hazards


Mining and land degradation

Figure 1.2: Physical (field) indicators of wind/water/salinity hazards

Remote sensing satellite images with high spatial resolution provide precise inputs to the identification of many quality features. Wind erosion index, isohyets and aridity index have been computed to understand the spatial variability of aeolian landforms in western Rajasthan. It has been found that mobile dunes like barchans start forming mostly in the areas bounded by 120 contour index which matches with isohyets of 250 mm in the southern part of the desert. Field-based measurements have shown that barchans or low dunes moved a maximum of 31 m yr^{-1} while parabolic dunes tend to move @ 3-5 m yr^{-1}. However, with time and in

conformity with higher wind speed, these crescent-shaped dunes attended higher elevation to the south of Dhanana villages in Jaisalmer district which has a matching highest wind erosion index of 480% and above. Wind erosion is also more evident in the Eastern part of arid Rajasthan (in Churu, Jhunjhunun and Nagaur) and is classified as low wind erosion index (15-29%) where low dunes and fence line dunes occur frequently. Such situations do not correspond to high wind speed but phenomena are related to human actions.

Impacts: Measurement through instrumentation shows substantial variations in the annual soil loss rate due to wind activity in different severity zones 83.3 t ha^{-1} yr^{-1} under a very severe category 50 t ha^{-1} yr^{-1} (severe), 12.2 t ha^{-1} yr^{-1} (moderate) and 1.3 t ha^{-1} yr^{-1} under slight category. Conversion of these soil loss rates into equivalent loss of soil depth resulted in a loss of 0.55 cm yr^{-1} and 0.01 cm yr^{-1}, for the respective categories. The severity of wind erosion has impacts on crop health. Crop production loss due to wind erosion under all the severity categories was assessed using Soil Test Crop Response (STCR) equations. It revealed that in very severely affected areas, the yield gap of major crops as compared to negligibly affected areas varied from 57 to 82%, of which about 9-67% was contributed by wind erosion for different crops. Yield reduction due to wind erosion was found to be 195 kg ha^{-1} yr^{-1} for pearl millet in very severely affected areas whereas it was 93 kg ha^{-1} yr^{-1} for moth bean and 229 kg ha^{-1} yr^{-1} for cluster bean.

1.5 Western Rajasthan: Scope for Land Restoration and Possible Strategies

The UNCCD under its programme for land degradation neutrality suggests monitoring of three elements for improving land conditions; land use and land cover, soil organic carbon, and Net Primary Productivity (NPP). In this study, the present status of land use/ land cover in western Rajasthan has been analysed. As per agricultural statistics of the state (Table 1.4), during 2019-20 periods, the total crop area in western Rajasthan was about 167.16 lakh ha, representing 44% area while the net sown area was 31%. About 58.20 lakh ha or (8% area in each category) were covered under culturable wastelands and fallow land area. The major concern and challenge are to come out with a strategy to utilize such 16% of lands with judicious and scientific interventions. These areas may be considered as the hotspots of changes, but their extent and geographical distribution need to be identified for targeting those lands for restoration purposes.

District	Culturable waste land	Fallow Land	Total cropped area	Forest	Land not available for cultivation	Permanent pasture and other grazing lands	Land under miscellaneous tree crops & groves	Net sown area
Barmer	188797	550429	1916447	33375	205396	203515	4931	1630989
Bikaner	522015	495260	2168688	104912	294983	49852	1133	1573598
Churu	25004	122180	1720228	6624	68046	37023	4	1127024
SriGanganagar	17029	154274	1315032	60519	73718	129	1135	786486
Hanumangarh	1965	38701	1492384	19061	58462	4653	245	847293
Jaisalmer	2084371	254731	1180109	28474	579357	87182	457	804582
Jalore	21031	184155	940641	23634	123079	47360	55	657297
Jhunjhunu	7199	80834	627943	40045	38024	39237	30	386167
Jodhpur	9610	492577	1878479	10312	225092	121639	19	1397156
Nagaur	11075	218141	1869149	18874	158612	70971	533	1296758
Pali	41131	183496	878102	86797	198191	91314	510	631640
Sikar	11967	104329	728902	61190	56610	39237	46	501133
Total area	2941194	2879107	16716104	493817	2079570	792112	9098	11640123

Table 1.4: Land use statistics of western Rajasthan for 2019-20 (area in ha.)

1.6 What has changed in IGNP area: A case study of Jaisalmer District?

The Indira Gandhi Nahar Project (IGNP) is a large surface water transfer project constructed during the 1960s in the heart of the desert area with the objective of using this water to transform the extensive sandy wasteland of the western part of Rajasthan into greenery. Within Rajasthan, the canal is 445 km long passing through the sand dune-covered terrain in 7 of 12 arid districts. The IGNP Stage-I is restricted to Sri Ganganagar, Churu, Bikaner and Hanumangarh districts and the Stage-II to Jaisalmer and Barmer districts. The entire project area serves a vast Culturable Command Area (CCA) of 19.63 lakh ha land of the region. Like many big irrigation canal projects, IGNP witnessed vast prosperity in agriculture as well as experienced the problem of salinity and waterlogging but also became a region of reduced wind erosion activities.

1.6.1 Water management through Farm pond structures in canal and groundwater irrigated regions of western Rajasthan

Water management with technological intervention on the traditional systems and big irrigation canal projects (IGNP and Narmada) are providing water security. From traditional village ponds (nadi) to micro-farm ponds (diggi), there is a radical transformation in the process of water conservation. The scope for bringing more area under agriculture has been observed. Many farm ponds were constructed which are locally called the Diggi. From the year, 2000 onwards, farmers in the IGNP area in Jaisalmer district have started constructing such small farm pond structures in individual cropland. Canal water is transferred to diggies which farmers utilize as per irrigation requirements. Farmers pump out water from diggi using the electric motor and then apply it to the field by micro-irrigation devices such as sprinklers and drip systems. The Government too has recognized the importance of diggi and has a provision to help the farmers with subsidy for the construction. A standard diggi (110 m x 110 m x 2 m) can store about 25 lakh liters of water. To reduce the construction cost, these diggies are also lined with High-Density Polyethylene (HDPE) sheets of 300 to 500-micron thickness.

A GIS and remote sensing-based assessment was carried out for generating information on irrigated croplands, diggi, or farm ponds and the impact on wind erosion hazards in the IGNP area of Jaisalmer district from the year 2000 to date. The assessment used a NDVI prepared using Landsat 5 (TM) satellite data of February month and extracted temporal information on the extent of the area under irrigated croplands. It was found that irrigated croplands have increased six times from 13798 ha in 2001 to 80514 ha in 2021. The assessment also included extracting information on the number of diggi or farm pond structures constructed during the same period. Using Google Earth images and Sentinel-2A satellite images, diggi of three different sizes could be mapped. The mapping indicated that the number of diggies has increased about 10 times since 2000, from a merely 400 increased to 4500 number during 2021. When these maps were analysed in GIS with respect to the desertification map, the areas where irrigated croplands have increased matched with the increasing number of diggi structures. Such areas were either barren or left as fallow lands even though canals were existing. These lands have developed substantial green cover which has impacted the reduced sand movement for the most part of the year. The wind erosion affected area has shown decreasing trend; from 8.64 lakh ha or 94.60% area to 7 lakh ha or 76.70% area. Most of these improvements have occurred in the canal command of Mohangarh-Nachna-Sultana-Ramgarh in the district (in the form of crop cover/ afforestation/shelterbelts (Figure 1.3).

Another interesting finding from the satellite images is the spread of diggi structures to the tail end of IGNP canal south of Dabri village in the Jaisalmer district. The images reveal the fact that through the construction of farm pond structures, people living in remote locations of desert areas are able to conserve canal water and utilize such water for growing crops as well as providing a solution to drinking water facilities for the region's growing livestock. A remote sensing and limited field survey-based exercise by the author indicated substantial expansion in irrigated croplands. Spatio-temporal analysis of classified images of NDVI showed that groundwater irrigated areas during the rabi period increased from merely 7% in 2000 to about 21% in 2020 (Figure 1.4).



Tree plantation as wind break has been effective in stabilizing sand dunes and roads near Shetrawa village in Jodhpur is sand free now



A typical model of horizontal pattern of wind break put over a very active sand dune area in Jaisalmer district



Sand spread and sand encroachment in chick pea crop area in IGNP Command area



Tube wells facilitating irrigated cropping in dune areas (interdunes); reducing the vulnerability to wind erosion



Construction of Diggi helping farmers in both canal and groundwater irrigated area



A satellite image (Google Earth) showing sprawling occurrence of diggi in Pugal tehsil of Bikaner district

Figure 1.3: Changing faces of arid land surfaces, agriculture and water management



Figure 1.4: FCCs of Landsat Satellite Images showing temporal changes in rabi crop area (marked) over Jodhpur District

1.7 Policy issues to achieve Sustainable Development Goal (SDGs) and Land Degradation Neutrality (LDN) targets

Reduction in economical and biological productivity of arid land of India through desertification processes e.g. wind erosion, soil salinity, vegetation degradation, etc., poses a major challenge to agricultural production systems of the region. Degradation of land is not only of concern for the arid regions. In other parts of the world, however, through other degradation processes and due to increasing human pressure on land. Therefore, there is an urgent need for action to protect our motherland from degradation and to sustain the future of people in the world. Arising from these concerns, United Nations member states in the UN sustainable development summit held in New York in September 2015 formulated a resolution, "Transforming our world: The 2030 Agenda for Sustainable Development", for peace and prosperity for people and the planet, now and into the future. The resolution was agreed upon by all countries - developed and developing - in a global partnership with 17 sustainable development goals

(SDGs). All the member states recognized that ending poverty and other deprivations must go hand-in-hand with strategies to tackle climate change and work to preserve our lands, oceans, and forests. Among the SDGs, goal 15 is dedicated to "Life on land: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss". To achieve the goal, land degradation neutrality (LDN) is targeted as "By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought, and floods, and strive to achieve a land degradation-neutral world". Does achieving neutrality in land degradation indicate a total stop in land degradation processes? Whether it is feasible to totally check naturally occurring land degradation processes? All these questions are clarified in the definition of LDN by the Parties to the Convention as a state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems. As stated earlier in this article, the selected three global indicators: land cover, land productivity, and carbon stocks indicators can be assessed through three metrices: land cover change, net primary productivity (NPP) and Soil Organic Carbon Stock (SOC). The associated metrics are quantified for each land type at the baseline setting period (prior to LDN implementation), during at least two intermediate monitoring points and at the end of LDN implementation. The "one-out, all-out" principle is used to evaluate the indicators and metrics and determine LDN status, according to which, degradation occurs when (compared with baseline) SOC decreases significantly or NPP decreases significantly, or negative land cover change occurs. Member countries pursuing LDN are encouraged to use additional indicators/metrics for ecosystem services and social and economic outcomes that address their national or sub-national priorities and to include these as part of LDN monitoring. In India, work on the restoration of degraded lands has been going on since 2015 after the announcement of the Bonn Challenge target, following which India was to restore13 Mha of degraded land by 2020 and a further 8 Mha by 2030.

As a part of LDN target setting, the previous target of restoring 21 Mha degraded land has been increased to 26 Mha during COP14 held during 2-13 September 2019 in New Delhi. The arid region of India covering Rajasthan state have a major portion of total degraded lands in India, therefore much focus on LDN implementation is required in the region. LDN can be achieved by scaling up good practices and pilot activities through large-scale transformative projects and programmes (TPPs), which are to be developed by participating countries and UNCCD together. Several technologies developed at the ICAR-CAZRI, Jodhpur during the last six decades since its establishment have huge potential to develop large-scale TPPs and a few of them are sand dune stabilization by checkerboards, shelterbelt plantations, integrated farming systems, livestock centric production systems on grasslands/ rangelands, horticultural production system on degraded lands, solar farming, etc. Financing land degradation neutrality is another challenge for most developing countries. Implementation of TPPs requires a huge amount of funds. While international mechanisms such as the LDN fund cover a very small fraction of the global estimates for the cost of land degradation, it is essential that the participating country–especially those in land degradation hotspots– have a strong national strategy and supporting policies in place to address the issue. In India, there are several Government policies that are linked to sustainable land management. However, there is a strong need to identify the degradation hotspots in the country which are to be targeted for achieving LDN targets along with its baseline status following three global indicators as discussed above. Thereafter, suitable land degradation management programmes can be identified, which are best suitable according to the degradation type in selected degradation hotspots. Therefore, urgent actions are required by policymakers to successfully achieve the LDN target of 26 m ha in India by 2030.

1.8 Summary

This study indicates that the western part of Rajasthan is witnessing a more agrarian as well as anthropogenic transformation. The desert area is greener now as per satellite images analysed through temporal NDVI data products. The area under desertification has reduced in Rajasthan. Institutional efforts like that of CAZRI's role since 1959 and other institutes are effectively providing local level solutions to check sand mobility, and its encroachment upon the croplands, roads and railway lines. Wind erosion studies, resource

inventory through advanced remote sensing and other geospatial technologies in agriculture/ farming practices are a boost to address the present issues of land degradation and restoration. The quantified database generated from the local level is an asset to provide clues to global activities for the COP vision.

In case of the Global climate change scenario which indicates a rise in surface air temperature by half a degree in most parts of India in the second half of the 20th Century and all India precipitation is projected to rise by 4 to 5% during the same period Indian Meteorological Department (IMD), such changes in the hot arid region will have an adverse impact on crop production and livestock productivity while that will provide an opportunity for increased length of favourable growing season in the cold arid zone. Today, desert regions are witnessing new developments. Integrated approaches for combating desertification like sand dune stabilization, shelterbelt plantation, soil and water conservation, improved agroforestry, management of cropland, pasture and range areas, saline sodic soils, rehabilitation of mine spoils and treatment of industrial effluents by institutes like Central Arid Zone Research Institute (CAZRI) Jodhpur has shown positive results. Various crop production technologies like FYM management, optimum tillage, intercropping, rainwater harvesting, and pressurized irrigation systems have helped sustainable crop production. New varieties of crops (CZP-9802 and CZ-IC 923 of pearl millet, Maru Guar of cluster-bean; CAZRI Moth 1,2,3) grasses (CAZRI-2178 of *Cenchrus ciliaris*, CAZRI-76 of C. setigerus and CAZRI Sewan-1 of *Lasiurus sindicus*) and horticulture crops (Maru Gaurav in Karunda (*Carissa carandas*) and Maru Samridhi in Lasora (*Cordia myxa*) has provided high yielding varieties to the farmer. Techniques for efficient rainwater management, the introduction of new arid fruit and fodder crops, forest trees suitable for arid regions, management of plant diseases and insect pests, enhancing gum exudation from trees, etc. have improved the scope for a better price to the farmers. For controlling the degradation of the rangelands, salt-affected lands, water-eroded lands, mine spoils, etc., different packages of practices have been evolved. Once the technologies are known, these are tested in farmers' fields, and the economic benefits from the practices are worked out and disseminated to the farming community.

However, there is a concern and caution for the rational use of natural resources. Water resources from two big canal projects need to be utilized with a sustainable approach. In the energy sector, there is a challenge to effective power generation and its distribution for agriculture and public use. Solar plants have been set up extensively on the sandy, stony, and saline wastelands in desert regions, providing opportunities for land diversification and economic benefits. Water harvested from solar panels has been experimented with successfully for growing food and fodder crops to help rural livelihood. Sand dune stabilization processes are not only greening the desert but also helping earn carbon credit. All these processes will lead to achieving the sovereign target by UNCCD for a land degradation neutrality world. However, our programmes will have to be focused on three concurrent actions: (1) avoiding new degradation, (2) reducing existing degradation (adopting sustainable land management practices) while increasing biodiversity, soil health, and food production; and (3) ramping up efforts to restore and return degraded lands to a natural or more productive state. Our actions will be judged by what changes have occurred in the Land use /land cover, Soil Organic Carbon and change in Net Primary Productivity within a time frame. Finally, the desertification problem in India has prompted the nation to exploit its potential in all spheres especially in the arid ecosystem to face the new challenges in the event of climate change.

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Steering Ecological Restoration of Coalmine Degraded Lands Towards Achieving UNSDGs: What Needs to be Done?



CHAPTER TWO

Sneha Bandyopadhyay, Subodh Kumar Maiti
Department of Environmental Science and Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand - 826004



Mine photo (KD heslong - CCL)

CHAPTER 2

2.1 Introduction

Coal mining industries plays a very significant role in the country's economy. Amongst conventional fossil fuels, coal, the second largest source of primary energy, accounts for 30% of total energy consumption globally and 55% of country's energy demand as well (ICC, 2019). Being the dominant source of global energy arena, coal fulfils about 38% of global electricity demand and 84% in India, the World's 3rd largest energy consumer after China and USA (Ministry of Mines, 2022). More than 94% of India's coal comes from surface mining, which is also known as opencast mining. As most coal deposits in the country are covered by forests, a substantial amount of coal production through surface mining involves the complete removal of vegetation, soil cover and overlying rocks (the overburden [OB]), and the loss of biodiversity and ecosystem services, which inherently damages and pollutes the environment (Haigh, 1992). The process of natural, ecological succession, which takes place concurrently with plant succession, takes time. Several ecosystem functions of mined land required a longtime to develop through natural processes. Therefore, it is indispensable to incorporate some ecosystem management tools that can accelerate the recovery of mine-degraded land. In India, the pit plantation method has been widely used whereby the initial vegetation cover on derelict sites is established by selecting fast growing, exotic, drought resistant, high biomass yielding tree species (e.g., *Albizia lebbek, Dalbergia sissoo, Eucalyptus* spp., *Gravellia* spp., *Casuarina* spp). Figure 2.1 shows the schematic revegetation approach for successful restoration of coal mine degraded lands. In a developing country, like India, several Coal India Limited (CIL) subsidiaries have encouraged mixed revegetation strategies along with the formation of medicinal garden as ecosystem stewardship of post mining degraded landscape. According to the global biogeographic distribution mapping, medicinal plants such as *Phyllanthus emblica L.* (Amla), *Terminalia bellerica* (Bahera), *Terminalia chebula* (Harad), *Azadirachta indica* (Neem), *Terminalia arjuna* (Arjun) are indigenous in most of tropical and subtropical country, including India.

Therefore, medicinal plant species should be considered for sustainable restoration approach of degraded ecosystem targeted during United Nations Decade of Ecosystem Restoration (2021 – 2030). Apart from that, development of fruit orchards on post-mining land is not only a promising approach to manage but also a source of economy to local people and stakeholders (Bandyopadhyay and Maiti, 2022).

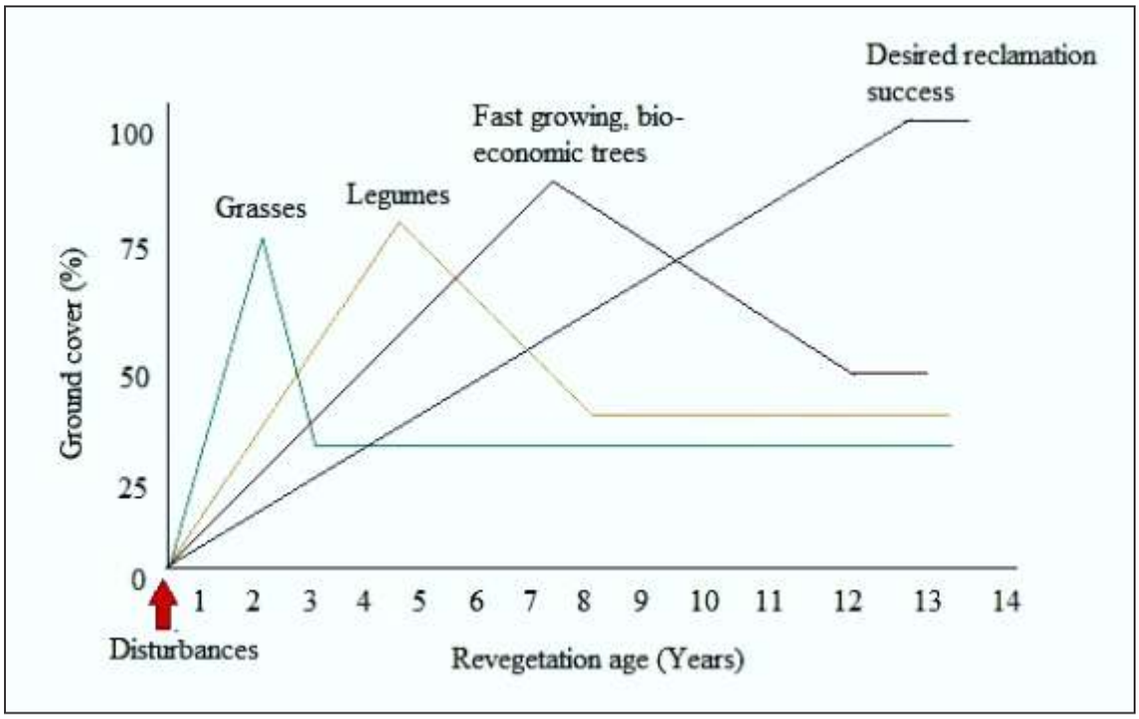


Figure 2.1: Schematic presentation of revegetation approach for successful restoration

2.2 Importance of grass-legume seeding in mine soil restoration

Numerous issues affect the sequestration and preservation of soil organic carbon (SOC), some of which are driven by human-induced activity, such as the low adoption rate of sustainable soil management techniques. Agroforestry, eco-restoration parks, and fruit orchards are the most often used post mining land uses in India (Maiti, 2013). To re-establish the characteristics of a natural ecosystem, it is crucial to restore the degraded areas. In recent years, the applications of grass–legume seeding as a reclamation strategy has gained momentum for the improvement of nutrient-deficient mine spoil. Leguminous species contribute to the nitrogen supply in abandoned sites during the early stages of reclamation, so it is crucial to study the early interactions between the impoverished mine spoil and the development of pioneer species (grasses and legumes) in a degraded ecosystem in order to monitor the recovery trajectory. Legume species are one of the significant options for soil carban (C) sequestration in Post Mining Ecosystem (PME) and plays a critical role to mitigate climate change. Soil Organic Carban (SOC) has an impact on soil properties that are related to aggregate stability and soil aggregation. The management of legume residues affects soil aggregation, hence influencing soil carban (C) sequestration. Naturally, the legume species fix nitrogen (N) through biological nitrogen fixation (BNF) which, in turn, contributes to carban (C) sequestration. The extent of soil carban (C) sequestration differs among various leguminous species in accordance with total biomass production, decomposition rates, and conversion of liable carban (C) to soil recalcitrant carban (C) (Maiti, 2013).

Revegetation with grass and legume species as a restoration strategy has been widely used, but a sustained mixture of grass and legume species is rare; instead, the majority of studies reported either legumes or grass species alone. For instance, in Indian scenario, Kumari and Maiti, (2019) showed the rate of SOC accumulation was higher under legume *Stylosanthes hamata* (1.57 Mg C/ha/year) than grass *Cenchrus ciliaris* (1.27 Mg C/ha/year). Another study, conducted by Kumari et al. (2022), aimed to evaluate the potential of grass (*Pennisetum pedicellatum*) and legume (*Stylosanthe shamata*) revegetation to restore the soil fertility of an industrial solid waste dump in central India. The study reported an increase of

1.61% of Soil Organic Matter (SOM) and 1.03% of SOC at a 5-year-old revegetated site, concluding that the direct seeding of grass–legume mixture possibly restores the soil fertility and enhances biomass production that helps to prevent land degradation and achieve UN sustainable development goals such as SDG-13 (climate action).

2.3 International Standards for the Practice of Ecological Restoration

Ecological restoration contributes in substantial ways to protecting biodiversity and human wellbeing, but many restoration projects and programs, however well intentioned, have underperformed. Application of principles and standards can increase effectiveness of ecological restoration efforts by establishing criteria for technical implementation across different ecosystem types. They also provide a framework that engages stakeholders and respects socio-cultural realities and needs, which can be applied to both mandatory (i.e. required as part of consent conditions) and non-mandatory restoration (i.e. the voluntary repair of damage) toward achieving intended goals. Thus, the use of clear and carefully considered principles and standards underpinning ecological restoration can reduce the risk of unintended damage to ecosystems and native biodiversity, and help to develop high-quality projects and programs amenable to monitoring and assessment.

The International Standards for the Practice of Ecological Restoration are as follows (SER, 2019):

(a) Address restoration challenges including:

- Effective design and implementation
- Accounting for complex ecosystem dynamics (especially in the context of climate change)
- Navigating trade-offs associated with land management priorities and decisions

(b) Highlight the role of ecological restoration in connecting social, community, productivity, and sustainability goals

(c) Recommend performance measures for restorative activities for industries, communities, and governments to consider

(d) Enhance the list of practices and actions that guide practitioners in planning, implementation, and monitoring activities, including:

- Appropriate approaches to site assessment and identification of reference ecosystems
- Different restoration approaches including natural regeneration
- The role of ecological restoration in global restoration initiatives

(e) Include an expanded glossary of restoration terminology

(f) Provide a technical appendix on sourcing of seeds and other propagules for restoration.

Society for Ecological Restoration (SER) and its international partners produced the Standards for adoption by communities, industries, governments, educators, and land managers to improve ecological restoration practice across all sectors and in all ecosystems, terrestrial and aquatic. The standards support development of ecological restoration plans, contracts, consent conditions, and monitoring and auditing criteria. Generic in nature, the Standards framework can be adapted to particular ecosystems, biomes, or landscapes; individual countries; or traditional cultures. As the world enters the UN Decade on Ecosystem Restoration (2021-2030), the Standards provide a blueprint for ensuring ecological restoration achieves its full potential in delivering social and environmental equity and, ultimately, long-lasting economic benefits and outcomes.

2.4 International Principles for the Practice Of Ecological Restoration

(a) Engages stakeholders

Ecological restoration projects recognize and acknowledge the interests and contributions of diverse stakeholders, particularly local stakeholders, and actively seek their direct involvement to provide mutual benefits to both nature and society.

(b) Draws on many types of knowledge

The practice of ecological restoration benefits from a combination of acquired practitioner knowledge, Traditional Ecological Knowledge, Local Ecological Knowledge, and scientific discovery.

(c) Ecological restoration practice is informed by native reference ecosystems, while considering environmental change

The use of reference models enhances the potential for native species and communities to recover and continue to reassemble, adapt, and evolve.

(d) Ecological restoration supports ecosystem recovery processes

Practitioners enhance the natural recovery carried out by plants and animals in interaction with each other and their shared environment.

(e) Ecosystem recovery is assessed against clear goals and objectives, using measurable indicators

In the planning phase of restoration projects, the project vision, targets, goals, and objectives are clearly identified, along with specific indicators used to measure progress.

(f) Ecological restoration seeks the highest level of recovery attainable

Ecological restoration aims for the highest practicable level of recovery appropriate to the circumstances.

(g) Ecological restoration gains cumulative value when applied at large scales

Ecological restoration projects can have beneficial outcomes regardless of their spatial scale. However, many ecosystem processes operate at larger spatial scales, such as the watershed or basin level, and scaling-up restoration actions is required to address some ecological and global sustainability needs.

(h) Ecological restoration is part of a continuum of restorative activities

Ecological restoration is one of many strategies that can, to varying degrees, contribute to biodiversity conservation, increase carbon sequestration and the delivery of other vital ecosystem services, improve human health, wellbeing, and livelihoods, and enhance positive human connections with nature.

But, above all the raw overburden material produced by mining activities possesses poor physico – chemical characteristics, devoid of nutrients (Nitrogen (N), Phosphorous (P), Potassium (K), organic matter, microbial activity that restrict natural vegetation succession and subsequent pedogenesis (natural soil formation i.e., mine spoil to mine soil). Hence, artificial revegetation on mined – out land with or without organic amendments can accelerate nutrient cycling, weathering and disintegration of parent rocks and thus the change of mine spoil characteristics to that of restored environment (Maiti, 2013).

2.5 "*Forest Smart*" Mining Approach

As a concept, forest-smart mining can be understood as mining that acknowledges the interlinkages between forests and other land uses – including socio-economic and cultural uses, and ecosystem services – and that actively seeks to avoid or reduce any loss or damage to those uses. At its most basic, forest-smart mining means following the mitigation hierarchy when planning and developing mining projects, namely:

(1) avoiding any negative climate impacts and biodiversity loss;

(2) minimizing any impacts and losses that still occur;

(3) rehabilitating and restoring forest cover and biodiversity;

(4) offsetting any remaining negative impacts or losses through substitution or compensation (Ekstrom et al., 2015)

As a practice, forest-smart mining entails the implementation of a range of approaches and tools that span the mitigation hierarchy. It is typically guided by an overarching policy commitment to no net loss of forest cover, or even by a commitment to net gain where there is potential for reforestation or afforestation. Forest-smart approaches at the higher end of the mitigation hierarchy include undertaking strategic and cumulative impact assessments, identifying 'no go' areas for mining, minimizing polluting waste and avoiding accidents. Options at the lower end of the mitigation hierarchy include land restoration and the development of carbon and biodiversity offsets. To be effective, offsets must demonstrate equivalency, yet this is difficult given the timeframe between the loss of forest carbon and/or biodiversity and the reversal of this loss (or even net gain) as a result of offsetting, and given methodological challenges in quantifying the amount of carbon held by forests now and in the future. Reforestation does not guarantee functional ecosystems or biodiversity; indeed, many ecosystem services cannot be offset, and mature (or 'old')

forests – which play a specific role in carbon sequestration and other ecosystem services – cannot simply be replaced. Offsets must also demonstrate permanence to ensure the long-term protection of forests (Baccini et al., 2017).

2.6 Conceptual Model of Six Phases of Ecological Restoration

The systematic reclamation planning of derelict mine lands can be divided into six steps, such as (1) geomorphic reconstruction, (2) soil reconstruction (core phase), (3) hydrological stability, (4) vegetation restoration, (5) landscape rebuilding and (6) eco-restored landscape monitoring, amongst which, soil reconstruction is the fundamental phase. The six phases of reclamation should be regarded not only as a simple combination of parted steps, but also as an a organized procedure.

2.6.1 Topographic or Geomorphic Reconstruction/ Geomorphic Reclamation

Macdonald *et al.* (2015) defined geomorphic reshaping as a critical foundation step for high-quality restoration. At microscale study, stability of reshaped landform and topographic development depends not only on the restored mine soil (RMS) properties but also on soil texture, placement and arrangement of particles. Fleisher and Hufford (2020) proposed the advantageous aspect of geomorphic reclamation on conventional reclamation strategy by reconstructing heterogeneous environment that blend into neighbouring landscapes. Environmental heterogeneity due to geomorphic layout is expected to further improve of ecological niches available and thereby enhance the diversity of plant species relative to other conventional recovery practices. This approach improves topographic variability and stability by restoring concave hillslopes identical to mature land shapes and integrating primary and ancillary drainage (Martin- Duque et al. 2010). The significance of geomorphic reconstruction cannot be ignored since the subsequent landforms are the backbone on which rest of reclamation planning are implemented and possible land use takes place. Geomorphic reclamation process can therefore support plant-assisted restoration by improving services such as availability of water and variability in microhabitat (Byrne et al. 2017; Vasquez and Sheley 2018). Increasing evidence favors geomorphic architecture as a means of reducing sediment losses by up to half that of conventional reclamation strategies.

2.6.2 Soil Reconstruction

Feng et al. (2019) emphasizes the aim of soil reconstruction to enhance restoration success (reclaimed mine soil quality and productivity) through either natural regeneration or artificial amendments (nutrient cycling) by suppressing different negative effects including compaction, acidity, carbon loss. Burger (2011) proposed different aspect of usage of topsoil, seed pools, woody debris litter layers on restored mine site for not only increment of soil organic matter and nutrient pools but also to prevent exotic or invasive species. Several important things [reduction in bulk density, improvement water retention capacity, increment of cation exchange capacity (CEC) and nutrient retaining capacity, improvement of soil aggregate stability, infiltration capacity and soil structure] eventuate throughout the pedogenesis (soil development), most being accredited to the influence of root growth, the existence of decomposed organic matter and soil microbial functionalities.

2.6.3 Hydrological Stability

Interrelationship among water, soil, and vegetation depicts the importance of hydrological stability on reconstruction of soil and restoration of vegetation cover. Feng et al. (2019) defined the negative effect of deforestation on hydrology like transportation of sediments (soil erosion), downstream water yields, flooding peak and proposed for more attention to be paid on traditional reclamation techniques. In this regard, Burger (2011) opined hydrological flow can be restored through placement of loose Restored Mine Site (RMS), water storage, infiltration, drainage and groundwater recharge. Zapico et al. (2018) proposed the way to attain the efficient control of sedimentation and erosion through an integrated management of RMS, hydrology, vegetation, topography and landscape aesthetics.

2.6.4 Vegetation Restoration

Comprehensive vegetation cover would be a component of growth of landform, RMS quality, hydrological reclamation and landform strategy. Though the formation of vegetation cover may be slow, but it recovers surface environments through

the interactions between soil and plants. According to Frouz et al. (2013), plant community can be an indicator function of landscape design and development, RMS health and hydrological restoration. Feng et al. (2019) reviewed that the plant-soil interaction accelerates nutrient cycling, soil faunal community development, infiltration and water retention capacity. Macdonald *et al.* (2015) proposed mixed plantation for restoration purpose as well as to build up forest as the soil condition on restored site are highly variable and sensitive to stressors.

2.6.5 Landscape Rebuilding/Landform Reconstruction

Conventional reclamation strategies comprise of terrestrial reconstruction categorized by uniform topography and linear slopes. Feng et al. (2019) emphasized the way to rebuild landscape through topographic changes (land consolidation), hydrological stability (water regime and erosion control), improvement of soil properties (physico-chemical, biological), vegetation establishment, gardening and other artificial aesthetic methods to achieve multiple ecosystem services and restored mine site.

2.6.6 Eco-Restored Landscape Monitoring

Restoration could be deemed to be effective when the site can be maintained for its intended land use without much more management interference than any other land in the region being used for a same purpose. Aftercare explains the critical mechanism of soil and vegetation management afterwards the preliminary revegetation in order to certify that the optimal land use is accomplished within a realistic time frame. This is an important and critical part of the entire eco-restoration strategy and should be considered exactly from the planning stage. The method will include soil quality enhancement, vegetation handling and supervision that is more intense than usually associated with land for that specific purpose. The aims of aftercare, that should be endured for minimum 2–10 years, are:

(I). To assure that the plants are developed and overcome the preliminary restraints on growth on degraded site.

(ii). To construct a sustainable soil–plant system, with adequate nutrient 'capital' and turnover to sustain the vegetation.

(iii). To assess the vegetative cover, i.e. species present, species richness and relative abundance, density, distribution of canopy cover, influx of new species, if any.

(iv). To observe development of soil, rooting depth, moisture improvement through periodic analysis of soil and its nutrient content.

(v). To develop the fertility until a usual nutrient and biogeochemical cycle develops, as it is mandatory to assure good soil profile along with vegetation cover in successfully developed reclaimed site (Maiti, 2013).

2.7 Restoring Mine Degraded Ecosystem for more than to achieve reclamation success

2.7.1 Sustainable Mining: Achieving UN-SDGs

Generation of huge Over Burden (OB) dump and voids during surface mining cause severe landscape disruption and significant disturbances in pedospheric ecosystem. Despite of having different pros and cons, coal mining industry is indispensable worldwide for socio-economic development. Before the twenty-first century, the aim of Post-Mining Ecosystem (PME) restoration was mainly confined to "Ecological Restoration v 1.0", i.e. "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SERI, 2004). With the evolution of the restoration ecology domain in the twenty-first century, the aim is modified to "Ecological Restoration v 2.0", i.e. "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed to reflect ecosystem value and to provide Ecosystem Goods and Services (EGS) for socio-economic wellbeing". Additionally, European Union Member States have emphasized the significance of the mining industry to fulfill the minerals need for consumer products, besides a successful transformation towards achieving the United Nations Sustainable Development Goals (UNSDGs); therefore, gradually, mining industries are getting involved with the related issues of carbon accounting and carbon emission mitigation (Pellegrino and Lodhia, 2012). Incorporation of carbon trading approach ("cap

and trade" or "emission trading system") could provide substantial, environmental, social, and economic co-benefits such as sustainable ecosystem (SDG-12), improved resource efficiency (SDG-9), ensured energy security (SDG-7), and certified employment (SDG-8) in mining sector. The emergence of such "green and self-sustaining" approaches to regulate carbon emissions from land-use change provides a prospect formining sectors to exacerbate their sustainability credentials through carbon finance (Hirons et al., 2014). Therefore, in recent decades, the focus of global research has shifted from evaluating reclamation successin afforested post-mining ecosystem to providing EGS for a clean, sustainable environment by accelerating CO_2 offset potential and regaining carbon dynamics in the vegetation-soil-atmosphere C cycle.

2.7.2 Sustainable mining – Generating EGS

The development and survival of global population depend directly or indirectly on overexploitation of abundant ecosystem resources. As per the FAO and UNEP, (2020), the natural forest ecosystem continues to get reduce by 420 million hectares during last three decades (1990–2020) at unprecedented rates due to massive anthropogenic land-use changes to support urbanization and the industrial revolution (IPCC, 2014a, b). In a nutshell, forest ecosystems have the potential to provide a wide range of ecological functions, Ecosystem Goods and Services, societal and environmental profits such as carbon sequestration, climate regulation, water purification, biomass production, nutrient cycling, habitat provision, cultural and aesthetic benefits that are currently subjected to strong pressure due to mining activities, other infrastructure explosion, and agricultural expansion (Carrasco et al., 2014; Margono et al., 2014). Figure 2.2 provides a schematic representation of achieving biodiversity and ecosystem services through mine restoration.

Ecosystem degradation and biodiversity loss jeopardize ecosystem function, resilience, and its ability to provide a continual flow of ecosystem services to present and future generations. The novel concept of ecosystem services can be defined as "the direct and indirect contributions of ecosystems to human welfare and subsistence" (MEA 2005; TEEB 2011; IPBES 2014), which is of current interest due to its potential to integrate the ecological, economic and social beneficial aspects (Bouwma et al., 2018). Evaluation of the economic value of EGS due to deforestation is thus obligatory to support proper LULC decision-making policies for restoration of coal mine degraded land that can comprehend the trade-off among ecosystem services (ES) provision, biodiversity conservation, carbon sequestration, and mine restoration. Hence, the revegetation approach to coal mine degraded sites would provide a range of EGS, depending on site-specific socio-economic conditions, and bio-physico-chemical characteristics (De Groot et al., 2012).

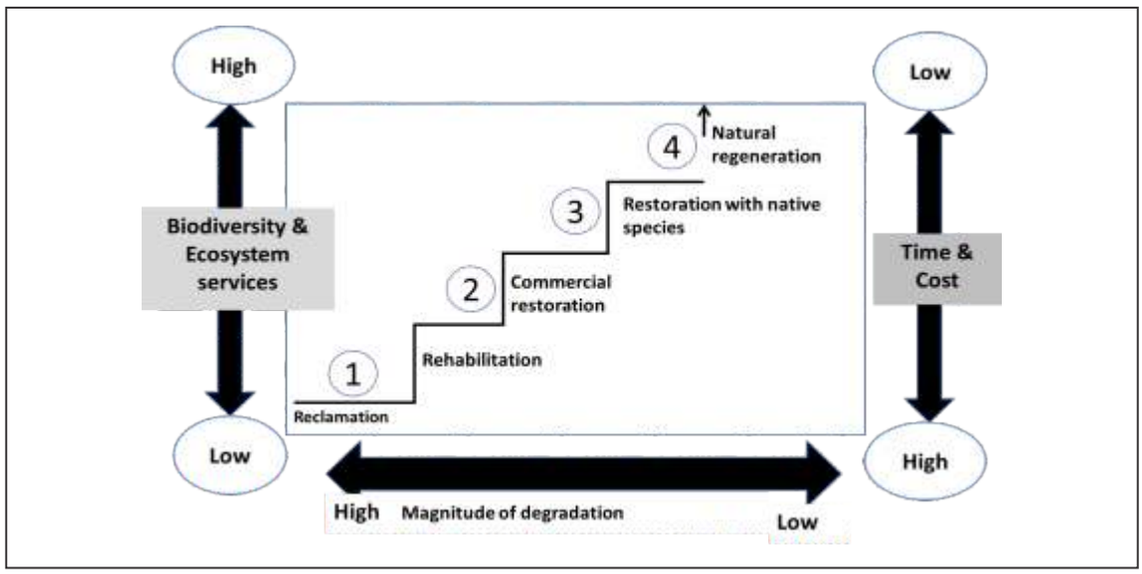


Figure 2.2: Stairway to Restoration of Biodiversity and Ecosystem Service (Adapted from Chazdon, 2008)

2.8 Criteria of Eco-Restoration Success

For a realistic restoration goal, Hobbs and Norton, (1996) stated that restoration is an attempt to force transitions towards a desired state. Cairns, (1996) defined that restoration is returning existing habitats to a known past state and to an approximation of the natural condition by repairing degradation, removing introduced species, or reinstatement. According to Koebel, (1995), the restoration project should integrate taxonomic, habitat, functional, structural, and conceptual approaches to achieve its general objectives. The general objectives consist of the following:

a) to determine if the restoration meets the required criteria outlined in the restoration plan

b) to determine if selected biological and ecological attributes have been restored

c) to implement an adaptive management plan to improve and direct the restoration trajectory based on the analyses of the above two objectives.

However, it is very difficult to restore the damaged ecosystem to the state that resembles the original in all respects. Therefore, a successful restoration project seeks to achieve only its objective of recreating a stable new community having a diversity and productivity similar to that of the forest originally present on the site. Thus, restoration projects need to have achievable and realistic goals that are dynamic and amenable to the changing nature of the environment (Figure 2.3).

For clearly achieving an ecological restoration, Toshihiko (2002) suggested a model with the following four steps:

(a) ***Exploration or ecological inventories:*** It includes the current status of existing natural habitats and their flora and fauna, should be obtained in order to understand the current conditions in the target area.

(b) ***Diagnosis:*** The present status of the target area must be evaluated in terms of the stage of natural succession or artificial degradation, and the desired form of natural conditions as a practical goal should be specified. It is also important to understand the difference between the current conditions and the desired form.

(c) ***Prescription:*** This step includes the planning of countermeasures and implementation of action, involving a combination of maintenance and restoration.

(d) Care: In changing the physical environment,

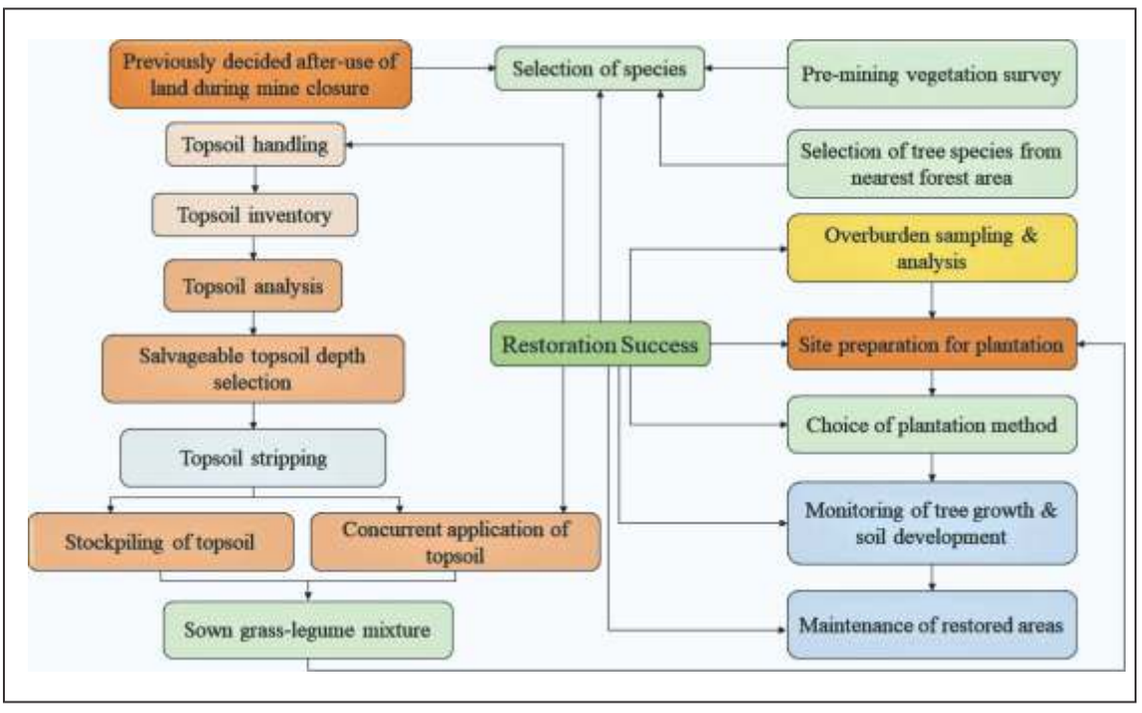


Figure 2.3: The Approaches for Successful Ecological Restoration in Surface Coal Mine-Degraded Lands

any additional treatments such as introduction of desired species or removal of undesirable ones may be required to approach the final goal. At this stage, monitoring work is very important, and in some cases the process should be taken back to the first step. Then a cyclic process will be needed to approach the final goal, i.e. a natural and healthy environment, supporting a rich biodiversity and sustainable ecosystem.

2.9 Concept of Evaluation of Soil Health

Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, and connects agricultural and soil science to policy, stakeholder needs and sustainable supply- chain management. The terminology, concept and operationalization of soil health are still evolving. It is now defined by mostagencies, such as the US Department of Agriculture (USDA-NRCS) defines soil health as "the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans." A better understanding of the main components of the soil system and the synergy between them should lead to a holistic approach to characterizing soil functioning. A holistic approach is not easy to define because soil is a complex system, where physical, chemical and biological characteristics and processes are involved and interact. Such an approach has been recently represented and adopted by the concept of soil quality or soil health (SH). Quantification is important in managing soil-health, associated ecosystem services as well, hence, the multifunctionality and diversity of soil requires multiple indicators to be quantified and integrated into an index. Consequently, sound knowledge of the quantitative effects of different soil management practices and land uses on soil functioning is needed to develop a holistic index. Such an index should portray those complex relations in a reliable manner (Congreves et al., 2015; Doran, 2002; Idowu et al., 2009; Morrow et al., 2016; Velmourougane and Blaise, 2017). Broadly, soil-health indicators can be classified as physical, chemical or biological (Bünemann et al., 2018), although these categories are not always clearly delineated, as many properties reflect multiple processes. To be used as a soil health indicator, a parameter should satisfy several criteria, which include being: relevant to soil health, its ecosystem functions and services; sensitive, by changing detectably and quickly without being reflective of merely short-term oscillations; practical, by being conducted cheaply and with a short turnaround time; and informative for Management (Rinot et al., 2019).

2.10 Integrated Mine Soil Quality Index (Imsqi): Tool to Evaluate Restoration Success – A Case Study

2.10.1 Study Area

A field study was conducted at the three afforested Over Burden (OB) dumps (RMS5, RMS10, RMS25) of Singrauli open-cast project (OCP) of Northern Coalfields Limited (NCL), a subordinate company of the Coal India Limited (CIL), Madhya Pradesh, India. The Singrauli coalfield is spread over nearly 2202 km^2 out of which the coal reserves are identified in the north-western part of coalfield by the Geological Survey of India, covering an area around 220 km^2. The study area is characterized by undulating, hilly terrain, 300–500 m aboveMSL (mean sea level). It is well defined by a prominent east-west trending fault along with Gondwana rocks (gneiss, quartzites, schists, phyllites) of Precambrian age. The area experiences a tropical climate with three definite seasons: summer (March–June), south-west monsoon (June–September) and winter (November–February). The maximum temperature in summer (during May–June) goes as high as 48°C, and in winter (during November–February), it varies between 4–21°C. The average annualrainfall of the area is approximately 1000 mm, out of which 95% is during the rainy season.

2.10.2 Formulation of IMSQI

Three major steps were followed to calculate the integrated mine soil quality index (IMSQI). First, to identify the minimum data set (MDS) based on weighting factor, Principal Component Analysis (PCA) was performed on 17 selected soil physicochemical and biological properties. Principal components (PCs) with minimum 5% variance of the datasets and large eigen values (≥1) were considered to generate minimum data set (MDS). To compare soil characteristics within a

specific PC based on correlation test, the retained PCs were subjected to varimax rotation (Vasu et al., 2016). Pearson correlation test was employed to check redundancy of variables and to eliminate them from the index if there was more than one highly loaded variable observed under the same PC (Masto et al., 2008). If the variables were highly correlated with each other ($r \geq 0.7$), the variable with the highest factor loading was retained for indexing; if variables showed high factor loading but not correlated with each other, each factor was retained for indexing. High factor loadings were defined as having absolute values within 10% of the highest factor loading (Andrews et al., 2002).

Second, non-linear scoring techniques were employed to convert the MDS into a dimensionlessvalue varying from 0 to 1 after defining the variables for the MDS. An equation based on a sigmoidal curve with an asymptote varying from 0 to 1 was used to calculate the score of an individual soil parameter.

$$S = \frac{a}{[1 + \left(\frac{x}{xo}\right) b]}$$

where x = value of individual soil characteristics, "a" = maximum dimensionless value of the soil characteristics (=1.00), x0 = mean value of each soil characteristics, and b = slope of the sigmoidal curve equation.

To obtain a sigmoidal curve, the slope was assumed +2.5 (less is better) and -2.5 (more is better). After calculating the score of each loading variable, the variables for MDS from each observation were weighted using the PCA results. The variance percentage explained by individual PC was divided by the variance percentage explained by all factors showing eigenvalues ≥ 1 to calculate the weighting factor (Wi). Then, the calculated Wi was normalized and used to calculate IMSQI. The final normalized weights were calculated as per the equation below:

Normalized weight = $PCA\sigma_i^2 / (\sum W_i/100)$

Where, $PCA\sigma_i^2$ is the variance explained by the individual Pcs.

Third, IMSQI was computed according to the following weighted-addition equation, using scoring values and the weighting factor of each PC (Andrews et al., 2002):

$$IMSQI = \sum_{i=1}^{n} W_i \times S_i$$

where Wi was the weighting factor of the soil quality indices and Si was the non-linear score.

The final measured IMSQI was considered an overall indicator of Technosol quality, where a higher IMSQI value corresponded to better soil quality. The IMSQI was further validated by determining the relationship between IMSQI and vegetation characteristics.

2.10.3 Results and Discussions

Integrated mine soil quality index was developed with 17 selected soil physiochemical and biological characteristics as total data set (TDS) and subjected to PCA to define crucial soil properties. In this study, three PCs with eigenvalue ≥ 1 explained 93.83% of the total variance in the total dataset (TDS) that was analyzed for the estimation of IMSQI (Table 2.1). PC-1 explained 25.56% of the total variance in the TDS with a high factor loading for organic carbon, CEC and MBC. MBC had the highest loading (0.936) and was significantly ($p < 0.05$) correlated with the other high factor loading variable under PC-1 (Table 2.2). As MBC had the highest loaded factor, MBC opted for the MDS (minimum dataset). However, relying on a single soil parameter, formulation of IMSQI has not been preferred (Mukhopadhyay et al., 2016). Thus, the soil characteristic with the next highest loading factor, CEC in this case, was selected to complete the MDS. PC-2 explained 16.36% of the total variance in the TDS and showed a high loading factor for EC and total nitrogen, therefore, both were selected for the MDS. PC-3 explained 14.83% of the variance in the TDS and showed high loading factor for exchangeable potassium and DHA. PC-4 explained 13.99% of the variance in the TDS and showed high factor loading for fine earth fraction and bulk density. Similarly, as PC-1, only the highest loaded factor (fine earth fraction) was selected for the MDS. PC-5 and PC-6 explained 12% and 11% of the variance in the TDS and showed high factor loading for clay and moisture content, respectively. Overall, the high loaded variables from the PCs were selected for MDS, which were MBC, CEC, EC, total nitrogen, exchangeable potassium, DHA, fine earth fraction, clay and moisture content.

The percentage of variance explained by the respective PCs determined the weight of the loaded variable chosen for the MDS. The weight was divided evenly if more than one variable had significant loading under the single PC and was correlated with each other. When the variables were not correlated with each other, all the parameters were given the full weight. By normalizing the weight between 0 and 1, the final IMSQI was determined as follows:

IMSQI = 0.2725 × S (MBC+CEC) + 0.1743 × S (EC+TN) + 0.1580 × S (Ex K+DHA) + 0.1492 × S (FE) + 0.1284 × S (Clay) + 0.1174 × S (MC).

Principal Component	PC1	PC2	PC3	PC4	PC5	PC6
Eigen value	4.346	2.781	2.521	2.379	2.049	1.874
Variance (%)	25.567	16.360	14.831	13.996	12.056	11.025
Cumulative variance (%)	25.567	41.927	56.759	70.755	82.811	93.835
Fine earth fraction	0.152	-0.174	0.196	**0.909**	0.041	-0.114
Sand	0.797	0.296	0.122	-0.092	0.425	-0.084
Silt	-0.620	-0.273	-0.097	0.119	-0.698	0.003
Clay	-0.065	0.088	-0.005	-0.115	**0.920**	0.171
Bulk density	-0.175	0.203	-0.122	**0.906**	-0.293	0.044
Moisture content	-0.019	0.086	0.034	-0.161	0.073	**0.966**
WHC	0.332	0.506	0.090	0.263	0.182	0.718
pH	0.450	0.791	0.056	0.125	-0.132	0.086
EC	0.241	**0.833**	-0.380	-0.089	0.245	0.164
Organic carbon	**0.804**	0.047	0.489	-0.164	0.116	0.216
Available nitrogen	0.332	-0.284	0.080	-0.450	0.461	-0.006
Total nitrogen	0.168	**-0.884**	-0.306	-0.027	-0.099	-0.113
Av P	0.635	-0.230	0.483	-0.477	0.234	0.149
Exchangeable K	0.149	0.134	**0.848**	-0.189	0.160	0.347
CEC	**0.888**	0.011	-0.320	0.126	-0.081	0.285
DHA	-0.148	-0.010	**-0.913**	-0.261	0.083	0.199
MBC	**0.936**	0.148	0.244	0.021	-0.037	-0.132

***Bold face factors correspond to the parameters included in the index**
***Bold face italic factors correspond to the highly loaded parameter**

Table 2.1: Results of principal component analysis of soil parameters from reclaimed mine soil chronosequence sites.

Source: *Bandyopadhyay* et al., *2020*

Depending upon IMSQI, soil properties in the RMS25 improved among the chronosequence afforested sites, suggesting the beneficial effect of revegetation on the recovery of soil quality. Different parameters of soil quality were also reported by several authors under different land uses.

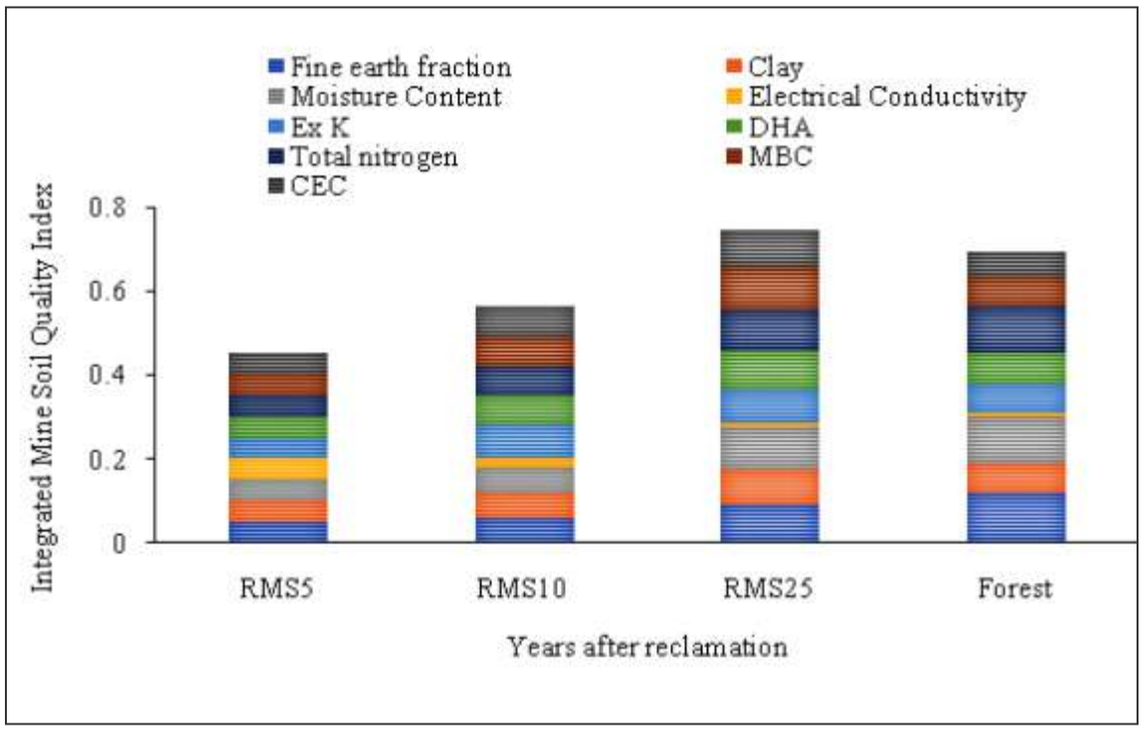
For instance, Mukhopadhyay et al. (2016) reported pH, coarse fraction, SOC, EC, DHA, calcium, P, and sulphur were the best parameters to evaluate RMS quality. The IMSQI obtained using the PCA is presented in Figure 2.4, where the influence of each soil indicator parameter on estimated IMSQI is also shown. The calculated IMSQI varied from 0.455 in 5 years old reclaimed dump to 0.746 in 25 years old reclaimed dump.

	FE	BD	Clay	MC	EC	SOC	TN	Ex K	CEC	DHA	MBC
FE	1	0.718*	-0.157	-0.259	-0.249	0.008	0.081	-0.021	0.140	-0.438	0.190
BD		1	-0.345	-0.098	0.027	-0.367	-0.182	-0.316	0.037	-0.124	-0.143
Clay			1	0.220	0.304	0.155	-0.112	0.275	-0.103	0.183	-0.063
MC				1	0.247	0.231	-0.239	0.383	0.225	0.192	-0.150
EC					1	0.113	-0.631	-0.058	0.358	0.384	0.218
SOC						1	-0.055	0.676*	0.591	-0.467	0.858**
TN							1	-0.350	0.199	0.273	0.012
Ex K								1	-0.089	-0.625	0.342
CEC									1	0.167	0.715*
DHA										1	-0.376
MBC											1

***Correlation is significant at 0.05 level (2- tailed)**
****Correlation is significant at 0.01 level (2- tailed)**

Table 2.2: Pearson correlation coefficients between the highly loaded variables from the principal component analysis

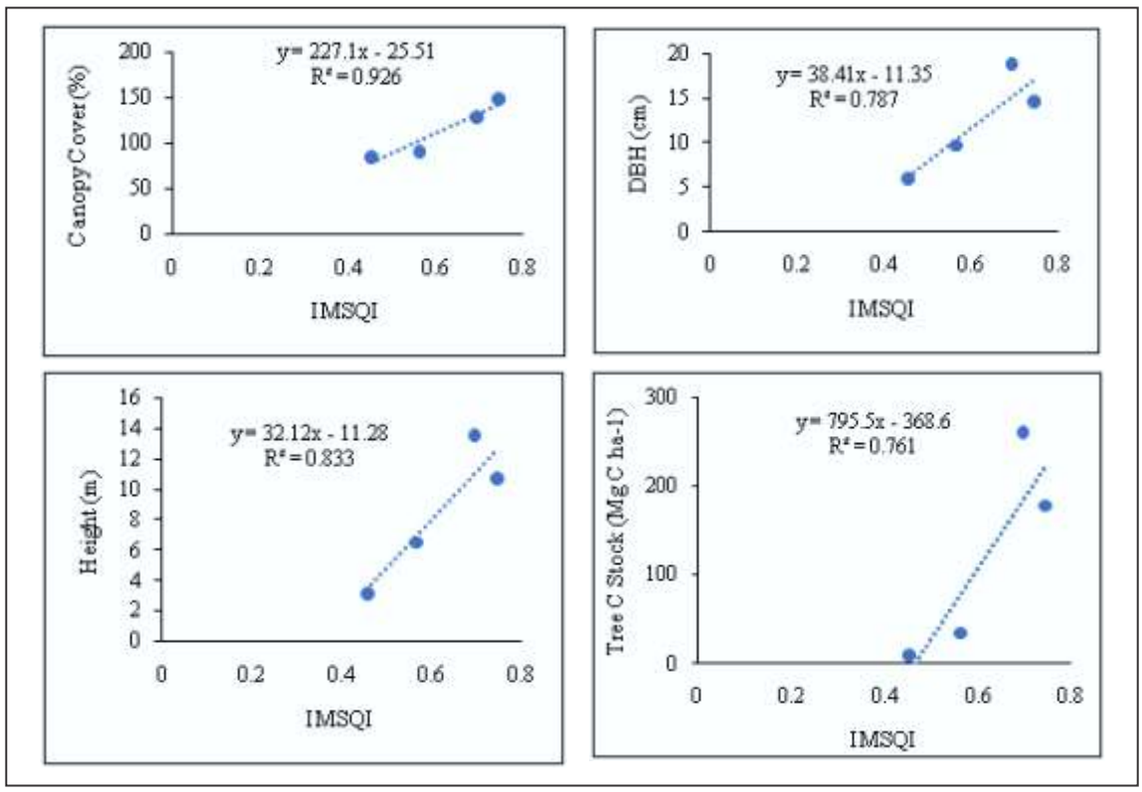
Source: *Bandyopadhyay et al., 2020*



Source: *Bandyopadhyay et al., 2020*

Figure 2.4: Contribution of each soil indicator parameter on calculated IMSQI with age of reclamation.

Regression analysis with various vegetation characteristics such as DBH, canopy cover, and height have been conducted in order to validate the IMSQI. The DBH (R^2 = 0.79), canopy cover (R^2 = 0.93), height (R^2 = 0.83) and tree carbon stock (R^2 = 0.76) of plant species are strongly correlated to the IMSQI (Figure 2.5). The functional utility of the IMSQI is confirmed by these regression results. The IMSQI observed for the 25-year-old site (0.746) is higher than that of the reference forest (0.695) to some extent, suggesting soil recovery with time. It has been reported that it usually takes 20 years or more for disturbed soils to reach the levels of native soils in semiarid mined lands (Macdonald et al., 2015).



Source: *Bandyopadhyay* et al., *2020*

Figure 2.5: Correlation between mine soil quality index and plant growth parameters (a) canopy cover (b) DBH (c) tree height (d) tree carbon stock.

Therefore, it is proposed that eco-restored mine sites with an IMSQI of > 0.500 should be considered as ecologically sustainable post mining land, where adequate reclamation strategies have been adopted. The reclamation age was found to have a significant effect on the microbial and nutritional properties of the mine soils. Therefore, the IMSQI, calculated based on the soil indicator parameters such as fine earth fraction, moisture content, exchangeable potassium, total nitrogen, cation exchange capacity, clay content, electrical conductivity, dehydrogenase activity and microbial biomass carbon, could be used as a model for evaluating the progress of the reclamation. This IMSQI can be extended to other mining sites, but validation for each site is suggested.

2.11 Soil Metagenome Analysis – Future Potential Tool to Evaluate Restoration Success

Besides indexing, multidisciplinary approaches aiming at providing such indicator parameters have been proposed recently. Previous studies have proposed that the comparative "assessment of microbial communities" from restored chronosequence sites to reference sites (forest) may contribute to the evaluation of restoration success in degraded lands. Though this concept has been established in different agroecosystems globally, but in the Indian scenario especially in mining context, it remains obscure. In this regard, metagenomics, a new field with an additional set of high throughput sequencing tools, offers an excellent approach to study the entire diversity, adaptability and evolution of microorganisms surviving in post-mining degraded ecosystems.

One of the first significant advances in characterizing microbial communities in extremely acidic mine environments was achieved through the application of high-throughput sequencing of whole DNA from a biofilm obtained from within the Richmond Mine, California (Tyson et al., 2004). As this community comprised only a few individual species, their entire genomes could be reconstructed from the metagenome, which revealed information about the unique metabolic processes that they employ to survive in such an

extreme environment. This highlighted the importance of microbes in environmental impacts from mining and opened the door to the use of metagenomics for characterizing mine microbial communities. Soil microbes are more than just indicators of ecological function, they are increasingly recognized as facilitators of the belowground metabolic recovery required for subsequent aboveground restoration (Harris, 2009).

Despite acknowledgement of the link between above and belowground communities (Bardgett and van der Putten, 2014), there is still a lack of mechanistic understanding on how microbial communities facilitate restoration of highly degraded environments such as post-mining landscapes. For example, fungal communities are known to play a major role in stabilizing soil structure, and recent studies have demonstrated that restoration managers can exploit hyphal networks between plants and mycorrhiza (Richter and Stutz, 2002). However, other soil functions such as C, N and P cycling arise out of a complex network of interactions between different components of highly diverse soil microbial communities and are central to aboveground plant growth and survival. Little is known regarding the complexity and functions of bacterial and archaeal communities (BAC) in soils present after significant environmental degradation, such as observed in mining operations, and more critically, how they may be used in novel ways to shape the above-ground outcome of post-mining ecosystem restoration (Kumaresan et al., 2017).

Table 2.3: The application of metagenomic analysis in different forest ecosystems restoration.

Ecosystem	Experimental design	Sequencing platform	Findings	Reference
Revegetated grassland and farmland, China	Topsoil (10 cm depth) DNA isolation, Shotgun metagenomic	Paired 250-bp IlluminaHi Seq 2500 platform Paired 150-bp IlluminaHi Seq 2500 platform	Actinobacteria, Proteobacteria, Acidobacteria abundant phylum. Amino acid metabolism, Xenobiotic biodegradation and metabolism as abundant pathway.	Guo et al., 2018
Revegetated iron ore mine dump, Brazil	Mixed superficial soil sample (0-2 cm) DNA extraction, Shotgun sequencing,	NextSeq 500 Illumina platform	Baseline study producing helpful insights to microbial community along rehabilitation chronosequences after iron ore mining.	Gastauer et al., 2019
Reforested mine site, USA	Composite sample of chronosequence sites, Shotgun sequencing,	Paired end 101-bp IlluminaHi Seq platform	Taxonomic and functional changes indicate a shift from copiotrophic to oligotrophic groups.	Sun and Badgley, 2019
Lignite mine tailing, Gujarat	Chronosequence sampling with amplicon and shotgun metagenome sequencing	IlluminaMiSeq 2×300 bp platform HiSeq 4000 Illumina platform	Predominant phyla found as Firmicutes, Bacteroidetes, and Proteobacteria. Annotated genes and proteins related to energy metabolism, cellular processing and signaling, stress response, virulence and defense, membrane transporters, C metabolism, N fixation, S metabolism	Singh et al., 2022

Metagenomics study covers the entire genome of all microbes inhabiting any habitat including soil and water without in vitro culturing, prior individual identification, or amplification (Abulencia et al., 2006; Kunin et al., 2008). Recently, it has been used as a prominent tool for the analysis of interacting soil microbes and their specific and interlinking functions. Table 2.3 illustrated the application of metagenomic analysis in different ecosystems during forest ecosystem restoration. Remarkable developments were observed in metagenome sequencing using NGS technologies, comprising isolation of metagenomics DNA directly from environmental sample, fragmentation, generation of sequence clone library, and high-throughput sequencing to acquire detailed information. Function- and sequence-driven screening can lead to functionality of the metagenome. Later on, sequencing technologies such as Roche 454, Illumina, and Applied Biosystem SOLiDTM rendered proper understanding of complete genome sequencing without using traditional Polymerase Chain Reaction (PCR) or cloning. Because almost 99% of the microbes in various environments are still far being cultured in media, metagenomics offers a path to identify the complete microbiome profile, phylogenetic relationship, species diversity and abundance, metabolic abilities, and functional characteristics of the inhabiting microbes (Dubey et al., 2020). Metagenomic approaches have emerged as a hub for understanding the ecological and evolutionary record of microorganisms, which is perhaps the most important, vital, and less explored biological area because of the diverse millions of metagenomic reads and their functional implications (Zarraonaindia et al. 2013).

2.12 Conclusion

Conventional research on restoration of mine-degraded lands placed more emphasis on the establishment of the plant community and amendments to increase soil fertility. Afforestation of mine degraded lands using native bioeconomic plant species would also enhance ecosystem productivity and generate ecosystem services as well. Moreover, post-cessation of mine closure, successful eco-restoration of mined-out land is an essential approach to recover ecosystems as pre-existing one. In this regard, recently the focus has shifted from just redeveloping the forest to assessing the health of the reclaimed site and quantifying the reclamation progress of the revegetated sites by different approaches such as, indexing, modelling, and remote sensing. Additionally, eco-restoration has a profound impact on native microbial populations which could be used as an indicator of successful restoration, providing evidence of functional gene cluster formation, recuperation of different metabolic pathway such as carbon fixation and nitrogen metabolism. So, with UN-SDGs, especially SDG-13 (climate action) and SDG-15 (life on land) are in mind, we recommend the incorporation of microbial genomics study as a potential tool to evaluate restoration success in Indian mining context.

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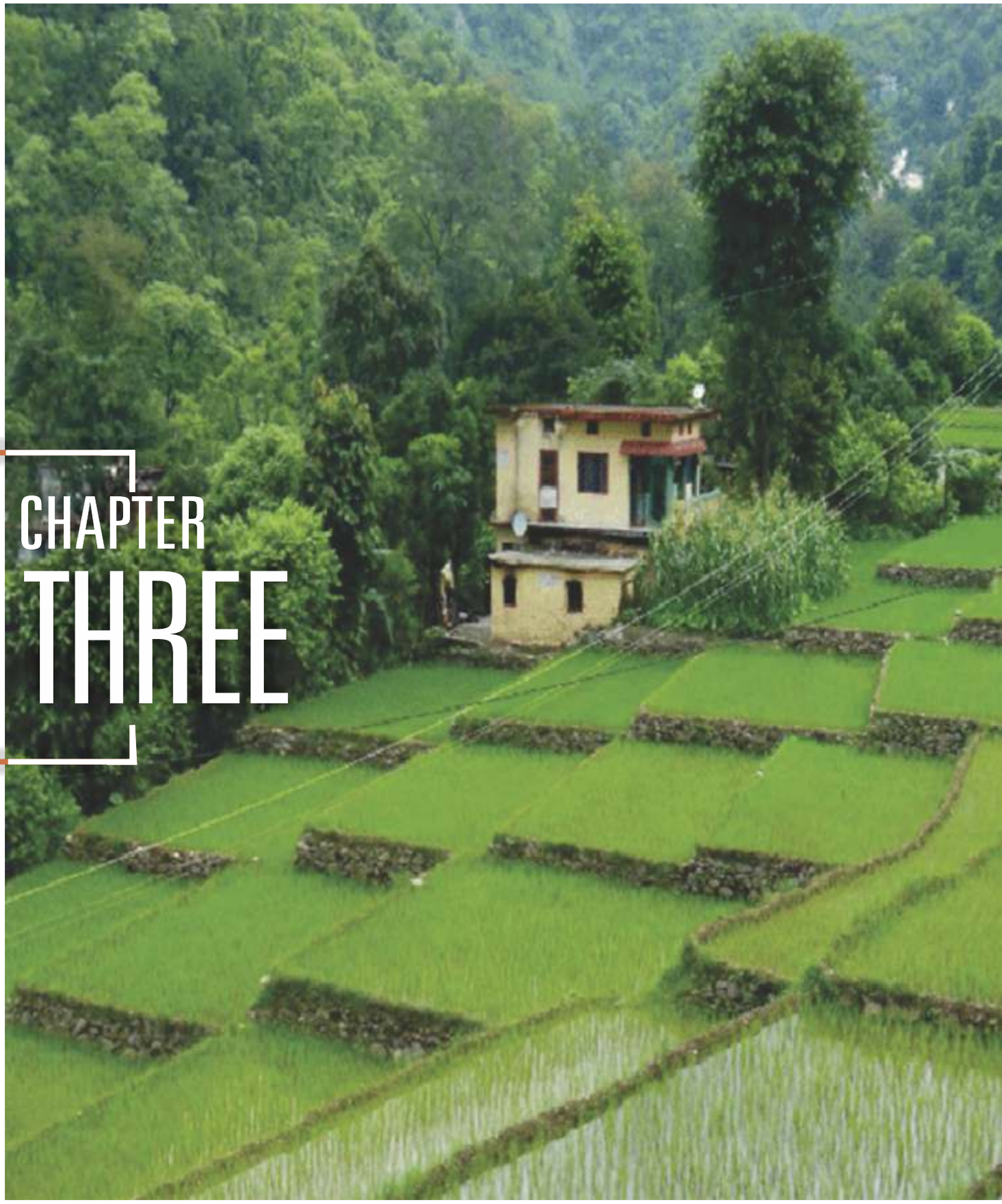
Soil Erosion Control Measures for Sustainable Land Management



CHAPTER
THREE

Debashis Mandal, Rajesh Kaushal, Gopal Kumar, Trisha Roy and M. Madhu
ICAR-Indian Institute of Soil and Water Conservation, Dehradun, Uttarakhand - 248195



Spurs for torrent control

3.1 Introduction

Land is one of the most vital natural resources of the world and is under tremendous stress due to the ever-increasing biotic pressures. Furthermore, degradation of cropland, water, energy and biological resources, that are vital for sustainable agriculture production, continues unabated. Degradation of land is one of the most serious contemporary environmental problems confronting the world today (Amundson et al., 2015; Mandal et al., 2020). According to United Nations Environment Programme, globally, degradation of land undermines the well-being of 3.2 billion people resulting in a 5 % reduction in total global net primary productivity (IPBES 2018). Soil erosion has been identified as one of the ten major threats the world soils are facing currently (FAO, 2019). Presently, almost 1.9 billion ha global area is affected by land degradation of which 85% area is contributed by soil erosion. Worldwide almost 36 billion tonnes of fertile soil is lost from agricultural lands with an economic burden of US$400 billion per year. Under equilibrium, the rate of soil loss through erosion is balanced by the natural rate of soil formation, without causing huge disruption in the ecosystem. However, with enhanced anthropogenic activities and increased human interference with nature, soil erosion rates have increased. The equivalent of one soccer pitch (approximately 0.74 ha) of soil is eroded every five seconds (FAO and ITPS, 2015); this data might help us fathom the intensity of the problem. Thus, the accelerated soil erosion rates are a huge threat to the sustainability of the entire ecosystem. Richard (2014) has highlighted that "Soil erosion may get us before climate change does" as history has witnessed the downfall of several prosperous civilizations due to mismanagement of its soils (Scholes and Scholes, 2013).

In India, harmonized database indicates 120.7 Mha or 36.7 % of the total land surface affected by some form of degradation, of which water erosion is the chief contributor affecting 68.4 % of the degraded area (NAAS, 2010). The economic cost of soil erosion in terms of loss of soil C and major nutrients like nitrogen, phosphorus, potassium and sulphur amounts to Rs 0.073 to 1.270 trillion (Mandal et al, 2021) while crop production losses are estimated to be Rs 292 billion (Sharda and Dogra, 2013). Thus, tackling

the soil erosion problem through robust and sound conservation technologies is the key to a country's development. Region-wise statistics show that Central region is the worst affected of all (59 % of its total area), followed by North-Eastern and Southern regions. It is a matter of great concern that about 37% of the total reporting area land mass suffers from various forms of degradation in India against 29% in the whole world. This is extremely serious because India supports 18% of the world's population and 18% of livestock population. The estimated cost of land degradation in India varies from 4-5.6% of the GDP depending on the extent of degradation as reported by different studies (TERI, 2018). The major share is due to loss of crop production of 13.4 million tones (Sharda and Dogra, 2013) due to water erosion amounting to a loss of $2.51 billion in monetary terms. The resulting loss of services from land degradation, including that of food provision, is not just a concern in itself but can in turn unleash a vicious circle of environmental degradation, impoverishment, migration and conflicts, often also putting the political stability of the affected countries and regions at risk.

We are standing at crossroads where it has become imperative to weigh out the pros and cons of any developmental activity to minimize environmental imbalance. The seventeen sustainable development goals (SDGs) put forth by the United Nations are based on this very principle. It aims to achieve holistic upliftment in the living conditions of humans across the globe in terms of health, nutrition, education, and economic growth *vis-a-vis* balancing and protecting the environment. Of the 17 SDGs, the first two aim to achieve no poverty and zero hunger while the 13th and 15th goals address the issues of climate change and land degradation neutrality (LDN), respectively to be attained within 2030. All these four goals are heavily dependent on the judicious and prudent management of global soil resources.

3.2 Impact of Climate Change on Land Resource

Climate change is likely to affect the global cycles of carbon, nitrogen, water and oxygen thereby distorting the structure of ecosystems and disrupting or diminishing the effectiveness of their auto functions. As predicted, global warming will intensify the hydrological cycle resulting in more intense rains, frequent floods and droughts, shifting of rainy season towards winter and significant reduction in mass of glaciers causing more flow in the initial few decades but substantially reduced flows thereafter. The deforestation, desertification and soil erosion are also disrupting the carbon cycle between pedosphere and atmosphere resulting in decline of soil carbon stock especially of soil organic carbon thus deteriorating chemical, hydrological and biological environment of the soil. Crop yields would get reduced due to low soil organic carbon especially if it is below one percent. Similarly, phytomass productivity on non-arable lands would also decline due to degradation of pasture lands and forest areas. Efforts are, therefore, needed to reverse the trend of declining soil organic carbon to sustain and enhance productivity under all types of primary production systems.

Climate change has increased risk and unpredictability for farmers (especially of small and marginal categories, which are most vulnerable and least able to adapt to the changes by warming and related aridity, and shifts in rainfall patterns and intensities resulting into growing incidence of extreme weather events. Projections of monsoon rainfall pattern over the Indian subcontinent indicate that by 2050, a 10% increase in the amount and 10% increase in the intensity of rainfall are very likely due to climate change, leading to increase in erosive power of rainfall. Based on the results of Sharda and Ojasvi (2006), it is projected that a 1% increase in rainfall intensity may increase the rainfall erosivity by 2.0%. Another study on interrill erosion by Ojasvi et. al (2006) indicates that 1% increase in rainfall intensity may increase soil loss from croplands by 1.5%.

By 2050, the erosion rates of water erosion class 5-10 t ha^{-1} yr^{-1} are expected to increase to more than 10 t ha^{-1} yr^{-1}, which is presently considered as the land degrading soil erosion rate. Hence, about 66 M ha area in our country under the erosion class of 5-10 t ha^{-1} yr^{-1} that covers mostly croplands will be additionally affected by higher rates of erosion due to climate induced changes in rainfall. This will result in significant increase in water erosion affected land degradation area from the current levels unless ameliorative measures are taken. These projections also suggest that a comprehensive knowledge-base on land degradation scenario due to various driving forces in our country should also be developed

and updated for the benefit of various stakeholders.

To overcome water shortages due to climate change in future, the interaction between 'land cycle' and 'water cycle' need to be properly understood to ensure optimal land resource management for sustained availability of water in channels/streams/rivers. It calls for checking and reversing land degradation by raising adequate green cover in forest, community, arable and non-arable lands to regulate monsoonal runoff and augment ground water recharge after meeting biotic needs on regular basis besides mitigating the impacts of floods and droughts.

3.3 Soil Erosion and its impact on ecosystem

Soil erosion is a significant ecological issue in many regions across the globe (Mondal et al., 2016). It leads to degradation of fertile soils and negatively impacts the environment and agricultural productivity (Mandal et al., 2020). Of the various types of erosion water erosion is the dominant class affecting almost 55 % of the eroded land surfaces (Bridges and Oldeman, 1999). According to Garca-Ruiz et al. (2015), locations with high rates of erosion or sediment yield are primarily found in semi-arid and sub-humid climates. Thus, it is plausible to assert that soil erosion is already severe in several regions of the world, including the United States, Australia, China, India, and portions of Europe, Africa, and South America, and may become worse as a consequence of climate change (Li and Fang, 2016).

At equilibrium condition, the rate of soil loss through erosion is neutralized by the natural rate of soil formation, maintaining natural balance in the ecosystem. However, with intensification of agriculture and more pressure on land resources globally the soil erosion rate has accelerated and is a major threat in the path of sustainable development (Mandal et al., 2021). Soil erosion causes decline in biomass productivity of land and affect economy, resulting from various biophysical and social factors including climate aberration and anthropogenic dominance, leading to loss of ecosystem services.

The annual soil loss rate in India is about 15.35 $t\ ha^{-1}\ yr^{-1}$ (Sharda and Ojasvi, 2016), which results in an annual loss of 5.37 to 8.4 Mt of nutrients, reduction in crop productivity, occurrence of floods/droughts, reduction in reservoirs' capacity (1% to 2% annually), and loss of biodiversity. Recent estimation of erosion-linked nutrient displacement due to water erosion of N, P, K, and S showed as 4.41 to 9.61, 0.387-2.31, 4.43, and 1.27-1.65 Mt, respectively. Loss of crop productivity, being one of many negative impacts of soil erosion by water, has serious consequences for the country's food, livelihood, and environmental security. Major rainfed crops in India suffer an annual production loss of 13.4 Mt (Sharda and Dogra, 2013) due to water erosion which amounts to a loss of Rs. 292 billion in monetary terms. Apart from economic loss, erosion-transported nutrients contaminate water bodies, pollute groundwater, and deplete soil fertility. The release of extra CO_2 into the atmosphere by organic matter dislodgement followed by decomposition has serious implications on climate change. Erosion also enfeebles soil's position in providing a secure habitat for both micro-and mesobiodiversity.

Quantifying the erosion of 1 mm topsoil from 1 ha in terms of soil C and major nutrients indicates a loss of 150-225 kg C, 12.97-28.26 kg N, 1.14-6.79 kg P, 13.03-25.5 kg K and 3.74-4.85 kg S (Mandal, 2014) and to replenish the lost nutrients in soil addition of 0.67-1.00 tons of farmyard manure (FYM), about 21.02-50.56 kg urea, 0-68.51 kg single superphosphate (SSP), 18.21-39.42 kg muriate of potash (MOP) and 0 to 3.42 kg of elemental sulphur (with 90% S) would be required. This is equivalent to Rs 2155/- to Rs 3742/- per ha per year as per the 2020-21 unsubsidized prices of fertilizers (Mandal et al. 2021).

The production losses of different crops indicated that the cereals faced the major losses (66% or 8.9 Mt), followed by oilseeds (21% or 2.81 Mt), and pulses (13% or 1.74 Mt) (Sharda et al., 2010). Besides the direct consequences of soil erosion loss in terms of nutrients, production or monetary losses, there are several other negative impacts of soil erosion on the environment.

Of the total sediment lost through gross erosion in India, 34.1% is deposited in the reservoirs, 22.9% is discharged outside the country (mainly to oceans), and 43.0% is displaced within the mainland. The displaced sediment can be a source of atmospheric C, as the C transported in the eroded sediment is more susceptible to

mineralization. It is estimated that almost 30 % of the eroded soil C is mineralized and in Indian scenario, this amounts to 34.61 Tg C yr^{-1} (Mandal et al., 2020). The liberated C is a major source of greenhouse gas responsible for accelerating the climate change problems. Also, the deposited sediment may lead to eutrophication of water bodies and nutrient enrichment with serious negative consequences. Analysis of sediment deposition in 4937 reservoirs indicated the average annual percentage capacity loss as 1.04% though it varies from 0.8% to >2% per year in smaller dams (1-50 Mm capacity) and from <0.5% to 0.8% per year in larger dams (51to >1000 Mm capacity). Siltation of smaller dams poses a serious threat to the ecosystem services as they cater to a wider population for domestic, agricultural, and industrial purposes.

Soil microorganisms are the key to regulate the C cycle, as they are directly involved in the mineralization and immobilization of C from organic matter. The microbial diversity in the soil is thus important to regulate the fate of SOC and maintain soil health and productivity. It is estimated that enhancing the soil biodiversity could result in 2.3 billion tonnes of additional crop production per year in USA with a monetary value of US$ 1.4 trillion (https://www.iucn.org/resources/issues-briefs/conserving-healthy-soils). Since soil erosion results C loss it also negatively impacts the soil biodiversity both above and below ground and reduces the soils productivity. Thus, the consequences of soil erosion is catastrophic and if left as such will be perilous.

3.4 Sustainable Land Management (SLM) for controlling soil erosion

Sustainable land management (SLM) comprises measures and practices adapted to biophysical and socio-economic conditions aimed at the protection, conservation and sustainable use of resources (soil, water and biodiversity) and the restoration of degraded natural resources and their ecosystem functions (https://www.fao.org/land-water/land/sustainable-landmanagement/slm-practices/en/).

The planning of landuse based on the assessment of the potential of land resources and accordingly selection of SLM measures (biological, agronomic and structural) and putting them into practice with the purpose of maintaining the productive capacity and restoring the degradation is the aim of all SLM practices. There are several SLM practices which have been tried, tested and successfully put into use. However, there's no single recipe for users. Thus, proper identification and selection of the SLM practices and approaches is one of the most important criteria in ensuring the effectiveness of land management and restoration.

According to Inter-Governmental Technical Panel on Soils (ITPS), soil management is sustainable if the supporting, provisioning, regulating and cultural services provided by soils are maintained or enhanced without significantly impairing the soil functions that enable those services or biodiversity. The balance between supporting and provisioning services for plant production, regulating services for water quality and availability; and for atmosphere GHGs composition are of specific concerns. Supporting services include primary production, nutrient cycling and soil formation, while provision services comprise of supply of food, fibre, fuel, timber and water, raw earth materials, habitat and genetic resources. Sustainable Land Management is a knowledge-based procedure that helps to integrate land, water, biodiversity and environmental management (including input and output externalities) to meet rising food and fibre demands while sustaining ecosystem services and livelihoods. Improper land management can lead to land degradation and a significant reduction in the productive and service functions (World Bank, 2006).

For prioritizing the erosion risk classes on the basis of intensity of erosion, a methodology or criteria was evolved depending upon the difference between site specific potential erosion rate and the T-value as presented in Table 3.1. Potential soil loss and tolerable soil loss were compared to analyze the erosion risk as an analytical basis for the region. On the basis of the results of the analysis, the degree of erosion risk was categorized into five classes. The top priority was given to the area where the difference between potential soil loss and tolerance value is >35 t ha^{-1} yr^{-1}. The remaining priority classes were normalized between 0 and 35 as 25-35 t ha^{-1} yr^{-1} (priority class 2); 15-25 t ha^{-1} yr^{-1} (priority class 3); 5-15 t ha^{-1} yr^{-1} (priority class 4) and 0-5 t ha^{-1} yr^{-1} (priority class 5).

Priority Class	(E-T) (t ha^{-1} yr^{-1})	Remarks
1	> 35	Needs special soil and water conservation measures
2	25-35	High priority for soil conservation
3	15-25	Medium priority for soil conservation
4	5-15	Less priority for soil conservation
5	0-5	Very less priority for soil conservation
6	<0	Requires no treatment
7	Non-soil area	Rock outcrops, glaciers and sand dune etc.

Table 3.1: Priority classes of erosion risks

Class 1 to Class 5 represents the priority order. Class 6 represents the areas requiring no treatment as the difference between E and T values is less than zero while the non-soil areas in the country are covered in Class 7.

For averting soil erosion and managing land degradation several technological options are available. Reliable and time-tested soil conservation technologies include contour planting, ridge-planting, no-till cultivation, crop rotation, strip cropping, and cover crops. Although the specificity of practices varies, all conservation measures reduce erosion rates. Each conservation measure may be used separately or in combination with other practices (Table 3.2). For reclamation of priority class 1, Sloping Agricultural Land Technology (SALT) is most suitable, especially for the shifting cultivation areas. The SALT method involves planting field and perennial crops in bands of 3-5 m width between double rows of N-fixing shrubs and trees planted along the contours. Similarly, Conservation Bench Terrace (CBT) system can be successfully adopted in mildly sloping agricultural lands under arid, semi-arid, and sub-humid climates for conserving in-situ rainwater, reducing runoff and soil loss, and enhancing crop productivity.

Priority Class	Land Use		
	Forest	Shifting cultivation/ Open grazing	Traditional Agriculture
1	Diversion drain and Gully plugging	Afforestation, SALT	CBT, Stone terracing
2	Gully Plugging, Check dams, and Staggered trenches	Gully plugging, Check dams, Staggered trenches and SALT	CBT, Stone terracing
3	Check dams, Bio-Engineering, and Contour trenches	Increasing the gap of cultivation	Contour vegetative barrier, Strip cropping and Hedge-row cultivation
4	Maintenance of forest density and Trenching	Cultivation once in >5-6 years	Contour bund cultivation across the slope, Cover crops and Vegetative barrier
5	Maintenance of forest density and Trenching	Cultivation once in >5-6 years	Mulch tillage, Soil surface management, Application of SOM, Strip cropping, Cover crops

SALT (Sloping Agricultural Land Technology) *is an integrated land management technique where different combinations like silvi-pastoral, agri-horti-pastoral, agriculture and aquaculture including wet cultivation is advocated as per land capability classes in sloppy lands.*

CBT (Conservation Bench Terrace) *system is suitable for 1-3% sloping lands. In the CBT system, land is divided along the slope in the ratio of 2:1. The lower 1/3rd area is levelled for collecting runoff from the upper 2/3rd area, which is left in its natural slope.*

Table 3.2: Management strategies for different land use under various priority classes

Source: *Sharda and Mandal, 2018*

The Indian Institute of Soil and Water Conservation has published erosion control measures at district level in the prescription mode for three southern states viz. Karnataka, Kerala and Tamil Nadu. The publications highlight the erosion problems of all districts and suggests different available erosion control measures region wise depending on the severity class of erosion. Such publications are highly beneficial for identification and execution of soil and water conservation measures at field level. The condition specific conservation measures as part of sustainable land management is presented in Table 3.3.

Conservation Measures	Slope <10%		Slope-10-33%	
	Low priority class		High priority class	
	Arable land	Non arable land	Arable land	Non arable land
A Agronomic Measures (Slope≤ 6%- agronomic measures alone; Slope >6% with other land management practices)				
Contour cultivation/farming	√		√	
Inter or mixed cropping	√		√	
Green manuring & Recycling crop residues	√		√	
Minimum soil disturbance	√		√	
Crop rotation	√		√	
Mulching	√		√	
Conservation tillage/Conservation agriculture	√		√	
Cover crops	√		√	
Fodder/ tea/ medicinal-aromatic crops on the terrace riser			√	
Broad bed and furrow (Black soil)	√			
Furrow opening in between the lines (Black soil)	√			
B Vegetative measures (At lower slope-alone, at higher slope with other conservation measures				
Vegetative barrier*/Mixed vegetative barriers*	√	√	√	√
Vegetative strips*		√	√	√
Vegetally* guarded conservation trenches and ridges (VGCTR)		√		√
Afforestation/reforestation		√		√
Grassed waterways	√	√	√	√
Live vegetative check dam (Bamboo)		√		√
Stream bank stabilization with bamboo and other species		√		√
*Species: Vetivera grass (*Vetiveria zinanoides*) ; Guatemala grass (*Tripsacum laxum*); Weeping love grass (*Eragrostis curvula*); Lemon grass (*Cymbopogon citrates*); Rosha/ palma rosa grass (C. *martinii*); Malabar (C. *flexuosus*); Hybrid Napier; Agave (*Agave Americana & Agave sisalana*); Geranium (*Pelargonium graveolens*); Mulberry (*Morus alba*); Pineapple (*Ananas comosus*)				
C Mechanical/Engineering Measures				
C.1 Bunding				
Contour/Field bunding/Trench-cum-bund	√	√	√	√

Table 3.3: Soil and water conservation measures on arable and non-arable land at different slopes and priority classes (Reproduced from Kannan et al., 2021)

Graded bunding (uniformly and variable graded)-Black soils	√			
Stone bund (Where stones are available onsite)	√	√	√	√
Compartmental Bunding	√		√	
C.2 Trenching				
Contour trenching		√		√
Continuous contour trenching		√		√
Contour staggered trenching		√		√
Graded trenching		√		√
Water absorption trenches		√		√
Half-moon trenches/terraces	√	√	√	√
Recharge pit		√		√
C.3 Terracing (Bench)				
Levelled terrace	√		√	
Inward sloping	√		√	
Outward sloping	√		√	
Puertorican type/vegetative	√		√	
Half-moon terraces			√	√
Conservation bench terracing	√			
Narrow based terracing			√	
D Drainage Line Treatments (DLTs)				
Earthen Check dam		√		
Sandbag check dam		√		
Brush wood check dam (BWCD)		√		√
Loose boulders check dam (LBCD)		√		√
Gabion check dam		√		√
RR check dam		√		√
Gabion terrace support wall		√		√
Retaining wall/ Revetment		√		√
Silt detention tank		√		√
E. Water Harvesting				
Community pond/Ooranies	√	√	√	
Embankment pond		√		
Pond renovation & Desilting	√	√	√	
Farm pond-Dugout	√		√	
Subsurface runoff collection wells			√	
Pond lining	√	√	√	
Roof top water harvesting	√		√	
Diversion Based water harvesting			√	√
SPECIAL PROBLEM AREA				
F Mine spoil area/ Land Slide Prone Area				

F.1 Vegetative				
Vegetative hedges		√		√
Brushwood check dam				√
Watling (live)				√
Double-row Brushwood dam / Log wood brush filled check dam				√
Grassed contour barrier		√		√
Bamboo plantation		√		√
Afforestation		√		√
Aerial seeding (very high slope or unapproachable area)				√
Turfing/Soding				√
F.2 Mechanical/Engineering Measures				
Contour bunds/Stone bund		√		√
Stone wall				√
Staggered trenches and planting		√		√
Loose Boulder check dam (locally available)				√
Diversion drain/ Interceptor drain				√
Nala bunds		√		
Gabion check dam				√
Gabion drop structures				√
Toe wall/toe drain				√
Retaining wall				√
Jute geo textiles for slope stabilization/ Coir Jeo textiles for stabilization of land slide areas (Slope >33%)				√
Stream Channelization (Retaining wall, Bank protection walls. Spurs with apron etc)		√		√
G Gullied and Ravine Land				
Bio fencing/social fencing		√		√
Peripheral bund		√		√
Peripheral bund supported by close plantation of bamboo		√		√
Safe disposal of water from gully head-Piped/chute spillway-		√		√
Bamboo on ravine bed and grass on slope		√		√
Bamboo based live check dams		√		√
Alternate land use system/Agroforestry		√		√
Mechanical/Engineering measures		√		√
Earthen check dam		√		√
Boribund check dam		√		√
Silt retention tank		√		√
Staggered trenching + plantation		√		√

The main purpose of the above-mentioned land interventions is to control soil erosion however, it improves green water, prevents land degradation, improves soil organic matter, enhance soil fertility, restore degraded land and help sustainably manage dryland environment. The above interventions of sustainable land management under different cropping system and land use promotes integrated soil-plant-water management. Integrated with, reduced biotic pressure-overgrazing, rainwater harvesting (in-situ and ex-situ) and SLMs are likely to improve crop-water productivity and soil health.

The selection of crops and cropping system is crucial part of the agricultural SLMs. The conservation measures and land managements options presented in Table 3.3 need to be integrated with the suitable crops /cropping systems/ agroforestry or tree-based cultivations. The ICAR-IISWC along with its eight research centres have developed/evaluated crop and tree-based land use and management practices comprising the conservation measures (Table 3.4).

Sr No.	Sustainable land Management practices/interventions	Intended /accrued benefits	Domain area
1.	Green manuring for conservation and production on eroded alluvial soils of Yamuna ravines. *Crotolaria juncea* L (sunhemp) and *Sesbania aculeata* (Dhaincha) are grown with 10-20 Kg N application and turned up in soil and 35 to 50days and 60 to 75 days respectively. Wheat/Mustard in Rabi season is grown.	Moisture conservation, biomass addition, higher production of subsequent crop	Indo-Gangetic alluvial plains covering states of Punjab, Haryana, Delhi, Uttar Pradesh, Uttarakhand, Bihar and West Bengal
2.	Intregrated nutrient management for increasing crop yield in shivalik region (inm, N:P:K:Zn::100:40:20:25 kg ha^{-1} along with FYM @ 2.5 t ha^{-1} is applied under maize crop)	Improved soil fertility, productivity and income, improved soil conditions	Haryana, Punjab, HP and other degraded land of Shivaalik region
3.	Green manuring for resource conservation and productivity enhancement in red soils of bundelkhand region Sun-hemp is sown in kharif season during monsoon (IInd week of July) by broadcasting method with seed @60 kg/ha. After 50-55 days, standing crop of sun-hemp is turned into the soil with the help of a mould board plough.	Reduction in runoff and soil loss, increase in available nutrients and soil organic carbon, high soil moisture high crop production,	Red soils of Bundelkhand regions (12 districts)
4.	Inter cropping of Gram + Indian mustard (8:1) for efficient utilization of soil moisture and increasing returns. Indian mustard (Pusa Bold) in chickpea (JG 16) are grown in a ratio of 8:1.	Higher water productivity, increase in crop yield. Reduced insect and pest damage	Bundelkhand region, rainfed regions of M.P. and Rajasthan
5.	Sambuta a non-grazing species as a suitable vegetative barrier for soil & water conservation in sloping highlands of Eastern Ghats region. Vegetative barrier are permanent strips of dense grasses grown across a slope to reduce runoff, capture sediment and resist soil erosion. Grass is planted on miniature bunds	In-situ rainwater conservation, reduction in runoff and soil loss by 2/3rd, strengthening earthen bunds and gully stabilization	Eastern Ghats region of Odisha, area of shifting cultivation,

Table 4: Some of the sustainable land management practices developed/ evaluated by ICAR-IISWC Dehradun and its eight research centres, primarily aimed at reducing erosion, improving soil conditions and land productivity in croplands.

	at 15 cm distance with a row spacing of 20 cm in staggered rows.		
6.	Ragi + Pigeon pea intercropping (5:2 row proportion) for higher productivity in tribal areas of Odisha & Eastern Ghat region.	Higher crop yield with with minimum runoff, soil and organic carbon loss.	Red soils of eastern Ghat high land region of Orissa,
7.	Sorghum + Pigeon pea intercropping for stabilizing productivity in south-eastern Rajasthan, sorghum population is kept normal while pigeon pea population remains only 30-40%	Higher sorghum grain equivalent yield, higher rain water productivity	Rainfed condition for hot semi-arid region with medium-deep black soils of south eastern Rajasthan
8.	Castor + Green gram intercropping for delayed monsoon conditions in south-eastern Rajasthan, castor and green gram in separate row across the slope in 1:2 ratio i.e. 30 cm apart, so that distance between 2 castor rows remains 90 cm, plant-to-plant distance in castor as 60 cm and in green gram as 10 cm	Higher castor grain equivalent yield, ever under delayed monsoon condition, reduced soil erosion.	Hot semi-arid region with medium black soils of south- eastern Rajasthan, northern Gujarat and Western Madhya Pradesh
9.	Opening contour furrows at 6 m horizontal interval after every kharif sowing in field to promotes in situ moisture conservation while facilitating safe disposal of excess runoff. Opens 40-50 cm wide and 20-30 cm deep furrow by pushing the excavated soil towards both sides of furrow, the excavated soil is not used for bund formation and it is pushed away from the furrow to avoid any stagnation of water outside the furrows	Increased water productivity by more than 25%, production by 26% and income increase 40%.	Kota, Baran, Bundi, Jhalawar and part of Sawaimadhopur and Tonk districts and adjoining districts of west Madhya Pradesh
10.	Water mill based integrated farming system (IFS) for north - western Himalayas, piggery and poultry integrated with fishponds, form a significant source of nutrients for fish production, reducing over 50% input cost of fish feed, fish farming, agriculture, poultry, piggery, rabbitry, goatary, water mill, irrigation network etc.	Higher and sustained income, resource conservation and recycling	Northwest Himalayas covering the state of Uttarakhand, Jammu & Kashmir and Himachal Pradesh
11.	Composite fish culture in water harvesting structures, primary source of water for watershed ponds is rainfall & runoff from the surrounding area	Additional income and resource productivity.	North western Himalayan watersheds
12.	Paddy-fish integrated farming system for north-western himalayas, exotic common carp (*Cyprinus carpio*) is most suitable for culture in paddy fields. Indian major carps such as catla (*Catla catla*), rohu (*Labeo rohita*) and mrigal (*Cirrhinus mrigala*) and others like	High water and resource productivity.	Wide range of mid-hills and foothills of north-western Himalayas, particularly in paddy fields

	catfish (*Clarius* spp.), murrel (*Channa* spp.) And exotic silver carp (*Hypophthalmichthys molitrix*) can also be cultured in paddy fields of north-western himalayan region., tall-growing and long-duration paddy varieties are preferred for paddy-fish integration. Other paddy varieties, viz; govind, pant-10 and pant-12 can also be considered for the cultivation		near irrigation or stream channels, where sufficient water is impounded for long period.
13.	Maize + cowpea intercropping for resource conservation and higher productivity. Maize varities such as Vivek, Makka Hybrid 9, Vl Makka 88, Vl Makka 42, Vl Makka 14 And Kanchan are suitable for cultivation in north-western Himalayan region. Cowpea varieties Pusa Komal and Pusa Rituraj (for green pods) are suitable for cultivation as inter-crops in the region. Row to row and plant to to plant spacing for maize is kept as 90 x 20 cm with two rows of cowpea as inter-crop with 30 cm spacing	Reduction in runoff, soil loss, increased net production and income, improved soil health	States and regions where maize crop is grown extensively as a kharif crop, particularly Uttarakhand, Himachal Pradesh and J&K
14.	In-situ sunhemp mulching in rainfed maize based cropping system for higher productivity. Growing sunnhemp in between maize rows during rainy season and its recycling as surface mulch after 30 to 35 days of maize sowing at row spacing of 90 cm with plant spacing of 20 cm. Sunhemp @60 kg seed/ha is sown in the inter row spaces in maize on the same day.	Increases the yield of maize and yield of succeeding wheat crop, moisture conservation, reduced erosion	Western Himalayan regions
15.	Conservation tillage for management of natural resources in maize toria cropping system. One ploughing is done just after harvest of maize crop and another ploughing before sowing of toria, Toria residue obtained after its harvest is applied as mulch during 1st week of march and incorporated into the soil by ploughing. Crop residue of maize is applied as surface mulch after sowing of toria.	Reduced runoff, soil loss and nutrient loss, moisture conservation, improved soil physical conditions	Western Himalayan regions
16.	Vegetative barriers (Napier grass) on shoulder bund of terrace and sodding on riser. Napier clumps planted along shoulder bund of terraces (plant to plant distance: 60 cm) and the same grass sodded on the riser to protect the riser from breaches due to heavy rainfall	Riser stabilization, fodder and biomass production, reduced erosion.	Western Ghat region, mod and lower western Himalayan region,
17.	Technology of artificial ground water recharge through dried and defunct well and use for higher productivity. A low-cost physical filter is used for	Increased net production, higher cropping intensity and income	Central region of Gujarat, parts of MP and Maharashtra

	removing sediment from agricultural runoff.		
18.	Drumstick based agri-horti system on mahi ravine. Drumstick + green gram-fennel alley cropping and drumstick as block plantation on	Increased net production, income and soil organic carbon, reduced erosion	Central Gujarat and parts of Maharashtra.
19.	Stubble Mulch Farming tillage techniques which comprises of one mouldboard plough + one cultivation along the contour, no planking to retain surface roughness, crop sowing along the contour and application of chopped pearl millet straw @ 2 t ha^{-1} on the surface, in intercropping (Cow pea+ Castor)	Yield increase 45 to 177%, soil OC improvement, moisture conservation and higher NPP	Rainfed region of Gujarat and Maharashtra
20.	Tank silt- removal and application (ICAR-CRIDA) for soil amelioration. Tank sediment was found rich in clay as it contained 58% of clay as against targeted soil having about 15% clay.	Soil health improvement, high water availability, effect, ground water recharge	Andhra Pradesh, Karnataka and Tamil Nadu
21.	Vegetative filter strips on sloppy land, in between the crop for water and soil conservation in addition to generate compensatory or additional income. For Notrth Western Himalaya region, slips of grass species of guinea, khus khus and bhabar along the contour line with paired rows in a staggered fashion at 1m vertical interval	Reduction in runoff, soil loss, silt and nutrient retention, additional biomass.	Western Himalayan region
22.	Vegetative filters strips of *Eulaliopsis binata* and *Dichanthium annulatum* grasses having 1-2 m width at spacing of 45 m.	*Reduction in soil loss,* nutrient loss and increase in total biomass and crop yield.	*Central Gujarat* region
23.	Conservation furrow in groundnut – pigeon pea intercropping pea. A conservation furrow opened at 45 DAS with *chip kunte* implement between two rows of pigeon pea in finger millet + pigeon pea (paired row 8:2) inter cropping system in southern dry zone of Karnataka	Overcome effect of dry spell, high net production	Tumkur, Bengaluru (Rural), Ramanagara, Kolar, Chikkaballapur, Chitradurga, Mysore and Mandya districts
24.	Compartmental bunding - Making square compartments on field to retain rainwater and soil was found beneficial in terms of yield gain of 40, 35, 38 and 50 per cent in sorghum, sunflower, safflower and chickpea, respectively	Moisture conservation, safe, reduced soil erosion, improved production	Dry region of Karnataka and Maharashtra
25.	Contour bund (Bottom width 1.8m, height 0.45m and side slope 1: 1.5) with grass sodding (*Cenchrus ciliaris, Cynodon dactylon* and *Dichanthium annulatum*) on bund for soil and moisture conservation	Reduction in runoff, soil loss and nutrient loss	Red soils in Bundelkhand region

Table 5: Agroforestry technologies for soil and water conservation

S. No.	Sustainable land Management practices/ interventions	Description	Performance	Impact
1.	Silvipastoral systems for wasteland utilization	Growing of trees of shiham (*Dalbergia sissoo*, 9x9 m), bhimal (*Grewia optiva*, 4x4 m), kachnar (*Bauhinia variegata*, 4x4 m) and Eucalyptus (3.5 x 3.5 m) in combination with Gorda grass (*Chrysopogon* fulvus). Trees are lopped at 75% intensity after they have attained the age of 7 years.	Yield of 4.3-5.4 t ha^{-1} from Gorda grass; fodder yield of 362 kg ha^{-1} yr^{-1} and 262 kg ha^{-1} yr^{-1} from kachnar and bhimal respectively; 64 t ha fuelwood yield from shisham, (19 years); 75 q ha^{-1} yr^{-1} from bhimal and 105 cu ha^{-1} timber yield after 12 years from Eucalyptus. Over a period of 18 years, the B: C ratio calculated at 12% discount rate was 1.6 and with an IRR of 25%	Higher biomass production and economic returns
2.	Mango-Jasmine based two-tier horticultural system	Use of chemical fertilizer (NPK) along with vermicompost (50%) in mango along with in-situ sun hemp mulching @30 kg $tree^{-1}$ in the circular trench.	Average 12.5 t ha^{-1} mango fruit upto 40-50 years. Net benefit of 76000-80000 ha^{-1} Employment of 130-140-man days ha^{-1} $yeat^{-1}$ on 10-year cycle.	Conserve soil and moisture on sloping land and can build organic matter.
3.	Sapota based agri-horticulture system with soil moisture conservation practices:	Bench terracing as best soil and water conservation measure for restoring highly degraded ravines of Western India. Under circumstances where terracing is not feasible, trenching could be a significant step to restore ravines through Sapota plantation	Sapota with trenches and bench terraces reduced runoff by 16–34% and soil loss by 15–25%.	
4.	Agroforestry system of cowpea + castor + sapota for controlling soil erosion and enhancing system productivity	Growing of cowpea and castor in the interspaces of Sapota	Reduced total soil loss and runoff by 37.7% and 19.1%. Cowpea equivalent yield increased by 82-162% as compared to sole crop and sole tree plantation.	Improving productivity, reducing soil erosion and mitigating climate change

5.	Contour hedgerow systems (*Gliricidia sepium* and *Leucaena leucocephala*) with miniature trenches:	Staggered planting of hedgerows at 0.5 × 0.5 m spacing in two parallel lines with miniature trenches (0.3 m width and 0.3 m depth) in between two lines	The runoff and soil loss were reduced by 23-32% and 49-53% respectively.	Improving productivity, reducing soil erosion
6.	Hedge rows (*Gliricidia sepium*) hedgerow and grass filter strip for erosion control.	Growing of hedgerow species viz., *Gliricidia sepium* and *Indigofera teysmanni* – integrated with local grass species - Sambuta (*Saccharum* spp). The hedgerow species were planted at a spacing of 0.5 m × 0.5 m in staggered double rows and the grass filter species was planted in a single row at 0.3 m.	The runoff and soil loss were reduced by 32% and 35% respectively, sequestered 0.41–1.42 Mg ha^{-1} yr^{-1} carbon in the 0.6 m soil depth, improved soil moisture by 22–43 mm in dry spell, increase in grain yield by 49%.	Improving productivity, reducing soil erosion and mitigating climate change
7.	Alley cropping Agroforestry system for Improvement of Soil Health.	Involves growing of Glircidia in hedgerow and growing of finger millet (*Eleusine coracana*) on 5 and 10% land slope in combination with conservation treatments	Gliricidia + Trench planting (G + TP) reduced run-off by 29%, soil loss by 45–48%, and loss of soil organic carbon (SOC), N, P and K by 42–47, 62–65, 54–58 and 51–56%, respectively over control. Reduced run-off increased soil moisture storage by 11–29%. Intensive pruning of Gliricidia plants for 5 years yielded greater fresh leaf biomass (12–17 Mg ha^{-1} $year^{-1}$), The SOC, N, P and K conservation efficiencies of G + TP were 42–47, 62–64, 54–58 and 51–56% on 5 and 10% land slope, respectively	Enhancement of productivity, soil erosion and nutrient losses
8.	Rehabilitation of degraded lands through lemon grass in	Growing of lemon grass variety Krishna and Palmarosa grass on degraded bouldary	Provides average herbage and oil yield of 500 q ha^{-1} and 237 kg ha^{-1} in Lemon	

	Himalayan foot hills.	lands	grass and 300 q ha^{-1} 254 kg ha^{-1} in java grass respectively. Net benefits of Rs 42250 ha^{-1} yr^{-1} and 32 750 ha^{-1} yr^{-1}. B:C ratio after four was 1.90 for lemon and 1.78 for java grass	
9.	In-situ soil moisture conservation in bamboos for the rehabilitation of degraded lands	Involves growing of bamboo species (*Dendrocalamus strictus* and *Dendrocalamus hamiltonii*) in conjuction with semi-circular trenches.	Semi-circular trenches depicted 16% higher soil moisture as compared to control treatment (without trenches). Soil moisture was 45% higher in *D. hamiltonii* and 25.1% higher in *D. strictus* as compared to fallow treatment during the summer season, Silt deposition was higher under *D. hamiltonii* (50.1%) as compared to under *D. strictus* (48.6%). No soil loss was observed after 5th year.	Enhancing biomass, conserving soil moisture and reducing soil erosion
10.	Canopy management techniques for enhancing biomass and resource conservation in agroforestry trees	Involves managing *Morus alba* through pollarding and coppicing	Leaf yield was also maximum (10.54 kg/ tree) in case of lopping. As compared to fallow plot 9.8 % more soil moisture was observed in pollarding treatment. Coppicing reduced the runoff from 37.9 (coppicing treatment) to 45.3 % (coppicing + turmeric treatment) and soil loss by 73.3 % (coppicing) as compared to fallow plots.	
11.	Agri horticultural system of Kinnow Mandarin-toria using drip irrigation	Growing Kinnow Mandarin-toria on degraded lands through scheduling of irrigation and mulching	The system produced 28.12 t ha^{-1} of kinnow fruits with drip irrigation. Benefit cost ratio of the system is 5.10 when calculated for 20-year life of tree payback period of 7 years.	

12.	High density plantation of multipurpose trees for fodder and fuelwood production	Growing of Bhimal (*Grewia optiva*), Shisham (*Dalbergia sissoo*) and kachnar (*Bahunia variegata*) at close spacing of 2x2m (2500 trees ha-1).	After 11 years, provide 22 q ha^{-1} green fodder from bhimal, 24 q ha^{-1} green fodder from kachnar and firewood ranging from 40-45 t ha^{-1} from bhimal and kachnar and 00 t ha^{-1} from Shisham. B:C ratio of 3.70-4.41 from shisham, 1.46-2.32 from bhimal and 1.20 from kachnar	Biomass production from degraded lands
13.	Multitier agroforestry system for integrated resource conservation on in India:	Mulltitier plantation of drumstick (*Moringa oleifera*) with *Gliricidia sepium* hedgerow and ginger (*Zingiber officinale*): pigeonpea (*Cajanus cajan*) (8:2).	intercropping gave minimum mean runoff (8.26 %) and soil loss (3.45 Mg ha^{-1}). Intercropping saved 74 % more soil organic carbon, 64 % more phosphorus and 66 % more potassium, respectively than broadcasted finger millet cultivation (traditional farmers' practice).	Checks soil erosion and nutrient losses. Higher biomass production and diversification of existing land use system
14.	Peach based agrihorticulture system for marginal lands	Growing of peach as an over-storey and blackgram - toria as under-storey crops. Pits are filled with 75 % sieved soil and 25% gravel (<10 mm diameter).	Peach yield 9 t ha^{-1} in 6th year which increases till 15th year. It gives additional yield of 3.55 q $ha^{-1}$from black gram and 3.58 q ha^{-1} from toria. B:C ratio of 3.50 with payback period of 7 years.	Productivity enhancement
15.	Aloe vera cultivation in interspaces for supplementing productivity of ber orchards	Growing of *Aloe vera* in the interspaces of ber (*Zizyphus mauritiana*) plants.	The system provides 76 q ha^{-1} yr^{-1} of ber fruits 300 q ha^{-1} yr^{-1} fresh leaf of *Aloe vera* can be harvested from single cutting upto 4-year cycle. Net income of Rs 75000 as compared to Rs 35000 from sole ber	Eco-intensification, higher income, higher biomass production and diversification of existing land use system
16.	Ber based agrihorticulture system for	Growing of ber (*Zizyphus mauritiana*) along with blackgram.	Average fruit yield of 40.5 q ha^{-1} in 5th year. Net return of Rs 36000	Resist adverse climatic condit--ion, moisture

	marginal lands		ha^{-1} yr^{-1}. Runoff and soil reduction by 25 % and 27% as compared to sole ber.	stress, check soil erosion and provides higher productivity
17.	Aonla based Agrihortisilvipas--ture system	Growing budded or grafted saplings of Aonla (*Emblica officinalis*) with Dholu, (*Chrysopogon fulvus*) and Napier (*Pennisetum purpureum*) and perennial pulse (Arhar) crop.	Upto 20 q ha^{-1} of Aonla fruits. 23.8 q ha^{-1} of Dholu grass and 111.3 q ha^{-1} of Napier grass. Reduction in runoff to 8-13%. Discounted net returns of 11, 28, 500 with pay back period of 4 years.	Reduced soil erosion, moisture conservation, biomass recycling nutritional security and improved soil OC
18.	Aonla based Agrihorticulture systems for sloping lasnd	Growing budded or grafted saplings of Aonla *(Emblica officinalis*) with live sunhemp as mulch (@20 kg $plant^{-1}$) and growing maize in the interspaces.	29 kg $tree^{-1}$ in 4th year to 69 kg $tree^{-1}$ in 10th year. B:C ratio of 4 calculated for 50 years life cycle with payback period of 5 years. 16.4 q ha^{-1} maize from the interspaces of Aonla	Moisture conservation, reducing runoff and soil loss, nutritional security and improved soil OC
19.	Kinnow based silvipasture system for degraded watersheds.	Plantation of kinnow is done at 4 m x 4 m spacing. The understorey is planted with bhabar grass (*Eulaliopsis binata*) at 50 cm x 50 cm spacing after minor levelling.	Early returns and higher productivity	
20.	*Leucaena leucocephala* and *Eucalyptus hybrid* for soil and water conservation	*Leucaena leucocephala* and *Eucalyptus hybrid* were grown either as block plantation or in alley farming at 4.5 m with maize (*Zea mays*), *Chrysopogon fulvus* (grass) or turmeric (*Curcuma longa*)	Contour tree-rows or leucaena hedges reduced the runoff and soil loss by 40% and 48%, respectively, over the maize plot, reducing soil loss to about 12.5 Mg ha^{-1}. Managing leucaena as contour hedgerows eliminated crop yield reduction in alleys. Land equivalent ratios of agroforestry land uses were comparable or even better than monocropping systems	Increase in crop yield and reduction in runoff, soil loss and nutrient loss

21.	Bamboo and Anjan grass for enhancing productivity of mahi ravines.	Staggered contour trenches 0.6 m (width) x 0.6 m (depth) x 1.8 m (length) are dug out at 5m x 5m spacing (Bamboo plantation) in ravine bed across the slope with the heaping of excavated soil on downstream side of trench in the form of a bund for moisture retention. Anjan grass are planted in monsoon season at a spacing of 50 cm apart on contour in staggered fashion, if the slips are readily available otherwise seeds of anjan grass @4.5 kg ha^{-1} can be sown in lines 30 cm apart on contour in case of the non-availability of the slips.	Green grass @ 7.1 t ha^{-1} yr^{-1} was obtained from stabilized gully slopes. Grass yield of 10 t ha^{-1} yr^{-1} from gully bed. After 7 years1000 bamboo poles ha^{-1} yr^{-1} can be harvested. The system has ability to asorbs more than 80% of rainfall. Soil loss was reduced to less than 1 t ha^{-1} yr^{-1}. B:C ratio was 1.85	Reduction in runoff, soil loss, increase in biomass production and income, improvement in soil organic carbon.
22.	Reclamation of gullies with bamboo plantation as live check dams.	Bamboo saplings are planted in two staggered rows with 2 m x 2 m spacing (plant to plant and row to row) to act as live check dam without any other soil and water conservation measures. The spacing between two live check dams is kept as 10 m. In between the live check dams bamboo plantation is done at 4 m x 4 m spacing in staggered manner.	Absorb more than 80% of rainfall. Reduced runoff, soil loss. Reduced the nutrient losses: 50-67%. Benefit cost ratio works out to be 1.96-2.09	Reduced runoff and soil erosion, higher biomass production and income, carbon sequestration, greening gullies.
23.	Bamboo-based bio-engineering measures with staggered contour renches:	Bamboo plantation with staggered contour trenches for ravine reclamation, staggered contour trenches of 0.5 m (width) x 0.5 m (depth) x 2 m (length) are dug out at 4 m x 4 m spacing in ravine beds across the slope		Higher carbon stock, soil retention, higher net primary production and income

		prior to onset of monsoon,		
24.	*Grewia optiva* + hybrid Napier based silvipastoral system for degraded lands containing more than 70 % of boulders.	Growing *Grewia optiva* and hybrid Napier using lopping and pollarding as management practices.	229 q ha^{-1} biomass from tree (28 q ha^{-1}) and grass (201 q ha^{-1}). B:C ratio 0f 1.4-1.8 with payback period of 8 years when calculated for 11 year cycle at 10% discount rate.	Fuelwood, leaf fodder, grass fodder and fibre production, improves soil fertility - rehabilitation of degraded land
25.	High yielding provenances of Bhimal (*Grewia optiva*) for north-western Himalayas	Growing of high yielding provenances of Bhimal provenances *viz*., IC Chamba, IC Bhaintain and IC Malas	Average fuelwood yield from 16-21 kg 100 m^{-1} length, green fodder of 98-106 kg 100 m^{-1} and bark fiber ranging from 8.3-11 kg 100 m^{-1}. Revenue of Rs 599-684 100 m^{-1} length. Increase fodder productivity to an extent of 20% over less productive provenances.	Reducing dependency on forests
26.	Drumstick based agri-horti system	Drumstick + green gram-fennel alley cropping and drumstick as block plantation on		Increased net production, income and soil organic carbon, reduced erosion
27.	Horti-pasture development in medium to deep ravine of Chambal using staggered contour trenches.	Aonla, Bamboo and Dhaman grass (*Cenchrus cilliaris*)		Averting soil erosion, improved net production, improved soil OC and
28.	Mango based agri-horti system	Mango is intercropped with cowpea and Toria upto 8 years or until the closing of canopy after which shade loving crop like turmeric is introduced. as intercrop on degraded and marginal lands. Mango+Cowpea-Toria	Mango yield of 7 t ha^{-1} upto 10 year. Net benefit of 12, 282-16,849. After 10 year the income is 29,800.	Development of productive land use, improvement in soil conditions, reduced erosion and income enhancement, carbon sequestration

29.	Bamboo for economic utilization of river bed lands	Growing Male bamboo (*Dendrocalamus strictus*) at close spacing of 3 m x 3m	Bamboo gives early returns in form of harvestable culms after 5th year. Weight of culms ranged from 5-6 kg culm^{-1} in 6th year to 15-18 kg in 20th year.	Annual returns from 5th year onwards. Build-up of soil OM. Soil moisture conservation.

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Joint Mangrove Management:
A science-led and people-centric approach to restore and sustain mangroves of India



CHAPTER
FOUR

V. Selvam[1] and B. Nagarajan[2]

[1]Devipattinam, Ramanathapuram, Tamil Nadu - 623514

[2]Institute of Forest Genetics and Tree Breeding, Coimbatore, Tamil Nadu - 641 002

4.1 Introduction

The east and west coasts of India and the coastal zone of Andaman and Nicobar Islands are endowed with luxuriant mangroves, which perform a number of protective and productive functions. Scientific studies conducted after the 1999 Super Cyclone in Odisha and the 2004 Asian tsunami clearly show that mangroves have the capacity to function as barriers against such natural hazards and associated storm surges. These studies show that mangroves not only reduced the loss of human lives and property but also avoided the degradation of land, water and other resources of the coastal zone by reducing seawater inundation inland (Das and Vincent, 2009; Danielsen et al., 2005). Regarding productive services, the mangrove wetlands are well known for providing livelihood security to millions of fishing families. These wetlands are rich in fishery resources and support commercial, subsistence and recreational fisheries and contribute to marine fisheries in a significant way. The study conducted on the relationship between mangroves and marine fisheries indicates that in India, 1.0 ha of healthy mangroves contributes about 1.86 ton of marine fish production per year (Annebonia and Kavi Kumar, 2019). In recent times, the role of mangroves in increasing the adaptive capacity of the local community to predicted sea level rise and increased frequency and intensity of cyclones and storm surges is well appreciated. The Intergovernmental Panel on Climate Change (IPCC) considers that the conservation and restoration of mangroves will increase protection against sea level rise and storm surges (IPCC, 2022). The mangroves integrated with fish farming play an important role in enhancing the adaptative capacity by providing a physical barrier to increasing sea level and cyclones and, at the same time, ensuring sustained income (Selvam et al., 2012). All these indicate that the restoration and conservation of mangroves should be a primary objective of the mangrove management programmes. A science-based and people-centric participatory management approach, which relies on the identification of fundamental causes of degradation, the appropriate method of restoration and empowerment of the stakeholders, particularly the mangrove user community, is essential in achieving this primary objective.

4.2 Primary causes of degradation of Indian mangroves

4.2.1 Mangrove Management during the colonial period

The primary causes of the large-scale degradation of mangroves in India are the management practices initiated during the colonial period, which continued even during the post-colonial period.

4.2.2 Conversion of mangroves to agriculture

Initially, British administrators considered mangroves as a breeding place of malaria and home for wild beasts and hence, better to be cleared (Pargiter, 1885). Cleghorn (1861) mentioned that the mangrove belts of Godavari and Krishna deltas could be cleared to increase the area of cultivation and easy movement of British troops. Apart from these, the British government considered only a few species of mangroves such as *Heritiera* to have value as timber. Less or no value attached to the mangroves by the British administrators initially led to the large-scale clearing of mangroves for agriculture.

The clearing of Sundarbans mangroves was the first to start in as early as 1783 when a proposal was made to the Governor-General of British India for clearing Sundarbans mangroves with the objective of bringing the Sundarbans' "waste" into cultivation. As shown in Table 4.1, in 1873, the Commissioner of Sundarbans showed how much areas of mangrove had already been destroyed and how much was planned to be cleared in the future (Hunter, 1875). This indicates that the primary aim of the British Bengal administration initially was to reclaim the mangrove wetlands for agricultural development. According to Hossain (1895), about 41958 ha of the land was under mangroves in the Bhitarkanika region of Orissa (currently Odisha), which were mainly exploited for firewood and posts for cottage-building. Like Sundarbans, the mangroves of Odisha were also cleared for agriculture by farmers as well as officials of the Kanika Raj. Outsiders were also allowed to clear the mangrove for rice cultivation. For example, in 1879, the Raja of Kanika granted a European about 900 ha of mangrove forest for conversion into agriculture.

Category	Area in ha
Mangroves already cleared for cultivation	279226
Mangroves set apart for further clearing for cultivation	155822
Mangroves not leased for clearing	1027445
The area occupied by navigable rivers, canals, and creeks	488027
Total area	**1950520**

Table 4.1: The total area of Sundarbans mangroves in 1873, area already cleared, and area earmarked for future clearing

4.2.3 Constitution of mangroves as Reserve Forests

When the mangroves of Sundarbans were rapidly converted into agricultural land, William Schlich, who was the Head of the Forest Department in the Bengal in 1876 took the first step to bring the mangroves under management. He wrote an article in the *Indian Forester* in which he explained the values of Sundarbans mangroves and the silviculture potential of many mangrove species and urged the British government to stop the practice of converting mangroves into agriculture. He also suggested bringing the entire Sundarbans under forest management (Schlich, 1876). Accordingly, Sundarbans mangrove forests were divided into four blocks namely, Bagerhat, Khulna, Satkhira and 24-Parganas, the first three were declared as Reserve Forests in 1879, and the 24-Parganas block was declared as a Protected Forest in 1878 as per the Indian Forest Act, 1878.

Similarly, the mangroves in the Godavari and Krishna districts of the Northern Circars of the Madras Presidency were notified as Reserve Forests between 1886 to 1890 (Anon, 1901). According to Hemmingway (1907), the mangroves of Godavari extended for a length of 35 miles (56 km) from Coringa in the north and Narasupur in the south with an average width of 5 miles (8 km), which is approximately equal to 44800 ha. The Pichavaram mangroves in modern-day Tamil Nadu were declared as Reserve Forest in 1893. Though the flora of the mangroves of the west coast of India was explored and documented during the early period of colonial rule none of the mangroves were brought under Government control. This may be due to the small size of the mangroves and poor stocking. Most of the mangroves of the west coast remained under the control of the Revenue Department both during the colonial and immediate post-colonial period (Qureshi, 1957).

4.2.4 Clear felling of mangrove forests

The main aim of the management of Indian mangroves during the colonial period was to produce firewood for railways, iron smelting, sugarcane and cotton mills, brick kiln, and local consumption, particularly in the nearby cities and towns (Rao, 1957). In the specific case of Sundarbans mangroves, it was to produce timber, firewood and thatching materials for the whole of Bengal and Calcutta. In all these mangroves, clear felling was the system employed to exploit the mangrove forests (Curtis, 1937; Mathuada, 1957). As per this system, an entire forest division or a part of it is declared as a working circle, which is divided into many felling series, and each felling series is further divided into annual coupes. The size of the annual coupes is decided by the rotation age of the forest for exploitation. The age of the forest (trees of major stock of the forest or targeted species) at which the maximum sustainable yield can be achieved is known as the rotation age. Thus, for example, if the area of a felling series of a mangrove forest is 500 ha and its rotation period is 20 years, then the area of one annual coupe will be 25 ha, and the number of the annual coupe will be 20. In the first year, trees in the first coupe will be felled, and in the felled areas new growth will be achieved either through natural or artificial regeneration or by both. In the second year, a similar process will be followed in the second coupe, and this will continue until felling is completed in the 20th year in the 20th coupe. In the 21st year, the first coupe will be ready with a stock of trees of rotation age, which will enter into the second felling cycle. Theoretically, it looks like a simple exercise but in practice, it is complex, and required enormous and reliable mathematical and statistical data.

In Sundarbans mangroves, where good quality mangrove timbers were available in plenty, selection cum improvement felling (selective

felling of trees of exploitable age at frequent intervals) was employed and wherever the quality of the wood considered as poor, a clear-felling system was adopted to exploit large quantities of mangrove timber and firewood. Table 4.2 shows that about 5 lakh ton of wood was exploited from the Sundarbans mangroves in the year 1928-29 alone (Curtis, 1931). In the case of mangroves of Godavari, Krishna and Cauvery delta, which the British foresters considered stocked with poor quality wood, the following methods of the clear-felling system were employed:a) clear felling but retaining trees less than three inches grith, b) simple coppice system (natural regeneration through shoots that originate from stumps or stools) and c) coppice with standards (leaving a few matured trees in the felled area for regeneration from seeds along with coppice shoots). The rotation age ranged from 5, 15, 20, and 25 years (Curtis, 1931). By these methods, large areas of mangroves were clear-felled in Godavari, Krishna, and Cauvery delta every year (Anon. 1896) (Table 4.3).

Moundage of the boat	Number of boatloads	Mounds of forest produce exported out of Sundarbans
100 mounds and less	59038	2889275
125 to 200	12677	2071900
225 to 300	4381	1165400
325 to 400	1968	711975
425 to 500	1912	882550
525 to 1000	3761	2871525
1100 to 2000	1109	1536300
2100 to 5000	487	1397100
Over 5000 mounds	6	33500
Total	**85339**	**13359525**

Table 4.2: Quantity of mangrove wood exploited from the Sundarbans mangroves during 1928-29 (one mound is equal to 37.32 kg)

	Coupe I felled in 1893-94			Coupe II felled in 1894-95		
	Area (acres)	Yield (ton)	Revenue (Rs)	Area (acres)	Yield (ton)	Revenue (Rs)
Masulipatanam working circle	1160	-	-	1062	125	312
Avanigadda	2280	2614	6545	1690	1114	2784
Repalle	1690	1821	4560	806	1981	4954
Total	**5130**	**4435**	**11105**	**3558**	**3220**	**8050**

Table 4.3: Area of mangrove clear felled and yield obtained in the mangroves of Krishna delta during 1893 to 1895

4.3 Mangrove management during the post-colonial period

Little changes were made in the policy and procedures of forest and mangrove management in the post-colonial period, particularly regarding state ownership, denial of access to the forest resources by the local people, and forest economics remained the central theme of forest management. The role of forests contributing to the national economy was given more importance rather than giving priority to the local people's needs (Gadgil and Guha, 2013). As a result, the same silvicultural system, clear felling, was followed in the large-scale exploitation of mangrove wood during the post-colonial period. As an example, the area of mangroves clear felled, yield realized and revenue earned in the Tamarankottai Reserve Forest in the Muthupet

region of Tamil Nadu is shown in Table 4.4 (Karunakaran, 1971). In some locations, a considerable area of mangroves is dereserved for other purposes. For example, in the Maravakkadu Reserve Forest in Muthupet, Tamil Nadu, about 800 ha of degraded mangrove was converted into salt pans in 1978. Felling of trees by the Forest Department and dereservation of Reserve Forests were stopped only after the promulgation of the Indian Forest (Conservation Act, 1980).

Year	Tamarankottai Reserve Forest			
	Coupe Number	Area in ha	Yield in ton	Amount in Rs.
1960-61	I	53.82	365.00	7151.00
1962-63	II	40.47	327.50	9000.00
1963-64	III	40.47	260.50	9050.00
1966-67	VII	40.47	336.67	5500.00
1969-70	VIII	40.47	388.00	7000.00
	IX	40.47	116.60	3400.00
1970-71	IV	40.47	43.00	5500.00
	V	40.47	43.80	4305.00
	VI	40.47	43.00	4305.00
	X	40.47	-	5021.00
		418.50	**1924.07**	**60232,00**

Table 4.4: Area of mangroves exploited by clear felling in the Taramankottai Reserve Forests in the Muthupet Region

4.4 Changes in biophysical condition due to clear felling system of management

The clear felling of mangrove trees on large scale during the colonial and post-colonial periods triggered a chain reaction as shown in Fig. 4.1. Exposure of mangrove soil due to clear felling caused evaporation of soil water, which in turn caused subsidence of sediment leading to changes in the topography of the clear-felled areas into shallow troughs. Subsidence of sediment is a common feature in wetland soils, which are exposed to prolonged solar radiation (Allen, 1984 and USDA, 1995). Allen (1984) explained that the evaporation of soil water in peaty areas results in subsidence for two reasons. Peat soil is commonly underlined by and frequently interbedded with fine sediments that are susceptible to compaction when water from the peat is drained out or removed by evaporation. Secondly, peat soil, which is common in mangrove wetlands due to the accumulation of decaying plant materials, has certain physical and chemical characteristics that lead to extreme volume changes upon drying, leading to subsidence. According to FAO (1994), nearly 80% of the mangrove soil volume is made up of water and these soils are prone to subsidence due to compaction and dewatering and insufficient and irregular supply of fresh sediments. Selvam et al. (2003) observed this phenomenon in the clear-felled areas in the Pichavaram and Muthupet mangroves in Tamil Nadu. As shown in Fig. 4.1, the development of hypersaline conditions due to subsidence and subsequent stagnation and evaporation of tidal water prevented the natural regeneration of mangrove species. Failure of mangrove regeneration in the clear-felled areas both by coppice shoots and seeds was reported in many of the Annual Administration Reports of the Forest Departments of the Madras Presidency starting from the late 1890s. The Working Plans of mangroves prepared during the post-colonial period mentioned these areas as saline blanks. Restoration of these saline blanks with mangrove species posed great challenges to the colonial and post-colonial foresters. A clear-felled degraded mangrove area is shown in Fig 4.2.

Since the foresters of both the colonial period and independent India were not cognizant of the above chain reaction triggered by the clear-felling system of management, their attempts to restore mangroves in clear-felled areas were not successful (Selvam, 2021).

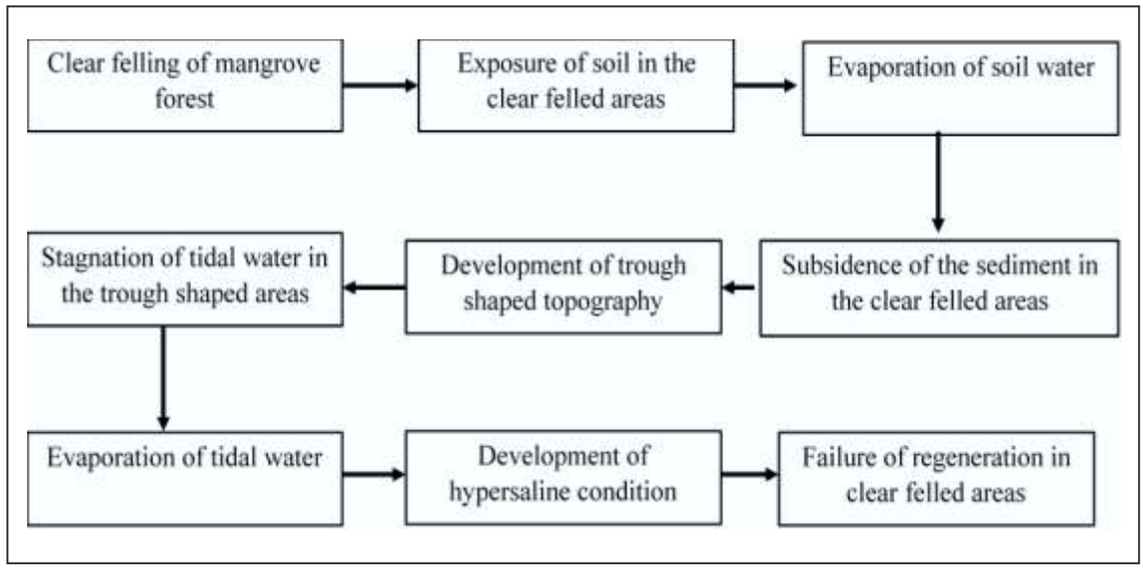

Figure 4.1: Chain reacting triggered by the clear-felling system of management practice leads to large-scale degradation of mangroves



Figure 4.2: Degraded clear-felled mangrove area with cut stumps and stagnant tidal water

4.5 Hydro-ecological approach to restore degraded areas

4.5.1 Demonstration of tidal water canal method of mangrove restoration

Having understood that the development of the hypersaline condition in the clear-felled areas due to unscientific past management practices as the primary cause of degradation, it was hypothesized that these trough-shaped degraded areas could be easily restored if facilities were provided for regular flushing by tidal water. To test this hypothesis, a 10-ha degraded area was selected jointly with the Tamil Nadu Forest Department and the local community. The topographic map of this area was prepared with the help of a professional survey group, which showed that the trough-shaped area was about

45 cm below the benchmark. On the basis of the topography, a canal system was designed to ensure the free flow of tidal water in and out of the degraded trough-shaped area during the high tide and low tide (Fig. 4.3 a and b). The canal system consisted of the main canal with 3m (upper width) × 1.8m (bottom width × 1m (depth) dimension and feeder canals with 1m × 0.60 m × 1m dimension. The feeder canals were aligned at 45^{0} to the main canal. The main canal, in turn, was connected to a deep natural channel located close to the degraded areas. The canal system was established before the onset of the northeast monsoon season, expecting that during the monsoon low saline water will flood the degraded areas, which would help in reducing the salinity level rapidly.



Figure: 4.3 (a)



Figure: 4.3 (b)

Figure 4.3 a and b: Canal system for free tidal flushing in degraded mangrove areas

In the demonstration site, 4800 propagules of *Rhizophora* spp and 28000 of *Avicennia marina* were planted, the former along the banks of the canal and the later in the plain portion, as per the distribution of these species in healthy mangroves. The survival of *Rhizophora* and *Avicennia* plantations was 66% and 72% respectively in the first year, but from the second year onwards a large number of propagules of these species were brought into the demonstration site by tide currents and started establishing themselves. Before setting the tidal water canal system, the soil of the demonstration site was unsaturated with water, and hence, groundwater was collected from 6 points, and its salinity varied from 82 to 94% (mean 88%). After tidal flushing was established the soil was saturated with water and hence, pore water was collected in five randomly selected points and its salinity was monitored for a period of five months, starting from the peak summer month of May to September. The average salinity of the pore water varied from 17.8 to 53%. The observation of natural regeneration, good growth and reduced level of salinity in biologically available water clearly showed that the canal system is the effective method of restoring the degraded areas of Pichavaram mangroves (Selvam et al., 2003)

4.6 Joint Mangrove Management

The results of the scientific method of restoration were communicated and shared with all the stakeholders, including the Forest Department and the local community, through formal and informal meetings and by organizing field visits to the demonstration site. During these interactions, the following three important questions were raised by the stakeholders: (i) How do we upscale mangrove restoration efforts? (ii) How will the canal system for tidal flushing, which is artificial and prone to siltation, be maintained? (iii) How will social pressure, if any, on restored and other healthy mangroves be handled?

4.7 Joint Mangrove Management Process

In response to the above concerns, a community-centered Joint Mangrove Management (JMM) approach was worked out along the lines of the Joint Forest Management principles and implemented first in the Pichavaram mangroves. The primary aim of the approach was to engage and empower stakeholders, particularly the local community, socially, technically and institutionally to restore and sustain mangrove wetlands. To achieve this, the following process which consists of several steps was employed.

4.7.1 Situation analysis

The purpose of situation analysis was to understand (i) land use and land cover within and near mangroves, (ii) the degree and causes of mangrove degradation, (iii) the assessment of forestry and fishery resources associated with mangroves, (iv) degree of dependency of the local community on mangroves, (v) the traditional and changing systems of resource utilization and their perception about the past and present status of the resources, (vi) current management practices and (vii) level of participation of the community and other stakeholders. A combination of scientific and participatory tools was used to analyze the situation.

4.7.2 Selection of participating hamlets

Hamlets rather than revenue villages were selected as the social unit to implement mangrove restoration and conservation activities because in hamlets (i) the community is mostly homogenous, (ii) the traditional controlling system is dominant rather than the political system, (iii) there is trust among different groups of the community and (iv) decision-making and conflict resolution are comparatively easier. For selecting the hamlets, socio-economic backwardness, the intensity of utilization of mangrove resources and willingness to take active participation in JMM were used as the criteria.

4.7.3 Participatory rural appraisal

In the project hamlets, a set of participatory methods such as social mapping, historical timeline, seasonality calendar, organizing transect walk in the mangrove wetland, resource mapping, livelihood analysis, matrix rankings, etc. was used. These methods ensured the active participation of both women and men in the appraisal, and to express their perceptions and perspectives relating to the complex inter-relationships between the mangrove environment and livelihood of local people, governance and dynamics in the resource availability and management of mangroves. It also helped in the identification and prioritization of major concerns

of the mangrove-dependent communities that need to be resolved to improve the socio-economic condition of the communities, and conservation and sustainable management of mangroves. The participatory rural appraisal (PRA) also provided ample opportunities to establish a rapport with the men and women of the hamlets, which was an unintended result but provided a strong base to mobilize the people to form a community-based organization (Fig. 4.4).



Figure 4.4: Participatory Rural Appraisal in a mangrove user village

4.7.4 Setting up a community-based institution

A gender-balanced, community-based organization called Village Development and Mangrove Conservation Council (VDMC) was set up in each of the identified hamlets. It provided a platform for all the stakeholders to jointly discuss the major concerns identified through PRA and take a collective decision to address them. The structure of this village-level organization included a General Body in which one adult male and female from each willing family were enrolled as members. It functioned as the decision-making body. The second tier of this institution was an Executive Committee in which, apart from the local community other stakeholders such as the Forest, Fisheries, Rural Development Department and M. S. Swaminathan Research Foundation (MSSRF) 2002 also participated as members. It was made compulsory to give 33–50% representation in the Committee to women. The Executive Committee functioned as the planning and implementation body. The kinship ties, shared lineage and socio-economic, homogenous nature of the hamlet community formed a good basis for this institution to embark on collective actions. The VDMC helped engage the people as active participants. Community engagement in the intervention planning and implementation of the activities is essential to ensure effective and equitable socio-economic development and long-term conservation and management of mangroves. The VDMCs were created primarily to prioritize issues to be solved, arrive at a consensus as the basis for action, and ensure that all sections of the community are participating in the planning and implementation. The VDMC also provided an opportunity for women, and other marginalized and powerless sections of the community to become part of the decision-making structure and process (Fig. 4.5).



Figure 4.5: Meeting of the leaders and members of the Village Development and Mangrove Council

4.7.5 Mangrove management unit

For each participating hamlet, a mangrove management unit was identified jointly by the community and the Forest Department. This management unit is an area of the mangrove wetland which was traditionally utilized by the people of that hamlet for livelihood and subsistence before the mangroves were declared as Reserved Forests. The identified unit consisted of both degraded and healthy mangroves.

4.7.6 Preparation of a microplan

For each hamlet that participated in the JMM, micro-plans were prepared jointly by the community and the stakeholders. In this process, responsibilities were delegated to the communities, which created an opportunity for them to take informed decisions about local issues related to their livelihoods and management of the mangrove resources. The plan contained details of the actions to be taken to solve the issues relating to mangrove restoration and conservation, and interventions needed to address the socio-economic concerns of the community identified and prioritized through PRA. In some villages, mangrove restoration was not the foremost priority of the communities. There were other more pressing economic and social concerns that the communities wanted to address first, and as a principle of participatory development, it was accepted, and plans were prepared according to the priority list made by the community. In some villages, socio-economic concerns and issues relating to mangrove restoration and conservation were addressed simultaneously. The plan helped in mobilizing funds from internal and external resources, and manpower from the hamlets. The micro-plan also provided details of the timeline and the roles and responsibilities of each stakeholder in its implementation.

4.7.7 Implementation of the microplan

The Executive Committee implemented activities according to the micro-plan with the support of stakeholders; MSSRF (2002) facilitated the process. Funds obtained according to the micro-plan were directly deposited in the accounts of the community-based institution, which took responsibility for the proper utilization of the funds. The active participation of local people in decision-making, planning and taking responsibility for the activities always improved the effective implementation of the plan,

enhanced the results and reduced the time and investment required in the long term.

4.8 Piloting of the hydro-ecological restoration technique

When the JMM approach was being worked out, the causes for degradation of other mangroves in Tamil Nadu, Krishna and Godavari regions in Andhra Pradesh and Bhitarkanika and Devi mangroves in Odisha were also analysed by participatory research. The records of the State Forest Departments showed that most of the mangrove forests of the Godavari delta such as Coringa and Upputeru, and the Krishna delta such as Yellichettidibba, Nachugunda and Sorlagondi were declared as fuel Reserved Forest during 1886–87 (Anon., 1896). As mentioned earlier, large-scale clear-felling of mangrove trees in these mangroves was started immediately after their notification as Reserve Forest. In the clear-felled areas of Muthupet, the Godavari and Krishna mangroves soil subsided as in the case of the Pichavaram mangroves causing the topography to become trough-shaped, resulting in the development of hypersaline condition and failure of regeneration of mangrove species.

Since the primary cause of degradation of most of the mangroves of the east coast of India was similar to that of Pichavaram mangroves, where the hydro-ecological method of restoration was developed and demonstrated, it was decided to extend this mangrove restoration method and JMM approach to all other mangroves on the east coast on a pilot scale. As shown in Table 4.5, the mangrove restoration method was pilot tested in 1400 ha with the participation of the local communities and State Forest Departments of Tamil Nadu, Andhra Pradesh and Odisha. Apart from restoration, healthy mangroves of about 12,000 ha were also brought under participatory management (Fig. 4.6) (MSSRF, 2002).

State	Name of the mangroves	Area restored (ha)	Healthy mangrove under JMM (ha)	No villages participated	Total families participated in JMM
Tamil Nadu	Pichavaram	250	200	4	697
	Muthupet	375	800	4	506
Andhra Pradesh	Krishna	355	2600	4	930
	Godavari	165	6840	6	884
Odisha	Devi	257	1560	10	1435
		1402	12000	33	4452

Table 4.5: Area of degraded mangrove restored and healthy mangroves brought under conservation during pilot testing of new Joint Man-grove Management approach



Figure 4.6: A healthy restored mangroves with a canal for tidal flushing

4.9 Evaluation and replication of Joint Mangrove Management and hydro-ecological approach of mangrove restoration

The Ministry of Environment and Forests (now Ministry of Environment, Forest and Climate Change), GoI formed a four-member Sub-Committee (Office Memorandum vide letter no. J-22012/19/92-CSC(M) dated 20.03.2000) to take stock of mangrove restoration, afforestation, conservation and different aspects of mangrove management. The Sub-Committee visited mangrove sites in Tamil Nadu, Andhra Pradesh and Odisha, where a science-based and community-centred mangrove restoration and conservation approach was being pilot-tested.

The Sub-Committee recommended the inclusion of this approach in the guidelines for National Mangrove Conservation and Management and replication of the same in restoring saline blanks that exist in the mangroves of Tamil Nadu and Andhra Pradesh (MoEFCC, 2006). Later, the same approach was applied to the restoration of the mangrove wetlands of Odisha and Maharashtra. According to the Forest Survey of India (2017), mangrove forest cover in India has been increasing since 1993, and the hydro-ecological and Joint Mangrove Management approach developed and demonstrated on a pilot scale in all the major mangroves along the east coast of India played a catalytic role for such positive changes in the mangrove cover of the country.

4.10 Conclusion

The results of this study clearly show that in the participatory research and management of natural resources, including mangroves, local and traditional knowledge, observations and perspectives of local people form the basis for designing sound, applied research and development and demonstration of practically feasible and sustainable management practices. A major factor for the success of this JMM initiative was that in the tripartite arrangement among the facilitating agency (MSSRF), government agency (State Forest Department) and local people (mangrove user communities), each partner recognized and respected, and contributed and complemented to the strength of the others, which needs to be extended to restore the remaining degraded mangroves and sustain healthy mangrove areas. However, a recent review indicates that the village-level institutions established (variously named as Village Development and Mangrove Council, Eco-Development Committee and Village Forest Council) for JMM are being increasingly marginalized in decision-making and planning. The leaders and members of these village-level institutions have a feeling that they are being used by the NGOs and Forest Departments to implement projects. This study also shows that there was no major change in the conviction and attitude of the communities toward JMM, but the Forest Departments in almost all the states are distancing themselves from genuine participatory management. One of the reasons could be the quality of human resources available at the disposal of the State Forest departments. When the present JMM was initiated in the late 1990s, JFM was at its peak, and there was huge political and administrative support for it. Both managerial and field staff of the Forest Departments were constantly exposed to the concept and thoroughly trained on the process to be followed to achieve true participation of the community. The present younger generation of both managerial and field-level staff has limited exposure to the participatory approach and practical training in JFM. Hence, they are not much convinced that people's participation is necessary for the long-term sustainability of the mangroves. Moreover, declaring all the mangroves as Wildlife Sanctuaries has also complicated the participatory process further. To improve the situation, the State Forest departments have to enhance the understanding and capacity of the younger generation of officials to participatory management, which can be achieved through more formal and informal training. There is a need to revisit the curriculum of the Indian Forest Service and Range Officers and other field staff training, which reflects the colonial legacy aimed at exploiting the forest rather than the present need for participatory sustainable management.

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Restoration of Degraded Forest Landscape



CHAPTER FIVE

N. Bala
Forest Research Institute, Dehradun, Uttarakhand - 248 006



Soil and water conservation measures for restoration of degraded hills

5.1 Introduction

In India, forests and people are inextricably linked since; millions of people live adjacent to or within protected areas and harvest forest products (Kothari et al., 1989). India occupies only 2.4% of the world's geographical area, yet supports about 18% of the world's human population; it has only 0.5% of the world's grazing land but supports 18% of the world's cattle population. Thus, there is tremendous pressure on our land-based natural resources. India is endowed with a variety of soils, climate, biodiversity and ecological regions. About 50.8 mha land area (15.8% of the country's geographical area) is arid, 123.4 mha (37.6%) is semi-arid and 54.1 mha (16.5%) area falls in the dry sub-humid region. All put together, about 228 mha area, i.e., 69% of the geographic area of the country is dry land - arid, semiarid and dry sub-humid (Arya et al. 2009). The Forest Survey of India, GoI conducts periodic assessments of the state of its forests through remote sensing (ISFR, 2021) and these assessments are the benchmarks for measuring changes in forest cover. As per the latest **State of Forests Report India** has been able to preserve and expand its forest wealth despite tremendous anthropogenic pressure. According to ISFR (2021), India's forest cover increased to 7,13,789 sq km, or 21.71 % of the country's geographical area, as against 7,12,249 sq km two years ago. This was the net gain made over two years while forests were cut down in some areas, they emerged in others. The total forest and tree cover of the country is 8,09,537 sq km, which is 24.62 percent of the geographical area of the country. The current assessment shows an increase of 1,540 sq km (0.22%) of forest cover, 721 sq km (0.76%) of tree cover and 2,261 sq km (0.28%) of forest and tree cover put together, at national level as compared to the previous assessment i.e., ISFR 2019 (ISFR, 2021). The sector has highly ambitious targets to achieve, yet there are significant implementation challenges. India's forests are continuously disappearing. Between 2017 and 2020, 72,673.03 hectares (726 square km) of forest land have been recommended for diversion (Sood, 2022).

With close to 30 per cent of its geographical area already affected, land degradation is definitely among India's most pressing environmental problems. To make matters worse, almost all

Indian states have recorded an increase in degraded land in the past 15 years, with the most rapid increase being noted in the biodiversity-rich northeastern states. There are about eight major processes of land degradation active in the country. Water erosion is the most pronounced process, followed by vegetal degradation and aeolian processes. Area-wise Rajasthan, Jammu and Kashmir, Gujarat and Maharashtra have high proportions of land undergoing degradation. A total of 97.85 million ha area of the country is undergoing land degradation i.e., 29.77% of the Total Geographic Area (TGA) of the country (SAC, 2021). The area undergoing Desertification and Land Degradation (DLD) during timeframe 2011-13 and 2003-05 is observed as 96.40 million ha (29.32% of the TGA) and 94.53 million ha (28.76% of the TGA), respectively. A cumulative increase of 1.45 million ha area (0.44% of the TGA) undergoing DLD is observed between timeframe 2011-13 to 2018- 19 whereas, between timeframe 2003-05 to 2011-13, a cumulative increase of 1.87 million ha area (0.57% of the TGA) was observed.

Degradation refers to reduction in productivity and/or diversity of a forest due to unsustainable harvesting, fire (except for fire dependent eco-systems), pests, and diseases, removal of nutrients and pollution or climate change (TERI, 1998). Subsequent to enactment of Forest Conservation Act, 1980, rate of diversion of forestland has declined drastically to around 0.021 million ha per annum (ICFRE, 2000). Loss of natural regeneration, low growing stock and low productivity are important parameters indicating forest degradation.

Loss of natural regeneration is loss of future potential biomass. Over-grazing and repeated fires eventually affect relatively hardy species too and their ability to regenerate. The soil is also rendered less fertile because of destruction of organic matter. Forest fires also result in loss of natural regeneration. An FSI sample survey conducted in 1995 found that annually fires affect some 53 to 54 percent of forest areas. Majority of fires are deliberate to facilitate collection from ground of commercially important non-timber forest produce as 'Mahua' (*Madhuca indica*) and 'Sal' (*Shorea robusta*) seeds. It also results in new flush of grass or *Diospyros melanoxylon* (tendu) used for rolling country made cigarettes (TERI, 1998). As a consequence, natural regeneration is either absent/inadequate in 53% of the country's forest.

Desertification/ Land Degradation is an issue of global concern and threatens productivity of land, water, biodiversity, ecology, economy, and people. There is an urgent need to stop and reverse the process of land degradation, and efforts at national and international levels are emerging to combat desertification and land degradation. Sustainable management of soil, water and human society are required for protecting the land from further degradation.

Science and technology organizations can play an important role in restoration of land degradation through documentation of best practices/success stories for upscaling, capacity building of the stakeholders on restoration of degraded lands, development of site-specific models for restoration, selection of site matching species and nursery techniques for quality planting stocks and planting techniques as well in providing the carbon benefits of the restoration of the degraded land to the local communities for enhancing their livelihoods.

5.2 Potential of increasing green cover in degraded lands

The gap between deforestation and afforestation can be narrowed down (Toky, 1992) and even exceeded through socio-biological rehabilitation by growing multipurpose trees and adopting new land use systems. Degraded lands are present in various forms i.e., salt affected lands, waterlogged areas, shifting dunes in arid and semi- arid regions, degraded hilly areas etc. These wastelands and other degraded lands provide ample opportunity to develop green cover and plantations as renewable source of fuel wood. Suitable trees and grasses may be grown at degraded sites using optimum management practices to sequester higher amount of C in these degraded soils (Vaidya et al., 2017). Reclamation of degraded lands has huge potential for carbon(C) sequestration to counteract the climate change (Purakayastha et al., 2016).

It is important to remember that forest restoration is more than just planting trees. It's about reinstating the balance of the ecological, social and economic benefits of forests and trees within a broader pattern of land use. In some cases, this is best achieved by assisting the natural regeneration of local plant species, while in others, the planting of trees and other vegetation helps speed up the process of restoring the health and productivity of degraded landscapes (https://www.un.org/en/un-chronicle/forest-restoration-path-recovery-and-well-being-0). The need for rehabilitation is not to be justified by cost-benefit or scientific and technological proof, but rests on a value judgment to sustain natural capital for present and future generations (Mentis, 2020).

Land degradation is increasingly becoming a major concern in India which is reflected in the commitment to achieve land degradation neutral status by 2030 as a signatory to the UNCCD. Forest Research Institute, Dehradun in tandem with its sister institutes under Indian Council of Forestry Research and Education (ICFRE) is addressing this issue by developing suitable models of restoration for various degraded lands e.g. Coal mine overburden dumps, limestone mines, salt affected soils, degraded hills, waterlogged areas, desert dunes etc. These research findings are then taken to different end users through 'Direct to consumer' scheme. This also includes hands on training on the package of practices developed. Potential of restoration of different degraded lands are narrated in the following section in the form of package of practices. These packages of practices are taken from the research works carried out at Arid Forest Research Institute, Jodhpur (Bahuguna, 2012).

5.3 Restoration of degraded hills

5.3.1 Description

Disturbances to the natural habitats through overgrazing, vegetation removal and mining is a common feature in most of the hilly dry areas throughout the world leading to the biological invasion and land degradation i.e., desertification. The Aravallis in north-western part of India is an ancient mountain and one of the oldest geological formations in the world and the home of many tribes. Mining activities, operation of stone crushers and pulverisers and removal of existing vegetation are disastrous causing environmental degradation in the region. Because of over-exploitation and over-grazing one can see barren hills devoid of vegetation throughout the Aravalli ranges. When put under protection from human or livestock interferences these disturbed habitat may take longer time to recover naturally. But the process of rehabilitation may be accelerated by afforestation and soil and water conservation. Such conservation measures including rainwater harvesting may provide a basis for environmental recovery by facilitating plant growth and vegetation cover because of improvement in infiltration rate, soil water and the availability of soil nutrients. The most effective method to rehabilitate degraded hills are through integration of afforestation adopting rainwater harvesting and involving local people in the programme.

Hills of varying height with pediments near Gauapada village in Banswara, Rajasthan (Fig. 5.1) were selected and taken up for evaluating efficacy of different rain water harvesting structures and afforestation technique in restoration of the degraded hills. The land is dry-sub humid with average annual rainfall 1050 mm from 1993 to 2010 with 53 numbers rain days. Seventy- five plots were laid out in June, 2005 covering about 17 ha area in <10%, 10-20% and >20% slope categories. Five rainwater harvesting (RWH) structures including a control were contour trenches (CT), box trenches (BT), V-ditches (VD) and Gradonie ditches (GD). The RWH structures were of 30 running meters length in each plot except in the control. The excavated soils of the RWH structures were heaped towards the down slope. Thirty- five seedlings per plots (@ 500 plants ha^{-1}) of *Zizyphus mauritiana, Acacia catechu, Azadirachta indica, Emblica officinalis, Dendrocalamus strictus, Gmelina arborea, Holoptelia integrifolia* and *Syzigium cumini* were planted under mixed plantation in August, 2005. Concrete tanks of 1000 litres capacity were constructed to collect one twentieth of run-off water to measure water and nutrient losses. Soil water, nutrients, soil organic carbon, plant growth, diversity of regenerated tree/shrubs and herbaceous vegetation and biomass of trees/ shrubs and herbage were recorded throughout



Source: *G. Singh ICFRE, AFRI, Jodhpur*

Figure 5.1: View of the site before intervention, Bamboo and Aonla plants, different rain water harvesting structures and site after intervention (anti clockwise from top left).

the experimental period.

Relatively greater soil water availability in <10% slope resulted in greater survival and growth of the planted seedlings in lower slopes than in the higher slopes. Despite of low SWC better performance of *H. integrifolia* in 10-20% slope showed its preference to soil condition i.e., light soil. *A. catechu* performed best in <10% as well as >20% slope indicating its preference of clayey soil. Relatively better performance of *Acacia catechu* and *Z. mauritiana* in BT plots; *E. officinalis* and *H. integrifolia* in CT plots; and *A. indica* in VD plots indicated the suitability of these rainwater harvesting structures for the respective species. V-ditch and Box trench facilitated water distribution in upper soil layers for vegetation growth, whereas, contour trench facilitated water storage in deep soil profile that was utilized for the growth of tree seedlings.

5.3.2 Expected benefits associated with the package of practice

Adoption of improved water conservation and harvesting technologies contributes to increase in groundwater recharge, soil nutrients and biomass production and supports a higher number of plants, whereas afforestation under protection increases diversity and productivity and help restore these degraded hills along with the benefits of carbon sequestration. Gradonie and V-ditches enhance productivity of the grass/herbaceous layer productivity and the best was V-ditch. Rainwater harvesting through different structures extended water availability in down slope wells up to February (instead of December) for domestic use as well as for livestock. Grass production increased from 15000 pulia in 2005 to 36000 pullia (1 kg each) in 2010, in collective harvesting (Fig. 5.2). However, it was observed in January each year that about10 persons were collecting fodder grass from the area each day i.e., 6750 kg of grass. After grass cutting in November about 15 persons with an average head load of 10-20 kg used to collect fuel wood of *Lantana camra* and *Prosopis juliflora* up to June each year. Thus, this restoration effort not only restored degraded hills by increased biological diversity, soil water and nutrient status and soil carbon storage but also

enhanced in the economy of the local people, who started purchasing milching animals due to increased fodder supply at place and sending their children to school for education, who were otherwise engaged for collecting fodder and fuel wood from a longer distance earlier. Increased income through harvesting of fodder grasses (also from selling of grass), fuel wood and increased population of milk producing animals are some of the benefits related to development in livelihood status and human resources.



Figure 5.2: Head loads of grass (left) and fuel wood (right) from the restored area.

Environmental	Economic	Social
Increase in production per unit area at the site as well as the adjoining agriculture area	Increased landscape value and economic status	Diversion of children to education. Improvement in social status. Reduction in time of fodder and fuel wood collection. Increase in social status. Reduction in time in collecting/utilizing water./Increased agriculture production Reduced time in fuel wood collection by the villager. Increase in social status.
Improvement in soil nutrient status and productivity	Increased land value	
Increase in diversity of flora and fauna	Increased fodder and fuel wood supply at the nearest place and increase in population of milching animal	
Reduction in soil and water loss at site and increase in water availability	Increased income due to increased land productivity. Reduced silting in water storage dam/rivers	
Increased soil carbon stock by 26.97 tones ha^{-1} by 2010	Increased land productivity and its value	
Increased vegetation cover	Reduction in soil loss and increased productivity	

Table 5.1: Expected benefits associated with this practice

5.3.3 Lessons learned

- Rainwater harvesting improved soil water and nutrients status, facilitated rock disintegration to form soil, and enhance vegetation diversity from 39 to 92 number of species in a 5 year period.
- Contour trench and Box trench were best for enhancing soil water plots.
- *Azadirachta indica* performed best in V-ditch areas, *E. officinalis*, *H. integrifolia* and *Z. mauritiana* performed better in contour trench and *A. catechu* in Box trench areas.

- This practice has enhanced the carbon stock by 26.97 tones ha^{-1} in 2010 compared to 2005. Rainwater harvesting increased water availability at site up to February (as compared to December, earlier) for the livestock.
- Participation of local people was in the form of labour during implementation of this practice, whereas, the area was maintained and utilized by village committee to get benefits of fodder and fuel wood.
- This practice can be replicated at local level, sub national level, sub regional and international level with some adaptation depending upon the requirement for fodder or fuel wood and the topographical conditions of the area.
- Forest department of Rajasthan has adopted this in many places, but it will be more appropriate to adopt it according to the efficiency of the structure for herbage yield/ plant biomass production.

5.3.4 Steps to be taken/operational procedure

- Protection of the area from wildlife, livestock and other anthropogenic disturbances by means of erecting fencing (ditch fencing, stone fencing, barbed wire fencing etc.) or by social fencing.
- Arrangement of saplings of suitable species or raising nursery
- Establishment of soil and water conservation structures as per slope variations with excavated soils of the RWH structures heaped towards the down slope position as per Fig. 5.2.
- As a thumb rule, 1000 running meter contour trench of 45 x 45 cm^2 cross section per ha may be constructed (will depend on amount of rainfall in the area).
- Seeding/ direct sowing of seeds of different species like *Acacia Senegal, Acacia catechu, Jatropha curcas* etc. (locally growing species) on the heaps/bunds.
- Digging of pits for planting (45 x 45 x 45 cm^3 size).
- Planting of suitable trees and bamboo species at 4 x 5 m spacing (in areas with 700-800 mm rainfall).
- Life saving watering in the plantation establishment phase.

5.4 Restoration of waterlogged lands

5.4.1 Description

Indira Gandhi Nahar Pariyojana (IGNP) is one of the most gigantic projects in the world aiming to check desertification and to transform desert wastelands of western Rajasthan into agriculturally productive area (Fig. 5.3). In the canal command area, water logging and consequently salinity problems are increasing at an alarming rate. Kapoor and Denecke (2001) estimated 55,000 ha water logged area out of the total 18,60,000 ha command area in IGNP. Water logging has been a major problem in the irrigated belts. Canal command areas are increasingly being rendered unproductive and barren through water logging and consequent secondary salinization. Engineering solutions such as ground water pumping and surface drainage are too expensive. The best way is effective utilization of plants (in particular tree plantation), which remove the excess water through transpiration. Potential of using trees to control water logging and salinity is now a well-established fact. However, it is important to find out suitable tree species for a particular set of surroundings.

A number of species have been tried for the purpose of bio-drainage and their suitability for salt tolerance under water logged conditions. Eucalyptus was found to be the most useful for the purpose along with few other species (Hussain and Gul, 1991; Moezel et al., 1991). Karajeh et al., (1994) recommended cultivation of *Eucalyptus camaldulensis* tree as a management option for lowering water table. Thakur and Chhabra (1999) have recommended plantation of Eucalyptus and Bamboo to prevent water logging and salinity caused due to seepage in canal command area. Improvement in soil properties was observed in such plantations (Dass and Ahuja, 1998) along with other environmental benefits. However, information pertaining to canal

command area particularly in arid zone of northwestern India is very few, compared to the gravity of the problem.

An attempt was made to remove excess water from the land through bio-drainage and to increase vegetation cover and productivity of a waterlogged area in Indian desert. Seeds of four tree species viz. *Eucalyptus camaldulensis* Dehnh., *E. fastigata* Deane & Maid., *E. rudis* Endl. and *Corymbia tessellaris* (F. Muell.) K.D. Hill & L.A.S. Johnson were procured from CSIRO, Australia. Raised bunds (60 cm high, 60 cm wide and 2 m apart) were prepared in waterlogged (inundated water of 15-25 cm) area to provide comfortable root zone for young seedlings. Seedlings were raised in the nursery and planted on the raised bunds at a spacing of 2 m in blocks after attaining average height of 30 cm. Observations on growth and physiological parameters recorded periodically. Transpiration and photosynthesis rates were recorded using ADC make LCi portable photosynthesis system. Biomass estimation was conducted four and half year after transplantation during February 2008, Representative plants having dimensions equivalent to mean height and girth were felled in triplicate. Measurements on crown spread were recorded. Foliage, branches and stems were separated and their fresh weight recorded. Dry weight of each component was recorded after oven drying samples at 75^{0}C. Roots of each plant were excavated carefully to observe the pattern of root growth and depth of rooting under the influence of water logging and their fresh and dry weights were recorded. Ground water was monitored through observation pits in each species. Soil samples were collected initially and afterwards February 2008, and were analysed as per standard methods of Jackson (1973).

Area protection, soil working and plantation of *Eucalyptus camaldulensis*, *E. fastigata, E. rudis* and *Corymbia tessellaris* on raised bunds, improved vegetation cover with simultaneous decrease in water table. Performance of *E. rudis* was best with respect to growth, biomass, transpiration rate and overall bio-drainage potential. *E. rudis* maintained uniform transpiration and photosynthesis rate throughout the year. Ground water level receded by 145 cm in *E. rudis* plot compared to 90 cm, 70 cm and 60 cm in C. *tessellaris, E. camaldulensis* and *E. fastigata,* respectively within a period of four and half year. Soil organic carbon, electrical conductivity, NH4 and NO_3 – N were high in *E. rudis* and low in *E. fastigata.* The results suggests that *E. rudis* has high potential to be used as an efficient bio-drainage species for restoration of canal command waterlogged area. Apart from the planted species, *Prosopis juliflora, Tamarix dioca* and *Saccharum munja* also have come up in the area with recession of ground water table as natural succession and contributed significantly for further lowering of ground water table and increasing productivity. Soil working in the experimental area resulted in soil aeration, good contact of seeds from nearby trees with soil and regeneration of *E. camaldulensis.*



Plantation area before intervention



E. rudis on raised bund



Plantation area 5 years after intervention

Figure 5.3: Water logged area in IGNP command area before and after restoration work

Agriculture land rendered out of production because of waterlogging could be restored by adopting this practice.

5.4.2 Expected benefits associated with the package of practice

The growth behavior, biomass accumulation by the plants and physiological parameters suggests that *E. rudis* has high potential to be used as an efficient bio-drainage species in Indira Gandhi Nahar Pariyojana (IGNP) command area with low salinity level. Apart from the planted species, *Prosopis juliflora, Tamarix dioca* and *Saccharum munja* also have come up in the area with recession of ground water table as natural succession and contributed significantly for further lowering of ground water table and increasing productivity. The result suggests that along with tree species shrubs and bushes can also play a major role in increasing productivity of waterlogged area. Soil working may be a viable option in assisting regeneration of local species growing nearby.

Environmental	Economic	Social
Restoration of waterlogged area	Increased land productivity	Economic return from increased biomass production.
Increase in biomass production per unit area	Increased landscape value	Increase in income from agriculture.
Improvement in soil status	Increased land value	Reduced time in fuel wood collection and diversion of children to education.
Increase in carbon stock both in soil and tree	Increased fuel wood supply	

Table 5.2: Expected benefits associated with this practice

5.4.3 Lessons learned

- Area protection, soil working and plantation of *Eucalyptus camaldulensis, E. fastigata, E. rudis* and *Corymbia tessellaris* on raised bund, improved vegetation cover with simultaneous decrease in water table in a waterlogged area in IGNP.
- *E. rudis* was best with respect to growth, biomass, transpiration rate and overall bio-drainage potential. It maintained uniform transpiration and photosynthesis rate throughout the year.
- Ground water level receded by 145 cm in *E. rudis* plot compared to 90 cm, 70 cm and 60 cm in *C. tessellaris, E. camaldulensis* and *E. fastigata*, respectively within a period of four and half year.
- Soil organic carbon, electrical conductivity, NH_4 and NO_3 – N were high in *E. rudis* and low in *E. fastigata*.
- Apart from the planted species, *Prosopis juliflora, Tamarix dioca* and *Saccharum munja* also have come up in the area with recession of ground water table as natural succession and contributed significantly for further lowering of ground water table and increasing productivity.
- Soil working in the experimental area resulted in soil aeration, good contact of seeds from nearby trees with soil and regeneration of *E. camaldulensis*.

5.4.4 Steps to be taken/operational procedure

- Protection of the area from wildlife, livestock and other anthropogenic disturbances by means of erecting fencing or by social fencing.
- Arrangement of saplings of suitable species or raising nursery.
- Soil working and preparation of raised bunds of size 60 cm width, 60 cm high and 2 m apart (for dense planting).
- Planting of saplings on raised bunds at 2 m spacing.
- If required, watering at the time of plantation for facilitating soil and root contact (usually not required because of water logging condition).

5.5 Dune stabilization

5.5.1 Description

The soils of western Rajasthan are low in nutrients and experiences soil and water erosion of varying intensity. Community is suffering from fodder and fuel wood scarcity in the region, whereas, high human and livestock population are leading to mismanagement of the sandy terrain causing reactivation of sand and land degradation. This moving sand encroach productive agricultural fields, human habitation, canal, road, railway tracks and water bodies. Plantation of only tree species may not solve the problem. Involvement of surface vegetation may be one of the best techniques for effective control of sand drift and reducing reactivation of sand dunes. For this an experiment was laid out in a split plot design with three replications. Different plant species viz. *Acacia tortilis, Prosopis juliflora* and *Calligonum polygonoides* of about 20 cm, 40 cm and 15 cm in height, respectively were planted in September, 1996 at spacing of 5 m x 5 m and in a pit size of 45 cm^3. Species were considered as the main plot with 75 plants per species. 9.0 g of DAP (di-ammonium hydrogen phosphate) was spread in each pit as basal dose and about 20 g of BHC (y-hexachlorobenzene) was used by thoroughly mixing with the soil to protect the seedlings from termite attack at the time of planting. *Cassia angustifolia* (one meter away from the seedlings and at 60 cm interval between the rows i.e., six rows) under shrub and *Cenchrus ciliaris* grass (60 x 20 cm spacing and similar to *C. angustifolia*) were sown in the monsoon season of 1997 to provide surface vegetation. In addition to the *C. angustifolia* and *C. ciliaris* plots, there was a control plot. Thus, there were nineplots (three species x three vegetation type) in each replication, with 25 plants in each plot. *Calligonum polygonoides* was the most suitable species, which provided better micro environment and helped in developing effective surface vegetation to control sand drift. Combination of *C. polygonoides* with *Cassia angustifolia* was the best to control sand drift and to improve biodiversity and ecology of the arid areas. Introduction of under shrubs like *Cassia angustifolia* and grasses (i.e., *Cenchrus ciliaris*) along with the tree species provided beneficial effects in controlling sand reactivation and drift, particularly, at the time when planted seedlings

attain the size of a tree facilitating free air movement under the canopy resulting in reactivation of sand drift. Further, dunes are also deficient in soil organic matter and nutrients, particularly nitrogen. This study suggests that the micro-windbreaks of C. *angustifolia* can be raised in advance or simultaneously with plantation during onset of monsoon to provide effective surface vegetation.

5.5.2 Expected benefits associated with the package of practice

A combination of *Calligonum polygonoides* with *Cassia angustifolia* was the best to control sand drift and increasing socio-economic benefits for the desert dwellers. At the age of 50 months, *A. tortilis* produced 5.2 t ha^{-1} fuel wood as compared to 7.00 t ha^{-1} from *P. juliflora* and 7.15 t ha^{-1} from *Calligonum polygonoides*. *Cenchrus ciliaris* produced green fodder of 1.22 t ha^{-1} $year^{-1}$ with *A. tortilis,* 1.58 t ha^{-1} $year^{-1}$ with *P. juliflora* and 2.23 t ha^{-1} $year^{-1}$ with C. *polygonoides*. *Cassia angustifolia* produced dry leaves of 0.76 t ha^{-1} $year^{-1}$ with *A. tortilis*, 0.96 t ha^{-1} $year^{-1}$ with *P. juliflora* and 1.39 t ha^{-1} $year^{-1}$ with C. *polygonoides* with market cost of Rs 9120, 11520 and 16720, respectively @ Rs 12 kg^{-1}. State Forest Department of Rajasthan and Ministry of Rural Development helped in funding as well as dissemination of this practice. The local people offered the labour required for the implementation of this practice.

Environmental	Economic	Social
Improvement in soil nutrient status and productivity	Increased land value	• Improvement in social status • Reduced time in fuel wood and fodder collection by the villagers and diversion of children towards education.
Increase in carbon stock by 3.72 tones C ha^{-1} with *A. tortilis*, 5.24 tones C ha^{-1} with *P. juliflora* and 5.66 tones C ha^{-1} with *Calligonum polygonoides*	Increase in fuel wood production	
Increase in diversity and land productivity.	Increased income by harvesting grasses and leaves of C. *angustifolia* for medicinal use	
Increased vegetation cover for effective control of sand drift	Fuel wood from adult neighbour and fodder & medicinal leaf of C. *angustifolia*	

Table 5.3: Expected benefits associated with this practice

5.5.3 Lessons learned

- Involvement of under shrubs and grasses as the surface vegetation along with the planted tree species provides beneficial effects in controlling sand drift and sand dune movement. *Cassia angustifolia* utilized as the surface vegetation is a medicinal plant.
- Increased income through harvesting of leaves of *Cassia angustifolia* and fodder from *Cenchrus ciliaris* grass and decrease in time of collections of fuel wood and fodder are some of the benefits related to development of livelihood and human resource.
- Environmental benefits and productivity enhancement from the agriculture land due to control of sand deposition are the additional benefits.
- Introduction of surface vegetation along with tree plantation improved soil nutrient status and increase in diversity and land productivity.
- Application of this practice increased carbon stock by 3.72 t C ha^{-1} with *A. tortilis*, 5.24 t C ha^{-1} with *P. juliflora* and 5.66 t C ha^{-1} with *Calligonum polygonoides*.
- A farmer can get Rs 16720 ha^{-1} $year^{-1}$ by selligng C. *angustifolia* leaves from C. *polygonoides* plot as compared to 9120 ha^{-1} $year^{-1}$ from *A. tortilis* based system.

5.5.4 Steps to be taken/operational procedure

- Protection of the area from wildlife, livestock and other anthropogenic disturbances by means of erecting fencing (stone fencing, barbed wire fencing etc.) or by social fencing.

- Arrangement of saplings of suitable species or raising nursery (preferably *Calligonum polygonoides*).
- Sowing of *Cassia angustifolia* seeds in advance to create micro-windbreak or during plantation time in between shrub/tree rows.
- Add 9.0 g of DAP (Di-ammonium Hydrogen Phosphate) in each pit as basal dose.
- If termite infestation is there then apply Phorate granules or any other termiticide in the pit and mix well with the soil to protect the seedlings from termite attack.
- Planting of saplings at spacing of 5 m x 5 m and in pit size of 45 x 45 x 45 cm^3.
- Sowing of *Cassia angustifolia* seeds one meter away from the seedlings and at 60 cm interval between the tree rows i.e., six rows. Alternatively, sowing of *Cenchrus ciliaris* grass (60x20 cm spacing and similar to *C. angustifolia*) at the onset of monsoon to provide surface vegetation
- Life saving watering in the plantation establishment phase.

5.6 Rehabilitation of degraded land through seed sowing to increase land productivity and combat desertification.

5.6.1 Description

In order to minimize the adverse effects of the environment and to increase the supply of fodder and fuel wood from the marginal/degraded lands, introduction of woody perennials is a common practice in dry areas. Many schemes like desert development, wasteland development and externally aided programmes are on way in order to combat desertification and to mitigate the adverse effect of this calamity. Millions of seedlings raised in nursery are planted under afforestation activities every year to increase green cover, improve fodder and fuel wood availability. The common species under plantations are *Acacia tortilis, A. senegal, A. nilotica, Zizyphus nummularia* and *Azadirachta indica* under rainfed conditions. *Dalbergia sissoo* and *Eucalyptus camaldulensis* are raised under irrigation in Indira Gandhi canal command area. Sowing of seeds of tree species particularly; *A. senegal, A. catechu, Jatropha, Z. mauritiana* etc along the rainwater harvesting structures or field bunds is common in dry areas, where the performances of regenerated seedlings are found equally good as the planted seedlings. This practice may be adopted in rehabilitation of degraded lands including sandy areas giving major emphasis on site preparation and selection of suitable drought hardy species. To prove this, an experiment was carried out at AFRI experimental farm during drought period of 2002 and found encouraging and implementable.

The experiment was laid to study the effect of site preparation and seed sowing of *Azadirachta indica* and *Colophospermum mopane* on germination and seedling establishment of these tree species (Fig. 5.4). The climate of the site is arid with mean annual rainfall of 420 mm and the mean annual pan evaporation is 2025 mm indicating high water deficit in the area. The soil is loamy sand with low soil organic matter and nutrients and is slightly alkaline in reaction. Topography of the land under experimentation is almost flat. The experimental site is located in the city of Jodhpur in western part of the state of Rajasthan. In this, fruits of *A. indica* and *C. mopane* were collected from the experimental area. Site was deep ploughed to remove the existing vegetation and to enhance water conservation. Half kg of dry fruits was weighed and number of fruits counted in triplicate for both the species. Weighed fruits were broadcasted in July, 2001. The broadcast seeds were mixed through further ploughing to ensure seed burial in the soil. Average number of seeds in each plot were 1530 and 955 for *A. indica* and *C. mopane*, respectively. Measurements of germinated seedlings were taken at different time interval. Some plants were also excavated to monitor root growth and its penetrability of the hard layer of calcium carbonate for better survival under harsh environment.

Germination percent for *A. indica* and *C. mopane* was 54% and 94% with respective population of 27500 and 30100 seedlings ha^{-1}. The survival reduced to 1.2% and 9.7%, respectively after one year, but still provided more than 300 plants per ha. Root of *C. mopane* seedlings was more than two fold larger as compared to *A. indica* plants. Shoot and root dry biomass of *C. mopane* were 5-fold higher than the biomass of *A. indica* seedlings. Biomass allocation was high in root in both the species. Best field survival of *C. mopane*

seedlings was due to their deep rooting behavior, which penetrated even hard layer of calcium carbonate to extract water/nutrient from the deeper soil layers during harsh conditions.



Source: *G. Singh (ICFRE, AFRI), Jodhpur*

Figure 5.4: Regeneration of C. *mopane* under the canopy of same tree (left) and performance of 8 years old C. *mopane* plants grown through seed sowing (right).

5.6.2 Expected benefits associated with the package of practice

Broadcasted seed based seedlings/ regenerated seedlings proved better growth and performance than the planted one under harsh environmental conditions. Some of the best performers are *Acacia senegal*, *A. catechu*, *Jatropha curcas*, *Azadirachta indica* and *Colophospermum mopane*, though they vary in performance among themselves. The reduction in cost for raising nursery plantation, transportation etc are the economic benefits. The seed sown seedlings show better root development and penetrating even hard soil layer, which enhance survival even during harsh environmental conditions. This species is also suited to mild saline/alkaline conditions and can be replicated in similar area. Forest department of Gujarat had procured the seeds of C. *mopane* from AFRI and utilized it in rehabilitating the degraded land of the Gujarat state.

Environmental	Economic	Social
Increase in land productivity under improved soil nutrient status	Increased landscape value and economic status	Improvement in social status resulting in diversion towards education
Reduction in soil and water loss and combat desertification	Decrease in soil loss involved due to wind erosion	Improved air quality and human health
Increased soil carbon stock and biomass	Increased fuel wood supply	Reduced time in fuel wood collection by the villagers
Increased vegetation cover	Increased landscape value and enhancement in productivity	Increase in social status

Table 5.4: Expected benefits associated with this practice

5.6.3 Lessons learned

- C. *mopane* is able to establish and flourish in habitats characterized by arid or sodic soils.
- It is a preferred fuel wood and fodder species.
- *Azadirachta indica* is another multipurpose species and is well adapted to the dry areas.
- These species could be grown under direct seeding to rehabilitate the degraded lands of varying categories.

- Success of this practice emphasizes the importance of site preparation and conservation of soil and water resources and seed broad casting as an effective solution to improve the vegetation status as low cost technology and could be beneficial for the poor in the dry areas.
- This experiment demonstrating growth and performance of C. *mopane* is a viable strategy in the direction of rehabilitation of degraded land through seed broad casting.
- Based on the experiences elsewhere and this experiment, some more species are suggested for direct seed sowing:
    a. *Acacia jacquemonttii* and *Clerodendrum phlomides* in bare dune
    b. *Colophospermum mopane* in sandy plain including slight alkaline/saline conditions *Acacia senegal* in gravelly area,
    c. *Acacia catechu, A. leucophloea* and *Acacia ferrugiana* in gravelly/rocky pediments with relatively greater rainfall.

5.6.4 Steps to be taken/operational procedure

- Selection of species based on soil type and rainfall regime as described in previous section.
- Collection of seeds of the selected species.
- Preparation of the site with deep ploughing and removal of unwanted weeds to enhance water conservation.
- Broadcasting /direct sowing of seeds during the onset of monsoon.
- One shallow ploughing to ensure seed burial and better seed –soil contact.

5.7 Summary

Suitable restoration models with package of practices have been developed for various degraded forest lands of India such as degraded hills, waterlogged areas, degraded sandy plains, and desert dunes. In most of these practices protection of the area from biotic interference/ disturbances has been the key to success along with selection of species, soil and water conservation measures and planting method. Participation of local people played a crucial role in these efforts. Over time the restored areas have altered microclimate of the area, improved soil moisture, soil nutrients status, biodiversity and overall productivity. The flow of benefits is realized in the form of fodder, fuel wood, fruit, medicinal plants and a host of other services for the local people. There has been additional carbon sequestration in biomass and soil, habitat creation for wildlife and improvement in air quality. In coal mine areas of Dhanbad such restoration works have also created recreational opportunities for the people around and a green space for socialization and religious activities as well.

Forestry interventions for restoration/reclamation activities are essentially a long term proposition. There is no proper feedback on whether the desired benefits are enjoyed by the concerned society or not. We need to develop better evaluation and monitoring system of projects. This will foster a clearer understanding of the many forms of Forest Landscape Restoration that are possible, and enable us to achieve a more precise balance of objectives for projects, suited to the circumstances of people and place. Such assessment should be made to determine how closely the reclaimed site functions, in comparison to similar undisturbed sites, as an ecosystem and also help taking necessary corrections, and improvement in future for such interventions. Quantification of carbon regulating services (e.g. inflow and outflow of carbon) in restored areas is also important to understand mitigation capacity or carbon stored in ecosystem, as one of the key components of climate change. India has committed under Bonn challenges to restore the degraded land that could sequester more carbon from the atmosphere and also bring extra income opportunities for rural societies. Hitherto, limited attention has been paid to account carbon and nutrient regulating services in restored experimental plots and livelihood support of local communities.

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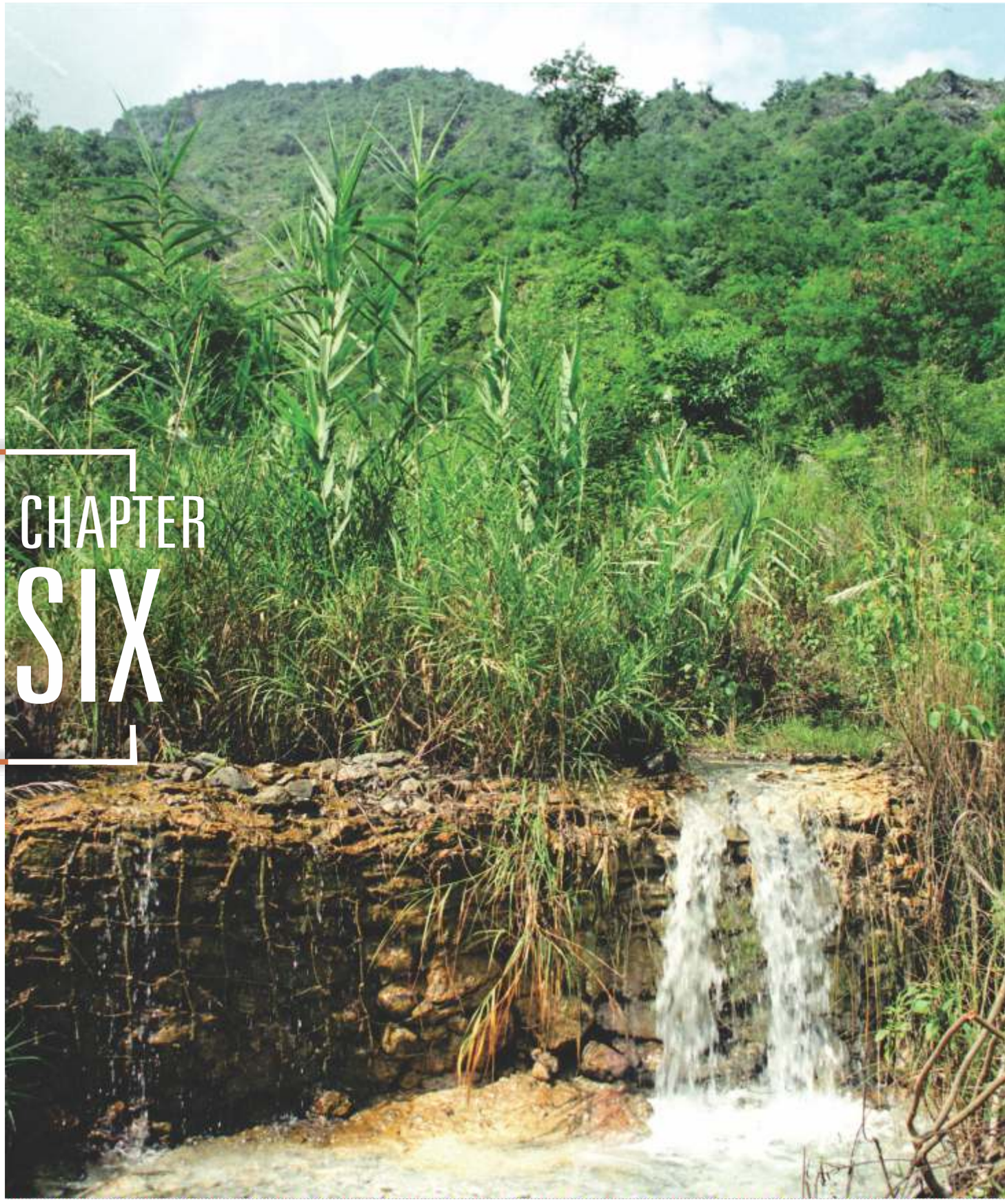
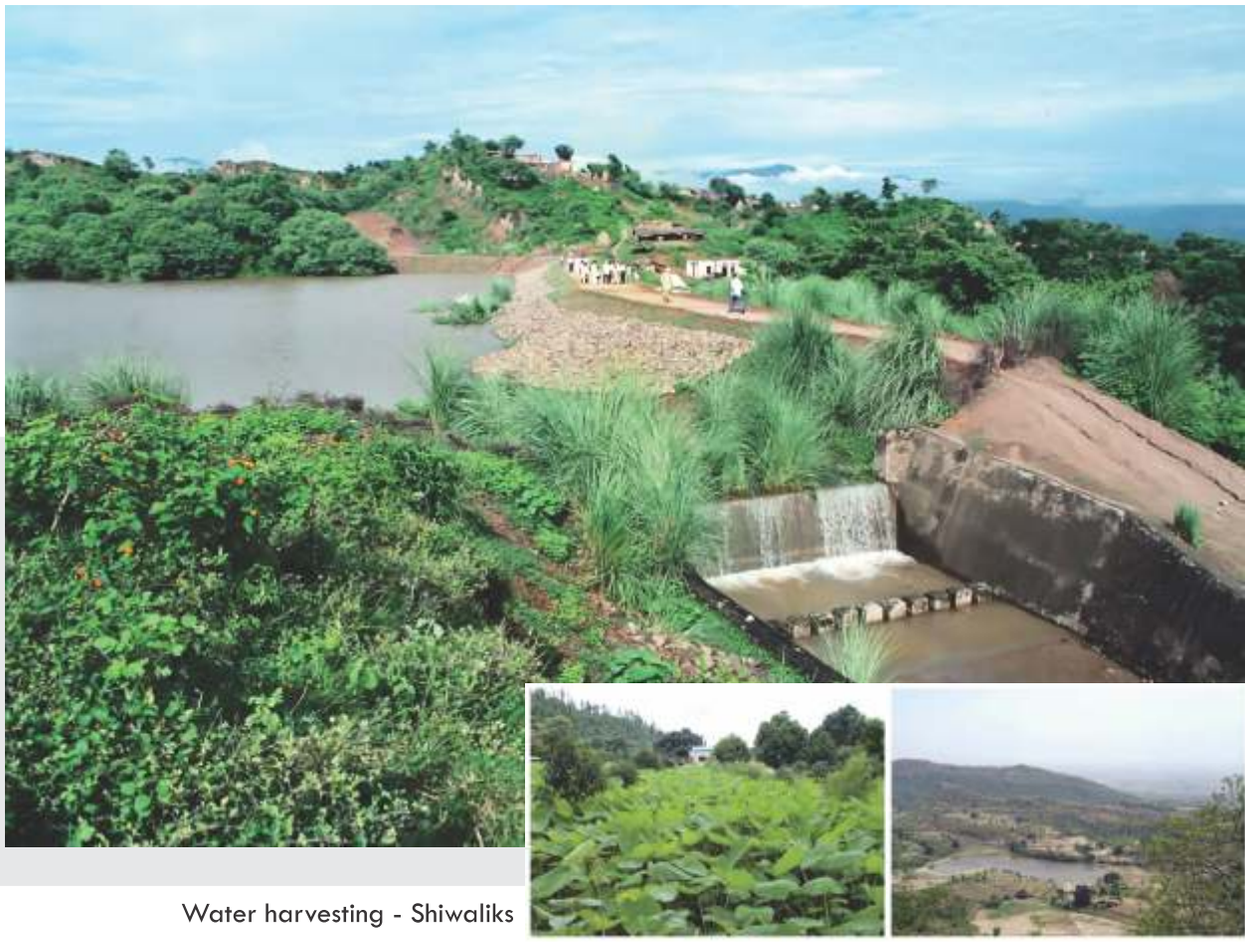
Soil and Water Conservation Measures For Land Restoration and Sustainable Agriculture



CHAPTER
SIX

Prabhat R. Ojasvi
ICAR-Indian Institute of Soil and Water Conservation, Dehradun, Uttarakhand - 248195



Water harvesting - Shiwaliks

6.1 Introduction

6.1.1 The Concept of Land Degradation Neutrality (LDN)

An intergovernmental working group (IWG) established at COP 11 defined LDN as 'a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems' (ICCD, 2016). There are two ways to implement LDN: (a) Prevent, avoid or minimize land degradation through (i) national and local land use planning that fully accounts for the potential and resilience of land resources; (ii) the adoption of sustainable land management practices; and (b) rehabilitate or restore degraded land by reducing the drivers and impacts of current land degradation processes and by the adoption of measures for rehabilitation and recovery (Minelli et al., 2017).

The LDN response uses hierarchy of Avoid > Reduce > Reverse land degradation without compromising the right of land users including small and marginal farmers and the indigenous population and within the domain of national targets guided by the global level of ambition. The indicators identified to assess LDN are (i) land cover (land cover change), (ii) land productivity (net primary productivity, NPP), and (iii) carbon stocks (soil organic carbon, SOC). Neutrality is achieved when the area of losses equals the area of gains, within each land type, and across land types, at a national scale.

6.1.2 The Land Degradation

During 1990–1991, the United Nations Environment Programme (UNEP) for the quantitative assessment of the world status of land degradation adopted the definition as "Desertification/land degradation is land degradation in arid, semi-arid and dry sub-humid areas resulting from adverse human impact. Processes of degradation include water erosion, wind erosion, sedimentation, reduction in the diversity of natural vegetation, and salinization and sodification". Soil erosion due to water and wind, chemical degradation, and physical deformation prominently cause land

degradation. A widespread agent of land degradation is water erosion (Fig 6.1), which occurs persistently and covers a large area and leads to ecosystem degradation even in favourable climatic conditions.



Figure 6.1: Some land degrading processes in favorable climatic conditions due to water erosion

6.1.3 Land Degradation in India

In India, 104.2 Mha out of 141 Mha cultivated area is affected by various degradation processes (NAAS, 2010). The annual gross soil erosion due to water in our country is 5.11 billion t yr^{-1} which occurs at an average rate of 15.6 t ha^{-1} yr^{-1} and causes annual nutrient loss equivalent to 8 Million t yr^{-1} (Sharda and Ojasvi, 2016). The crop production losses due to these degrading driving forces are very significant, which are due to water erosion (13.4 Mt), salinity (5.66 Mt), and alkalinity (11.18 Mt).

6.1.4 Status of Soil Erosion and Soil Loss Budget

The percent area under various rates of erosion is presented in Fig 6.2 which shows that about 49% area of the country is under the land degrading rate of erosion (>10 t ha^{-1} yr^{-1}). The gross erosion of the country is 5.11 Gt yr^{-1} or 15.59 t ha^{-1} yr^{-1}. Out of the total gross erosion, 34.1 % of eroded sediment is deposited in the reservoirs, 22.9% is discharged outside the country (mainly to oceans), and 43.0% is displaced within the river basins. The river basins of northern India contribute about 81% of the total sediment yield from the landmass, while the share of the southern river basins is 19% (Sharda and Ojasvi, 2016).

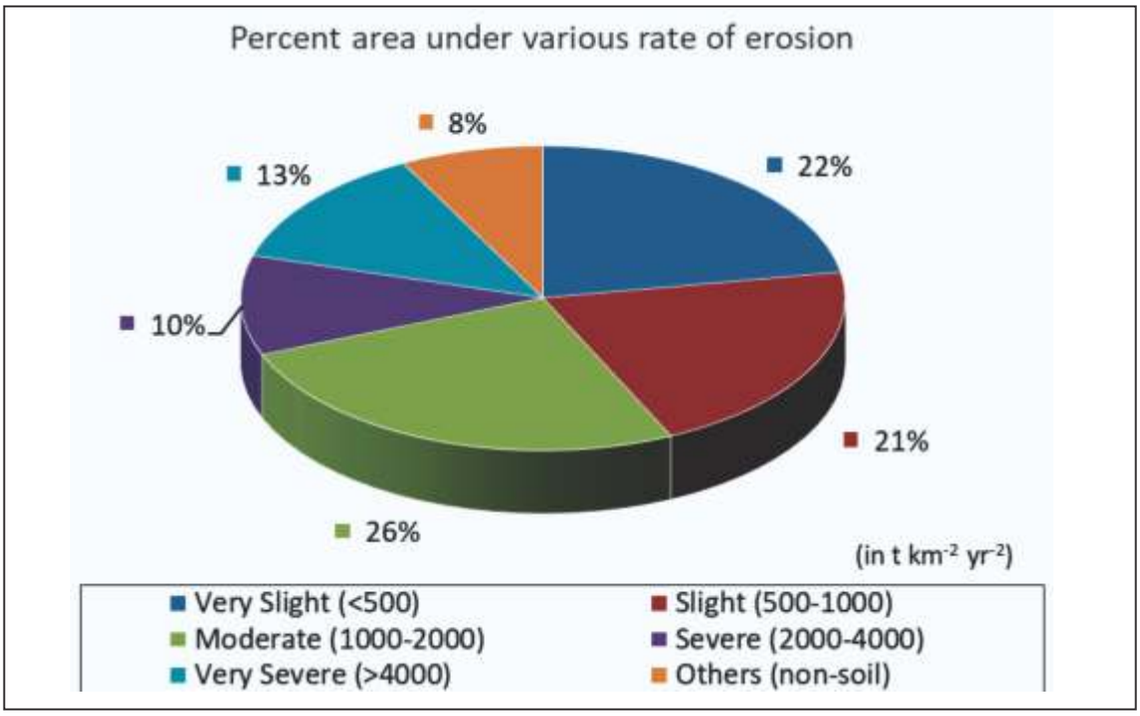


Figure 6.2 : Area under different rates of soil erosion

6.1.5 Offsite Impact of Erosion: Sediment Deposition in Reservoirs

There are about 5000 medium and large reservoirs in India. The average annual percentage capacity loss due to sediment deposition in these reservoirs is 1.04% of gross capacity, which amounts to 1.7 Gm^3 loss of storage capacity every year (Fig 6.3). This is a significant loss of water resources and is an indicator of huge intangible economic losses. However, sediment deposit varies from 0.8% to >2% per year in smaller dams (1–50 Mcum capacity) and from <0.5% to 0.8% in larger dams (51 to >1000 Mcum capacity). Siltation of smaller dams poses a serious threat to their ecosystem services as they cater to a wider population for domestic, agricultural, and industrial purposes.

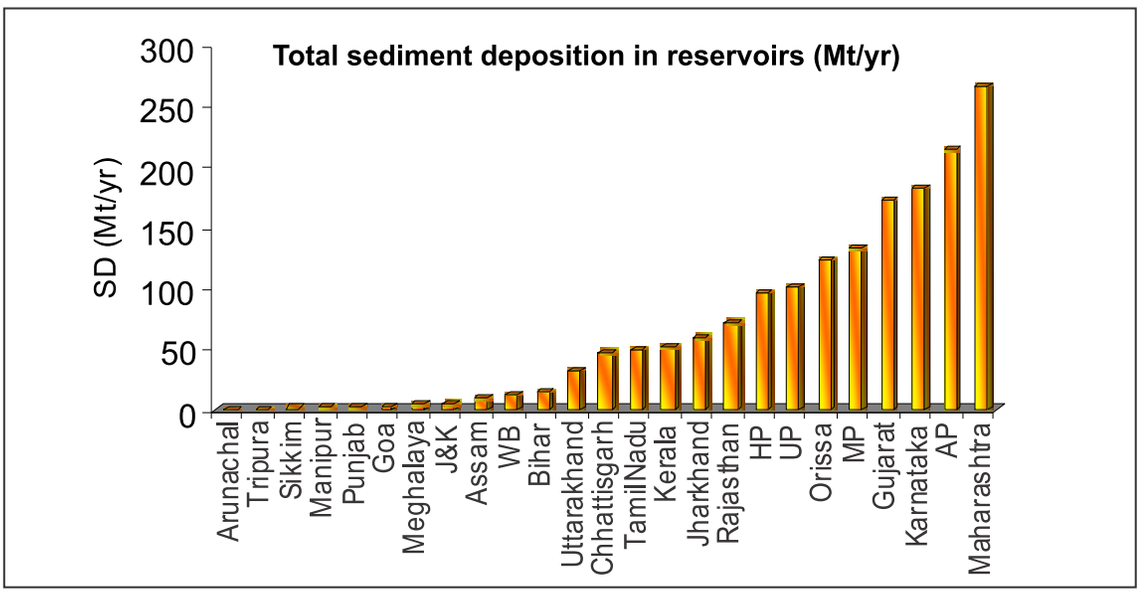


Figure 6.3 : Total loss of storage capacity due to sediment deposition in different states

6.1.6 Economic Impact: Production and Monetary Losses of Crops Due to Water Erosion

Economic losses due to the reduction in yield of crops because of erosion has been worked out for 27 major cereal, oilseed and pulse (COP) crops cultivated in the rainfed areas (Sharda and Dogra, 2013). The country as a whole loses 15.7% of its total production of COP crops, which is equivalent to ₹ 292.03 billion in monetary terms as per the MSP.

6.1.7 Climate change and Changes in Erosion

Projections of monsoon rainfall for the Indian subcontinent indicate that by 2050, a 10% increase in the amount and a 10% increase in the intensity of rainfall are very likely. A 1% increase in rainfall intensity may increase rainfall erosivity by 2.0% (Sharda and Ojasvi, 2006). A 1% increase in rainfall intensity may increase soil loss from croplands by 1.5% (Ojasvi et. al, 2006). Hence, by 2050, the erosion rates of water erosion class 5-10 t ha^{-1} yr^{-1} are expected to increase to more than 10 t ha^{-1} yr^{-1}, which is presently considered as the land degrading soil erosion rate. As a result, about 66 Mha area in our country under the erosion class of 5-10 t ha^{-1} yr^{-1} that covers mostly croplands will likely to be additionally affected by higher rates of erosion due to climate-induced changes in rainfall. This will result in a significant increase in water erosion-affected land degradation area from the current levels unless ameliorative measures are taken.

6.1.8 Importance of Soil and Water Conservation Practices

Control and management of soil erosion are crucial because when the fertile topsoil is eroded away the remaining soil is less productive with the same level of input. While soil erosion cannot be completely curtailed, excessive erosion must be reduced to manageable or tolerable land to minimize adverse effects on productivity. The latest annual soil loss rate in our country is about 1539 t $km^{-2}yr^{-1}$ (Sharda and Ojasvi, 2016) which is less than the previously estimated rate of 1635 t $km^{-2}yr^{-1}$. This is attributed to the adoption of soil and water conservation practices over the past 30 years period. Gross erosion is most prominently influenced by land-use factors. River basin-wise assessment of soil erosion revealed that erosion rates across the basins have a negative correlation with increasing agriculture area (Fig 6.4). This is attributed to the adoption of appropriate conservation measures and irrigation practices.

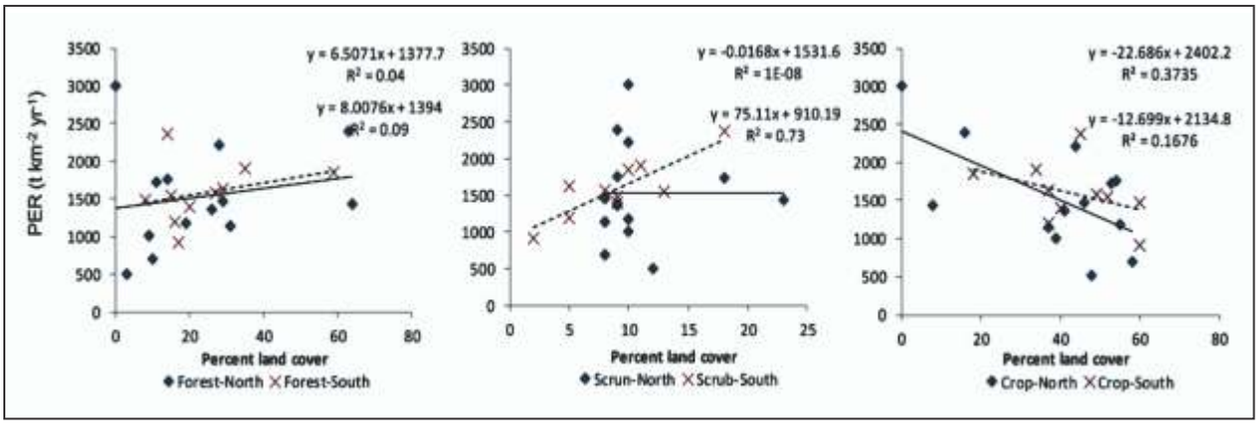


Figure 6.4 : Erosion rates in northern and southern river basins as influenced by land use factors

6.2 Soil And Water Conservation Measures

There are two types of measures for soil and water conservation i.e. bio-engineering/structural measures and biological measures. Bio-engineering measures are permanent and semi-permanent structures that involve terracing, bunding, trenching, check dams, gabion structures, loose/stone boulders, crib walls, etc. along with the suitable vegetation component, while biological measures are *in-situ* measures that involve forestry, agroforestry, horticulture and agricultural/agronomic practices.

A number of biological and agronomic management practices are available for controlling soil erosion. Important among these are no-till, reduced tillage, crop rotations, cover

crops, residue and canopy cover management, vegetative filter strips, riparian buffers, agroforestry, and soil synthetic conditioners. There are differences among these biological practices in relation to their mechanisms of erosion control. These measures mainly improve the microbial and fertility condition of the soil. Biological measures such as crop residues, using manure, and applying conditioners are in direct contact with the soil surface and thus serve as buffers (e.g., residues) or thin films (e.g., conditioners) protecting the soil. In contrast, standing vegetation (e.g., cover crops) reduces soil erosion through the protective effect of its canopy cover which intercepts raindrops above the soil surface and by the mulching effect of residues produced by the growing vegetation.

6.2.1 Farmers' Field Based Biological Measures

Biological measures are applicable in the landscape of ≤2% slope. Agronomic measures are recommended in the case of very slight to slight erosion rates. When practiced regularly, they sustain and improve soil fertility and hence crop productivity. Increasing soil organic C concentration through conservation practices is the key to controlling soil degradation and improving productivity. The response of conservation practices can be significant in preventing C loss from croplands as shown in Fig 6.5. Various conservation practices listed as follows for croplands have been found to be effective for such output in different agroecological regions.

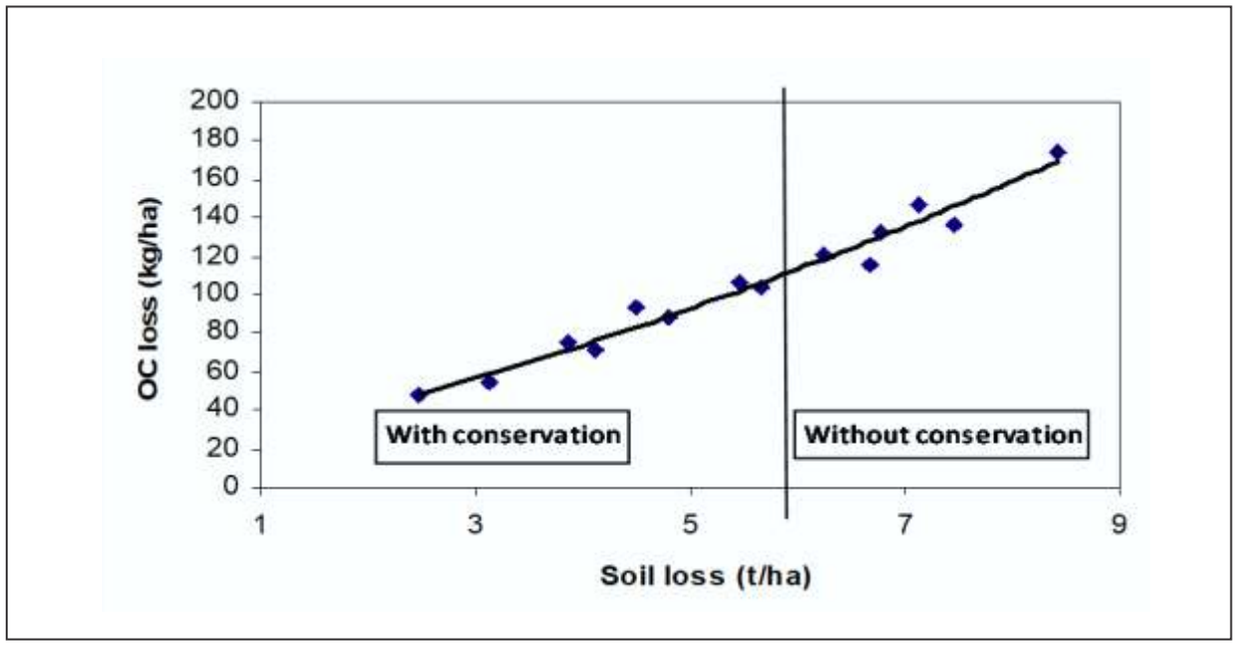


Figure 6.5: An example of loss of organic carbon from cropland with and without conservation measures

Conservation Practice	Representative Picture
Contour farming Contour farming or sowing across the slope is the first step in agronomic measures for soil and water conservation in mildly sloppy lands. However, the effectiveness of this practice depends upon rainfall intensity, soil type, and topography of a particular locality.	

Intercropping

The cultivation of two or more crops simultaneously in the same field with a definite or alternate row pattern is known as intercropping. It may be classified as row, strip, and relay intercropping as per the crops, soil type, topography, and climatic conditions. Erosion permitting and resisting crops should be intercropped with each other. Intercropping provides better coverage on the soil surface, reduces the direct impact of raindrops, and protects soil from erosion, and improves soil fertility. Some kharif season intercropping systems are maize+ (cowpea blackgram, soybean), maize+tuber crops (colocasia, turmeric), sorghum+(groundnut, cowpea, redgram, peigonpea), castor+(greengram, sesamum, groundnut, clusterbean).





Mulching

Mulch is any organic or non-organic material that is used to cover the soil surface to protect the soil from being eroded away, reduce evaporation, increase infiltration, regulate soil temperature, improve soil structure, and thereby conserve soil moisture. Hence, it can be used in high-rainfall regions for decreasing soil and water loss, and in low-rainfall regions for soil moisture conservation. Organic mulches improve organic matter and consecutively improve the water holding capacity, macro and micro fauna biodiversity, their activity, and the fertility of the soil.





Conservation tillage

In this practice at least 30% of the soil surface should remain covered with crop residue before and after planting the next crop to reduce soil erosion and runoff, as well as other benefits such as C sequestration. This term includes reduced tillage, minimum tillage, no-till, direct drill, mulch tillage, stubble-mulch farming, trash farming, strip tillage, etc. The concept of conservation tillage is widely accepted in large-scale mechanized crop production systems to reduce the erosive impact of raindrops and to conserve soil moisture with the maintenance of soil organic carbon. Conservation tillage improves the infiltration rate and reduces runoff and evaporation losses. It also improves soil health, organic matter, soil structure, productivity, soil fertility, and nutrient cycling and reduces soil compaction.





Organic farming

Organic farming is an agricultural production system that is devoid of the use of synthetic fertilizers or pesticides and includes organic sources for plant nutrient supply *viz*. FYM, compost, vermicompost, green manure, residue mulching, crop rotation, etc. to maintain a healthy and diverse ecosystem for improving soil properties and ensuring sustained crop production. It is an environmentally friendly agricultural crop production system. Soil erosion rates from soils under organic farming can be 30–140% lower than those from conventional farming.





Cover crops

The close-growing crops having high canopy density are grown for the protection of soil against erosion, known as cover crops. Legume crops have good biomass to protect soil than row crops. The most effective cover crops are cowpea, green gram, black gram, groundnut, etc.



Land configuration techniques

Adoption of appropriate land configuration and planting techniques according to crops, cropping systems, soil type, topography, rainfall helps in better crop establishment, intercultural operations, reduces runoff, soil and nutrient loss, conserves water, efficient utilization of resources and results in higher productivity and profitability. Ridge and furrow, broad bed furrow, micro-catchment water harvesting and half-moon terrace are important to land configuration techniques. Micro-catchment water harvesting ensures plant survival up to 90% under rainfed conditions.









Agroforestry measures

Agroforestry is a sustainable land management system that includes the cultivation of trees or shrubs with agricultural crops and livestock production simultaneously on the same piece of land. It is an emerging technology for effective soil and water conservation and comprises a wide range of practices for controlling soil erosion, developing sustainable agricultural production systems, mitigating environmental pollution, and increasing the farm economy. The leaf litter addition act as a protective layer against soil erosion improves soil health and moisture retention capacity of the soil and increases crop productivity.

Types of agroforestry systems are Agri-Silviculture (crop + multipurpose trees), Agri-Horticulture (crop+ fruit trees), and Silvi-pasture System (MPT+grass). Fruit tree species like lemon (*Citrus limon*), mango (*Mangifera indica*), ber (*Ziziphus mauritiana*), and aonla (*Phyllanthus emblica*) can be successfully planted in agricultural fields and on degraded and low fertile lands with some restoration measures. Grass species such as *Cenchrus ciliaris* (buffel grass), *Cenchrus setigerus* (birdwood grass), *Dichanthi umannulatum* (marvel grass), *Panicum*







antidotale (blue panicgrass), *Panicum maximum* (Guinea grass), *Brachiaria mutica* (para grass) and *Pennisetum purpureum* (elephant grass) are effective. These systems have the potential to reclaim eroded and degraded lands.	 

6.2.2 Structural measures for farmers' field

Structural or mechanical measures or engineering structures modify the land slope, to convey runoff water safely to the waterways, by reducing runoff velocity and thereby sedimentation in the field. These are recommended where land slope is >2% and up to 45%. These measures are either used alone or integrated with biological measures to improve the effectiveness of the control measures. In highly eroded and slopy landscape biological measures should be supplemented by mechanical structures. A number of permanent and temporary mechanical measures are available such as terraces, contour bunding, vegetative barriers, diversion drains, geo-textiles. These measures are the best management practices for moderate to high erosion rates and highly sloppy lands.

Conservation Practice	Representative Picture
Bunding **Contour bund:** Contour bunding is used to conserve soil moisture and reduce erosion in the fields having 2–6% slope and mean annual precipitation of <600 mm and non-clayey soils. The spacing of the bund is dependent on the erosive velocity of runoff, length of the slope, slope steepness, rainfall intensity, type of crops, and conservation practices.	

Graded bund: Graded bunds are bunds with longitudinal slopes made to drain out the excess runoff water safely in fields having 6–10% land slope and rainfall of>750 mm with the soils having less infiltration rate (<8 mm/h).

Peripheral bunds: Peripheral bunds are constructed around the gully head to check the entry of runoff into the gully. It protects the gully head from further erosion. It creates a favourable condition for the execution of vegetative measures on gully heads, slopes, and beds.

Bunding reduces runoff and soil loss by 64% and 80% in high rainfall regions. Bunding is a very effective measure of water conservation in all rainfall situations.





Bench Terraces

The land slope converted in a stepped land by cutting the upslope and filling the downslope portion to create level land or terraces. It reduces the degree and length of slope and thus reduces runoff velocity and soil erosion and improves water infiltration. It is recommended for lands having a slope of 4-33% but generally adopted for lands having more than 33% slopes. Where plenty of good-quality stones are available, stone riser terracing is recommended.





Vegetative barriers

Vegetative barriers are alternatives to bunding where grass strips usually 1.0 m wide with 2-3 lines of grass clumps are laid in place of bunds. Some of the effective grasses are Khus and Munja in the semi-arid region of central India, Khus, Bhabhar and Munja in Shiwaliks, Panicum (Guinea grass), Napier and Smbuta in the lower Himalayas, Khus, Guinea and Marvel in black soil region, Dhaman, Anjan, and Sewan in arid regions, Napier and Guetamala grasses in southern hill regions. This practice reduces runoff and soil loss by 18-31% and 23-68%. Higher yields of maize and wheat are achieved on conserved moisture by about 32% and 10%.





6.2.3 Bio-Engineering Measures for Landscape Treatment

The impact of soil and water conservation technologies is visible only when a large area like watershed and landscapes are treated. Therefore, conservation practices should be carried out at field, watershed, and landscape scales. The impacts of watershed development with the continued adoption and practice of conservation technologies are realized with improvements in hydrology, soil health, productivity, environment, livelihood, and social equality.

However, it is neither desirable nor feasible to treat the entire watershed area to achieve the intended objectives. In such situations, partial/critical area treatment in a watershed may have a triggering effect in creating a favourable environment by dissipating the impact of degrading forces and improving the moisture regimes which in turn could accelerate the process of natural ecological succession and various hydro-geomorphic changes. It has been established that if 25 percent of the catchment area is covered by various soil conservation practices, a 50 percent reduction in sediment yield could be achieved.

Bioengineering is the integration of engineering design and technology into living systems for achieving longer stability and durability in structure. Engineering or mechanical measures are called the first line of defence. Different site-specific bioengineering measures are used to reduce the eroding effects of runoff water and these may be classified as, drainage line treatment structures, slope stabilization structures, and river or torrent bank protection structures. In this section, various practices for landscape treatment are described.

6.2.4 Contour trenching

Trenches are constructed at the contour line to reduce the runoff velocity for soil moisture conservation in the areas having <30% slope. Bunds are formed on the downstream side of trenches for the conservation of rainwater. These can be either continuous contour trenches or staggered contour trenches. Continuous contour

trenches can be made up to 10-20 m long having a width and depth of 30 cm x 30 cm. Equalizers of 20-25 cm width are placed at suitable intervals to prevent breaching of the trenches. Staggered contour trenches are 2-3 m long and spacing between two rows of the contour is kept as 3-5 m. Trenching is highly effective in the plantation of slopes under rainfed conditions, recharge of springs, and rehabilitation of degraded slopes (Fig. 6.6).



Figure 6.6 : Different types of contour trenchingand plantation on denuded slope with trenching

6.2.5 Wattling

Wattling is a measure for slope stabilization and promoting vegetation on steep slopes of deep gullies, landslide affected areas, roadside slopes and mine spoil areas where trenching is not feasible. It reduces the slope length effectively and it is placed at a vertical interval of 5-7 m for a slope up to 45° and at a vertical interval of 3 m for a slope of more than 45°. In this technique bundles of live branches are laid in shallow trenches. In the growing season, these branches form a strong line of vegetation. At steep slopes, the bundles are held in position with wooden pegs. This technique is quite useful on denuded slopes (Fig. 6.7). The functions of wattling are to catch debris, armour, and reinforce the slope.

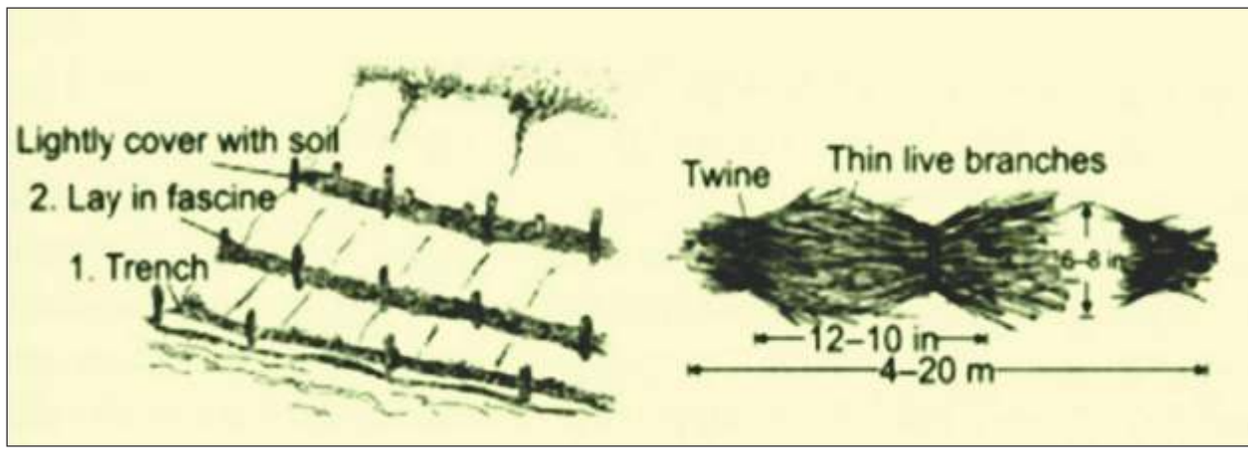


Figure 6.7 : Layout and material for wattling a degraded slope

6.2.6 Brushwood check dam

Brushwood check dams are constructed in small gullies (1.2-2.1 m deep) for checking further development in the gully by using wooden posts. These may be single [post] dams and double [post] dams depending upon the severity of the situation. Wooden posts 10-15 cm in diameter are driven into the bed and bank of the gully to a depth of 0.75-1.0 m below the surface with a 0.6-0.9 m interval. The upstream side of the dam is filled with shrubs and litter (Fig. 6.8).



Figure 6.8 : Brushwood check dam with rope tied post, wire mesh tied to post, and wooden log tied posts

6.2.7 Loose stone check dam

Loose stone check dams or dry stone masonry check dams are constructed at the upper reaches of the drainage line to check runoff velocity in steep and broad gullies as drainage line treatment structures. It is preferred in areas having suitable-sized stones adequately available. For constructing this structure, the gully bed is excavated to a depth of 0.3 m and it is hand packed with stones. Flat rectangular stones of size 20-23 cm are preferred. Its height is kept about 0.5-0.6 m above ground level and its top width of around 0.5 m.

6.2.8 Gabion check dam

Gabion check dams (stone wire crates) are semi-permanent check dams used for drainage line treatment. These are preferred in second or third-order streams for the retention of debris and accumulating sediment. Gabion structures are multipurpose and suitable for drainage channels and unstable slopes as check dams, retaining walls, and spurs. Where good size stones are not available, Katta (gunny bag) filled wire crates are also effective. The used gunny bags are filled with a mixture of nala bed sand or gravel with cement in a ratio of 1: 16 for better stability and longer durability. For channelizing flash floods in streams flow channelizing check dam (FCCD) are suitable to control the mass erosion of stream banks. These structures are 0.5-.75 m high and maintain the flash flood wave at the centre of the stream (Fig. 6.9).



Figure 6.9 : Debris deposited by FCCD and centralized flow in stream after a flash flood

6.2.9 Brush Mattress

A brush mattress (brush matting or brush barrier) is a combination of the thick layer of interlaced live willow branches of about 2 to 3 years old placed against the sloped bank face with rock at the base. Both are held in place by wire and stakes. They are placed perpendicular to the bank with their basal ends inserted into a trench at the bottom of the slope in the splash zone and the willow branches sprout after plantation. The brush mattress has the ability to slowdown velocity along the bank and start sedimentation. Gradually the brush mattress develops a strong network of interlocking roots and stems (Fig. 6.10).

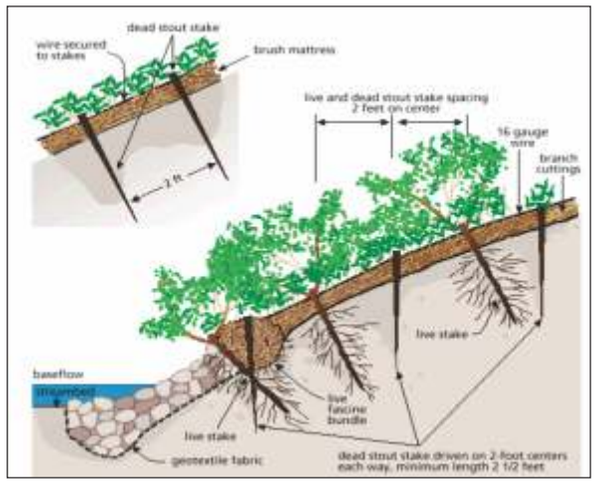




Figure 6.10: Brush mattresses on the river bank

6.2.10 Revetment

Riprap (dikes or rock revetments) protects the bank against erosion by providing a blanket of rock materials installed on the surface of the bank. Before installing the riprap, the bank is graded to a stable slope and a cover of bedding material is laid to check the leaching of the bank through the riprap, and then riprap is placed on the top of bedding material. An appropriate size of riprap material must be chosen for better stability. For best stability, elongated, angular stones are most preferred over round, smooth stones. The riprap blanket should be properly tied into the bank at the upstream and downstream ends (Fig. 6.11).

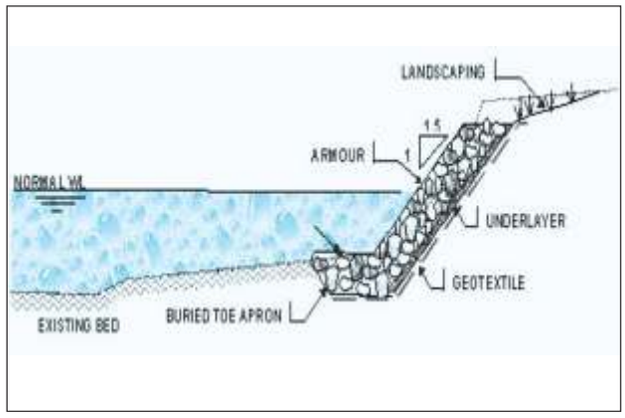




Figure 6.11: Rock revetment for shore protection of a large water body

6.2.11 Live crib wall

Live crib wall made of interlocking logs or timbers in a boxlike structure and filled with rock, soil, live cuttings, or rooted plants, that are intended to develop roots and grow for further strengthen and protection of stream bank from erosion. This is used to stabilize the toe of a steep bank slope and protect it from undercutting, where the volume of soil to be stabilized is relatively small. Crib walls should be installed at an angle of 10–15° towards the slope to increase stability (Fig. 6.12).

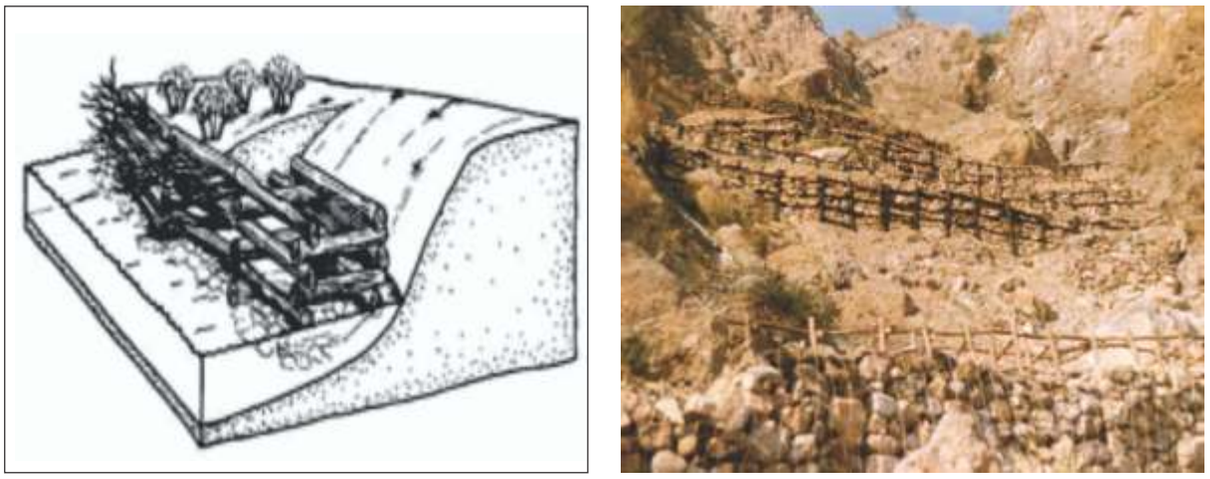


Figure 6.12 : Live crib wall for riverbank and stabilization of steep slopes

6.2.12 Geotextiles

Geotextiles (Bhoovastra) are woven or nonwoven nets of natural or synthetic textile fibres used in soil conservation and slope stabilization work. It has immense role during the initial establishment of vegetation on highly degraded sloping lands by holding the vegetation in place and conserving moisture and fine soil particle at the place. With geotextile application, fast-growing and locally available grass or shrub species should be incorporated. The natural fibre geotextile materials biodegrade in about 2 year by which the vegetation gets well established. Coir geotextile is more durable than the jute geonet. It can be effectively used for stabilizing steep slopes of 35–80°. The geotextile nets are laid on the site to be treated by inserting live wooden pegs at 0.3 m interval and grass seeds or grass clumps are planted in the net hole diagonally at a spacing of 10 cm by 10 cm to develop armour on the slope (Fig. 6.13).

Figure 6.13 : Geotextile cover for unstable degraded slopes



Jute netting is used to protect the bare land slope from the direct impact of rain thereby reducing splash erosion. It retains soil moisture, increases infiltration rate, enables vegetation to establish, and reduces landslides along roads.

6.2.13 Retards

Retards are used to reduce the erosive force of water before it strikes the stream bank, thereby protecting the outside bank and bed of a bend or meander from erosion and also from mass failure

of the bank due to undercutting. These are constructed parallel to the eroding banks and have some projection towards the stream bank. The retards are integrated with the planting of suitable vegetation in the silted area. Retards are effective measures for realigning the stream flow entering a bridge or culvert structure (Fig. 6.14). Permeable retards are more preferred over impermeable ones.



Figure 6.14 : An established retard of full grown trees along the stream bank

6.2.14 Retaining wall

The retaining wall is used to provide support to loose hill slopes from slipping down and stability to river banks. It protects fields, roads, habitations, etc. that have steep slopes at one side. Generally, for retaining walls having a height up to 6 m, its base width is kept as 2/3rd of its height. The base width is reduced in a step manner up to the top of the retaining wall. It is made of masonry, stone, brick, concrete, timber, and gabion. Gabion retaining walls are preferred where erosive factors due to water are dominant (Fig. 6.15).



Figure 6.15 : Retaining wall for stabilizing steep slopes

6.2.15 Spur

Structures constructed transverse to the river flow and projected from the bank into the river are known as spur. A properly laid out and constructed gabion spurs are a very effective bio-engineering measure for stream bank erosion control (Fig. 6.16). Spurs are constructed in series to protect a vulnerable length of the river bank. Spurs deflect the erosive flood current away from the river bank and cause siltation in the interspace of two spurs. In the long run, the vegetation grows along and around the spur to further strengthen the protection of the river bank.



Figure 6.16 : River bank protection by bio-engineering measures of gabion spurs and vegetation

6.2.16 Ravine reclamation

Deep and dissected ravines can be successfully reclaimed by planting bamboo (*Dendrocalamus strictus*) on gully beds and suitable grass like anjan grass (*Cenchrus ciliaris*) on side slopes. This checks water erosion in the ravines and provides fodder as well as regular supplementary income from bamboo harvest. Steep drops in ravines are protected by constructing drop structures. In a period of 4-5 years, ravine slopes are stabilized with their productive utilization (Fig. 6.17).



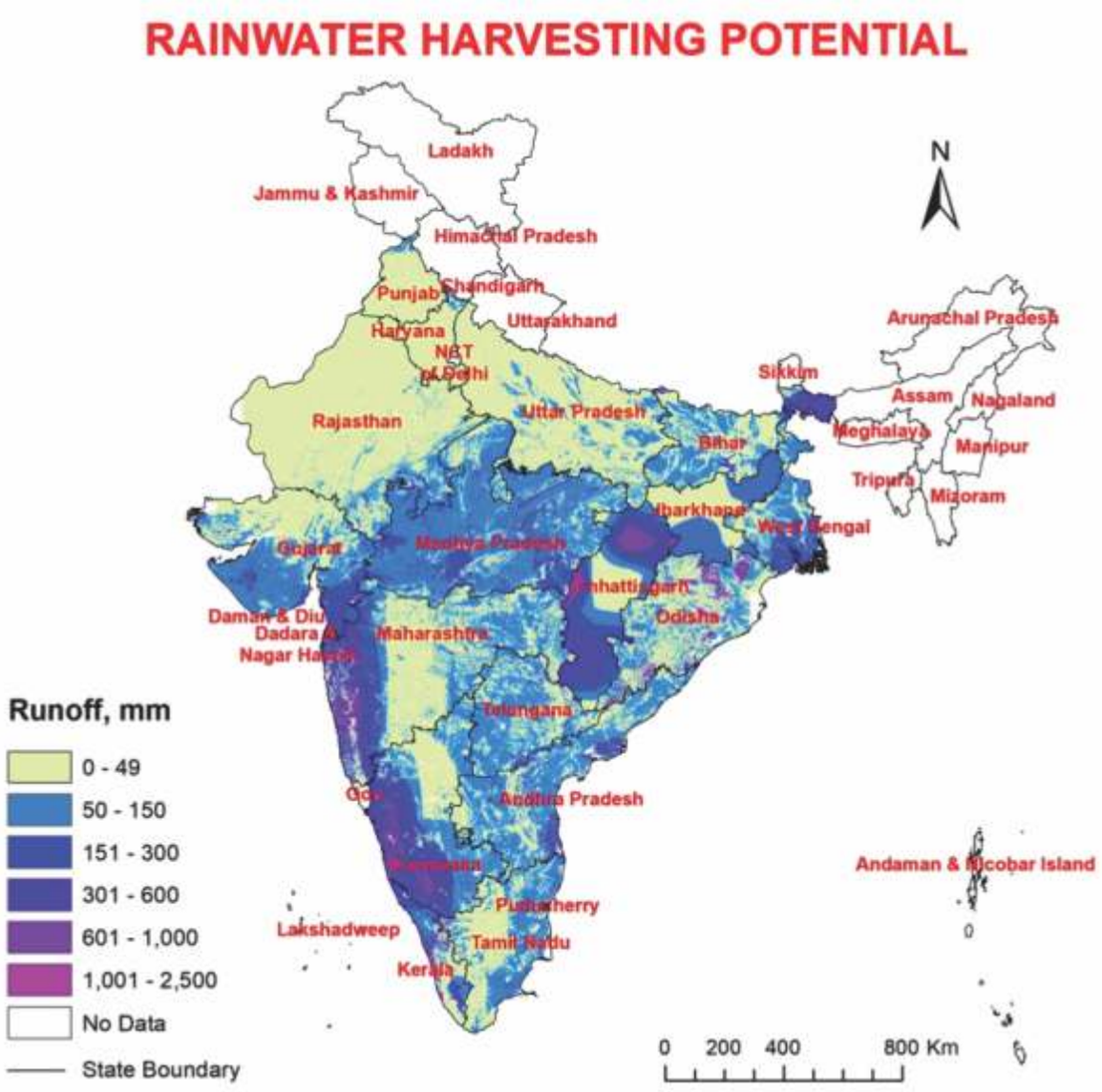
Figure 6.17 : Various conservation measures for treatment of ravine land

6.3 Rainwater Harvesting

Out of 4000 BCM of rainfall in our country, the estimated available river flow water is 1869 BCM, and a typical water balance would reveal that our drainage systems carry approximately 40% of the received rainfall. The remaining 60% is attributed to evapotranspiration and natural

groundwater recharge, the latter component being very meagre. The concept and perspective of looking into salvaging the apparently lost ~60% of the total water resources as runoff-soil storage and majorly to evaporation (in the absence of any productive vegetative growth) is the core objective of rainwater harvesting technology. Hence, to tap the difference between the precipitation received and the present utilization, measures are to be taken to maximize the use of precipitation. This can be achieved through well-planned water conservation schemes for managing unused rainwater with a focus on water storage (*ex-situ* and *in-situ*) for deferred use and enhanced groundwater recharge while controlling runoff, siltation of water bodies and evaporation.

Recently, rainwater harvesting potential geo-database is developed based on a sound hydrological methodology to provide factual information on the harvestable water in different agro-ecological regions of the country (Figure 6.18 and Table 6.1). On average, the annual harvestable runoff potential in 15 states is 112 BCM, which can be suitably utilized for supplemental irrigation to rainfed crops, groundwater recharge and rehabilitation of degraded and wastelands.



Source: *Ojasvi et al., 2022*

Figure 6.18 : Rainwater harvesting potential database of India (15 states)

S. No	Particular	Unit	Data
1.	Total harvestable runoff	MCM	112048
2.	Total harvestable runoff	M ha-m	11.2
3.	Available water for protective irrigation	MCM	33614
4.	Area that can be irrigated with tow irrigation	Mha	22.41
5.	Available water for ground water recharge	MCM	78434

Table 6.1: Total harvestable runoff available for irrigation and groundwater recharge for 15 States of India

Source: *Ojasvi* et al., *2022*

6.3.1. Rainwater Harvesting Techniques

Rainwater harvesting and recycling is widely adopted technology by the individual farmers as well as by the community of beneficiaries. These small-scale water storage systems provide the access to water right at the site where it is needed, thus making its utilization efficient (Fig. 6.19). Several examples have shown that creation of water storage capacity in watersheds increased irrigated area by 65 to 585%, increased groundwater table by 1 to 2 m, and significantly increased the yield of various crops.



Figure 6.19 : Rainwater harvesting structures in different agro-ecological regions

The water use efficiency of harvested water can be optimized through solar energy-based micro-irrigation system. Depending upon the area to be irrigated, 1 to 3 hp solar pumps can be used for lifting water and operation of the micro-irrigation system (Fig. 6.20). Cultivating vegetable crops such as cabbage, brinjal, tomato and chilli with this system has yielded up to 5:1 benefit-cost ratio, energy saving of 356 kWh and avoided CO_2 emission of 357 kg per cropping cycle that is obvious with the use of diesel pumps.

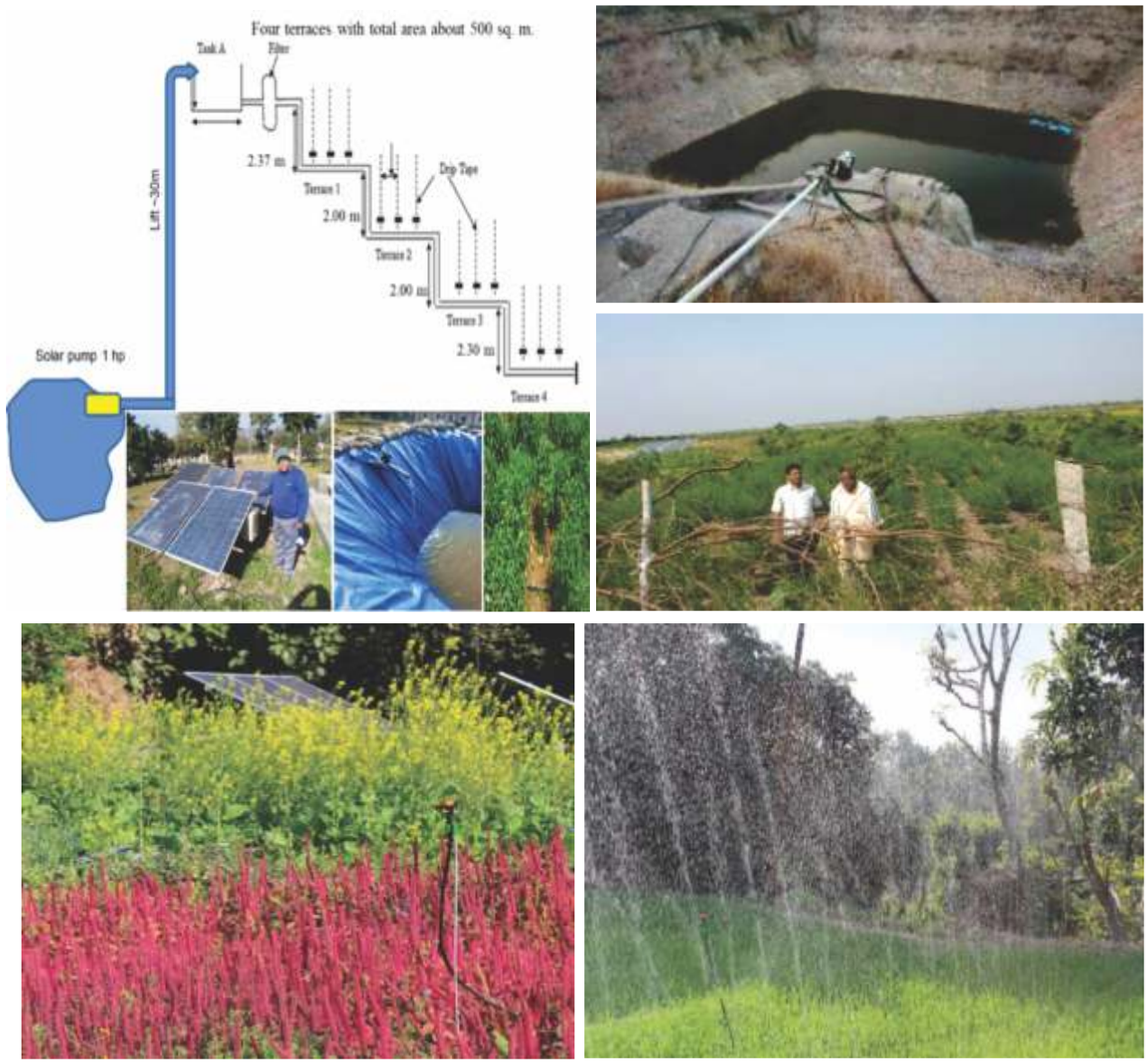


Figure 6.20 : Water harvesting with solar powered micro-irrigation based utilization systems

6.4 Way Forward

There is a continuing drive to address land degradation by policy-making institutions at the highest levels, for example, the United Nations Sustainable Development Goal (SDG)"15.3: By 2030, combat desertification, restore degraded land and soil, including land affected by desertification". Effective action is urgent because it is anticipated that a large number of people will

inhabit dryland regions, which will certainly be affected by land degradation and climate change. Hence following are suggested so that effective planning based on the factual data and facts could be undertaken to mitigate land degradation as well as the adverse impacts of climate change.

- Sustainable agriculture: comprehensive and ecosystem-based approach is required
- Requires nationwide soil and water resource inventory and database of watershed measurements
- Advanced computation tools to analyze and document the region-specific impacts
- Synergy with the global programs
- The dedicated government program for neutralizing land degradation
- Such efforts are likely to change the way conservation projects are implemented in the future

6.5 Conclusions

Natural resources of land, water and vegetation are under great stress in the country, especially in areas characterized by marginality, inaccessibility and fragility and compounded by high-intensity erratic rainfall, steep topography, large-scale deforestation and faulty management practices. This results in an increased frequency of disasters such as landslides, floods, droughts, siltation of reservoirs and deterioration of water bodies. Integrated watershed management (IWSM) in different agro-climatic regions requires the adoption of appropriate soil and water conservation technologies and crop management techniques to prevent land degradation, maintain soil fertility and ensure environmental security for achieving sustainable productivity. The strategies in IWSM programmes include land configuration systems, agronomical measures, alternate land use systems, run-off harvesting and recycling methods and measures for control of mass erosion problems. Experiences of integrated watershed development programmes in various agro-climatic regions have indicated that they have a great potential for moderating floods in downstream areas, improving in-situ moisture conservation and groundwater recharge for increased biomass production and are economically viable with tremendous environmental externalities.

However, greater emphasis is needed on strong institutional mechanisms to ensure the sustainability of these programmes. Water harvesting and groundwater recharge, location-specific and cost-effective technologies for erosion control and flood moderation, suitable plant materials and integrated farming systems for higher production and conservation of natural resources, contingency planning for undertaking calamity relief works during floods and droughts for generating productive employment and diversification for new market opportunities based on demand-driven growth need to be promoted. Modern tools and procedures should be deployed for proper auditing of available water resources and taking informed decisions about the impact of watershed development programmes on a river basin scale. The impacts of micro-watershed development programmes need to be scaled up at the macro level to critically analyze the shifts in flow patterns, perenniality of streams and rivers and mitigation of land degradation during extreme events.

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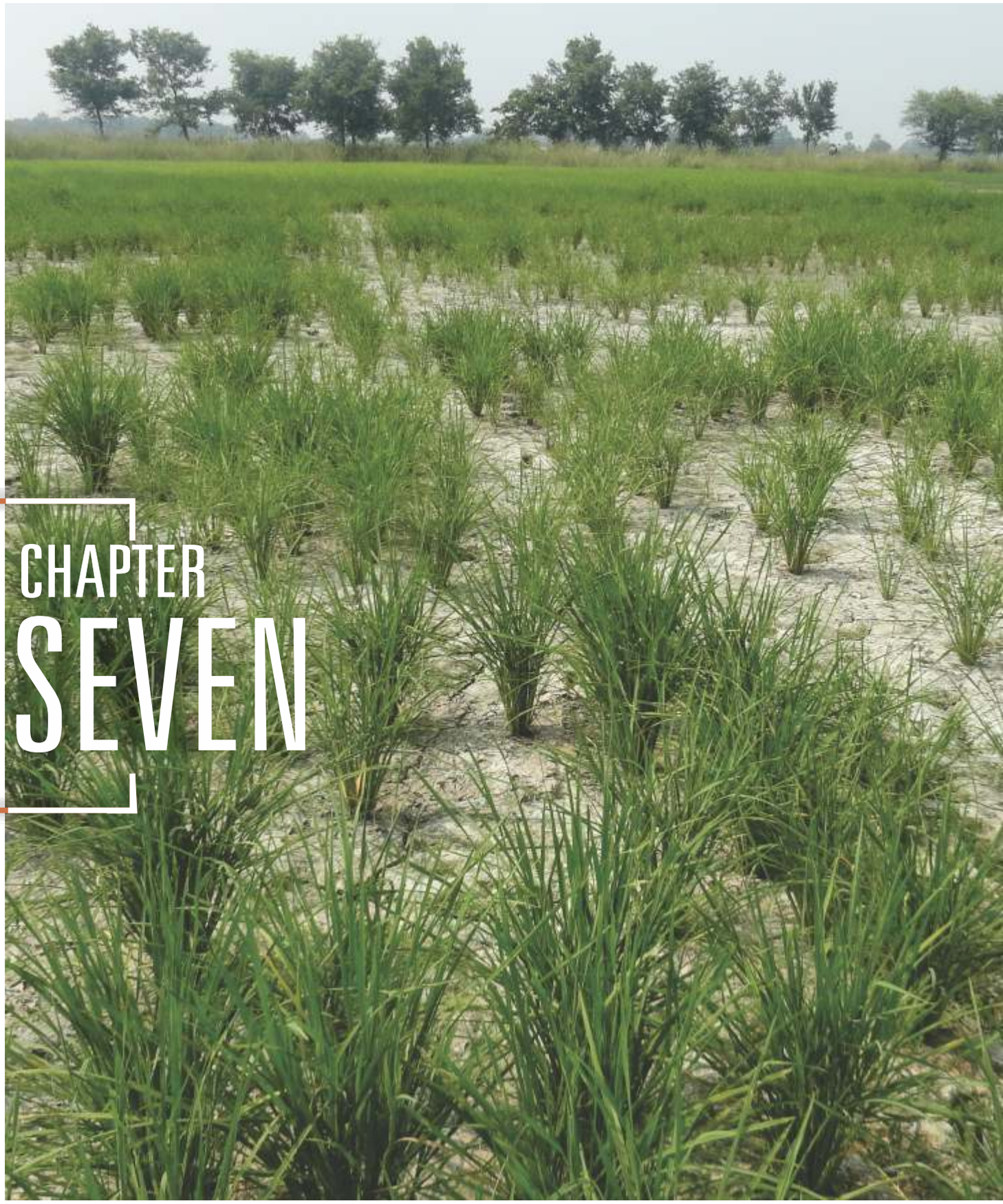
Techniques for Reclamation of Sodic Soil



CHAPTER
SEVEN

Nirmalendu Basak, Arvind Kumar Rai, Parul Sundha, Priyanka Chandra, Sandeep Bedwal, Rajendar Kumar Yadav, Parbodh Chander Sharma
ICAR-Central Soil Salinity Research Institute, Karnal, Haryana -132001

7.1 Introduction

Sodicity is a serious ecological threat, leading to land degradation and affecting crop growth and production in arid and semi-arid regions across the world. In India, ~ 6.73 Mha of land is salt-affected, comprising 3.77 and 2.96 Mha of sodic and saline soils, respectively (Sharma et al., 2015). The disproportionate larger salt accumulation and presence of alkalinity adversely affect soil structure and properties, thereby constraining agricultural production (Rai et al., 2021a; Basak et al., 2022). The degree of adverse effects of sodicity depends upon the nature and quantity of electrolytes, soil texture, cultural practices, use of crop cultivars, stages of the crop, and climatic factors (rainfall, temperature, and relative humidity) (Chhabra, 1996). The behaviour and properties of sodic soils are also diverse. They require specific technologies for their reclamation and management to maintain their long-term productivity (Abrol et al., 1988; Rai et al., 2021b). The degraded sodic soils could be brought under cultivation by adopting chemical, physical and biological measures of reclamation (Qadir et al., 2008; Fan et al., 2012; Ahmad et al., 2013; Ivits et al., 2013; Singh et al., 2016). The neutralization of CO_3^{2-} and HCO_3^- ions and removal of part or most of the exchangeable sodium and its replacement by the more favourable calcium ions in the root zone facilitate the reclamation/rehabilitation of sodic soils. The reclamation of such soils is generally achieved either by treatment with chemicals such as gypsum (Kanwar et al., 1965; Abrol and Bhumbla, 1979; Anonymous, 2006), low concentration of mineral sulphuric acid, ferrous sulfate, iron pyrites (Boras, 1968), elemental sulfur (Samuels, 1927; Sharma et al., 2019) or by the use of organic amendments viz., farmyard, poultry, green/brown manure, pressmud, spent wash, biochar, or by integrated use of chemical and organic amendments. The choice of a chemical amendment at any place will depend upon its relative effectiveness which depends on its efficiency in improving the soil properties, crop growth and the relative costs involved. The time required for an amendment to react in the sodic soil and its efficiency for effectively replacing adsorbed sodium is also a major consideration, in the choice of an amendment. Several studies have attempted to evaluate the effectiveness of various amendments under varying soil and climatic conditions.

Soil sodicity is a water-mediated process, therefore irrigation with alkali water or water having high sodium adsorption ratio (SAR); water having a relatively greater amount of Mg^{2+} than Ca^{2+} shows the problem of sodicity (Qadir et al., 2018; Sheoran et al., 2021a). Therefore, the neutralization of alkalinity in alkali water by treating water soluble Ca^{2+}, or diluting sodic water for reducing SAR or conjunctive application of alkali/ high SAR water is recommended for the safe utilization of this kind of poor-quality water (Minhas et al., 2019). Adoption of agroforestry systems on sodic soils could be a feasible intervention for generating additional returns *vis-a-vis* improvement in the quality of degraded sodic soil lying barren for only one or several reasons. Beaking of the hard *kankar* (calcium carbonate) layer barried in several sodic soils is recommended for the planting of fruits and agroforestry trees. Thereafter, gypsum (external calcium), and farmyard manure as nutrients source is applied to neutralize alkalinity and replacement of exchangeable sodium and creates a congenial soil environment. This practice often called 'a pit-auger-hole technique' of tree plantation is advocated for reducing plant mortality (Singh, 2022; Kumar et al., 2022). For greening barren or productive sodic land, suitable agroforestry trees are selected which have low mortality and are tolerable to harsh conditions of extreme sodicity (Singh et al., 2022).

7.2 Sodic soil reclamation agents

Generally, two broad kinds of reclamation agents are available for reclamation and productive use of sodic soil. The first category is mineral or chemical amendments viz., gypsum, pyrites, inorganic sulfur/ mineral sulphuric acid, aluminium chloride, flue gas desulfurized gypsum, farmyard manure, and the second category includes agricultural waste, city waste compost, and green manure. The action and efficiency of chemical amendments for reclamation are fast, and economic return is received at very early stages; whereas, the reclamation efficiency of organic amendments is time-taking and payback periods are long. Further, the chemical amendments for sodic soil reclamation can be broadly grouped

into three categories: a. calcium supplying salts (Ca^{2+} soluble), e.g. calcium sulfate (mineral gypsum/synthetic $CaSO_4.2H_2O$ in thermal plants (flue gas desulfurized gypsum), calcium chloride; and b. acids or acid-forming substances, e.g. sulphuric acid, iron sulfate, aluminium sulfate, lime-sulfur, sulfur, pyrite etc. Besides, organic sources such as farmyard manure, pressmud, corn stalks, municipal solid waste compost, sewage sludge, crop residue are also being used as promising amendment sources. Soil organic matter improves soil structure and aggregation, increases hydraulic conductivity, and promotes higher nutrient levels and improve cation exchange capacity ".

In addition to mine and industrial gypsum; seawater, and some chemical plants are sources of by-product marine gypsum and by-product chemical gypsum, respectively. Of late, the by-product phospho-gypsum or fluoro-gypsum, or boro-gypsum, depending upon the source, are the available reclaiming agent. The chemical preparation hydrofluoric acid and aluminium fluoride using fluorite at different units in Surat, Mumbai, and Thane produce fluoro-gypsum as a by-product. In the Maharashtra and Tamilnadu states the Boro-gypsum is generated at the plant which refines calcium borates (colemanite and ulexite) to produce boric acid and borax. Although, there is no report available regarding the use of boro gypsum and fluoro-gypsum as amendment sources; however, other chemicals like marine gypsum, phosphogypsum, flue gas desulfurization gypsum, and fly ash etc. are being researched for agricultural implications.

7.2.1 Available reclamation agents

7.2.1.1. Mineral gypsum

Gypsum ($CaSO_4$, $2H_2O$) is soluble in water and, largely available in semi-arid and arid regions. The key advantage of using gypsum as the amendment is relatively rapid reclamation, it is widely available, easy to handle, and low cost. Soluble Ca (Ca^{2+}sol) is released upon dissolution of gypsum and neutralizes free alkalinity (CO_3^{2-} /HCO_3^-) and a part of the Ca^{2+}sol exchange Na^+ from the soil (equations 1 and 2). Further, the degree of sodium saturation, soil texture, crop/cropping system selected for cultivation, degree of improving status, quality, and quantity of irrigation water are the key factors that govern the status of reclamation and possibilities of resodification. The reacted Na^+ needs to be leached by applied water. The mega project initiated by the World Bank, European Union, Haryana Land Reclamation and Development Corporation (HLRDC), Uttar Pradesh Bhumi Sudhar Nigam (UPBSN), and other developmental agencies, ~ 2.10 Mha of sodic lands have been reclaimed in India. Prolonged irrigation with sodic water irrigation leads to soil sodification, undesirable cost of cultivation, non-performance of the crop, and under-productivity. Unfilled grains reflected spikelet sterility usually happened because of bicarbonate irrigation (high RSC) for both rice and wheat crops returning a significant loss of yields and income (Rasouli et al., 2013; Singh et al., 2021). This problem is further distressing with anticipated changes with the rise in temperature, and uneven behaviour of rainfall. The increase in temperature raises evapotranspiration demand (ET) for the crops and thus imports a larger quantity of salt load in the case of alkali water irrigation. The amelioration of sodicity stress in different agroecosystems using different amendments is summarized in Table 7.1.

$Na_2CO_3/NaHCO_3 + Ca^{2+} + SO_4^{2-} = Na_2SO_4$ (leachable) $\downarrow + CO_2 \uparrow$

Na-[Clay micelle]-Na + Ca_2+ + SO_4^{2-} = [Clay micelle]-Ca + $Na_2SO_4 \downarrow$ (leachable)

7.2.1.2 Phosphogypsum

Phosphoric acid-generating plants produce phosphogypsum (PG) as a by-product. Because of rapid dissolution, PG produces an acidic reaction and creates a leaching solution with greater electrolyte concentration, facilities for particle aggregation, and further improves the infiltribility of sodic soil (Gharaibeh et al., 2014). Nearly eleven million tons of PG has produced in India annually and this valuable resource is a good source for reclamation. In addition, it also supplies essential plant nutrients like Ca, S, and P, which may readily be available for crop production. Application of PG @ 10 Mg ha^{-1} increased grain yields of both rice and wheat (Nayak et al., 2013b). The deterioration effect of Mg-rich water is copes with PG application and slows down the injurious effect of exchangeable magnesium percent (EMP) in semi-arid regions of central Asia (Vyshpolsky et al., 2008). However, the occurrence of heavy metal and radioactive

contamination in PG is the key issue for the limited application of PG on a pilot scale for crop production rather than its use in the cement and brick industry and construction of the road (Saadaoui et al., 2017).

7.2.1.3 Pyrite

Iron pyrite (FeS_2) carries 15-30% of S has limited commercial value and is advocated to reclaim sodic or saline-sodic soils (Jaggi et al., 2005). Sequential biochemical oxidation of FeS_2 generates sulfuric acid, that mobilizes the native $CaCO_3$ and facilitates Na^+ displacement from the exchange phase. Further, SO_4^{2-} causes acidification and facilitates existing $CaCO_3$. The chemical oxidation of FeS_2 starts in this way:

$2FeS_2 + 7O_2 + 2H_2O = 2FeSO_4 + 2H_2SO_4$;

Further, *Thiobacillus ferrooxidans* oxidise Fe (II)

$4FeSO_4 + O_2 + 2H_2SO_4 = 2Fe_2(SO_4)3 + 2H_2O$; further,

$Fe_2(SO_4)_3$ is reduced and pyrite is oxidized by a chemical reaction as follows:

$Fe_2(SO_4)^3 + FeS_2 = 3FeSO_4 + 2S$

The generated elemental sulphur (S°) is then oxidized by *Thiobacillus thiooxidans* and liberates sulfuric acid

$2S° + 3O_2 + 2H_2O = 2H_2SO_4$

$Na_2CO_3 + H_2SO_4 = CO_2 + H_2O + Na_2SO_4$ (leachable)

$CaCO_3 + H_2SO_4 = CaSO_4 + H_2O + CO_2$

Na–[Clay micelle]–Na + $CaSO_4$ = [Clay micelle]–Ca + Na_2SO_4 (leachable)

7.2.1.4 Industrial waste

7.2.1.4.1 Fly ash

Thermal power plants generate fly-ash when coal is combusted. The eco-friendly recycling of fly-ash for agricultural use is a researchable issue because the disposal of ash into the open atmosphere is one of the key issues in developing countries. The results of earlier experiments show that the low pH in fly ash neutralizes alkalinity and decreases ESP by supplying Ca^{2+}sol and thereby, forty per cent of the gypsum requirement can be met by the application of the fly ash (Kumar and Singh, 2003). The bulky nature and presence of macro and micronutrients and fly ash trigger the integrated use of fly ash and organic amendments such as farmyard manure, sewage sludge, paper factory sludge, pressmud, crop residues, and composts combat sodicity and the beneficial impact of integrated use of fly ash and organic amendments can reduce heavy metal bioavailability (Sahin et al., 2008; Ram and Masto, 2014). The application of fly-ash @ 10.0 Mg ha^{-1} improved the grain yield of paddy up to 17 percent in sodic soil (Mongin et al., 2003).

7.2.1.4.2 Spent wash

The unwanted residual waste liquid produced during alcohol production at the sugarcane distillery industry is called spent wash causes environmental pollution in open dumping (Mohana et al. 2009; Kaushik et al. 2005). The acidic nature of primary biomethane spent wash carries a substantial quantity of organic matter as well as N, P, K, and Ca which are promising options for reclamation and improving the fertility of sodicity-affected soil. Application of five lakh litre of raw spent wash increased soybean seed yield up to 85% and reduced to 33% in sodic vertisols. Application of primary biomethane spentwash of 2.5 cm followed by leaching with two pore volume of irrigation water neutralize soil sodicity as microbial decomposition of spent wash produce organic matter and release of acidity which lower down SAR and ESP values of in calcareous sodic soil (Deshpande et al., 2012).

7.2.1.4.3 Press mud

The cane crushing in the sugar mill industry produces semi-solid pressmud. Around 25% of chemical fertilizers' requirement can be saved through the application of 10 Mg ha^{-1} of enriched pressmud without affecting cane productivity and quality further these practices restore the soil fertility (Rakkiyappan et al., 2001). Sulphidation pressmud and the recommended dose of chemical fertilizers sustained the rice and wheat yield in sodic groundwater areas for irrigation and decreased the EC and SAR in calcareous sodic soils (Yaduvanshi and Swarup 2005; Sheoran et al., 2021b).

7.2.2 Promosing amendments

A desirable amount of Ca^{2+} is required in soil water solution and soil exchange sites for

retaining the physicochemical properties of soil for plant growth and microbial activities. The Ca^{2+} is supplied directly as mineral salts or mobilization of calcium carbonate or supply of acid-producing substance from external sources. The nature and quantity of amendments applied for the replacement of Na^{+}ex in the soils depend on the soil properties including the extent of soil alkalinity/sodicity. Multiple construction and cement sectors appear in competition for gypsum use, therefore, mineral gypsum consumption is rising in developing countries (Anonymous, 2018). Therefore, with the competing demand in industrial sectors, the farming sector is facing concerns about poor availability and substandard quality of agricultural-grade gypsum. Advanced research is the need of the hour to synthesize alternate amendment sources and works on low gypsum application in conjunction with organics (Sahin et al., 2020; Sundha et al., 2020; Sheoran et al., 2021b; Sharma et al., 2019).

7.2.2.1 Acid and acid-forming substances

Mineral sulphuric acid is very reactive because it immediately neutralizes soluble CO_3^{2-} and HCO_{3-}, and on the dissolution of native calcium carbonate ($CaCO_3$), it produces calcium sulphate ($CaSO_4$). The conjunctive application of $CaCl_2$ or H_2SO_4 with $CaSO_4$ is more useful than sole $CaSO_4$ for efficient reclamation and increase water use efficiency (Prather et al., 1978). The treatment with acids/ acid formers in sodic water for neutralization of alkalinity (Qadir et al., 2001; Ganjegunte et al., 2018). However, large-scale adoption of sulphuric acid application is a problem because of the handling and application difficulties. However, the abundance of $CaCO_3$ in calcareous sodic soil has advocated the treatment of sulphuric acid for its reclamation. Therefore, a sulfurous acid generator (SAG) is a futuristic technology for sodic water treatment where elemental sulfur (S°) is burnt to produce sulfur dioxide (SO_2) gas in a chamber, which is further permitted to dissolve in sodic water to form sulfurous acid (H_2SO_3). The H_2SO_3 neutralizes CO_3^{2-} and HCO_{3-} of water to reduce the RSC of treated water. SAG or sulfuric acid and gypsum application is recommended at par paddy grain yield. The economic feasibility of neutralization of alkalinity by application of SAG and H_2SO_3 than the gypsum bed technology needs to further rectify (Zia et al., 2006). Therefore, a cost reduction through technological advancement of SAG and scheming of the acid applicator can provide an opportunity for the safe application of mineral sulphuric acid in high-value crops under protected cultivation. The autotrophic and/or heterotrophic microorganisms oxidize elemental S (S°) to H_2SO_4 which not only neutralizes CO_3^{2-} and HCO_{3-} and also changes Na_2CO_3 and/or $NaHCO_3$ and also neutralizes CO_3^{2-}/ HCO_{3-} from the system. S° is less soluble in water and oxidises on air exposure. Loss of S° as SO_x can minimize the SO_2 or other intermediate valence states, and therefore, it is recommended to oxidise S° in moist soil for ensuring the conversion into H_2SO_4 and recommended for reclamation of sodic soil (Chhabra, 1996). This is mediated by *Thiobacillus thiooxidans* performing the oxidation of S° (Brady and Weil, 2014).

$2S^{\circ} + 3O_2 = 2SO_3$ (oxidation (performed by microbes)

$SO_3 + H_2O = H_2SO_4$

It is advantageous to the application of S° on sodic soils when Na_2CO_3 and/or $NaHCO_3$ are abundant. The H_2SO_4 decreases the pH and Na_2CO_3/$NaHCO_3$ is converted to soluble and leachable Na_2SO_4.

$NaHCO_3 + H_2SO_4 = Na_2SO_4$ (leached out) $+ H_2O + CO_2\uparrow$

$Na_2CO_3 + H_2SO_4 = Na_2SO_4$ (leached out) $+ H_2O + CO_2\uparrow$

Na^{+}-[Soil]-Na^{+} $+H_2SO_4 = H^{+}$-[Soil]-$H^{+} + Na_2SO_4$ (leached out)

S° mobilizes $CaCO_3$ and Ca^{2+}sol is liberated and indirectly reacts with native soil lime ($CaCO_3$). The Ca^{2+}sol performs the exchange reaction with Na^{+} on the clay.

$CaCO_3 + H_2SO_4 = CaSO_4 + H_2O + CO_2$

Na^{+}-[Soil]-Na^{+} $+ CaSO_4 = Ca^{2+}$-[Soil] $+ Na_2SO_4$ (leached out)

The utilization of S° in sodicity reclamation has promising responses. Therefore, the presence of an appreciable quantity of $CaCO_3$ in sodic soils is effectively reclaimed (Brady and Weil, 2014; Sharma et al., 2019). The laboratory sodic soil incubation study claims a 32% transformation of SO_4^{2-} can be achieved in 120 days of incubation and this process reduced soil pH up to 8.4 from 10.1 (Kubenkulov et al., 2013). The reclamation

efficiency can increase with the removal of accumulated salt during incubation.

Therefore, S° formulation and microbial activity play a very important role in this process (Lawrence and Germida, 1988). After undergoing a biological reaction of S°, *Thio bacillus* liberates H_2SO_4 which, upon dissociation supplies H^+ (H_3O^+). The dissociation of H^+ displaces Na^+ from the exchange complex (Rupela and Tauro, 1973). An appreciable result with the conjunctive application of gypsum and S° and *Acidithio bacillus* than sole gypsum application reported in the reclamation of Brazilian alkali soil (Stamford et al., 2007). Around 84 days of incubation at neutral soil reported 16 and 22% oxidation of S° at 20 and 30°C and this incubation declined soil pH by 3.6 and 4.0 units and produced electrolytes around nine times (Yang et al., 2010). The S° powder is highly hydrophilic and is bioavailable for oxidation by *Acidothio bacilli* therefore, proper aeration is required for the complete oxidation of the added S° (Seidel et al., 2006). Some sodic soils contain an inadequate amount of the S° oxidizing bacteria, their enrichment may be necessary to achieve rapid S° oxidation (Rupela and Tauro, 1973). The expansion of crude oil refining produces flowers, prills, or bentonite granules which can extend the sodicity reclamation with proper utilization. However, these by-products have issues of dustiness, fire hazards, and slow rate of oxidation, therefore suitable formulation of prilled sulfur has some promise to emerge as a futuristic ameliorant for sodicity reclamation.

7.2.2.2 Marine gypsum

Brine water generates marine gypsum (MG). This by-product and marine gypsum is comparable with the production of the MG. The action of solar evaporation segregates MG. The $CaSO_4$, $2H_2O$ content of marine gypsum varies 89.7-92.6% as well as it bears NaCl, MgCl, MgSO, with a 0.5-2.1, 0.6, 3.4, and 3.5-7.7% and insoluble constituents, respectively. Nearly fifty kg of MG is generated for each ton of salt production. As solar salt production is probable to exceed 15 million tons, there may be increased availability of marine gypsum. As other electrolytes (NaCl, $MgCl_2$, and $MgSO_4$) are present as impurities in MG, therefore, the ionic strength of the aqueous solution may increase by decreasing the activity coefficient of MG (Anonymous, 2018).

7.2.2.3 Flue gas desulfurization gypsum

Flue gas desulfurization gypsum (FGDG) is an industrial by-product produced during the flue gas desulfurization process in coal-fired power plants. The process involves the wet scrubbing process that injects a lime or limestone reagent into the flue gas path to capture SO_2 as $CaSO_3$ which is then converted to $CaSO_4$ through forced air oxidation. Environmental emission standards impose SO_2 scrubbing to limit the atmospheric pollution caused by SO_2 emissions. FGDG is a good source of Ca and S, which can be beneficial for crop growth and production, especially for soils with very low Ca levels. Currently, FGD gypsum is being recommended as an amendment for saline-sodic soils in a few corners of the world, but very meager data is available on this work in our country. Co-utilization of FGDs with organic materials (manure, composts, bio-solids) may also provide many benefits when on agricultural land. Applications of FGDG in sodic soil improve physicochemical properties, neutralize alkalinity of sodic soil, and nutrient loss, supplement micro-nutrients for soil, and increase crop yield; thereby increasing productivity. FGDGs application reduces surface crusting and compaction, improves water infiltration and water holding capacity, increases aggregate stability, and checks water runoff and erosion (Norton and Zhang 1998). Application of wet and semi-dry FGD gypsum as an alkali soil resulted in decreased soil pH, and ESP (Wang et al., 2008). Besides beneficial effects, some reports also showed an increase in the concentrations of trace elements (e.g., As, Se, and B) in the plant tissue after land application of FGDG (Punshon et al., 2001; Liu et al., 2020). The gypsum can be utilized as an alternative to mined gypsum in the Indian context, provided its efficacy is established and issues related to by-product utilization (Sharma et al., 2020).

7.2.2.4 Manures

All types of manure (farmyard manure, green manure, poultry litter manure, pig manure) are abundantly available organic nutrient sources widely used as fertilizers. The cotton gin crushed compost and poultry manure application at rates of 5 and 10 Mg ha^{-1} in 5 years to sodic soil, decreased ESP (about 50%), compared to the unamended soil (Tejada et al., 2006; Ghosh et al., 2010). The application of poultry manure

enhances the concentration of water-soluble salts in the soil available for the utilization of plants for growth and development. In particular, the application of poultry manure and compost to soil can increase both the CEC and the soluble and exchangeable-K, which is a competitor of Na^+ under sodicity conditions, thus, limiting the entry of Na^+ into the exchange complex (Frenkel et al. 1978). Application of poultry manure biochar to sodic soils reduced soil pH and electrical conductivity (EC) and increased the soil Ca^{2+} and Mg^{2+} and available P (Sappor et al., 2017).

7.2.2.5 Municipal solid waste (MSW) compost and sewage and sludge

Recycling, reusing, and composting organic waste is viable options for the reclamation and rehabilitation of sodic soils. The Govt. norms endorsed mandatory composting of bio-degradable solid wastes produced from smart cities of developed and developing countries. Nitrogen and other crucial plant nutrients can meet through the application of city waste compost and sludge (Roig et al., 2012). For improving soil physical and chemical properties, and increasing soil microbial populations and activities an application of city waste, sewage, and sludge is frequently recommended (Bronick and Lal, 2005; Sundha et al., 2021), and helps higher nutrient levels and required cation exchange capacity (Jalali and Ranjbar, 2009; Sundha et al., 2020; von Lützow et al., 2002). The N and P availability are greatly affected during sodicity reclamation by gypsum application however, conjunctive application Gyp + city waste compost remunerated N and P scarcity and decreased the demand for gypsum for sodic soil reclamation (Sundha et al., 2017, 2023). Salt-ion chelating action of the organic component of city waste compost detoxifies the toxic ions, particularly Na^+ sodic soil treated with a conjunctive application of compost with gypsum (Tejada et al., 2006; Zaman et al., 2020), reduces plant pathogens, and increased the beneficial soil organisms and improves water holding capacity (Abawi and Widmer, 2000).

7.2.2.6 Acidified biochar

Biochar is a carbonaceous solid material, produced at high temperatures ranging from 300 to 1000°C under anaerobic environments has to pay attention as a soil amendment. Biochar application reduces soil alkalinity and declines ESP after reducing the sodicity stress for plants (Lashari et al., 2013; Chaganti and Crohn 2015; Sun et al., 2017; Sadegh-Zadeh et al., 2018). The Na^+ uptake of the crop is reduced by improving soil water holding capacity on the application of acidifying biochar (Akhtar et al., 2015). The conjunctive use of biochar-manure compost with pyro-ligneous reduced the soil pH and salinity stress in sodic soil (Lashari et al., 2013) and the larger concentration of Ca^{2+} and Mg^{2+} in biochar-manure compost exchange the Na^+ on the soil colloids are reduced salinity and SAR (Sadegh-Zadeh et al., 2018). The acidified biochars mobilized Ca^{2+} upon $CaCO_3$ dissolution and supplied Ca^{2+} and H^+ to the soil solution and eventually decreasing the SAR and soil pH. Therefore, low-cost approaches for manufacturing biochar are advocated for the future use of biochar as an amendment for profitable and sustainable sodicity reclamation (Saifullah et al., 2018).

7.2.2.7 Nano-scale materials and polymers

The coagulating behavior of nano-scale materials and polymers is used to check soil sodicity reclamation. The hydrolysis of these materials neutralizes negative charge soil colloids and "sweep flocculation" action through an amalgamation of impurities in an amorphous hydroxide precipitate is the mechanism of these compounds for sodicity when treating the alkali water (Luo et al., 2015). Upon liberation of H^+ ions by hydrolysis resulted in a substantial reduction in soil alkalinity and mobilize the dissolution of $CaCO_3$ to provide Ca^{2+}sol ions for reclamation of saline–sodic soils vis-a-vis checked the dispersion of saline–sodic soils and stimulate the development of aggregate structures, thereby ultimately improving soil physical properties. Polyacrylamide (10 ppm) improves the hydraulic conductivity of sodic soil resulting in Na^+ leaching. Application of polyacrylamide @ 10 mg L^{-1} dissolute $CaCO_3$ in the surface soil layer thereby reduces soil salinity and SAR and increased the pecan nut productivity by 34% upon unamended soil (Ganjegunte et al., 2011).

Sodicity induce stress	Soil property improvement Initial (I) and final (F) soil	Duration of experiments	Recommendations
Gypsum (Gyp) and pressmud (PM)			
Sodic soil irrigated with sodic water in rice-wheat rotation	Application of Gyp and PM decreased soil pH 1:2 8.4 and 8.6 in Location-I and 8.7 and 8.8 Location-II compared to initial soil pH1:2 9.1 and 9.7 with the irrigation water alkalinity of 5.1 and 6.9 me l^{-1}.	4 year (2014-2018)	The application of gypsum (7.5 Mg ha^{-1}) and pressmud (10 Mg ha^{-1}) sustains productivity in areas having sodic groundwater for irrigation (Sheoran et al., 2021 b).
Calcareous sandy loam soil with irrigation led by sodic groundwater in the rice-wheat system	Soil pH1:2 7.9 and 8.5, $CaCO_3$ between 2.8 and 4.4%; ESP 3.4-4.5% (I) and quality of irrigation water RSC 9.7 me l^{-1}, and SAR 11.5; The pH of untreated soil raised upto 10.4 and ESP touched 58.6%; F) when the amended soil (GR50 + farmyard manure) having pH 9.3 and ESP 38.8%; F; GR50 + green manure (20 Mg ha^{-1}) (pH 9.4 and ESP 39.5%; F) GR50 + wheat straw (@ 6 Mg ha^{-1}) (pH 9.6 and ESP 40.3%; F)	15 years (1991–2006)	Organic amendments mobilise $CaCO_3$ in calcareous soils and produce solubilize Ca ($Casol^{2+}$) and the $Casol^{2+}$ lower down the dependency on gypsum in sodic water irrigate for achieving sustainable yields (Choudhary et al., 2011) .
Iron pyrite (has 22% of total S); 8% of soluble sulfur) applied @75GR			
Sodicity reclamation by application with iron pyrite (have 22% of total S); 8% of soluble sulphur applied @75GR reclamation experiments; Rice-wheat	The initial soil pH1:2 10.4 and ESP 87%. (Site-I) (I); soil pH1:2 10.6 and ESP 98% and quality of irrigation water good for location but irrigation water having alkalinity of RSC 8.4 me l^{-1}, and SAR 13.7 (Site-II) (I); Pyrites reduced soil pH1:2 9.2 and ESP 29% (Site-I) soil pH1:2 9.4 and ESP 32% (Site-II) (F)	1 year 1992-1993	S content in pyrite varies between 6-8% at the time of its application (Sharma and Swarup, 1997).

Table 7.1: Gypsum and alternate amendment in the reclamation of sodic soils; I: initial soil; F: after amending

Application of phosphogypsum (PG) 75GR @10.0 Mg ha^{-1} in sodic soil; Rice-wheat	PG declined soil pH1:2 8.5 and ESP 18.3% (F) compared to soil pH1:2 9.8, $CaCO_3$ 2.1%; ESP 38.5 (I)	Three years (2006-09)	PG neutralized soil pH and ESP and improved the yield of rice and wheat than the equivalent dose of mined gypsum. Further, PG improved the soil physical, chemical and biological properties (Nayak et al., 2013 b).
Inorganic polymer: polymeric aluminium ferric sulfate (PAFS) 15 Mg ha^{-1} (~ 0.6% of the dry weight of soil in the 0-15 cm soil layer)			
Flue gas desulfurization (FGD) gypsum: synthetic gypsum produced as a by-product of industrial processes			
Halophytes cultivation in Chongming Island, the shore of Yangtze River, China	The FGD application @15.0, 30.0, 45 and 60 Mg ha^{-1} declined soil ESP up to 32, 21, 19 and 16% (F) compared to soil pH1:2 9.1; ESP 37% (I).	Two-year field experiment (2011-13)	FGD increased the concentration of Ca^{2+}sol on the soil cation exchange sites thereby increasing salt leaching efficiency (Li et al., 2015).
Elemental S° (average diameter of 0.075 cm) application decrease S° (500 µg g^{-1} soil) in Ropar, Punjab; silty loam alkaline soil	S° reduced soil pH1:2 9.7 at 60 water-filled pore space (WFPS) after 42 days of incubation); and soil pH1:2 8.8 at 120 WFPS after 42 days of incubation (F) compared to the initial soil alkalinity (pH1:2 10.2); $CaCO_3$ 3.8% and ESP 31.3% (I).	Laboratory incubation study	S° lower down the pH of sodic soil under saturated (thin layer of overlying surface water) and aerobic (60% WFPS) (Jaggi et al., 2005).
Wood chip biochar (WBC), biosolids co-compost (BSC), and green waste compost (GWC) were applied @ 75 Mg ha^{-1} in saline-sodic clay loam soil in San Joaquin Valley, California	Soil pH1:2 8.19; EC_e 23.1 dS m^{-1}; ESP 24.3% (I) and irrigation water EC_w 1.0 dS m^{-1}; SAR 4.1;WBC lowered down soil pH1:2 8.0; leached EC_e 4.1 dS m^{-1}; and declined ESP 1.5%; BSC declined soil pH1:2 7.9; ECe 4.15 dS m^{-1}; and ESP 1.0%; and GWC declined soil pH1:2 7.8; EC_e 4.1 dS m^{-1}; and ESP 1.5% (F).	Treated soils were incubated for thirty days and then leached with reclaimed water	Biosolids compost, green waste compost and biochar improved the physical and chemical properties of a saline–sodic soil when leached with reclaimed water chaganti crohn, 2015.

Sodicity induce stress	Soil property improvement Initial (I) and final (F) soil	Duration of experiments	Recommendations
Acidified rice straw biochar (ARSB) and acidified dicer wood chips biochar (ADWCB) were applied @ 110 Mg ha^{-1} in saline-sodic Karfun region, Iran	ASRB and ADWCB neutralized reduced EC_e 1.8 and 1.6 dS m^{-1} and SAR 11.0 and 9.5 (F) than the soil pH1:2 7.2; EC_e 15.5 dS m^{-1}; SAR 20.1, (I) and irrigation water EC_w 1.0 dS m^{-1}; SAR 4.1, $CaCO_3$ 9.3% (I)	The soil was incubated with acidified biochar followed by leached with moderate SAR water (2.5)	The solubilization of acidified biochars supplies H^+ which dissolute $CaCO_3$ and supplies Ca^{2+} in soil solution. The Ca^{2+} and H^+ in the soil solution replace the Na^+ that reside in soil colloids and facilitate the leaching of Na^+ from the saline-sodic soil (Sadegh-Zodeh et al., 2018).
Clayey texture saline-sodic of northwest India by conjunctive use of municipal solid waste compost @ 10 Mg ha^{-1} with mineral gypsum 25GR	GR25 gypsum + Delhi compost reduced soil pH1:2 8.7; EC_e 1.1 dS m^{-1}; GR25 gypsum + Karnal compost declined soil pH1:2 8.9; EC_e 1.0 dS m^{-1}(F) than the initial soil pH1:2 10.7; EC1:2 12.2 dS m^{-1}; ESP 70%; GR100 22.7 Mg ha^{-1} (I)	Treated soils were incubated for thirty days and then leached with SAR water	The purity of agricultural-grade gypsum is an issue, therefore conjunctive use of GR25 and 20 Mg ha^{-1} MSWC can be advocated for reducing alkalinity in soil under the use of poor-quality water (Sandha et al., 2020).
Coal combustion fly ash (FA) was applied to cultivate R-W in central Indo-Gangetic Plain, India.	25GR+2.5%(w/w) FA decreased soil 9.52, ESP 28.2% (F) than the soil pH1:2 10.1; EC_e 1.95 dS m^{-1}; ESP 69.7% (I). .	Feld experiment conducted during 2013–2014.	FA supplies of Ca and its Fe-Al sesquioxide upon hydrolysis produce moderately acidic pH. Therefore, the integrated application of 25GR + FA 2.5% application in sodic soil increased the yield to standard 50GR. This recommendation also increased soil organic carbon and improve the quantity of meso-aggregates (Mishra et al. 2019a).

7.3 Alternate management practice for sodicity reclamation

Here we critically pointed out the chemical amended used for sodicity reclamation technology which is very 'reactive' in nature and shows fast reclamation with high payback values. But these are costly affairs and depend on external logistics and may not always be available (Dagar et al., 2022). Oppositely, the 'adaptive' approach has the potential to improve the productivity of sodic soil by growing the salt-tolerant trees and cultivars in isolation or integration with crops (Plate 1). Chemical

amendments application and adoption of salt-tolerant crops/cultivars are effective to save ~ 75% of reclamation costs in sodic soils (Sharma et al., 2016). The organic acids liberate from plant roots mobilize the native calcite carbonates ($CaCO_3$) and release soluble Ca^{2+}sol, which take part in an exchange reaction with Na^+. Previous models demonstrate the feasibility of agroforestry systems for greening the degraded sodic soil by adapting the agroforestry model. The choice of species for alkali lands is determined by the ability of tree species to the survivability and withstand alkalinity and the toxic effect of Na^+ is the key point for the selection of agroforestry trees to grow in sodic soil. The mesquite (*Prosopis juliflora*), Horsetail She-oak (*Casuarina equisetifolia*), Babul, gum arabic tree (*Acacia nilotica*), Imli (*Tamarix articulate*), Eucalyptus (*Eucalyptus tereticornis*), Kikar (*Parkinsonia aculeata*) and Arjuna (*Terminalia arjuna*) have demonstrated a higher tolerance to sodicity (pH >10) (Dagar et al., 2001) and the potentiality for air-dry biomass production of these trees are 19-57 Mg ha^{-1} (Dagar, Singh, and Singh, 2001b). Trees can also be assisted in planting by using a 'pit-auger-hole tree planting technique' to prepare the planting dig because the sodicity creates a hard crust and the presence of *kankar* layer '$CaCO_3$-layer' make a hindrance for early root establishment of six-month-old sapling. Usually, a whole of 35 cm × 35 cm in dimension are prepared and a composite mixture of native soil, 3-5 kg of the amendment (gypsum), 8 kg farmyard manure, 10.0 g $ZnSO_4$, and a small quantity of insecticide for checking the termites are recommended to fill the dig for planting. Plantation of trees has multiple benefits viz., these produce fruits, fodder, timber, biomass and contribute towards environmental services such as carbon sequestration, increased the aesthetic values of the local environment, restore biodiversity and improve soil health with reduction of soil pH and ESP and increasing content in organic carbon (Singh et al., 1994, 2011, 2013; Datta et al., 2015) (Figure 7.1). In their long-term studies, Singh and Gill (1992), also reported positive phyto-remedial effects of trees raised on highly sodic soil in terms of reduction in pH, increase in organic carbon, and available P and K. Soil biological properties viz., microbial biomass carbon (MBC), nitrogen (MBN) and phosphorus (MBP) largely improve when tree based reclamation systems are adopted (Singh et al., 2012, 2022).





Plate 1: Trees and Fruit trees in sodic soil (pH 10.0) in Indo-Gangetic plain (Saraswati, Kurukshetra, Haryana) and Verisols (Barwaha, Khargone, Madhya Pradesh)

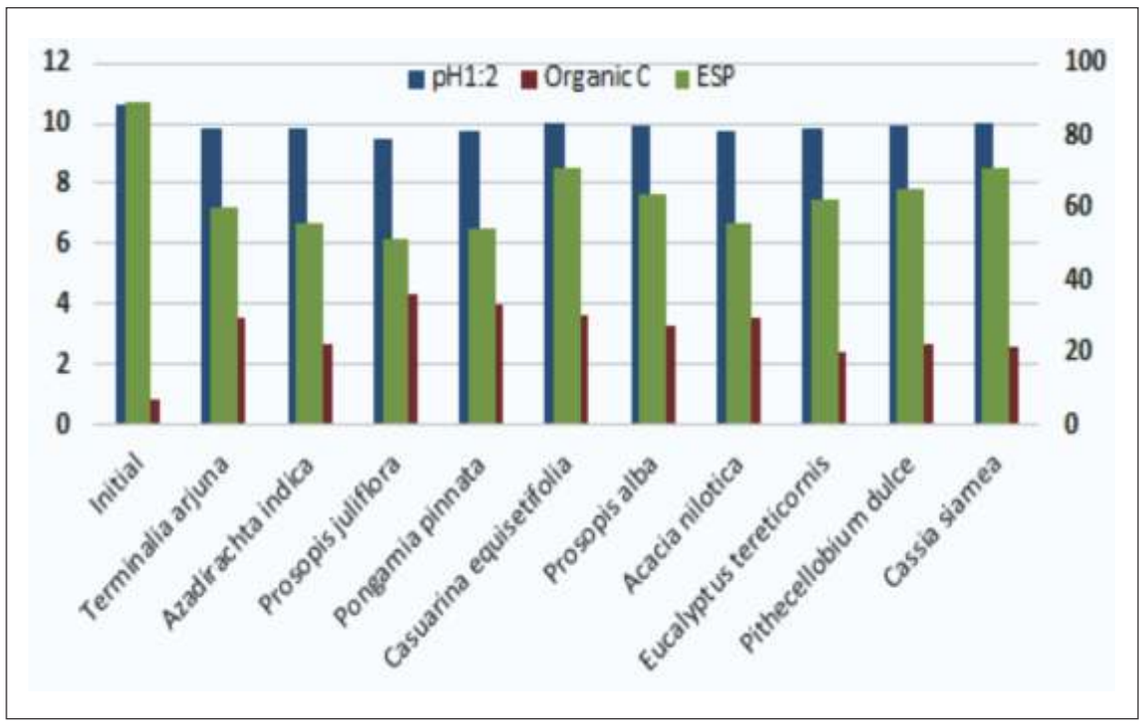


Figure 7.1: Ameliorative effects of trees on sodic soils at 0-15 cm soil depth after ten years of plantation; organic carbon (g kg^{-1}) and exchangeable sodium percent (ESP, %)

7.4 Conclusion

Soil sodicity is a serious issue principally to land degradation and subsequently, the threat to crop growth and yield in several irrigated commands and arid and semi-arid regions and ultimately undermine to achieve of the Sustainable Development Goals (SDGs), the Land Degradation Neutrality, and related environmental policies of Globe. The sodic soils are physicochemically and biologically disturbed, requiring definite reclamation amendments and cultural practices of rehabilitation for crop production. Therefore, the adoption of chemical, biological, hydro-technical, and agroforestry measures may be available options for greening the sodic soil. Gypsum is widely available, less in cost, and easy to handle therefore primarily used amendment for sodicity management. The agriculture segment is experiencing the matters of scarcity in the availability of reclamation grade gypsum and low-grade gypsum is available in pan India because there is an increasing gypsum consumption and it is foreseeable to grow at a yearly growth rate of around seven per cent from 2016-17 to 2021-22. Therefore, the conjunctive application of gypsum with organics amendments is advocated to reduce the dependence on the external supply of gypsum. Hence, promising amendments like pyrites, pressmud, and distillery spent wash are the choice for managing the rehabilitation of sodic soil. Evaluation of a few formulations like nanomaterials, polymers, acidified biochars, flue gas desulfurization gypsum (FGDG) and elemental sulfur-based formulation have the potentiality for substituting gypsum as an amendment. Integrated application of gypsum and the smart city waste compost application is a technical option for sodic soil reclamation programs. Now, large-scale field trials of low-cost alternative amendments are the need of the hour for sustainable and profitable use in sodic soils.

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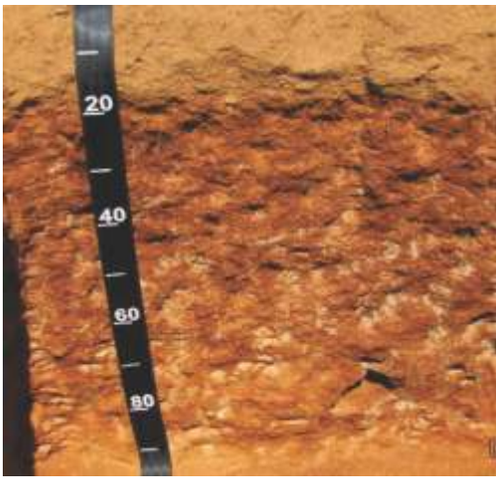
Sustainable Land Management in Rainfed Areas:
Practices and Approaches

CHAPTER
EIGHT







[1]G. Ravindra Chary, [2]V. Rama Murthy, V.K. Singh, K.B. Sridhar and B. Bhargavi

[1]ICAR-Central Research Institute for Dryland Agriculture Hydrabad, Telangana - 500 059

[2]ICAR-National Bureau of Soil Survey &Land Use Planning, Regional Centre, Bengaluru, Karnataka - 560 024

8.1 Introduction

Land is finite but the demand for various purposes is infinite. Land resources provide food and many other services including ecosystem services. Land provides an environment for agricultural production, but it is also an essential for improved environmental management, including source/sink functions for greenhouse gasses, recycling of nutrients, amelioration and filtering of pollutants, and transmission and purification of water as part of the hydrological cycle. Unabated land degradation is an issue of increasing concern globally. Land degradation threatens land quality and productivity, water quality, ecosystems, and livelihoods. This problem is further aggravated by climate change. UNCCD determined LDN as *"a state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems"* (UNCCD, 2016). Land degradation is defined as a negative trend in land condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity, or value to humans. (Special report on climate change and land Chapter 4 Land Degradation IPCC).

A study by Indian Space Research Organization (ISRO) reveals that about 97.85 mha area of the country is under land degradation i.e., 29.77% of the Total Geographic Area (TGA) of the country during 2018-19 out of which, about 23.79% is contributed by Rajasthan, Maharashtra, Gujarat, Ladakh UT, Jharkhand, Odisha, Madhya Pradesh and Telangana. Water erosion is the another major factor (11.01% in 2018-19) followed by vegetation degradation (9.15% in 2018-19) and wind erosion (5.46% in 2018-19) (SAC. 2021).

Land degradation (LD) and desertification affect around one-third of the land used for agriculture, undermining farmers' productivity, livelihoods, and food security (FAO, 2022). People in dryland areas, where land and water resources management are a challenge, are the most vulnerable in terms of the long-term ecosystem degradation. Competition between land uses, climate change, and urbanization along with demographic factors are main drivers for accelerating LD in the arid and semi-arid regions. The population and the food demand are expected to rise in the region, the challenge is how to increase productivity while using sustainably the natural resources. Interactions between land components (soil, water, vegetation/ biodiversity) and the effects of climate and human activities determine the productivity and sustainability of any land use system (FAO, 2019).

Soils and soil water will be adversely affected by climate change. First generation climate–carbon cycle models suggest that climate change will suppress carbon accumulation in soils and could even lead to a net loss of global soil carbon over the next century. Changes in soil carbon status is also a matter of concern under changing temperature and changing rainfall regimes, soil carbon not only important for growth and development of the crop but also for retention of water and nutrients and as an energy source for decomposition process in the soil. The risk of increased erosion is imminent in soils of dry agroecosystems. High and extreme precipitation will increase runoff primarily due to the inability of the soils to absorb and hold water. Extended dry periods will reduce vegetation cover which will result in substantial runoff. Such erosion events occurring frequently will lead to ecosystem change and also loss of soil nutrients. In addition, aridity can hinder surface decomposition and nutrient recycling, thereby affecting crop productivity.

8.2 Land degradation neutrality

The concept of land degradation neutrality (LDN) was to have more effective policy response globally to land degradation. Further, LDN was adopted as target for Sustainable Development Goal 15 and building capacity to achieve LDN is a primary goal of the UNCCD.

LDN is defined as *"a state where by the amount and quality of land resources necessary to support*

ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems". It aims to maintain the world's resource of healthy and productive land through a dual-pronged approach of measures to avoid or reduce land degradation, combined with measures to reverse existing degradation, such that losses are balanced by gains. India has committed to achieve LDN in 26 mha by 2030.

The goal of LDN is to sustain and improve the stocks of land-based natural capital and the associated flows of ecosystem services, to support the future prosperity of humankind. The objectives of LDN are: i) to maintain or improve the sustainable delivery of ecosystem services, from natural and managed ecosystems. This includes maintaining or improving productivity of land to enhance food security, and increasing resilience of land systems and populations dependent on them; ii) to seek synergies with other social,economic and environmental objectives through coherence between policies and measures that address separate environmental and development objectives, and iii) to reinforce responsible and inclusive governance of land. Govern land for the benefit of all, with emphasis on protection of land tenure rights of vulnerable and marginalized people. Avoiding and reducing land degradation on managed land requires the adoption of sustainable land management practices that seek to maintain land-based natural capital, for sustained delivery of ecosystem services. Reversing land degradation requires interventions that improve land-based natural capital, through restoration or rehabilitation. Land degradation can be : i) avoided by addressing drivers of degradation and through proactive measures to prevent adverse change in land quality and confer resilience, via appropriate regulation, planning and management practices; ii) reduced or mitigated on agricultural and forest land through application of sustainable management practices and iii) some of the productive potential and ecological services of degraded land can be restored or rehabilitated through actively assisting the recovery of ecosystem functions (Cowie et al., 2018).

Rainfed areas are defined as areas primarily dependent on rainfall and undependable groundwater for agriculture and allied activities. The rainfed areas shall accordingly include, i) rainfed cultivated area as the difference between net sown area (NSA) and net irrigated area (NIA), ii) irrigated area with undependable groundwater, iii) permanent pastures and other grazing lands, iv) cultivable waste lands, v) current fallows and vi) other fallow lands (NRAA, 2020). Rainfed agriculture is practiced in about 52 percent of net cropped area. It contributes 44% of food grains and supports 40% and 75% at human and livestock population, respectively and endowed with rich biodiversity. Besides this, it supports two third of animal population and a large area of horticultural crops. Thus, rainfed agriculture contributes immensely to country's food production and economy.

Out of 138.3 m total operational land holdings in the country, 58.14 m operational land holdings are totally unirrigated out of which 85 % account to marginal and small operational holdings (37.06 m marginal and 11.69 m small) while the total operational holdings under partly irrigated operational holdings are 17.21 m out of which 80% marginal (9.6 m) and small (3.49 m) operational holdings (DES, 2011). The challenge is to sustain these unirrigated and partly irrigated operational holdings in respect of stabilized productivity and profitability along with enhanced livelihoods at the backdrop of the twin problems of unabated land degradation and impacting climate change/variability. The spatial variability of soils in rainfed agroecosystems is typically associated with Entisols, Inceptisols, Alfisols, Vertisols and Aridisols. The major soil constraints that are limiting productivity of rainfed crops are shallow depth, low Plant Available Water Capacity (PAWC), sub-soil hard pans, very low subsoil saturated hydraulic conductivity, imperfect soil/land drainage, sub-soil gravelliness, calcareousness, low soil organic carbon, multiple nutrient deficiencies (Table 8.1).

Table 8.1: Major soil constraints in rainfed agroecologies

Climate/ Agroecological - subregion /Length of growing period	Major soil type(s) (Soil subgroups)	Major soil constraints	
		Physical	Chemical
a. Cold Arid			
1.1, 1.2 AERs <90 days	Skeletal soils (Typic Cryorthents, Typic Cryorthids)	Shallow depth, sandy texture, inadequate leaching, very low PAWC	Calcareousness, alkaline, low to medium organic matter
b. Hot Arid			
2.1,2.2,2.3, 2.4 AESRs <90 days	Desert and saline soils (Typic Camborthids, Typic Torripsamments, Typic Calciorthids, Typic Natrargids, Typic Salorthids, Ustochreptic Camborthids, Typic Paleorthids	Sandy texture, very low PAWC	Moderately calcareousness, alkaline, low organic matter
3.0 AESR <90 days	Mixed red and black soils (Typic Rhodustalfs, Typic Paleusterts)	Subsoil hard pans, low to medium PAWC	Slightly acidic, high sub soil density, alkaline, sub soil sodicity
c. Semi Arid			
4.2 , 4.4, 6.1, 14.1 AESRs 90-150 days	Alluvial soils (Typic Ustochrepts Fluventic Ustocrepts, Typic Eutrochrepts, Lithic Ustorthents)	Coarse soil texture, low to moderate PAWC	Multiple nutrient deficiencies
5.1,5.2,5.3, 6.1,6.2,6.3, 6.4 AESRs 90-150 days	Black soils Vertic Ustocrepts, Typic Chromusterts , Entic Pellusterts, Vertic Haplaquepts, Vertic Halaquepts, Typic Pellusterts)	Swell-shrink potential, very low subsoil saturated hydraulic conductivity	Slightly to strongly alkaline, calcareousness, N, P, Zn. S and B deficiency
7.1,7.2,7.3 AESRs 90-150 days	Mixed black and red soils Udic Rhodoustalfs, Typic Pellusterts, Typic Chromusterts, Typic Haplustalfs	Red soils: gravelliness, low PAWC, high sub soil bulk density. Black soils: very low saturated hydraulic capacity, imperfectly soil drainage	Low N, P, Zn, strongly to very strongly alkaline, calcareousness
8.1,8.2,8.3 AESRs	Red loamy soils (Typic Haplustalfs, Vertic Ustropepts, OxicPaleustalfs, Oxic Rhodustalfs, Typic Rhodustalfs	Gravelliness, low to medium PAWC, fine sub soil texture	Moderately alkaline, low CEC, multiple nutrient deficiencies (N, P, Zn)
d. Sub-humid			
10.1,10.2,10.3,10.4 AESRs 150-210 days	Black soils (Vertic Ustochrepts Udic Chromusterts, Entic Chromusterts, Typic Chromusterts)	High shrink swell potential, slowly permeability, high subsoil compaction	Calcareousness, alkaline, N, P, Zn deficiency

10.4 AESR 150-210 days	Red soils (Typic Plinthustalfs)	Sub soil gravelliness, low PAWC	Acidic, P fixation
11.0 AESR 150-210 days	Black soils (Entic Chromusterts)	Imperfectly drained, very slow saturated hydraulic conductivity in sub soil, gilgai micro relief, high shrink swell potential	Alkaline, calcareousness
	Red and yellow soils (Udic Rhodustalfs)	Gravelly sub soil, moderate permeability	Mildly acidic, low in N, P, B and Zn
12.1,12.2,12.3 AESRs	Red and lateritic soils (Typic Haplustalfs, Typic Plinthustalfs, Typic Haplustults)	Shallow depth, gravelly like quality sub soil, low PAWC, High bulk density of sub soil	Moderately to mildly acidic, low CEC, moderate to high P fixation, low in N, P, Zn, B, Ca, Mg, S, Mo, toxicity of Fe, Al, Mn
	Tarai soils (Aquic Hapludolls)	Weak soil structure, coarse to granular A-horizon, imperfect drainage	Calcareousness, alkaline, deficiency of N, P, Zn.
e. Humid to Per-humid			
14.2,14.3,14.4,14.5 AESRs >210 days	Brown forest and Podzolic soils (Typic Haplustalfs, Mollic Haplaquepts, Dystric Eutrochrepts, Lithic Udorthents, Typic Hapludolls)	Weak soil development, imperfectly drained, low PAWC	Mildly acidic to mildly alkaline
15.1,15.2,15.3,15.4,16.1 AESRs >210 days	Alluvial soils Aeric Fluvaquents, Fluventic Eutrochrepts, Typic Dystrochrepts, Aeric Haplaquepts, Typic Haplumbrepts, Umbric Dystrochrepts)	Medium to excess leaching of bases.	Mildly alkaline to strongly acidic, low to medium base saturation, moderate to low CEC, P fixation
16.2,16.3,17.1,17.2 AESRs >210 days	Red and lateritic hill soils (Typic Arguidolls, Cumulic Hapludolls, Typic Haplumbrepts, Typic Udorthents, Ultic Haludalfs, Typic Paleudalfs)	Limiting soil depth, Loamy skeletal soils, excessive leaching	Moderately to strongly acidic, low available P.

Source: *Velayutham* et al. *(1999)*

The magnitude of soil loss ranges from 5 to 150 t/ha/year depending on soil type, land use and slope. The multiple nutrient deficiencies in soils of rainfed crops and horticulture crops estimated to be 89% for N; 80 % for P; 50% for K; 41% for S; 48% for Zn; 33% for B; 12% for Fe; 13% for Mo and 5% for Mn. The declining factor productivity of fertilizers in rainfed agriculture is a matter of concern. Ensuring optimum fertility of soils in the backdrop of declining animal population is a key challenge. With the expected productivity levels and crop diversification, the demand for nutrients is bound to increase several folds. The soil organic carbon, which is a seat of major soil processes and functions, is 5 g/kg in soils in rainfed areas whereas the desired level is

11 g/kg soil. A severe depletion of SOC stock, to below the threshold level in the root zone, has adverse effects on biomass production, root biomass, residues recycling and agronomic yields because of reduction in the use efficiency of added inputs. Although about 80 mt of crop residues are produced annually in rainfed areas, their recycling is not done due to competitive uses and burning.

8.3 Sustainable Land Management

There are opportunities to avoid, reduce and reverse the negative trend in favour of sustainability and resilience. It will require identifying areas that are suited for applying sustainable land and water management practices and creating an enabling environment that assists land users to adopt these practices. Sustainable land management is the use of land to meet changing human needs (agriculture, forestry, conservation, infrastructure etc.), while ensuring long-term socio-economic and ecological functions of the land. Sustainable land management (SLM) involves a range of complementary measures for the protection, conservation and sustainable use of land resources (soil, water, biodiversity) and the restoration or rehabilitation of degraded natural resources and their ecosystem functions (Montanarella *et al.*, 2018). Sustainable land management is a building block for sustainable agricultural development, and it is one of the key elements in SDGs. Sustainable agricultural development, conservation of natural resources, and promoting sustainable land management are key objectives, and increasingly are being included in all agricultural development and natural resources management projects/ programmes.

Sustainable land management combines technologies, policies, and activities aimed at integrating socioeconomic principles with environmental concerns, so as to simultaneously:

- maintain and enhance production (productivity)
- reduce the level of production risk, and enhance soil capacity to buffer against degradation processes (stability/resilience)
- protect the potential of natural resources and prevent degradation of soil and water quality (protection)
- be economically viable (viability)
- be socially acceptable, and assure access to the benefits from improved land management (acceptability/equity)

SLM pursues to complement the often-conflicting objectives of intensified economic and social development while sustaining and intensifying the ecological roles of the land resources. Basically, practicing the principles of SLM is amongst the few possibilities which will enable income generation without jeopardizing the sustainability of land resources as a basis of production (Noe, 2014; Global Environment Facility, 2011). SLM includes not only soil and water conservation as a means for a sustained management of land, but also practice of agricultural activities on different land units which are capable to support arable and non- arable activities and growing of crops on suitable land with best management practices.

8.4 Sustainable land management in Rainfed areas: Practices

A combination of protection measures and wide-scale implementation of SLM practices are involved to achieve LDN with agroecoogy-specific strategies and practices. The LDN conceptual framework specifies a minimum set of three indicators to reflect the key processes already used for UNCCD reporting and proposed for the SDGs. These three indicators are: land cover, land productivity and carbon stocks. Furthermore, these indicators are complementary i.e., land cover is a highly responsive measure, reflecting land use dynamics, land productivity captures relatively fast changes in ecosystem function, while soil organic carbon reflects slower changes resulting from the net effects of biomass growth and disturbance/removal and is an indicator of resilience (Cowie et al., 2018).

8.4.1 Agro-ecology specific soil and water conservation measures

8.4.1.1 Terrace level measures

Contour Bunds: Contour bunds are laid across the major land slope along the contour lines in the areas having 1.5 to 6% land slope and having less than 600 mm annual rainfall. The minimum height of contour bund is 50 cm with a cross section of 1.61 m^2 having a vertical interval of 0.9 m and

the horizontal interval between the bunds may vary from 50 to 70 m depending on the land slope. Bunds are stabilized in 2 to 3 years by growing local grasses on them and are particularly recommended for red soils. The surplus runoff is safely disposed through waste weirs.

Graded Bunds: The graded bunds are constructed with a longitudinal grade of 0.2 to 0.4% having a vertical interval of 0.75 m to divert the runoff from the fields. The cross section area of the bund is 0.83 m^2 and the horizontal distance is 60 to 70 m. These bunds are more suitable for black soils with greater water logging in the periods of intense rainfall. With adequate vegetation the height of the bunds can be reduced to 50 cm. These bunds are recommended for the soils having less than 6% land slope. The graded bunds are connected to the water ways or water harvesting structures with waste weirs. In the watersheds soil conservation measures (bunding, trenching, drop structures, farm pond, nala bund, check dams, etc.,) have reduced runoff and soil loss.

8.4.1.2 Inter-terrace land management ractices

The sustainable management of soil physical environment has a significant role in water and nutrient uptake and losses, pollutant transport and also emission of greenhouse gases from soil. In rained agriculture, managing optimum soil physical environment are essential not only for sustainable management of soil and water resources but also for realizing yield potential of crops. In broad sense, the soil physical environment in rainfed regions can be improved through a) building *in situ* moisture reserves to tide over the recurring drought spells b) preventing loss of stored soil moisture (Table 8.2).

The approaches were on building in situ moisture reserves to tide over the recurring drought spells, disallowing subsequent loss of soil-profile stored moisture. Applicability of techniques so developed varied with the soil hydraulic characteristics. *In situ* moisture practices improve soil structure and porosity, increase infiltration and hydraulic conductivity, and consequently increase soil water storage that help crops to withstand moisture stress. These practices are agroecology specific i.e. physiography, rainfall pattern, soil type and crop. Off-season or summer tillage coinciding with pre-monsoon showers increases rainwater infiltration, moisture conservation and efficient weed control.

Subsoiling: Subsoiling in Vertisols in alternate year with horizontal spacing of 1.5 m or 2.0 m is recommended for Marathwada region of

Seasonal rainfall (mm)			
< 500	500-700	750-1000	> 1000
• Contour cultivation with conservation furrows • Ridging • Sowing across slopes • Mulching • Scoops • Tied ridges • Off-season tillage • Inter-row water harvesting systems • Small basins • Field bunds	• Contour cultivation with conservation furrows • Ridging • Sowing across slopes • Scoops • Tied ridges • Mulching • Zing terrace • Off-season tillage • Broad bed and furrow system (BBF) • Inter-row water harvesting system • Small basins • Field bunds • Subsoiling	• BBF (Vertisols) • Conservation furrows • Sowing across slopes • Tillage • Lock and spill drains • Small basins • Field bunds • Vegetative bunds • Zing terrace • Subsoiling	• BBF (Vertisols) • Field bunds • Vegetative bunds • Subsoiling

Table 8.2: Recommended *in-situ* moisture conservation measures for various rainfall zones in India

Maharashtra and it increased the yield of soybean whereas in scarcity zone of Andhra Pradesh, subsoiling in Alfisols with chisel plough @ 1 m distance for every two years increased the yields of pigeonpea, castor, groundnut, pearlmillet, cluster bean and castor.

Tillage Practices : Summer/off-season tillage has been found to be useful in increasing rainwater infiltration, retention of rainwater and minimizing the water evaporation by 'mulching' effect. In medium deep black soils in Southern Rajasthan, summer deep ploughing with raised bed of 40 cm width is recommended. On Alfisols, the problem of crusting and sealing is encountered during early stages of crop growth resulting in uneven germination and plant stand. Crust formation in Alfisols can be managed through shallow tillage imposed as additional intercultivation from sowing to the crop canopy formation were effective in breaking the crust, increasing infiltration rate, reducing runoff and soil loss and greater increase in crop yields especially during normal and low rainfall years (Pathak and Laryea, 1995). Under stress conditions, shallow tillage as an additional intercultivation has been found to be effective in breaking up the crust, improve infiltration and reduce moisture losses through evaporation by creating dust mulch. Deep ploughing is taken up to break hard pan and it improves physical characteristics of black soils. It has to be done to a depth of 22 cm (tractor plough) in Vertisol once in 3 years for faster penetration of rain water, to eradicate pernicious weeds which in turn results in higher crop yields. Deep tillage in alternate year and deep ploughing in alternate set row furrows up to 25 cm depth and application of FYM @5 t ha^{-1} is recommended for Northern Saurashtra for obtaining higher yield of groundnut. Primary tillage with Vibro Chiesel plough in maize is recommended for Southern zone of Rajasthan. In chronic drought prone areas, deep tillage (20-30 cm) was found specifically applicable to soils having textural profiles or hard pans. Under uni-modal (<500 mm) rainfall situation in semi arid regions with shallow Alfisols, sowing across the slope and ridging later was useful. It assisted in greater rainwater absorption and control of pernicious weeds. Extensive tillage of sandy soils (common to desert areas) made them more vulnerable to wind erosion. Superficial scraping to eliminate weeds was found adequate. Tillage increases macropores proportion which lead is drain out water rapidly after heavy rain (AICRPDA, 2003).

Levelling and bunding: Levelling of the soil and bunding is the simplest and most important operation required to effectively utilize the rainwater and uniform distribution of fertilizers and seeds under rainfed situations. Different types of bunds are suggested depending on soil type and rainfall pattern. For Alfisols having slopes more than 1.5%, contour bunding is found to be the most promising. Graded bunds are suggested in areas having higher rainfall with less permeable, deep heavy soils.

Contour cultivation : It is recommended for all types of soils having rainfall up to 1000 mm and slope varying from 0.5 to 4%. In some situations, it's desirable to provide a small slope along the row (cultivation across the slope) to prevent runoff from a large storm breaking over the small ridges formed during the contour cultivation.

Conservation furrows : Conservation furrows are made by opening furrows parallel to rainfed crop rows across the land slope in 3 to 4 weeks after the germination of the main crop. During runoff causing rainfall events, the rainwater gets concentrated within these furrows, infiltrates into the soil (root zone) and is available to the crop for meeting the evapo-transpiration demand.

Ridge and furrow systems : Opening of furrows at 50 to 60 cm apart across the slope in medium to deep black soils, after completion of primary tillage, during the second fortnight of June helps to lay out the field into ridges and furrows. This can be done through a ridger/plough attached to either tractor or bullocks. Cultivation of crops under ridge and furrow system across the major land slope with a gradient of 0.2 to 0.4% in land having 1 to 3% slope will conserve more rainwater *in-situ*. This is suitable for widely spaced crops with 60 cm or more row spacing. A field length of 60 to 90 m is optimum for cultivation of crops with ridges and furrows.

Broad bed and furrow system : On black soils, the problem of water logging and water scarcity occurring during the same cropping season are quite common. There is a need for an in-situ rainwater conservation and proper drainage technology on deep black soils to protect the soil from erosion throughout the season and to control

runoff. A raised land configuration "Broad-bed and furrow" (BBF) system has been found satisfactorily to attain these goals. This technology is more successful in medium to deep black soils having mean annual rainfall varying from 500 to 1300 mm with a maximum slope up to 5%. The BBF system consists of a relatively raised flat bed or ridge approximately 95 cm wide and shallow furrow of about 55 cm wide and 15 cm deep across the slope on a grade of 0.2 to 0.6% for optimum performance. The bed width also depends on the crops, soil type, and rainfall. After the direction of cultivation has been set out, based on the topographic survey, furrow making is done.

Raised bed and furrow System/ Raised and sunken bed system : Raised and sunken bed system consists of alternate raised and sunken beds and the width of sunken beds vary with mean annual rainfall. For example, in high rainfall areas (>1000 mm), 8 m wide raised beds alternated with 4 m wide sunken beds having elevation difference of 150–200 mm are suggested. The runoff from raised beds, where an upland *kharif* crop is seeded is captured in the adjacent sunken bed supporting a relatively highwater tolerant crop (rice). This system is advocated for Vertisols of high rainfall regions (> 1000 mm).

Compartmental bunding : In scarcity zone of Maharashtra and Northern dry zone of Karnataka, after receipt of southwest monsoon, the fields having slope of less than 1% are harrowed for weeds removal. Compartmental bunds of 4.5 x 4.5 m and 3 x 3 m on lands having slopes of 2% and 3%, respectively are formed either with tractor drawn/bullock drawn bund former (Fig. 8.1). This technology ensures rational moisture distribution as well as optimum moisture for better germination of seeds.



Figure 8.1: Water impounded in the compartment bunds

Continuous contour trenches : Contour trenches are in all slopes irrespective of rainfall conditions and for varying soil types and depths. Trenches can be continuous or interrupted. The size of the trench depends upon the soil's depth. Normally 1,000 to 2,500 cm^2 in cross section are adopted. The contour line was demarcated in the centre of the selected fields and parallel to these contour lines, continuous contour trenches (CCT) were excavated with cross section of 60 cm width and 30 cm depth. The interval between two adjacent CCTs depends on the recommended row spacing of selected fruit species. CCTs helped for higher productivity of agri-horti systems in Vidarbha region of Maharashtra Also in high rainfall intensity events, CCTs can be useful for draining excess runoff provided that all the CCTs should be joined at the end to the common drain.

Mulching : Mulching is referred as spreading various covering materials on the surface of soil to minimize moisture losses and weed population and to enhance crop yield. Mulching has also some other positive environmental effects such as temperature regulation of soil and plant roots, minimizes nutrient losses, cut down soil erosion and compactness, and improves physical conditions of soil. Mulches are of different types, including soil mulch, stubble mulch, straw or stover mulch, live mulch, plastic mulch and vertical mulch.

8.4.1.2 Crop residue management and carbon sequestration : Crop residues are a principal source of carbon which constitutes about 40% of the total biomass on dry weight basis. The organic C concentration in the surface soil (0-15 cm) largely depends on the total input of crop residues remaining on the surface or incorporated into the soil. Generally, farmers burn crop residues without recycling them. Therefore, shredding of crop residues to be mechanized. This will help in shredding of biomass into small pieces to facilitate easy mixing of the residue in the soil or compost/vermicompost pits. There are various methods of crop residue application to soil both in-situ and ex-situ.The in-situ system is an efficient method of recycling organic residues, since crop residues and animal waste are properly utilized directly into the soils with no nutrient loss. Higher yields with crop residues application result from increased infiltration and improved soil properties, increased soil organic matter and earthworm activity and improved soil structure after a period of 4 to 7 years. Annual inputs of biomass-C as crop residues significantly increased SOC sequestration and stock, following an asymptotic relationship between the SOC stock and the magnitude of the inputs of biomass C (Srinivasarao et al., 2012).

8.5 Sustainable land management in Rainfed areas: Approaches

Scientific land use planning is an important strategy for avoiding and or reducing land degradation in rainfed areas. Land Resource Inventory (LRI) is an assessment of the status and changing condition of soil, water and related resources at the field level. Lack of site-specific data, particularly on soils, and of situation-specific recommendations have been the causes of failure of most of the agricultural and other land-based development schemes that operated in the country in the past. A need was felt to fill the vital gap by generating site-specific soil and other land resources data. This could be systematically, efficiently and hence, effectively done by undertaking soil resource inventory using modern techniques, tools and facilities in a consortia mode. LRI at 1:10000 scale is expected to provide site-specific information needed for farm/ village level planning. It aims to provide the required site-specific database at village level. The detailed database generated at village level and its subsequent abstraction to mandal, taluk, district, state and country level will formulate the basis and provide the required information needed for prioritizing, initiating and executing any land-based developmental programmes.

8.5.1 Land management unit Approach

The LRI of several areas carried out in different states indicated lot of spatial variability in soils. Uniform management of fields often results in over-application of inputs in areas with high nutrient levels and under-application in areas with low nutrient levels (Ferguson et al., 2003). Application of variable rates of inputs has been proposed to avoid excessive use. Application of variable rates of inputs and to take up land based activities, needs partitioning of farmlands into land management units (LMU) that are homogenous with respect to soil properties like texture, depth, fertility etc. An approach to manage spatial variability within the region/fields is the identification of LMUs, which are subdivisions that have relatively homogeneous attributes in landscape and soil condition and can be used to implement SLM practices which results in enhancing land productivity, input use efficiency, and reduce environmental impact (Ferguson et al. 2003). The definition of classification of management zones, has been proposed as a cost-effective approach to improve crop management and reduce detrimental environmental impact (Khosla et al. 2002; Franzen et al., 2002).

ICAR- National Agricultural Technology Project (NATP) - Mission Mode Project on Land Use Planning for Managing Agricultural Resources - Rainfed Agro-ecosystem was implemented by 13 AICRPDA (All India Coordinated Research Project for Dryland Agriculture) centers in an area of

5258 ha in 16 microwatersheds across arid, semiarid and subhumid agro-eco-subregions. Based on the evaluation of the existing land use and land evaluation for suitability of crops, 932 on-farm trials were conducted in 603 ha at 1294 sites on 132 soil sub-groups on varying topo-sequences and the outcome distinctly indicated that in a micro-watershed at cadastral level (1:10000/25000) the scientific land use on a soila soil-landscape continuum couldcontinuum could enhance the land productivity from 20 to 50% compared to traditional land use (NATP-MM-LUP. 2006). The cadastral level soil-site specific cropping systems centred land use modules were developed/identified (Ravindra Chary et. al., 2008).

A methodology was developed to identify Land management Units (LMUs) (Ramamurthy et. al., 2016) and delineated 12 LMUs for Mysore district. The soil properties like texture, depth, landform and gravelliness and land qualities like landform, land use and climate were integrated to identify land units and production systems were super imposed on the delineated land units in GIS to identify the LMUs. Out of 12 LMUs, 3 are under irrigated and 9 under rainfed agriculture. LMU1 and 2 are canal irrigated areas and LMU3 is ground water irrigated. Therefore, one can find rice in LMU1 and 2 in all the seasons or minimum two seasons except tail enders. LMU 4 to 11 are red soils, whereas LMU 12 is black soil areas under rainfed condition. LMUs were evaluated for their suitability to major crops like rice, finger millet, cotton and tobacco crops. LMUs were evaluated for their suitability to major crops like rice, finger millet, cotton and tobacco crops. LMU 2 was found highly suitable for rice, LMU 7 for finger millet, LMU 5 and 7 for tobacco. LMU 7 was moderately suitable for cotton. LMU 2 dominated by very deep soils on very gently sloping lands in command areas whereas LMU 7 is characterized with deep soil on gently to very gently sloping land and 150-175 days length of growing period. In most of the LMUs nitrogen application is more than the recommended dose except LMU 3 for rice and LMU 4 for finger millet, whereas, in tobacco both N and P applications were more than the recommended. This indicated that farmers were applying higher doses of fertilizers, which may lead to adverse effects on soil environment and also increases the cost of production of crops. Under rainfed situation, though LMU 6 was rated only marginally suitable for most of the crops evaluated, however, actual productivity of crops is comparatively better. This is due to high input usage (N and K) and protective irrigation facilities. The inherent soil and climate limitations can be overcome by better management practices. Crop performance did not vary much within LMUs, because LMUs are homogenous with respect to climate and soil. Variation in crop performance in few LMUs was due to management practices adopted by farmers.

Based on the cadastral level soil resource information in the micro-watersheds, Ravindra Chary *et al*. (2005) developed Land Management Units (LMUs) for land resource management since these units are homogeneous and has a wider application. As a first step, the Soil Conservation Units (SQUs) and Soil Quality Units (SQUs) were delineated and secondly, the SCUs and SQUs are merged in GIS environment to delineate land parcels into homogenous Land Management Units with farm boundaries. A resilient, less risk prone farming system based on the land requirements and farmers' capacities can be developed to mitigate the drought and to address the unabated land degradation and imminent climate change. The SCUs are basically for soil and water conservation prioritized activities to mitigate drought and could be linked to programmes like MG National Rural Employment Guarantee Scheme (MGNREGS) in a watershed/ village to create physical assets like farm ponds etc. SQUs are to address soil resilience and improve soil organic carbon, problem soils amelioration and wastelands treatment and linked to various schemes and programmes in operational like National Horticultural Mission (NHM), Rashtriya Krishi Vikas Yojana (RKVY), etc. LMUs would be operational zed at farm level for taking decisions on arable, non-arable and common lands for cropping, agroforestry, agri-horticulture, etc., and further, for leaving the most fragile land parcels for ecorestoration. Rainfed land use planning modules should be based on these units for risk minimization, enhanced land productivity and income, finally for drought proofing.

LMU approach can also be used for evaluation of agroforestry systems both in arable and non-arable lands at agricultural landscape level. The allocation of land parcels for suitable land use types in arable lands and for eco-restoration in non-arable lands in various LMUs likely to

enhance land productivity and ecosystem services and likely to avoid and or reduce land degradation in long term.

8.5.2 Land capability approach

The earlier approach for avoiding and or reducing land degradation at landscape level is land use according to allocation of land capapbility. Land capability classification (LCC) is a system of grouping soils primarily on the basis of their capability to produce common cultivated crops and pasture plants without deteriorating over a long period of time. The capability is the inherent capacity of the land to perform at a given level for general land use (FAO, 1977). In this classification the arable soils are grouped according to their potentialities and limitations for sustained production of common cultivated crops that do not require specialized site conditioning or site treatment. Non-arable lands (soils unsuitable for long time sustained use for cultivated crops) are grouped according to their risks for soil damage if mismanaged. The capability of land is assessed on the basis of the native characteristics and suitability for agriculture, forestry, grazing, recreation and wildlife. And thus, the land is classified into different capability classes. This classification of land provides guidelines for rational use of land. Land capability classification provides guidelines for future orientation of land use (Singh and Dhillon, 1984). It is the soil and land use classification and therefore, a detailed soil survey is the basis of this classification. In fact, it is the quality of land, assessed on the basis of soil characteristics, external land features and similar environmental factors limiting land use. The information on this basis is useful for proper utilization and conservation of land.

8.5.3 Land suitability assessment approach (FAO, 1976)

Each plant species requires specific soil-site conditions for its optimum growth. The land suitability assessment provides the suitability or otherwise of the various land resources occurring in an area for major crops grown. This helps to find out specifically the suitability of the land resources like soil, water, weather, climate and other resources and the type of constraints that affect the yield and productivity of the selected crop. Land evaluation involves the assessment of land and soils for their potential for different uses involving matching the land qualities and requirements for the land use. For rationalizing land use, soil-site suitability for different crops needs to be determined to suggest the models for guiding the farming community to grow most suitable crop(s), depending on the suitability/ capability of each soil unit mapped. The adaptability of crops in one or the other area is the interaction between existing edaphic conditions and fitness of the cultivar under these conditions. Although, lot of data on crop production through experimentation have been generated by the SAU's and Crop Research Institutes. There is a need for land evaluation for various annual and perennial crop species to work out soil-site suitability models for optimizing land use and also for avoiding and or reducing land degradation. In the land evaluation, there are four steps namely (i) characterization of existing soil, climatic and land use conditions (ii) development of soil site criteria or crop requirements (iii) matching of crop requirements with existing soil and climatic conditions and (iv) choosing of the best fit among the crops and the selecting the same as the alternative crop strategy. Among the above four steps, the formulation of the soil site criteria to meet the crop requirements forms a vital and important step. For the development of crop requirements, one has to do either experimentation at each well characterized growing environment or take the help of published literature. Naidu *et al.* (2006) have compiled the soil-site requirement of major crops of India by reviewing published literature and consulting crop specific researcher teams.

Matching of crop requirements consists of comparing existing climate, soil and physiographic conditions with the soil-site criteria with respect to individual crop. On the basis of the degree and the number of limitations identified, the suitability class is established, viz., highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and unsuitable land (N1 & N2) for specific kind of land use. Land suitability subclasses are divided into land suitability units based on specific management requirements. The ratings used for defining each class are based on

the number and degree of limitations present. The S1 classes correspond to areas, which have a yield potential above 80% of the maximal attainable harvest within the climatic region of the area. This figure drops to 60% and 40% for classes S2, and S3.

In assigning the overall suitability class to any area, the limitation approach or law of the minimum is followed. According to this approach, even if all other factors are favourable for the crop and only one factor is likely to be a limitation, then that factor is given precedence in assigning the suitability class. The suitability classes and sub-classes are directly assigned to land units based on suitability criteria. A brief description of the orders, classes and subclasses used in the suitability assessment of major crops is given below:

Order S (Suitable)

Class S1 (Highly suitable) Land unit having no limitation for sustainable use or with not more than three slight limitations.

Class S2 (Moderately suitable) Land with more than three slight limitations but with not more than three moderate limitations.

Class S3 (Marginally suitable) Land with more than three moderate limitations but with not more than two severe limitations.

Order N (Not Suitable)

Class N1 (Currently not suitable) Land with severe or very severe limitations that may be overcome in time but cannot be corrected with existing knowledge at current acceptable cost.

Class N2 (Permanently not suitable) Land having limitations that will be very difficult to correct and use.

Participatory land use planning is a buzzword for achieving the different goals of the various stakeholders. In stressed ecosystems like rainfed areas, no single land use or single criteria has sustained the land productivities, income and ecosystem services. Thus, land use planning in rainfed regions should aim at increased land productivity in totality through various means from annuals to perennials by coping with aberrant weather and inherent unabated land degradation.

8.5.4 Productive Farming Systems : (A 3 x 3 Matrix Approach)

Productive farming systems are identified for drought prone regions based on annual average rainfall, land capability and soil order (Vittal and Ravindra Chary, 2007) (Fig. 8.2). Land use based farmstead plan state-of-the-art based agroforestry models linked to livestock and watershed management for soil and water conservation including water harvesting. Some of the subjects are hedge fencing, multipurpose tree species, bush farming, cereals/millets. Pulse/oilseeds/cotton, parkland horticulture, olericulture, floriculture cum IPM, home remedies, water harvesting, livestock, poultry, fisheries, apiary, etc. are some of the models suggested into higher value agricultural crops (medicinal, aromatic, dye yielding crops, etc.), and non-farm activities like value addition to agricultural products offer good scope for sustained increase in per capita income. Part of the farmstead could also be used for generating seed spices.

For the development of commons, these may be divided into small plots of 5-10 ha and can put on long lease of about 19 years to the user groups. The combination of systems such as fruit trees, silvi-pastures, multipurpose trees, or even pastures may be adopted on commons. Maximum number of trees per hectare may be limited by quantum of annual rainfall (product of rainfall in m and area in m^2) divided by volume of water one full grown tree transpires annually (a product of canopy area, surface area in m^2, and potential evapotranspiration in m per annum). Improved variety or new plant species suitable for the ecosystem and rejuvenation of social fencing of improved plant species may be attempted. In tree farming, the general cleanliness of the area is lost thus, encouraging new diseases and pests. Therefore, it is important to carry out weeding and form basins for the trees and furrows for *in situ* rainwater harvesting in the case of shrubs, grasses and fodder legumes.

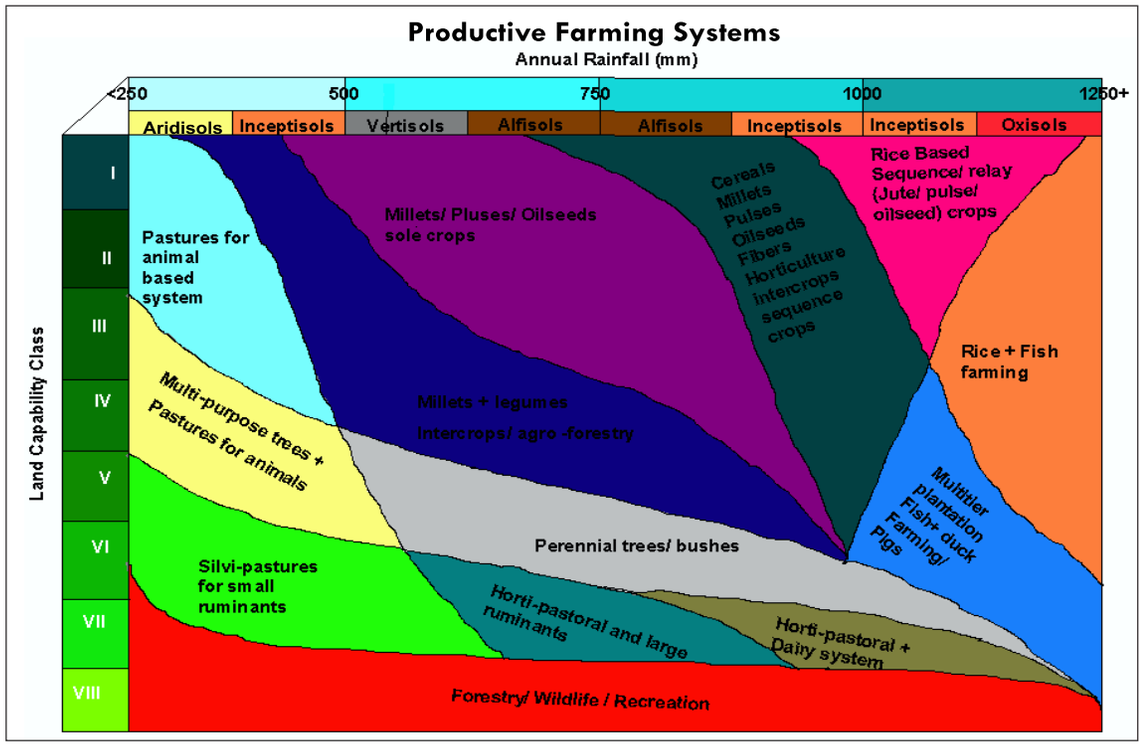


Figure 8.2: Productive farming systems matrix in rainfed regions

Alternate land use systems can provide stability of production and income through alley cropping, agroforestry, medicinal plants, horticulture, etc., in place of annual crops on marginal lands. They help in better soil and water conservation. Some promising alternate land use systems are shrub farming (henna, curry leaf, Jatropha, Karanji), horticulture systems (guava, ber, pomegranate, custard apple) and fodder species (Leucaena, glyricidia, Stylosanthes). At present, farmers' cropping systems are neither providing stability nor balancing input-output nutrient relations. Markets in the developed world are evincing a keen interest in organic farming. Rainfed agriculture involves fewer external inputs and provides good opportunities to adopt organic farming in hill and tribal districts of the country. It must be remembered that the objective of diversification is to spread risk, not to increase it through poorly conceived undertakings. Success or failure can depend on a number of factors; one of these is good information. Before plunging into new, costly ventures, the following advice is worth heeding. Anticipated benefits of crop diversification are alternative crops may enhance profitability, diversified rotations can reduce pests, labor may be spread out more evenly, different planting and harvesting times can reduce risks from weather, new crops can be renewable resources of high value products and soil health is taken care of land degradation is minimized. The emphasis here in agro-ecological analysis is on the processes and balance of resource supply and capture, and on the competitive and complementary relationships between the planned and unplanned (associated) biodiversity. Diversification strategies should be based on low external input strategies.

Agroforestry systems have attracted considerable attention as a sustainable pathway for enhancing the soil fertility. Trees contribute to nutrient build up through increased input of nitrogen through biological nitrogen fixation by trees, enhanced availability of nutrients resulting from production and decomposition of substantial quantities of tree biomass, greater uptake and utilization of nutrients from deeper layers of soil by trees and also through preventing soil and nutrient loss by way of controlling soil erosion (Nair *et. al.*, 2009). Improvement in organic carbon content, available N, P and K has been reported from different climatic regions involving both the leguminous and non-leguminous trees with varying density and the extent of improvement depends on the initial fertility status of the soil, age of the tree and the density of the trees in the system (Kaur *et. al.*, 2001).

Several studies have conclusively proved that inclusion of trees in the agricultural landscapes often improves productivity of the system while providing opportunities to create carbon (C) sinks. Carbon sequestration in agroforestry systems can be broadly divided into sequestration in to above ground and below ground plant parts. The amount of C sequestered largely depends on the agroforestry system put in place, the structure and function of which are, to a great extent, determined by environmental and socio-economic factors. Other factors influencing carbon storage in agroforestry systems include tree species and system management. The above ground carbon sequestration rates in some major agroforestry systems around the world are highly variable, ranging from 0.29-15.21 Mg/ha/yr. Substantial carbon is sequestered in below ground tree parts, part of which is added to the soil every year thus contributing to soil carbon.

Trees when planted on contour lines as erosion control structures arrest erosion by checking runoff and suspended sediment and help in stabilizing the conservation structures and acts as cover and reduce the impact of raindrop by enhancing the soil cover either with the live or dead tree parts. The effect of perennial vegetation in controlling erosion depends on number of factors such as canopy cover, ground vegetation, litter effects, root effects and changes in the physical properties of the soil (Wiersum, 1985). Besides arresting erosion, the trees on these structures provide fodder during the fodder scarce period and fuel wood which are valuable particularly under rainfed drought conditions. Further, in the recent years, high intense unseasonal rainfall events up to 150 mm/hr during crop season are experienced in various parts of the country causing crop and soil losses, particularly in black soils regions. Under such weather extremities, agroforestry systems are likely to minimize risks of total failure and provide some income to the farmers and with ecosystem benefits of reduction in soil loss.

8.6 Government's broad approach towards addressing land degradation through various schemes

Government of India, in the recent past has formulated National Policy on Agroforestry (NAFP, 2014) to sustain livelihoods, increase farmers' income, sequester carbon and to make agriculture resilient to predicted climate change scenario. The major policy goals are setting up a National Agroforestry Mission or an Agroforestry Board to implement the National Policy by bringing coordination, convergence and synergy among various elements of agroforestry scattered in various existing missions, programmes, schemes and agencies pertaining to agriculture, environment, forestry, and rural development sectors of the Government; improving the productivity, employment, income and livelihood opportunities of rural households, especially of the smallholder farmers through agroforestry; meeting the ever increasing demand of timber, food, fuel, fodder, fertilizer, fibre, and other agroforestry products; conserving the natural resources and forest; protecting the environment and providing environmental security; and increasing the forest / tree cover, there is a need to increase the availability of these from outside the natural forests. Several agroforestry practices/models have been developed by ICAR research institutes and State Agricultural Universities for different agroclimatic regions of the country. Such practices/models need to be upscaled by incorporating location specific adjustments.

Government of India (GoI) has already initiated few schemes to achieve LDN such as Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), National Rural Employment Guarantee Scheme (NREGA), Soil Health Card Scheme, Namami Gange, Rashtriya Krishi Vikas Yojana and National Afforestation Programme which are having vast potential to achieve LDN. National Rainfed Area Authority (NRAA) and Department of Land Resources, MoRD revised Common Guidelines for New Generation Watersheds. In the revised guidelines much emphasis is given on avoiding and or reducing land degradation, focus on non-arable lands, biomass generation, climate proofing and innovative institutional mechanisms.

8.7 Way forward

SLM practices in rainfed areas can generate both direct and indirect benefits and thus constitute a potentially important means of generating "win-win" solutions to addressing LDN. In terms of private benefits to farmers, by increasing and

conserving land-based natural capital. SLM practices contribute to improving soil fertility and structure, adding high amounts of biomass to the soil, causing minimal soil disturbance, conserving soil and water, enhancing activity and diversity of soil fauna, and strengthening mechanisms of elemental cycling (Woodfine, 2009).

Some action points suggested are:

- LDN indicators should be supplemented by national/sub-national level indicators to cover the land-based ecosystem services that are important in each context. Indicators of social and economic impact of LDN should also be included (Cowie et al. 2018).
- Recognize role of land managers, including indigenous people and local communities in the design, implementation and evaluation of sustainable land management practices.
- Growing of trees in association with crops in a unified agroforestry system helps in improving soil quality, sequestration of carbon to moderate global warming threat and other environmental and eco-system services. The farmers adopting agroforestry in their farmlands need to be compensated in monetary terms in the shape of carbon credits / other incentives. In the recent past, only a few projects in select states have been implemented to provide carbon credits to the selected stakeholders. A uniform policy need to be put in place to promote agroforestry for carbon sequestration, natural resource upgradation and other environmental services.
- Integrated land use planning for LDN could become the instrument for landscape management to deliver multiple environmental and socioeconomic objectives, including attaining Sustainable Development Goals (Cowie et al. 2018).

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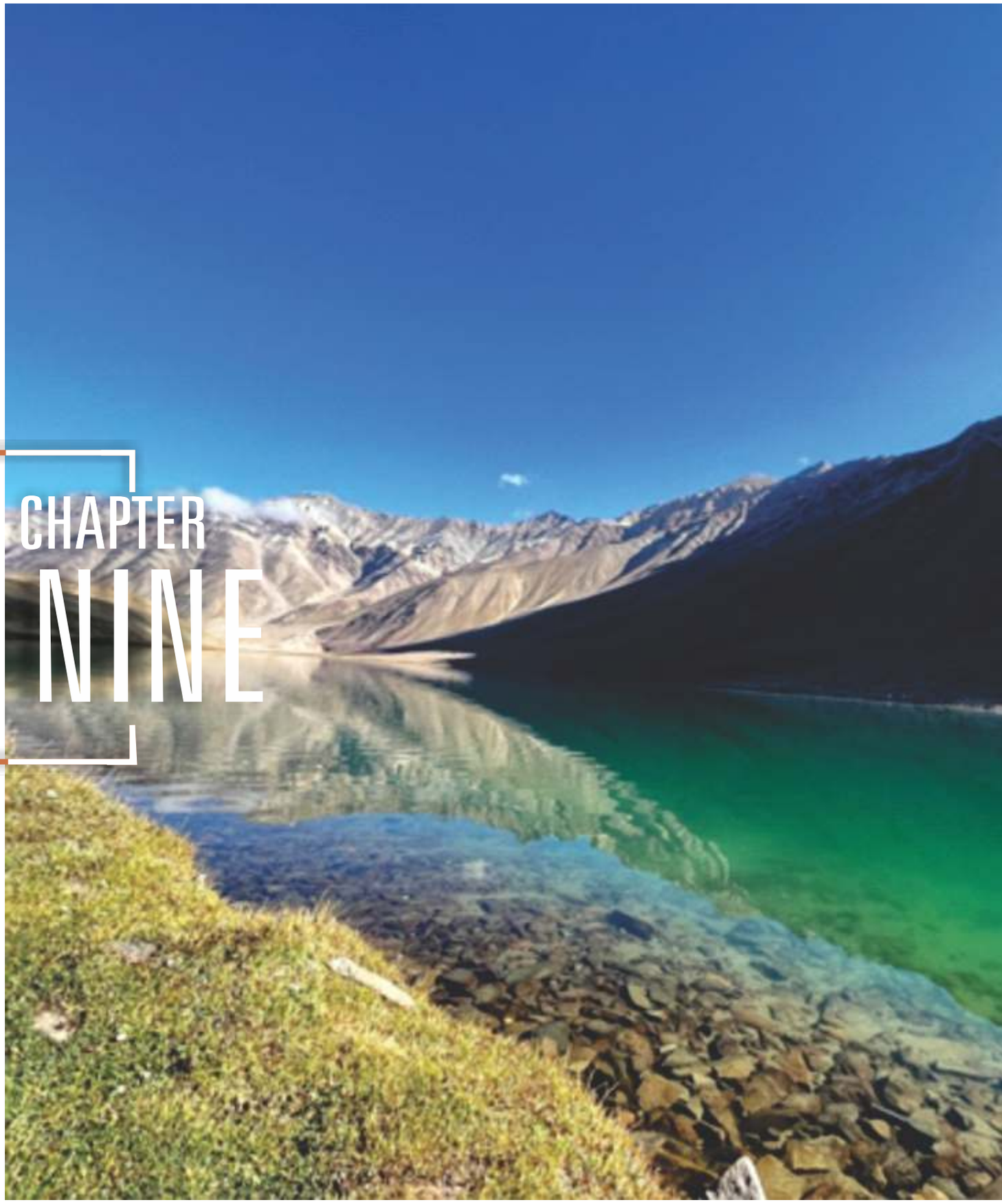
Restoring and Sustainably Managing Indian Wetlands



CHAPTER
NINE

Arghya Chakrabarty and Ritesh Kumar
Wetlands International South Asia, Module 003, NSIC Complex, Okhla Industrial Area, New Delhi – 110020

9.1 Introduction

Degradation and loss of wetlands imperil societal well-being in several ways, such as reduced water, food and climate security and erosion of invaluable cultural heritage. Disruption in the structure, functions and composition of wetlands ecosystems also adversely affects the biological diversity of species dependent on these ecosystems. While removing adverse stressors on the ecological character of wetland ecosystems is the necessary step towards their conservation and wise use, in cases where degradation has already occurred or when addressing the stressors is not feasible, ecological restoration is an appropriate intervention. There has been a renewed interest in the ecological restoration of wetlands in recent times, driven by several factors, including growing water stress and exposure to extreme events such as floods and droughts, however, with limited success and lasting impact. This chapter presents state of the art on wetland restoration and distils challenges. We recommend a pathway for upscaling human investment and political and institutional efforts for securing these vital 'kidneys of landscape'.

9.2 The need for restoring wetland ecosystems

Wetland is a generic term used for aquatic ecosystems located at the interface of land and water and combining attributes of terrestrial and aquatic ecosystems (Keddy, 2010). The Ramsar Convention (a multilateral environmental agreement on wetlands ratified by 172 countries to date, including India which ratified the Convention in 1982) uses a broad definition of wetlands as 'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six metres' (Ramsar 2016). To ensure connectivity between different habitats, Article 2.1 of the Convention provides that riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands may also be included within the boundary (Ramsar 2016). This broad-ranging definition thus covers a large category of inland aquatic systems (such as ponds, lakes, marshes, swamps and peatlands); coastal and nearshore marine ecosystems (such as coral reefs, mangroves, seagrass beds and estuaries) and human-made wetlands (such as rice–paddies, fish-ponds, and water storage areas as tanks, reservoirs, and dams).

India has a diverse wetland regime ranging from high altitude lakes of the Himalayas, floodplains and marshes of the Gangetic – Brahmaputra alluvial plains, saline flats of Great Indian Desert, tank studded Deccan Peninsula to extensive mangroves and coral reefs areas bordering the country's east and the west coastline (Kumar et al. 2017). As per the National Wetlands Atlas (SAC 2018), India has 15.86 million ha under wetlands, accounting for nearly 4.6 % of its geographical area. In terms of biogeographic zones, the coasts and the Deccan region have the maximum wetlands area, the proportion of natural wetlands being higher in the former and human-made in the latter (Figure 9.1).

Wetlands are critical for functioning of the water cycle (Bullock and Acreman, 2003). As water moves through the surface or underground, it passes through wetlands, which in turn regulate the quantity, quality and reliability of water. Wetlands provide vital water-related ecosystem services at different scales (for example clean water provision, wastewater treatment, groundwater replenishment) and thereby offer significant opportunities to address water management objectives with sustainable, and in several instances, cost-effective solutions (UNEP 2014).

The high altitude wetlands of Himalayas serve as headwaters for the ten largest rivers of Asia, the basins of which support nearly one-fifth of the global population (Trisal and Kumar, 2008). For several cities, wetlands were the primary source of water, and continue to be so, as reflected in the moniker 'city of lakes' given to Bangalore (Nagendra, 2010), Udaipur (Singh et al., 2018), Bhopal (Verma and Negandhi, 2011) and many others. For some, this water store can be highly significant, such as the water storage in Yamuna floodplains has been estimated to be equivalent to three-fourths of Delhi's water supply (Soni et al. 2009). Wetlands have traditionally been the backbone of agriculture practised in the Ganga-Brahmaputra floodplains. The waste treatment

capability of wetlands has been effectively used by the City of Kolkata which depends upon the East Kolkata Wetlands to treat nearly 65% of its wastewater, saving nearly Rs. 4,600 million annually in terms of avoided treatment cost (WISA, 2020). Wetlands act as major flood defence systems for cities such as Srinagar (Jammu and Kashmir) and Guwahati (Assam) (Kumar et al., 2017). In the hard rock Deccan Plains and arid regions of the country, there has been an age-old tradition of constructing tanks to store rainwater for use in irrigation and domestic water supply (Bhattacharya, 2015). The value of coastal wetlands as a buffer against tropical storms has been brought out by several researchers (Das and Vincent, 2009; Kathiresan, 2010). Wetlands are also intricately interwoven with the rich cultural and religious tapestry of the country, and several wetlands considered sacred (Singh, 2013).

Not withstanding the high value of ecosystem services that wetlands provide to society, these ecosystems continue to be degraded, polluted, encroached upon and converted for alternate uses. A wetland area trend index constructed by the authors for Indian wetlands based on 237 published data points for 1980 – 2014 using Wetland Extent Trends index method (Dixon et al., 2016) indicates an average decline in natural wetlands area by 41% and a near commensurate increase in area under human-made wetlands by 44% (Kumar et al., 2021). These trends are similar to those reported globally, wherein the natural wetlands have been on a decline, whereas the human-made wetlands are on increasing (Gardner and Finlayson, 2018). These trends are similar to those reported globally, wherein the national wetlands have been on a decline, wherein the human-made wetlands are increasing (Gardner and Finlayson, 2018).

There is a considerable body of research that highlights the increasing vulnerability of landscapes wherein natural wetlands have been degraded or lost (Dewan and Yamaguchi, 2008; Acreman and Holden, 2013; Marois and William, 2015). This is especially true for major urban areas in India, wherein large swathes of wetlands have been converted to give way for housing and other infrastructure (Kumar and Kaul, 2018). A positive relationship between an increase in the built-up area, increasing runoff, loss of wetlands and enhanced flood vulnerability has been observed for several cities, such as Mumbai (Zope et al., 2016), Bangalore (Ramachandra et al., 2019), and Chennai (Gupta and Nair, 2011). Extensive urbanization of floodplains and conversion of wetlands were identified as critical anthropogenic drivers of extensive damage due to 2014 extreme flooding in Kashmir (Romshoo et al., 2018). With the capacity of treating sewage limited to only 31% of total generation (ENVIS, 2019), pollution of wetlands is rampant. Wetlands are also degraded due to fragmentation of hydrological regimes, excessive siltation, encroachment, invasive species, unregulated tourism, and over harvesting of wetland resources (MoEFCC, 2019), although the intensity of drivers of change varies in different biogeographic zones.

9.3 Policy environment

Wetlands conservation was initially led by wildlife values, and several predominantly wetland landscapes such as Keoladeo, Harike, Kaziranga and Manas were declared as wildlife sanctuaries and national parks. Vedanthangal, Keoladeo, Khijadiya and Rangathittu were designated as protected areas under colonial laws and regulations (Kumar, 2019). The work on Indian birds and the passion of stalwarts such as Padma Vibhushan Salim Ali had a major influence on laying the foundation of a network of wetland-protected areas supporting large congregations of waterbirds (Ibid).

Organised efforts for wetlands conservation in India were mainly triggered by India's ratification of the Ramsar Convention in 1982 and the establishment of a separate Ministry of Environment and Forest (presently Ministry of Environment, Forest and Climate Change) in 1985. The Ministry established the National Wetlands Programme in 1986 to provide an overarching national programmatic framework and financial assistance to the state governments for the implementation of site management plans (MoEF, 1992). In 1992, the Ministry constituted a National Committee on Wetlands, Mangroves and Coral Reefs to advise the government on appropriate policies and action programmes for wetlands conservation, research and training

needs, and collaboration with international agencies. In 2001, the National Lake Conservation Programme was carved out of the former programme to address pollution issues in urban and peri-urban water bodies through interception, diversion and treatment of pollution load. Since March 2013, the two programmes have been merged into the National Programme on Conservation of Aquatic Ecosystems (NPCA). Beyond NPCA, wetlands located within protected areas are funded under the centrally sponsored scheme titled Integrated Development of Wildlife Habitats, whereas mangroves and coral reefs receive funding through a still separate funding stream.

Policy elements related to wetlands conservation and management are articulated in the National Environment Policy of 2006 which makes explicit recognition of wetlands as 'freshwater resources', and emphasizes integration of conservation and wise use of wetlands into river basin management involving all relevant stakeholders (MoEF, 2006). India's National Wildlife Action Plan (2017-2031) identifies conservation of inland aquatic ecosystems as one of the 17 priority areas, and envisages development of a national wetlands mission and a national wetlands biodiversity register (MoEFCC, 2017). Mainstreaming the full range of wetlands ecosystem services into developmental planning is listed as the objective of the national wetlands programme (MoEFCC, 2019).

Likewise, the integration of wetlands in river basin management has been identified as a strategy for the management of river systems (MoWR, 2012). The National Water Policy (2012) recommends adoption of a basin approach for water resources management and identifies conservation of river corridors, water bodies and associated ecosystems as an essential action area (MoWR, 2012). The National Action Plan for Climate Change includes wetland conservation and sustainable management in the National Water Mission and the Green India Mission (MoEF, 2008). The National Disaster Management Plan takes into account several non-structural measures for flood and cyclone risk reduction measures and makes direct reference to wetlands (NDMA, 2019). The national indicator framework for monitoring implementation of Sustainable Development Goals provides a mapping of various sectoral programmes towards assessing the country's progress on sustainable development goals (MoSPI, 2015), and makes several references to integrated management of wetlands and water resources.

Wetlands receive protection from a number of central enacted rules and regulations. Provisions of the Indian Forest Act, 1927, the Forest (Conservation) Act, 1980 and the Indian Wildlife (Protection) Act, 1972 define the regulatory framework for wetlands located within forests and designated protected areas. In 2017, the MoEFCC notified the Wetlands (Conservation and Management) Rules, 2017 under the Environment (Protection) Act, 1986, wherein state wetlands authorities have been constituted as nodal policy-making, programming and regulatory institutions for wetlands in the state. The structure of the Authority includes representation from all sectors, including water resources, thus providing a platform for balancing diverse sectoral interests related to wetlands. Several state governments (notably West Bengal, Odisha, Kerala, Manipur, Assam and Rajasthan) have also enacted their legislation pertaining to wetlands. Further, under the EP Act, coastal wetlands are protected under the Coastal Regulation Zone (CRZ) Notification (2018) and its amendments and the Island Protection Zone (IPZ) Notification 2011. The Environment (Protection) Rules, 1986 under the EP Act, empowers the Central government to prohibit or restrict the location of industries and carrying on of processes and operations in different areas including wetlands. The Indian Fisheries Act, 1897, The Water (Prevention and Control of Pollution) Act, 1974, and The Biological Diversity Act, 2002 provide instruments for regulating various development threats on wetlands. The Coastal Aquaculture Authority Act, 2005 prohibits the conversion of natural coastal wetlands such as mangroves, salt pans, estuaries and lagoons for aquaculture. Further, under the Biological Diversity Act, 2002, the Central Government can issue directives to State Governments to take immediate ameliorative measures to conserve any area rich in biological diversity, biological resources and their habitats especially when the area is being threatened by overuse, abuse or neglect. The said Act also gives State Governments the powers to notify areas of biodiversity importance as biodiversity heritage sites.

India ratified the Ramsar Convention in 1982. The 75th year of independence was commemorated by designating 75 wetlands to the List of Wetlands of International Importance covering an area of 1.33 million ha (Figure 9.1).

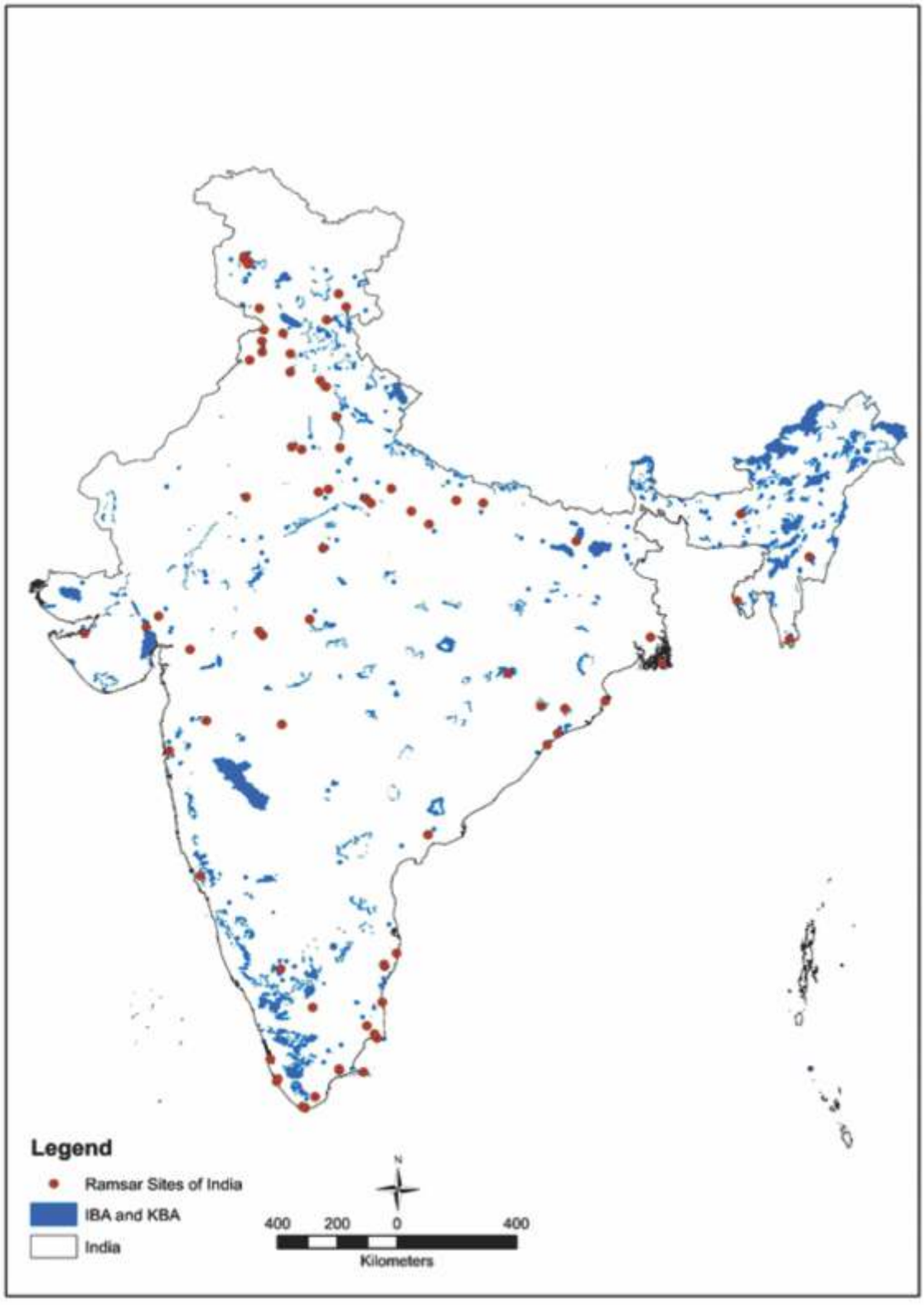


Figure 9.1: Location of seventy-five Ramsar sites and wetlands coinciding with important bird and biodiversity areas (IBAs) and key biodiversity areas (KBAs)

Ecological restoration of wetlands has received increasing support from international policy processes as well. The Ramsar Convention has called for restoration through several resolutions, notable being Resolution in CoP 10 on 'A Framework for processes of detecting, reporting and responding to change in ecological character', which resulted in the development of Ramsar Principles and Guidelines on Wetlands Restoration.

The United Nations General Assembly declared 2021-2030 as the United Nations Decade for Ecological Restoration, responding to the critical need to halt, prevent and reverse ecosystem degradation, and to effectively restore degraded terrestrial, freshwater and marine ecosystems across the globe.

The United Nations Biodiversity Conference, held in December 2022 in Montreal, Canada, ended with adopting the landmark Kunming-Montreal Global Biodiversity Framework (CBD, 2022). The Framework consists of four overarching global goals to protect nature, including: halting human-induced extinction of threatened species and reducing the rate of extinction of all species tenfold by 2050; sustainable use and management of biodiversity to ensure that nature's contributions to people are valued, maintained and enhanced; fair sharing of the benefits from the utilisation of genetic resources, and digital sequence information on genetic resources; and that adequate means of implementing the framework is accessible to all Parties. Target 2 (on the effective restoration of at least 30 percent of degraded ecosystems by 2030) and Target 3 (on the effective conservation and management of 30 percent of areas of particular importance for biodiversity and ecosystem functions and services) make a specific mention of 'inland waters', the term for wetlands in the Convention on Biological Diversity Processes.

The Sharm-el Sheikh Implementation Plan that resulted from the UNFCCC CoP 27 called for the protection, conservation and restoration of water and water-related ecosystems as a part of the adaptation actions (UNFCCC 2022).

9.4 Wetland restoration efforts and lessons learnt

The Society for Ecological Restoration (SER) defines ecosystem restoration as 'the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed'. The purpose is to move a degraded ecosystem to a trajectory of recovery that allows adaptation to local and global changes, as well as persistence and evolution of its component species. The SER Standards use the term restoration for the activity undertaken and recovery for the outcome sought or achieved. It is stressed that for an activity to be considered ecological restoration, it must result in a net gain for biodiversity, ecosystem health and integrity, and human well-being, including sustainable production of goods and services (Gann et al., 2019).

Restoration includes a spectrum of actions, including: (1) reduction of negative environmental and societal impacts, such as pollution and unsustainable resource use and management; (2) removal of contaminants, pollutants and other threats, often known as remediation; (3) rehabilitation of ecosystem functions and services in highly modified areas; and (4) ecological restoration, which aims to remove degradation and assists in recovering an ecosystem to the trajectory it would be on if degradation had not occurred, accounting for environmental change (FAO, 2021). The literature distinguishes between rehabilitation (wherein the primary objective is to improve ecosystem functions and ecosystem services in transformed ecosystems) and ecological restoration (wherein the aim is to put ecosystems on a path towards a state of high integrity, with natural state as a reference, taking into account climate change and natural ecological dynamics when setting objectives).

Public funds investments into wetlands, especially those of the central sector schemes administered by the MoEFCC, is on the basis of integrated management plans. These plans intend to address the drivers of adverse degradation, as well as maintain and enhance biodiversity and ecosystem services values. However, in several cases, these funds have also been directed at ecological restoration and rehabilitation. We discuss a few of such initiatives in this section and distil lessons learnt.

Restoring natural wetlands : Chilika, a brackishwater coastal lagoon situated in Odisha, and the base of livelihood security to more than 0.2 million fishers is an assemblage of shallow to very shallow marine, brackish and freshwater ecosystems and a hotspot of biodiversity. The

wetland went through a phase of reduced connectivity to the sea during 1950 – 2000 owing to increasing sediment loads from degrading catchments. There was a rapid decline in fisheries, with annual average landing dropping from 8600 kg to 1702 kg between 1985/86 and 1998/99 (Mohapatra et al., 2007). The rapid decline in ecosystem condition and the associated livelihoods of dependent communities prompted the Odisha state government to constitute the Chilika Development Authority (CDA) as a formal institution mandated to undertake conservation and management of the wetland. CDA, working with the state and national governments, a range of scientific organizations, as well as civil society organizations, mobilized the necessary evidence for ecological restoration. Measures put in place since 2000 included opening of a new mouth and dredging of a channel within the northern sector of the lagoon to ensure that riverine sediments are flushed out. These interventions were complemented by a basin scale participatory watershed management programme to contain silt loading from the catchments and enhance resources for community livelihoods (Kumar et al., 2020).

The response of the hydrological intervention and basin management has been rapid and sustained. After initial trophic bursts, the annual fish landing stabilized at nearly 13,000 MT (Raman and Das, 2019). Annual CDA censuses of Irrawaddy dolphins within Chilika reported an increase from 89 to 151 individuals between 2003 and 2022, as well as increases in habitat use, improvements in breeding and dispersal, and declines in mortality rates (CDA monitoring records, unpublished). Seagrass meadows expanded from 20 km^2 in 2000 to 172 km^2 by 2022, along with a significant decline in freshwater invasive species (CDA monitoring records, unpublished).

Located on the river Yamuna front, the Yamuna Biodiversity Park is an ambitious restoration project of the Delhi Development Authority and the University of Delhi. Since 2005, restoration of 157 ha barren and highly sodic floodplains has involved reintroduction of native plant species, landscaping, and creation of wetland habitats. Majority of the waste dumps and solid wastes accumulated on the floodplain have been removed. Agriculture on the floodplain has been regulated to prohibit the use of agrochemicals, and has been restricted to areas beyond 100 m on either side of the river channel. The higher elevation areas of the floodplain are being developed for improving the water quality of the wastewater which will be allowed to pass post treatment in the STPs (or in situ treatment on storm water drains) (Babu et al., 2013).

Restoring urban wetlands : Projects on urban wetlands restoration have centered on addressing pollution, reestablishing water regimes, and enhancing amenity values. Restoration of Bhoj Wetland in Madhya Pradesh, implemented during 1995-2005 with financial assistance from the Japan Bank of International Cooperation, is a noteworthy example. The Ramsar Site is a complex of two wetlands, the Upper Lake created in 11th century and the Lower Lake, created in the 18th century, and constitute the major source of water supply to Bhopal City. Rapid urbanization with insufficient waste management subjected the wetland to various environmental stresses, of which deterioration of water quality, reduction in water spread area and siltation were the most significant. Restoration was targeted at water quality improvement and enhancement of storage capacity. Desilting, deweeding, afforestation of catchments, creation of waste diversion and treatment infrastructure, curbing grazing and encroachment, and communication and outreach were implemented over a decade, leading to considerable improvement in lake ecosystem health (Verma et al., 2001, Pani, 2008).

The Hauz Khas, a historic waterbody in south Delhi, went dry by the sixties as the catchment flows were diverted and the water table depleted. Its restoration has involved diversion of treated wastewater, introduction of carp fingerlings, wetlands mediated treatment of inflows, and installation of aerators. The restoration has stabilized the water regimes, increased sighting of waterbirds, increase in groundwater levels and creation of a recreational avenue for the citizens (Bhatnagar, 2008; Roy 2016).

Communities living in and around have historically played an important role in conservation of urban wetlands. The case of restoration of Kaikondrahalli lake in south-east Bangalore is an example of collective action by concerned citizen groups. Till 2000, this urban wetland brimmed with freshwater and was a habitat for several species. By 2003, Kaikondrahalli lake went into prolonged drying as the inflowing channels were blocked and the solid waste dumped rampantly. Rejuvenation, implemented during 2009-11

involved concerned citizens group working with Bruhat Bangalore Mahanagara Palike (BBMP) to ensure catchment inflows into the wetland, realigning shoreline landuse to maintain waterspread area, diverting and treating waste from upstream sources, enhancing water storage capacity, managing grazing, and educating citizens on the diverse wetland values. As a result of the efforts, the lake regained much of its lost waterspread, with frequent sightings of diverse species (Nagendra, 2016).

Several urban wetland restoration projects in recent times have tended to bypass the mre complicated catchment restoration efforts, and instead leveraged availability of treated wastewater to restore water regimes.

Mangroves restoration : Mangrove restoration in India is an impressive turnaround story. As per biennial assessments published by the Forest Survey of India, the extent of mangroves in the country has increased from 4,046 sq km in 1987 to 4,975 sq km in 2019. The Global Mangrove Alliance, which maintains consistent global datasets on mangrove cover, has estimated that worldwide, since 1996, there has been a net global loss of mangroves cover by 3.4%, with the losses having occurred globally at rates twice the gains (Bunting et al., 2022). India is one of the few countries with positive trends in mangrove cover. Restoration efforts particularly picked pace after the Kalinga Super Cyclone (1999) and Indian Ocean Tsunami (2004), wherein mangroves sheltered hamlets located behind these swamps, absorbing the storm surges to a large extent. This success is attributed to immense efforts in mangrove plantations based on localised models, community engagement in their protection and upkeep and strengthening coastal zone regulation architecture. States like Maharashtra have established a separate Mangrove Cell to ensure a consistent focus on the conservation and management of these ecosystems (DasGupta and Shaw, 2013).

The MS Swaminathan Research Foundation is credited with the popularisation of the fish-bone model of mangrove restoration, which allows for the creation of hydrological conditions for the regeneration of mangroves. What started as an experiment in a small patch in Pichavaram, has now been successfully applied in Bhitarkanika (Odisha), and Krishna Delta (Andhra Pradesh). The integrated mangrove fisheries farming system, again from the stable of MSSRF, specifically addresses livelihood elements in the restoration of abandoned aquaculture farms in Tamil Nadu, Andhra Pradesh and other parts of the Indian coastline (Shah and Ramesh, 2022).

Restoring ponds : Historically ponds have played an important role in water security and livelihoods, however, with the advent of irrigation and water supply systems, and predominance of groundwater use, the relevance of these small wetlands has declined resulting in their degradation and rampant conversion for alternate land use. In 2005, the Ministry of Jal Shakti launched a Repair, Renovation, and Restoration (RRR) scheme (later merged with Prime Minister Krishi Sinchayee Yojana-2015) aimed at harnessing the irrigation potential of these aquatic ecosystems. Pond restoration has received increasing support in recent times, with the major interventions being restoration of hydroperiod, water depth and silt control. There are several grass root organizations and motivated individuals who spearhead restoration of ponds, as their revival directly contributes to local water security and livelihoods (Yadava and Goyal, 2022).

A deeper reading into the restoration initiatives provides several insights into the factors that underpin a successful wetland restoration and regeneration effort. Following are some of the major lessons learned.

Selection of appropriate restoration goals and pathways is critical. Clear and achievable restoration goals are critical to successful restoration. In Chilika, restoration targeted reestablishment of salinity regime, and used reestablishment of hydrological connectivity between the estuary and the Bay of Bengal as a pathway. Similarly, in the case of restoration of Yamuna floodplains, the project specifically targeted reestablishment of native vegetation. Similarly, in the case of Bhoj Wetlands restoration, clear targets in terms of water quality and water levels were established, and catchment level management was adopted as a restoration pathway. These clear targets and pathways allowed clear definition of restoration projects. In case of Loktak Lake, though the restoration project has identified viable restoration outcomes in terms of desired hydrological regimes and extent of vegetation, the pathway of restoration involving reoperation of Ithai Barrage is highly contested,

and not implemented thus far. In several urban wetlands, the restoration outcomes in terms of desired water quality standards require heavy investment in grey water treatment infrastructure. The outcomes are seldom achieved because of inefficiencies in infrastructure functioning, and poor addressal of catchment land use interactions.

Monitoring. Monitoring plays a crucial role in determining the success of ecological restoration and rehabilitation, as well as enabling replication and upscaling. In cases of Chilika and Yamuna Biodiversity Park, elaborate arrangements are in place to record changes in ecological and hydrological indicators. The monitoring data also instills confidence in decision-makers on the efficacy of their decisions regarding wetlands restoration and rehabilitation.

Management plays an important role in sustaining the benefits of restoration and rehabilitation. While restoration and rehabilitation efforts can bring the wetland to a desired condition, maintaining the condition requires putting in place arrangements for managing these ecosystems for maintenance of their ecological character. In case of Chilika, proactive basin-scale management has ensured that the restoration outcomes have been sustained over time, and the lagoon maintains a salinity gradient conducive for fish landings and habitats for dolphins and other species of high conservation values. Similarly, in Pichavaram, the Forest Department works with communities for maintaining the fish bone channels which provide the desired salinity regime for mangrove regeneration. In contrast, the dissolution of Lake Conservation Authority constituted as a part of Lake Bhopal Conservation and Management Project led to considerable dissipation of the gains made under the rehabilitation project, as water quality declined, water levels rendered unstable and pressures from intensifying catchment land use increased.

Standardization helps, but restoration and rehabilitation must take into account landscape and socioeconomic context. There is a tendency to standardize restoration and rehabilitation methods, which allows for replication and upscaling of best practices. However, it is important that restoration and rehabilitation measures take into account landscape and socioeconomic factors. A case in point is that of mangrove restoration. The National Decadal Wetland Change Atlas published by Space Application Center in February 2022 reports that between 2006/7 and 2017/18, the natural coastal wetlands declined from 3.69 million ha to 3.62 million ha. The intertidal mudflats have decreased by a whooping 116,897 ha and salt marshes by 5,647 ha. Mangrove plantation over inter-tidal mudflats is a prominent reason for this loss.

Institutions matter for restoration success. Successful ecological restoration and rehabilitation efforts were led by dedicated agencies (such as Chilika Development Authority, the Delhi Development Authority working with the Center for Management of Degraded Ecosystems of the University of Delhi) which ensured systematic implementation of the restoration plan, bringing on board partners and networks, and periodically evaluating success.

9.5 Scaling up wetland restoration – future priorities

It is apparent that efforts placed on restoring and rehabilitating Indian wetlands has not matched up with the rapid pace of degradation of these ecosystems. There is an urgent need to scale up efforts in this direction. Following are some priorities that need consideration:

Ecological restoration planning. Investment is needed in developing robust, sustainable and equitable wetland restoration and rehabilitation plans. A national system for prioritising wetlands in need of restoration may serve as a basis. Restoration may be guided by reference models - which describe the approximate condition the wetland would be had the degradation not occurred. Such reference models should also factor in the impacts of climate change. Restoration projects should have clear targets (informed by reference ecosystems), goals (medium to long term desired ecological and social condition), objectives (interim outcomes towards condition of recovery) and indicators (specific and quantifiable measures of attributes). The design of restoration plans must reflect the expectations and interests of stakeholders.

Capacity development. The lack of formal and systematic training and skill development opportunities to support wetlands restoration needs to be adequately addressed through

targeted training programmes, learning networks, field support and building practitioner-researcher collaborations.

Strengthening wetlands governance. Successful wetlands restoration requires governance arrangements that can ensure stakeholder engagement, incorporation of diverse worldviews and values, political ownership and continuity of action. The Wetlands (Conservation and Management) Rules, 2017 have mandated State Wetlands Authorities (SWA) as the nodal policy-making and regulating bodies. The SWA can play an important role in ensuring that there is appropriate policy and programmatic support for wetlands restoration within the state. Several states have also constituted District level wetland authorities, which provide a platform for district level monitoring and coordination of actions with government line departments. What is pertinent is that site level restoration is made the responsibility of a single department, which should ensure coordination with other line departments and agencies, experts and civil society organizations in implementing.

Building supportive knowledge systems. Effective restoration planning and implementation requires supportive knowledge systems that can assist in making evidenced based choices. Restoration interventions should be guided by best available knowledge, including traditional and indigenous ecological knowledge. Innovation and learning can be fostered by building practitioner-researchers collaborations. Effort should also be made to share practical and as well as scientific knowledge to support efficient implementation of restoration plans.

A major focus of science has been to unpack 'what wetlands are' in terms of unravelling the complexities of ecosystem structure functioning. This science has provided a robust basis of conservation. However, for wetlands to be effectively mainstreamed into sector plans and programmes, the pertinent questions are – 'what can wetlands do to meet development outcomes such as flood buffering, water security' and so on. This would require a science and knowledge system to demonstrate wetland functioning within a landscape. For most parts, this is an interdisciplinary endeavour, which requires wetland ecologists to work with hydrologists, social scientists, geographers, landscape planners and others.

Monitoring and evaluation. It is pertinent that restoration success is evaluated through a systematic monitoring and evaluation system that ascertains effectiveness of investment and application of human, financial and political capital. Monitoring can be directed at specific hypotheses (such as reestablishing hydrological conditions is sufficient for regeneration of native species). Engaging stakeholders in collection and analysis of data can help build stakeholder capability, as well as provide an environment of collaborative decision making. Finally, monitoring and evaluation provides the basis of adaptive management, by continually updating knowledge and adjusting restoration practices as an outcome. Each wetland restoration project must have an inbuilt component of monitoring and evaluation.

Emphasizing the significance of evaluating the management effectiveness of Ramsar Sites and other wetlands, especially in places where mechanisms are not already in place, the Contracting Parties to the Ramsar Convention at their 12th Conference of Parties in 2015 adopted a revised version of the Management Effectiveness Tracking Tool (METT), called the Ramsar Management Effectiveness Tracking Tool (R-METT), based on the Protected Area Management Evaluation (PAME) tool for effective management over time. This encourages wetland management authorities to evaluate the effectiveness of wetland management in collaboration with relevant stakeholders as appropriate.

Sector mainstreaming. Several sectors, such as water resources development, urban development, rural development to name a few, are including wetlands restoration within their plans and programmes. Unfortunately, the restoration practices adopted by the sectors seldom take a holistic view of wetlands as an ecosystem, and rather focus on a few elements (such as water regimes, or amenity values). Given the complexity of wetlands ecosystems, the outcomes of sectoral approaches are short lived and often counter-productive. It is therefore essential that all sectors are guided by a common national standard of wetlands restoration and rehabilitation.

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Precision Agriculture towards Sustainable Land Management in the Central Himalayan Region



Shailaja Punetha and Paromita Ghosh
G. B. Pant National Institute of Himalayan Environment, Kosi - Katarmal, Almora, Uttarkhand - 263643

10.1 Introduction

The central Himalayan region is a densely populated zone that exerts a lot of pressure on natural resources. The marginal hillsides and mountains are characterized by steep sloping land with less soil depth and have supported only subsistence farming characterized by poor yield, low farm productivity and extensive energy and labour inputs. It always faces the threat of high-intensity rainfall, cloud bursts, flash floods, landslides, snowfall, and drought. Therefore the introduction of precision agriculture technology can provide sustainability to scarce land resources and improve crop yields.

Sustainable land management practices are those optimum use of land with maximum output and which make causes the least damage to the natural environment, particularly soil. It consists of some simple measures such as soil nutrient balance and decreasing the gap between yields by using smart technologies. Precision agriculture is one such application that manages crop production more efficiently in an environment-friendly manner. Precision agriculture is a farming management concept that involves careful observation and timely response to inter and intra-variability in crops. It leads to a lower footprint of fruit and vegetable cultivation through enhanced resource efficiency and improved production. It follows the principles of four "R"s i.e. applying *the right source at the right rate at the right time and in the right* place that leads to sustainable land management (Roberts, 2007).

Farmers are trained to better crop production practices and improve their ability to decide on exactly what to grow and what inputs are required and how to optimize the controlled environment, irrigation, and nutrition doses. This leads to a more labour-efficient production system that can counteract the automation deficiency which characterizes Himalayan agriculture.

10.2 Methodology

The village cluster (Jyoli) selected for the study is located between 29°036'38" to 29°038'13"N latitude and 79°034'40" to 79°036'35"E longitude in Hawalbagh Developmental Block in Almora district, Uttarakhand in June 2020 to implement selected livelihood-supporting and income generating activities and conversion of barren land to cultivated land by adopting precision agriculture activities (Fig. 10.1 and Table 10.1). This village cluster is spread over 529 ha area, out of which 56 ha is under forests and a large area (122.1 ha) is under permanent pasture and grazing land. The area under cultivation is only 37.37 ha. To implement the environment-friendly, income-generating precision agriculture-based interventions, the following methodologies and approaches were adopted:

1. Need assessment of village community.
2. Exposure visits and model demonstrations.
3. Identification of stakeholders for technology implementation.

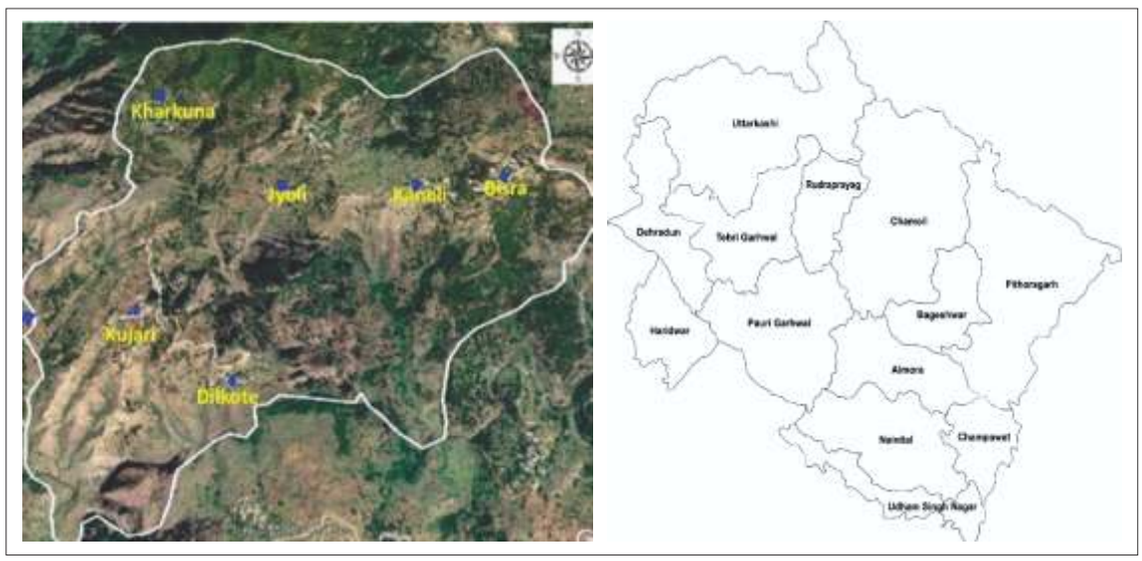

Figure 10.1: Location map of the village cluster

4. Baseline survey (at household level).

5. Implementation of packages of practices involved in precision agriculture among selected stakeholders.

6. Data collection and monitoring schedule.

Table 10.1: Precision agriculture-based livelihood enhancing and income generating activities promoted in Jyoli village cluster

S. No.	Name of Precision Agricultural technology	Advantages	Details of intervention
1	**Low-cost protected cultivation (Poly-houses 40 families)**	Greenhouse being the most efficient means to overcome climatic variability, vegetable production makes use of recent advances in technology to control the environment for maximizing crop productivity per unit area and increasing the quality of vegetable produce. It also protects the crops from wildlife like monkeys & wild bores etc.	• Farmers were provided with 30×10×8 ft. and 20×10×8 ft. size UV stabilized polythene sheets and 50% green shade net for ventilation. • The bamboo frame and labour to erect the poly house were provided by farmers • Technical guidance was provided at the time of poly house construction and cultivation of vegetables (agro-technologies) • Seed/seedlings/rootstock was given to selected families for free and tie-up was done with local Krishi Vigyan Kendra
2	**Mulching (40 families)**	Less infestation of weedicides retains the moisture in the soil, earlier quality harvest, increase in growth, early and more quantity vegetable growth, etc.	• Farmers were provided with a black mulching sheet of 25 microns • Technical guidance was provided at the time of the application of mulch
3	**Vermicomposting for organic farming (6 families)**	Vermicomposting is a method of preparing enriched compost with the use of earth worms which is one of the easiest methods of recycling farm waste and producing quality compost for farm use. Worm cast which is also known as black gold prepared using the *Eisenia fetida* species of earthworm survives best in the region. This compost is rich in nutrients, growth-promoting hormones and beneficial microorganisms, etc.	• Households were selected on a participatory basis, availability of area and inputs like cow dung and farm waste. • Compost pits of 6×6×3 ft were constructed with a single brick wall. • *Eisenia fetida* was provided to the selected farmers. • To prevent the movement of earthworms deep down, a concrete floor was prepared. • Whole structure was covered with erected bamboo and Polyethylene sheet to protect it from rainfall

The daily/weekly/seasonal data was recorded as brief details of activities by the farmers. Registers were provided to each farmer to record the daily inputs and outputs systematically accrued due to these livelihood practices. Output-input (O:I ratio) and net benefit to the HH were calculated for each activity.

10.3 Outcomes of Precision Agricultural technologies for Sustainable Land Management

10.3.1 Protected cultivation of organic vegetables

The climatic conditions of the Central Himalayan Region are suitable for off-season vegetable crops such as tomato, cauliflower, cabbage, vegetable pea, cucumber, French beans, capsicum, etc. in different zones in the hills which offers a huge potential for employment and income generation to the farmers. Off-season vegetable farming refers to the production of vegetables by using different agro-climatic conditions, adjusting the time of transplanting, selecting and improving the varieties, and/or creating a controlled environment. Several training programmes, as well as demonstrations, were conducted to scale up the technology in the selected village cluster. Growing vegetables in the polyhouse are the common method of precision agriculture that is popularised and adopted by the people of this region as SLM practice. A total of 40 polyhouses installed of two different sizes 300 m/sq.ft. and 200 sq.ft. area as per the availability of space (Figure 10.2). A total 0.01 ha barren area was converted into protected cultivation of vegetable crops. Nearly 20 diverse vegetable crops were cultivated organically by using locally produced vermicompost and vermi wash.



Figure 10.2: Construction of low-cost bamboo polyhouses in the village cluster

Vegetable crops such as tomato, onion, radish, coriander, capsicum, brinjal, beans, etc. were found suitable for the agro-climatic zone of this region, and hence can be recommended to other farmers also. It is to be mentioned that farmers attempted a range of combinations / sole crops of both vegetables and spices in these polyhouses and the land space devoted to each crop varies from farmer to farmer and from one crop to another. The total vegetable/spices production was estimated at 2616 kg (October 2020 - September 2022). Fresh vegetables were sold by farmers at their doorsteps and purchased by their neighbours, and they did not have to buy vegetables for their self-consumption. It is envisaged that other farmers in these villages will adopt these technologies and become self-sufficient in vegetable production and would also earn. The vegetables catered for their own consumption needs as well as for sale in the village and nearby shops were worth INR 1,19,795.00 (cluster of 40 farmers)with an overall cost-benefit ratio of 2.66.

10.3.2 Mulching practices

Mulching is a practice of covering the soil surface with organic or inorganic materials to reduce moisture loss and to balance wide variations in diurnal soil temperatures, especially in the root zone. It controls evaporation losses and minimized energy supply to the evaporating site by cutting off solar radiation falling on the ground. The major function of mulching is to limit the initial stage of drying which helps in optimum moisture conditions, reduced soil temperature, also containing seedling mortality, and improving crop stand. It also subdues weed flora and reduces weed competition with crops for water and nutrients making them available in larger quantities for crop plants. It also helps in improving water movement downward. The efficiency of mulches in preserving moisture has usually been established to be greater under higher rainfall, drought conditions, and during vegetative stages of crop growth when canopy cover remains scanty (Fig. 10.3).



Figure 10.3: Mulching practices under precision agriculture

10.3.3 Vermicomposting

Vermicompost is popular nowadays as it is a major component of the organic farming system. Vermicomposting has been emerging as an important source in supplementing and substituting chemical fertilizer in hill farming systems. There is a huge demand for vermicompost among hill farmers as it is used to increase the quality of agri-produce. Keeping this in mind for farming sustainability, 6 households were selected for the introduction of this technology and construction of vermicomposting units. As a result of the introduction of this technology, each household is producing nearly 2-3 quintals of vermicompost during every season and annually around 6-8 quintals of good quality vermicompost. This is being used by farmers for organic vegetable production (Fig. 10.4 a and 10.4 b).



(a) (b)

Figure 10.4: Construction of vermicomposting pits (a) and organic farming (b)

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Apatani Integrated Farming System of Ziro Valley, Arunachal Pradesh: A Sustainable Land Management Practice



Nada Tadi
Rain Forest Research Institute, Jorhat, Assam - 785 010

11.1 Introduction

The Apatani ethnic community of the Eastern Himalayan region has developed an integrated traditional farming system in the Ziro Valley, Lower Subansiri district of Arunachal Pradesh. This farming system is an integration of wet rice cultivation, forest management, bamboo plantation, and land & water resource management. The Apatanis live in a narrow valley where only 32 km^2 area is cultivable and a single small river flows through it. Due to the limited land and water resources, the community has developed highly efficient and sustainable land use practice for their subsistence and livelihood. The traditional farming system of Apatanis mainly consists of wet rice and finger millet cultivation, fish rearing, and homegardens accompanied by forest management practices in the hills surrounding the valley.

The rice fields are irrigated by a network of channels and bamboo/wooden ducts which allows for tapping and transfer of water from natural streams arising from the forests and rainfall to the fields (Figure 11.1). Two rice varieties viz., early-ripening and late-ripening are cultivated along with the rearing of fishes like common carp (*Cyprinus carpio* Linn.) in the rice fields. Finger millet is cultivated on the bunds of paddy fields. Chemical fertilizers, pesticides, etc. are not used by the farmers. The combined cultivation of rice, finger millet, and fish in the same field allows for the simultaneous production of three crops with low input costs and high outputs (Sarma and Goswami, 2015). The yield of the highly productive Apatani paddy-cum-fish agro-ecosystem ranges from 400 to 500 kg ha^{-1}, which is three to four folds higher than the state average paddy yield. The low cost of crop cultivation makes it economically viable and cost-effective form of organic agriculture (Rai, 2005).



Figure 11.1: Wet rice fields of Ziro valley

"Balu" and "Yorlu" are two different forms of home garden systems in the Ziro valley. The former is situated near the home, while the latter is located further away. These homegardens are used to grow a variety of crops, including vegetables and fruit trees.

The forests of surrounding hills and mountains are protected and managed for food, fuel wood, timber, and other forest products of socio-cultural importance, which also helps in soil and water conservation. The agroecosystems of the Apatanis demonstrate high ecological and economic

efficiency, enabling the community to achieve a high level of self-sufficiency (Sundriyal and Dollo, 2013). The integration of agriculture and resource management supports sustainable development in the region and benefits the local community.

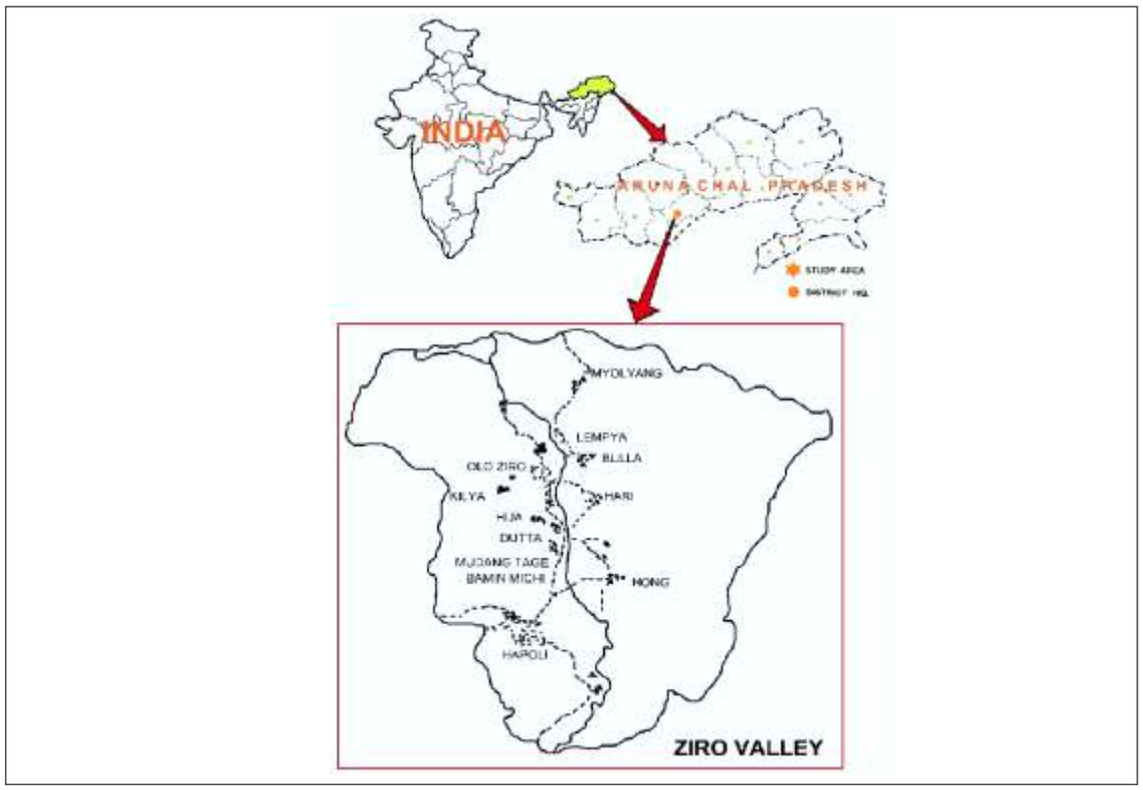
11.2 The Apatanis

The Apatani community is one of the major tribes in Arunachal Pradesh, with a population of around 43777 according to the Population Census, 2011. Apatanis belongs to the Tibeto-Mongoloid stock and speak a local dialect belonging to the Tibeto-Burman branch of the Sino-Tibetan language family.

The Apatanis are inhabitants of Ziro valley or Apatani Plateau in the Lower Subansiri district of Arunachal Pradesh and are settled in seven large villages: Hari, Biila, Hija, Dutta, Mudang-Tage, Hong, and Bamin-Michi. Apatani tribe builds their traditional houses using bamboo (*Phyllostachys bambusoides*) and timber from *Pinus wallichiana* and *Castanopsis* spp.

The Apatanis consider legendary "Abotani" as their ancestor and practice animism, including the worship of the Sun (Danyi) and the Moon (Piilo). Myoko, Murung, Yapung, and Dree are important festivals of the community.

The Apatanis are well-known for their indigenous system of permanent wet-rice cultivation integrated with fish culture and forest management practices. Unlike other tribes in the region, Apatani do not practice jhum cultivation. All the community members including men, women, and children are involved in agricultural activities, where men carry out the construction and maintenance of common irrigation canals, bunds, and fences to protect the crops from Mithun (*Bos frontalis*) and cattle, whereas women perform the work of paddy sowing in the nursery, land preparation, transplanting, regular weeding in paddy fields and home gardens, etc (Tayo *et al.* 2017).



Source: *Tangjang and Nair, 2015*

Figure 11.2 : Map of Ziro Valley

11.3 Physiography and Climate of Ziro Valley

Ziro valley or Apatani Plateau is located at 27°30′-27°40′N latitude and 93°57′- 94°12′E longitude at around 1564 m elevation (Fig. 11.2). The valley is surrounded by hills and mountains rising to heights of over 2438 m above mean sea level. The climate ranges from temperate to sub-tropical. The valley experiences the mean temperature of 12 °C to 25 °C in summer and -5 °C to 12 °C in winter with heavy frost, whereas the average annual rainfall is approximately 1,500 mm, which is mainly concentrated in the period from May to August, and there is little to no precipitation from November to February (Tangjang and Nair, 2015). The topsoil of the valley ranges from sandy loam to clay loam in texture with soil pH between 5.10 and 5.64 (Sundriyal and Dollo, 2013). The valley has 32 sq. km of cultivable area which is drained by a small river "Kwle" and numerous other streams arising from the surrounding hills and mountains. About 48.38% of the valley land is under paddy-cum-fish cultivation, followed by 32.64% clan forest, 16.41% bamboo forest, and 2.75% home garden (Yani et al., 2018, Rai, 2005).

11.4 Wet rice cultivation

Rice (*Oryza sativa*) is the staple food crop of Apatanis. Early ripening variety (e.g. Mipya) and late ripening variety (e.g. Emo) are cultivated in Ziro valley. A total of 16 native rice varieties have been identified, which shows differences in their height, grain properties, yield, nutritional value, crop maturity time, and ability to withstand diseases and insect infestations (Sundriyal and Dollo, 2013). The fields of early ripening varieties are located far from the villages whereas the fields of late ripening varieties are located closer to the villages. "Mipya" is versatile and cultivated in both high and low fertility conditions whereas "Emo" is cultivated in medium fertile soil.

The process of preparation of the nursery beds for the rice begins in February. The size of the nursery is around 48 m^2 having 3-4 nursery beds of size 4m x 3m (Dollo et al. 2009). The nurseries are established near the villages or in a narrow



Figure 11.3: Apatani women working in a wet rice field

valley to protect from strong winds. If nurseries are close to villages, small canals from nearby settlements carrying household and animal wastes are connected to them to provide nutrients for the good growth of seedlings. The seeds are sown by broadcasting and are maintained for around 2-3 months till a height of 12-15 cm for slightly dry fields and 15-18 cm for wet fields is attained.

Land preparation is started in March and completed by April. All the farm operations are carried out manually using a spade and other traditional agricultural implements (Figure 11.3). Transplanting is done from April to May while weeding is carried out 3-4 times a year and weeds are converted into compost by the traditional method of collecting the weeds in one place and covering them with a thin layer of soil to speed up the decomposition. Harvesting time starts from July for the early ripening variety and September-October for the late ripening varieties.

11.5 Finger Millet Cultivation

Finger millet (*Eleusine coracana*) is cultivated on the dykes/ bunds of the paddy fields (Figure 11.4). "Mipe/ Mipa" is an early ripening variety while "Pinchi/Pichi Sarse" and "Sarpu Sarse" are the late-ripening varieties of finger millet (Bouchery, 2011). These millets are also cultivated in rain-fed millet fields called "Lyapyo". The finger millet nursery is prepared in the homegardens through seed broadcasting. The methods, time, and size of nursery bed preparation are almost similar to that of rice. When seedlings attain a height of 12-16 cm, the transplanting is carried out using traditional implement called "Damu" (Dollo et al., 2009). It is used to make holes in bunds in which seedlings are transplanted. Before transplanting is done, 5-10 cm of the apical portion of seedlings is cut and removed to avoid drying and death of seedlings. Millets are mainly used with rice for local rice preparation.



Figure 11.4: Finger millets on bunds

11.6 Fish culture

Apatanis are well known for their integrated Paddy-cum-Fish Culture. Paddy fields are an ideal environment for fish farming due to their sturdy embankments, which help maintain the water at the desired level and prevent leaks, as well as cultivated fish from escaping during floods

(Nimachow *et al.* 2010). The commonly reared fishes include common carp (*Cyprinus carpio* Linn.), grass carp (*Ctenopharyngodon idella* Val.), silver carp (*Hypophthalmichthys molitrix* Val.), rohu (*Labeo rohita* Ham.), Catla (*Catla-catla* Ham.) and Mrigal (*Cirrhinus mrigala* Linn.) with *Cyprinus carpio* contributing to about 80 percent of fish production in the valley (Tangjang and Nair, 2015 (Fig. 11.5)). Typically, from April to May, shortly after the transplanting of paddy, juvenile fish fingerlings are released in the fields and allowed to grow until they are harvested in July. Generally, a water depth of 5 to 15 cm is maintained in the field which facilitates paddy cultivation and fish rearing.

An important feature of Apatani paddy fields is a long and narrow trench of about 50 cm depth called "*Hete/Parkho*" which is dug in almost every paddy field for providing shelter and spawning ground for fishes (Fig. 11.6). Even when the field dries up, water remains in the trenches for the fish to take shelter. Organic wastes from poultry, piggery, cattle, and agriculture (rice husk, decomposed straw, weeds, etc.) are the inputs used in this farming system (Yani et al., 2018). This system leads to an improved nutritional environment for the fish as a result of the manuring of the paddy fields and allows for better growth due to the larger surface area available during the full submergence of the paddy fields (Rai, 2005).



Figure 11.5: Fishes from paddy field



Figure 11.6: Hete/Parkho

11.7 Homegardens

The Apatanis have also developed homegardens to grow a variety of vegetables, fruits, maize, and finger millet. These gardens are of two types: the first is located near the house and is called "Balu", and the second is located at a distance from the village, close to paddy fields and forests, and known as "Yorlu" (Figure 11.7) (Sundriyal and Dollo, 2013). Various common vegetables such as *Allium* sp., *Cucurbita pepo, Cucumis sativus, Brassica juncea var. rugosa, Phaseolus spp, Lycopersicon esculentum, Brassica oleracea, Solanum kurzii, Colocasia esculenta, Zingiber officinale*, etc. along with maize and finger millet are cultivated in these homegardens. Additionally, fruit trees such as *Prunus* spp., *Pyrus* spp., *Malus domestica*, and *Actinidia* spp. are also grown in the homegardens. The harvests from these gardens are used for household consumption and sold in local markets. Every household has its own Yorlu or Balu or both and they are taken care of

throughout the year along with the paddy cultivation. Yorlu and Balu are the sources of seasonal fruits and vegetables which provide much-required nutrition to the community.



Figure 11.7: Yorlu

11.8 Forest

The hills and mountains surrounding Ziro Valley are covered by forests comprising different forest types, and *Phyllostachys bambusoides* plantations.

The subtropical pine forest consists of *Pinus wallichiana* as monoculture or mixed with other broad-leaved species such as *Castanopsis* spp, *Prunus cerasoides*, and *Pyrus pashia* (Fig. 11.8). The subtropical broad-leaved forests are composition of C. *tribuloides*, C. *indica*, C. *hystrix*, etc. which can grow as a monoculture or mixed with other broad-leaved species like *Quercus* spp., *Myrica esculenta, Alnus nepalensis, Magnolia lanuginose, Exbucklandia populnea, Spondias axillaris, and Chimonobambusa* sp.

The temperate forest is a mixture of various coniferous and broad-leaved tree species, including *Pinus wallichiana, Tsuga dumosa, Taxus baccata, Illicium griffithii, Rhododendron arboreum, Acer* sp., *Castanopsis* spp., *Quercus* spp., *Magnolia* spp, *Chimonobambusa* sp.

The plantation of *Phyllostachys bambusoides*, a monopodial bamboo species, is planted adjacent to the paddy fields (Fig. 11.9). Although these are maintained as monocultures, scattered trees of *Pinus wallichiana, Prunus cerasoides,* and *Pyrus pashia* can be found growing with *Phyllostachys bambusoides*.

The age-old practice of protecting and maintaining different types of forests in the surrounding hills and periphery of paddy fields ensures the supply of food, fuelwood timber, and other socio-culturally important forest products for the community. It also contributes to the control of soil erosion in the hills while providing a perennial supply of water through the natural streams rising from the forests. The runoffs from forests add organic matter and nutrients such as Ca, P, etc. to the soil in the fields (Klimaszyk et al. 2015).



Figure 11.8: *Pinus wallichiana* forest



Figure 11.9: *Phyllostachys bambusoides* plantation

11.9 Land and Water Management practices for Wet rice cultivation and Fish culture

The paddy fields are irrigated with the water coming from the streams arising from the forests on the hills and mountains surrounding the valley. The water from the streams is redirected and redistributed to rice field with the help of a network of channels and connecting pipes of bamboo or wood (Fig. 11.10). Dykes or bunds of 0.6 m to 1.4 m width and 0.2 m to 0.6 m height

(Nimachow et al. 2010) are constructed to maintain the water in the field for paddy and fish. *Houttuynia cordata* is allowed to grow on the bunds to strengthen their structure and barriers made of the wood of *Pinus wallichiana, Castanopsis* sp. or bamboo are cultivated to control the impact of water and prevent soil erosion. Traditional pipes made up of bamboo or wood are used for water supply to the fields. *Phragmites* sp, and *Ligustrum* sp. are also planted along the channel banks for soil erosion control (Kacha, 2022).

Traditionally, the irrigation system is managed by a group of farmers known as "*Bogo Ahto*" which is responsible for building and maintaining the water supply system and ensuring efficient and equitable water sharing among the members (Kacha, 2022).

Only spade is used in place of animals and machines for land preparation. Soil nutrients are maintained by incorporating various types of wastes from households, poultry, piggery, agriculture, and forests.



Figure 11.10: Bamboo pipes for water supply in the fields

11.10 Apatani farming as a Sustainable Land Management practice

The traditional farming practices of the Apatanis of Ziro valley rightly qualify as a SLM practice. This system integrates various traditional conservation and management practices for agriculture, forests, soil, and water which are well intertwined with their socio-cultural practices. Since the land and water resources are limited, Apatanis have evolved unique, efficient, and effective technologies which are economically viable and environmentally sustainable. This can be observed from the integrated cultivation of rice, finger millet, and fish in the same field which yields three crops simultaneously with low input costs and high outputs. Also, the efficient utilization of water through an elaborate system of channels and ducts for irrigating the paddy fields with minimum loss of soil and water combined with the practices of protecting and maintaining forest in the hills. Soil erosion control measures such as the construction of wooden or bamboo barriers or planting of *Phragmites* sp, and *Ligustrum* sp. (Kacha, 2022), etc. along the channel banks and the practice of incorporating wastes from households, poultry, piggery, cattle, forest and agriculture (rice straw, rice husk, paddy stubbles, weeds, etc.) into the soil to maintain and enhance

the soil fertility are some good examples of SLM practices of the Apatanis.

The ecologically viable traditional practice of integrating and maintaining multiple land use types ensures the continuity of species and varieties diversity through the cultivation and utilization of multiple species of agricultural, horticultural, and forestry crops. The self-sufficient management techniques of the Apatanis are highly effective in the conservation and management of resources and sustainable due to low dependence on external resources and technology (Dollo et al., 2009).

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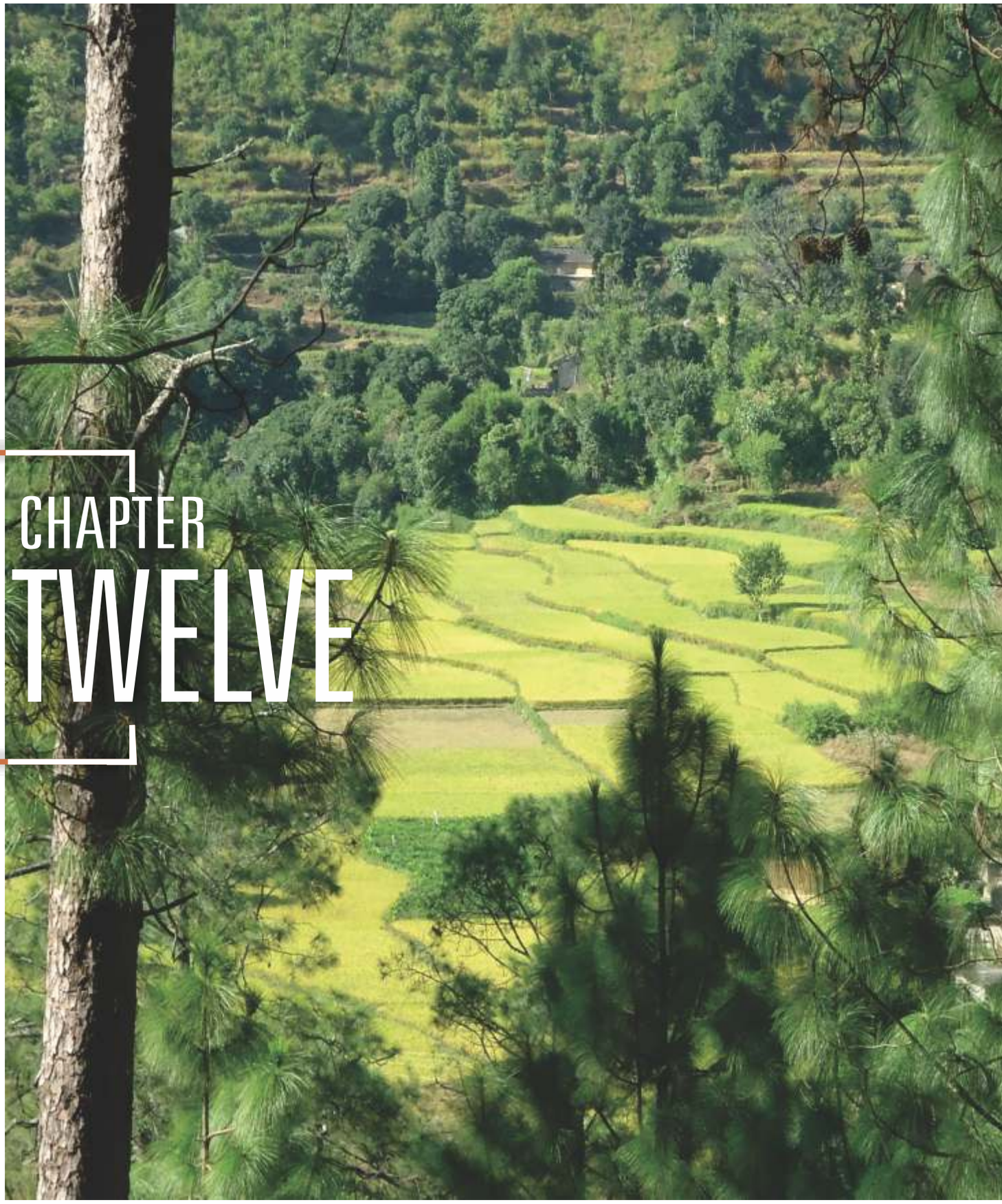
Eco-smart Model Village, Jeyoli
- A Case Study on Sustainable Land Management in Central Himalaya



CHAPTER
TWELVE

Paromita Ghosh
G. B. Pant National Institute of Himalayan Environment, Kosi- Katarmal, Almora, Uttarakhand - 263643

CHAPTER 12

12.1 Introduction

The Indian Himalayan region is rich in natural resources but characterized by steep topography with low soil depth and rainfed agriculture. The local population depend strongly on the forest for food, fodder and fuelwood. The Indian Himalayan region comprises of young fold mountains that are highly fragile and vulnerable. These young mountains are prone to natural disasters due to climatic events like heavy rainfall, snow fall, cloud bursts, landslides and drought. It is imperative to have location specific sustainable land management technologies to maintain the ecological stability and biodiversity and livelihood of the communities. The central Himalayan region is also densely populated and is heavily dependent on finite resources as primary production hubs like agriculture, forestry and livestock. The environment of the central Himalayan region is holocoenotic in nature (Singh, 2006) where an imbalance in any one component of environment is bound to bring imbalance in all other components of the environment. It leads to a chain of natural resource degradation and impacts the socio-economic conditions of the marginalized rural population. Therefore, adopting location specific sustainable land management practice, circular economy and ensuring the carrying capacity of the surrounding natural ecosystem is the need of the hour for the central Himalayan region. Sustainability can be brought about through initiatives and actions at sensitive locations through people's participation in their social, economic and environmental surrounding which are considered as the four pillars of sustainability (Hollingsworth, 2020).

Keeping in mind the four pillars of sustainability a community driven eco-smart model village was developed to improve livelihoods and foster ecological security in the central Himalayan region. The study aimed at the skill development of rural communities in the central Himalayan region through capacity building programmes to secure their livelihood and improve their quality of life through sustainable land development technologies.

12.2 The approach

A cluster of five villages in Jeyoli Gram Panchayat of Hawalbag block, Almora district, Uttarakhand were selected following the criteria of the Sansad Adarsh Gram Yojna technical document (SAGY, 2014) (Table 12.1). The development of eco-smart model village was conceived and initiated amidst COVID-19 pandemic in the year 2020 following all COVID-19 restriction protocols and has been planned as a five-year project. This study reports the preliminary findings obtained after intiation of interventions related to sustainable land development and data collected during the year 2020-2022.

S. No.	Criteria	Source of information	Website
1.	SC &ST population	District information centre (District at a glance for respective states)	Uk.gov.in/pages/display/983-districts
2.	BPL percentage	District information centre	Uk.nic.in/district-centres/
3.	Remoteness	Block revenue map (Department of land revenue)	https://revenue.uk.gov.in
4.	List of backward villages	District information centre	Uk.nic.in/district-centres/

Table 12.1: Criteria of village selection by Gram Sabhas and sources of information (SAGY Technical guidelines 2014)

The selected villages were Jeyoli, Kharkuna, Kaneli, Bisra, Dilkote, and Kujayari. The villages were located at 29°036' N latitude and 79°034' E longitude, approx. 1200 m above mean sea level. The village cluster was spread over 529ha area out of which only 37 ha land is under cultivation, 56 ha area is covered with fragmented forests and 122 ha is under pasture grazing land and representing mostly degraded land. Best practices and sustainable land

management technologies were identified and prioritized through house hold surveys and meetings with the stakeholders (Table 12.2) and finalized based on the demand of the people of the selected villages who held stake of the natural resources of the region. The sustainable land management technologies adopted, management issues addressed and the outcomes of the study are given in Table 2. Extensive demonstration and capacity building activities were carried out to popularize and saturate the region with sustainable land management technologies. During the year 2020 to 2022, a total of seventy six (76) events (training workshops, hands-on training workshops at farmer's field, and related activities and meetings etc.) were organized to demonstrate environment-friendly, income generating and livelihood enhancing sustainable land management technologies for improving and increasing the capacity of over 1653 stakeholders at the Jeyoli village cluster. Four meetings and three stakeholder participation programs were conducted for dovetailing the sustainable land management technologies adopted by stakeholders with schemes launched/ implemented by the state government through district administration, Almora along with local NGOs and cooperative societies for financing and handholding.

12.3 Outcomes

Ten sustainable land management technologies were identified and adopted in the village clusters that helped in improving the environment through conservation of soil, water, forest and croplands (Table 12.2). The technologies were adopted by 255 farmers and their annual income increased with the adoption of sustainable land management techniques (Table 12.3). Protected cultivation was the most popular technology adopted by maximum 66 farmers and it also provided considerable amount of monetary return to the farmers. Domestic and farm waste was recycled to prepare compost and used in the croplands as well as in protected cultivation which helped to increase crop yields and saved the cost of chemical fertilizers. Poultry farming led to maximum monetary return followed by pine jewellery making. Pine jewellery making can be upscaled as an important cottage industry. Pine bio-briquette prepared by the villagers saved the cost of LPG and extraction of fuelwood from the forests. About 1.5 hectares of land were planted with five multipurpose fast-growing tree species. *Alnus nepalensis* (nitrogen fixing tree), *Quercus leucotrichophora*, (fodder and fuelwood species) *Cinnamon tamala* (medicinal plant), *Toona ciliata* and *Salix alba* both of which are good timber and

S.No.	Sustainable land management technologies	Management issues addressed	Outcomes
1.	Rehabilitation of degraded land through the plantation of multi--purpose trees species	Afforestation/ reforestation, soil erosion control, livelihood security	Mixed Forest/ woodland with multiple ecosystem services
2.	Use of manure, vermicompost	Integrated soil fertility management	Healthy soil and productive farmlands Circular Economy
3.	Protected cultivation Polyhouse	Integrated soil fertility management Minimum soil disturbance	Healthy soil and increased crop production
4.	Ecological engineering through pine needle check dam	Water flow management	Soil erosion control Improved water percolation
5.	Pine needle bio-briquettes	Prevent forest fire, protect soil from acidity, and sustainable forest management	Less forest fire events, assist ground vegetation regeneration, reduce pressure on fuel wood

Table 12.2: Summary of sustainable land management technologies adopted, issues addressed and outcomes

6.	Pine needle and bark jewellery and *Rakhee* and Local motifs called "*Aipan*"	Green skill development	Enhance green economy
7.	Poultry farming	Nutrition and health management through feed, manure and soil. Type of feed has an important role in sustainability and carbon sequestration	Cycling of nutrients Poultry production is carbon neutral
8.	Beekeeping	Ecosystem services like pollination	Forest conservation and crop productivity
9.	Roof rainwater harvesting	Water management	Cropland and grazing land
10.	Multiple cropping	Vegetation management	Cropland, more yield from less land

used for producing cricket bats and other commercial goods were planted in the study site. *Alnus* and *Salix* grow well in moist area and were planted beside the ravine while *Toona ciliata*, a fire resilient species was planted along the boundaries, at the top ridges of fire prone and fire affected areas. *Cinnamon* and *Quercus* were planted in the central part of community land for facilitating the harvesting of leaves etc. The survival of selected species and their suitability ranking based on survival ability was in the order of *Toona ciliata* (80%) > *Salix alba* (79%) > *Alnus nepalensis* (75%) >*Cinnamon tamala* (73%) > *Quercus leucotrichophora* (70%). It is well known that different species show different growth increment due to internal factors like genetics and physiology, external factors like biotic and abiotic stresses that influence growth of plants in rehabilitated lands. A total of 330 saplings were planted in the community land during the planting season of 2020-2022 (Table 3). More suitable species will be selected keeping in view soil type and stakeholders demand in the next three years. Rooftop rainwater harvesting was done on two houses where roof was made of slate. Pipes and channels were fitted to collect the rain water that accumulated in a closed tanks beside the houses. The rain water harvested was calculated as per the formula (mean annual rainfall in mm x area of roof in m^2 x standard runoff factor (0.9) = Rainwater collected in litres. Rain water harvesting facilitated the conservation of 9840 litres of water which was used for the irrigation of home gardens and rearing of livestock. Besides, ten pine check dams helped to conservation of 1177 tonnes of fertile soil. The average dimensions of the check dams were 2-3m in length and 50 cm diameter and placed minimum 50 feet apart. Standard method was used to calculate the soil loss using the universal soil loss equation (USLE). Bee keeping is being promoted as an additional income generation activity for the farmers of the selected villages, but due to lack of flowering plants and scare of bee stings the farmers are reluctant to adopt the technology. Therefore, in the next phase floriculture and horticulture activities are being promoted to boost beekeeping practices as organic Himalayan honey has huge market demand. The sustainable land management activities adopted by the farmers at Jeyoli village cluster are given in Fig. 12.1 (A-K). Through the house hold surveys and participatory interaction, it was found that the education level, lack of awareness on land degradation, lack of interest in participating to community activities, labour crisis, lack of extension network and small fragmented land holdings affected the sustainable land management in the region.

Table 12.3: Summary of impacts of sustainable land management (SLM) technologies, during the study period 2020 to 2022

SLM technologies	Names of villages						Total no of farmers who adopted the technologies	Total expenditure (Rupees)	Total income (Rupees)	Total profit (Rupees)
	Jeyoli	Kharkuna	Kaneli	Bisra	Kujayari	Dilkote				
Rehabilitation of degraded land	Plantation in 1.5 ha community land was initiated (further plantation will be done after selection of more species through consultation with stakeholders to raise a mixed forest)							20000		330 plants planted in community land.
Biofertilizers, vermi composting	X	X	1	1	X	1	3	19000	9600	-
Protected cultivation (polyhouse)	26	X	13	6	18	3	66	50800	135039	84239
Pine needle check dams	10 check dams in common land							15000		1177 tonnes of soil conserved
Pine needle bio briquette	X	X	7	6	16	1	30	4800	5000	200
Pine jewellery, aipan	8	4	4	5	1	3	25	1500	21900	20400
Poultry farming	22	X	10	6	26	7	71	81252	300084	218832
Bee Keeping	5	4	1	3	10	2	25	117000	81000	-
Rainwater harvesting	X	X	X	X	X	1	1	21000	X	9840 litres of water harvested
Multiple cropping	X	X	X	X	X	X	X	X	X	X
Total	**61**	**8**	**37**	**30**	**71**	**18**	**225**	**345202**	**552623**	**323671**



A: Bio-briquetting



B: Poultry farming



C: Beekeeping



D: Local motifs "Aipan"making



E: Vermicomposting pits



F: Protected cultivation (Polyhouse)





G: Pine jewellery and "Rakhee"



H: Rehabilitation of degraded land



I: Rainwater harvesting measurements





J&K: Pine needle check dams

Figure 12.1 (A-J) : Glimpses of sustainable land management technologies practiced at the Eco-smart model village at Jeyoli

12.4 Conclusion

The Himalayan ecosystem abounds in ecosystem goods and services that needs proper planning and management for sustainability of the land. A multipronged sustainable land management involving multiple land use and innovative technologies and active participation processes led to an efficient resource management. The outcome is reduced presence on land resources or reduced land the pattern and forest resources, improved livelihood and reduced competition for grabbing land and other natural resources unmindfully. The sustainable land management interventions led to secure energy and food supply, promoted health and social justice and balancing of interests to assure a better quality life and more income. Thus, traditional knowledge based sustainable land management practices can achieve the land degradation neutrality in the central Himalayan region.

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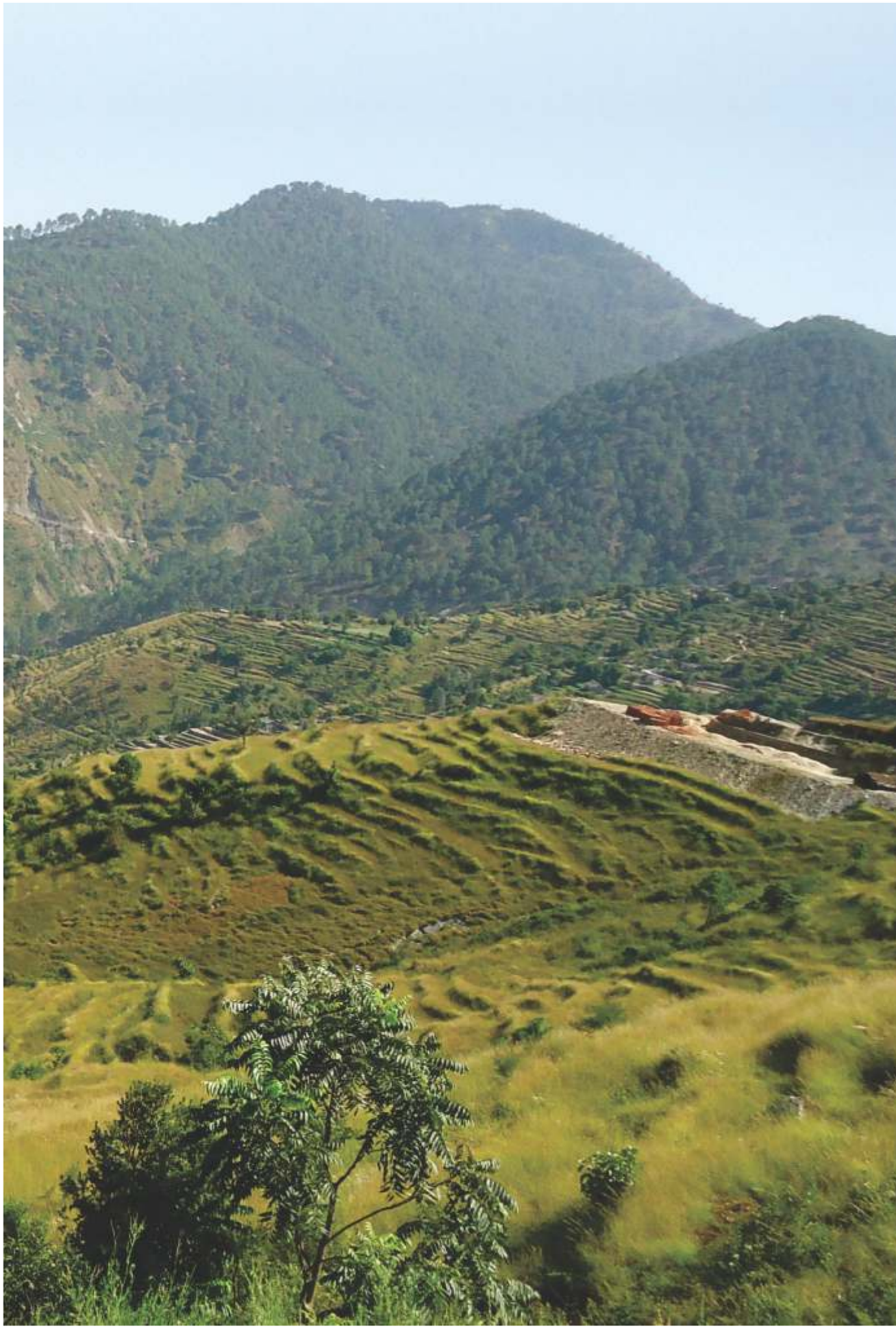

Restoration of Land under shifting cultivation: A case study with Cinderella agroforestry in the Indian Sub-Himalayas



Arun Jyoti Nath
Department of Ecology and Environmental Science, Assam University, Silchar, Assam - 788011

According to Nair et al. (2017), there is no better term than "Cinderella" to refer to forgotten agroforestry systems widely practiced by indigenous communities that are extremely location specific and very little is known outside their native areas of existence. The Hmar's are amongst the pioneer and the largest pineapple growing ethnic groups in the study area. According to them, the age of the traditional land-use practice is estimated to be more than a century. This system combines pineapple crop with fallow vegetation remnants and the subsequent plantations of cash-oriented multipurpose tree species in the same piece of land. The traditional knowledge vis-à-vis the practices has been transferred orally from generation to generation. Since the practice is carried out to improve slash-and-burn fallow lands, the pineapple agroforestry systems (PAFS) were distributed mainly on sloped lands. Sloppy terrains are highly susceptible to soil erosion, so the PAFS practices are vital to check soil erosion. The practice is solely to satisfy home consumption needs and boost farmers' economic benefits. Farmers growing pineapple possessed a high level of self-confidence, low level of scientific orientation and moderate knowledge in improving the system, economic condition, farm decision, risk orientation and decision-making. The statement on farmers' moderate level in the decision to improve the system, economic condition, etc., could be applicable for pure pineapple stands practising farmers, not necessarily to all pineapple growers that integrate trees as farm decision making. Our study (Reang et al. 2021, 2022) observed that farmers could effectively decide to integrate new components to get the best outcome from their farmlands.

The traditional PAFS practices begins with farm preparation by slash-and-burn of fallow vegetation and is carried out from January to April. Mature and/or large trees are selectively retained during the slashing process to aid for shade and also reduce soil erosion. Burnt remains and debris are left on-site for soil nourishment. No-tillage or irrigation is done during the farm preparation stage. With the onset of the first monsoon, annual crops (cereals, spices, rhizomatous crops, legumes etc.) are intercropped with fallow trees from May to June. After a period of three to four months duration, the primary AFS crop, pineapple is cultivated i.e. during September to November. During this cultivation process, the matured annual crops are harvested simultaneously and their residues are retained on-site to provide nutrients for the growing pineapple. In addition, a non-destructive management technique of trees is also carried at this stage through ring barking or girdling of the retained trees. This traditional method of tree management ensures no damage to understory crops, provide adequate shade, suppress weed growth, supply nutrients, and is also ecological sustainable. Ring barking or girdling is a practice to create a standing deadwood by allowing trees to naturally decay. The dead and decayed tree litter is a component of manure and aids micronutrients in soil. The girdling technique to create standing deadwood mass in the Hmar PAFS is shown in Fig.13.1.



Figure 13.1: Girdling of fallow live-tree (A) and a standing decaying tree mass (B).

Traditionally pineapple planting is done in and within rows at approximately 0.7 to 0.8 m spacing, incorporating about 4000 individuals in 0.1 ha. With ageing of the farms, the total number of individuals' increases through slips and suckers growth, resulting in a more dense stands. High-density of these plant individuals is reported to increase the yield and supplement other additional advantages like less weed infestation, protection to fruits from excess sunlight exposure and increased production of suckers and slips (Prakash et al., 2008). Farmers generally favoured suckers for planting materials. No fertilizers or manure input is done in the management process and weeding on average was carried out twice annually during the initial growing stages i.e. in 2 to 3 years PAFS stands.

The PAFS managers/owners reported the importance of shade, particularly during the early pineapple growth stage and fruiting season. According to these farmers optimum shade is necessary to ensure - proper growth, fruit quality and less crop damage. A study by Das et al. (2011) reported about 15-20% of pineapple fruit damage in the absence of adequate shade in Tripura state of India. On the contrary, the PAFS farmers progressively managed open canopy and straight trunk tree species to ensure optimum shade. A loose/open canopy tree is reported to permit adequate light transmittal, while straight growing trees horizontally occupy less space, thereby less interference to the growing understory crops. In particular, *Albizia* species are highly favoured and are managed for shade. In addition, these legume tree species aid in soil N_2 fixation, thereby improving the farm soil quality. Similarly, farmers' choice of *Albizia* species utilised for shade and weed suppression in the PAFS of the Garo tribes in Bangladesh was reported by Khaleque and Gold, (1993). This reveals the farmers' traditional ecological knowledge in tree species prioritisation for farm management acquired through long-term farming experience. In addition, management strategies include the planting of *Areca catechu* and *Musa* species in farm boundaries to serve as live-fencing, soil erosion control, windbreaks, and shelterbelts (environmental benefits).

Pineapple production yield declines approximately in 8 to 10 years. To maintain the productivity and economy out of these land-use systems, the shade trees, i.e., *Albizia* species are ring barked to gradually be replaced by tree species of high economic importance in these old stands. The domesticated multipurpose tree species under such stands primarily comprised *Areca catechu, Aquilaria malaccensis* and *Parkia timoriana* distributed all around the farms. Occasionally, some fruit trees like *Litchi chinensis, Mangifera indica,* etc. are introduced for both home consumption and sale. This combination of mixed multipurpose trees with pineapple under these traditional farming systems supplements for household consumption and market sale all year round. In addition, it is more ecologically sound compared to mono-pineapple stands. Finally, the much older PAFS stands, i.e. > 15years, had pineapple intercropped with rubber plants (*Hevea brasiliensis*). Field images of the transitions and different Cinderella species under the PAFS are represented in Fig. 13.2. This traditional AFS with a mixture of fruit trees, legumes, and rubber offers useful economic profits. In addition, the pineapple planted can effectively help reduce soil erosion (environmental benefits). Hence, this unique and highly intensified land-use system practiced by the ethnic Hmar community needs special attention for its promotion for degraded land restoration.

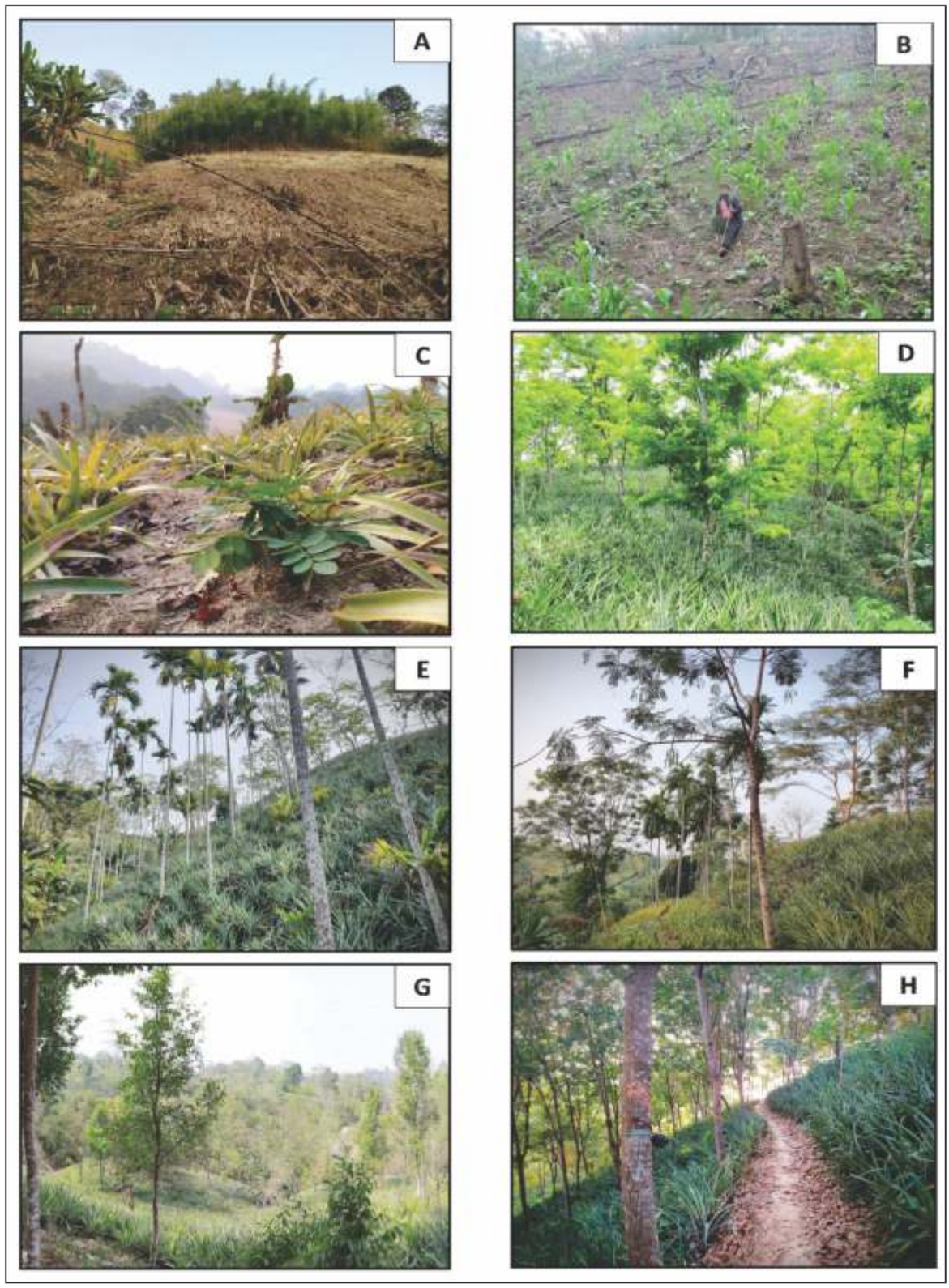

Figure 13.2 : Representative field images of the farm transitions under the Cinderella AFS practiced by the Hmar tribes in Cachar District, Assam, NEI. Farm preparation - Slash (A); after 4 months of burn (cropping phase) (B); Pineapple intercropped with fallow trees and propagation of *Albizia species* (C); Pineapple with multipurpose tree domestication phase: *Albiziaprocera* (D), *Areca catechu* (E), *A. catechu and Parkiatimoriana* (F), *Aquilaria malaccensis* (G) and *Hevea brasiliensis* (H)

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Name and email addresses of Contributors



P. C. Moharana
pcmoharana45@gmail.com



Priyabrata Santra
priyabrata.santra@icar.gov.in



J. P. Singh
Jai.singh@icar.gov.in



Sneha Bandyopadhyay
sneharupayan@rediffmail.com



Subodh Kumar Maiti
subodh@iitism.ac.in



Debashis Mandal
dmandalcswcrti@gmail.com



Rajesh Kaushal
kaushalrajesh1@rediffmail.com



Gopal Kumar
gkcswcrti@gmail.com



Trisha Roy
trisha17.24@gmail.com



M. Madhu
madhupmd@gmail.com



V. Selvam
vselvam45@hotmail.com



B. Nagarajan
teakguynew@gmail.com

Name and email addresses of Contributors


N. Bala
nbala@icfre.org


Prabhat R. Ojasvi
projasvi@gmail.com


Nirmalendu Basak
nirmalendu.basak@icar.gov.in


Arvind Kumar Rai
ak.rai@icar.gov.in


Parul Sundha
parul.sundha@icar.gov.in


Priyanka Chandra
Priyanka.chandra@icar.gov.in


Sandeep Bedwal
sbedwal519@gmail.com


Rajender Kumar Yadav
rk.yadav@icar.gov.in


Parbodh Chander Sharma
parbodh.chander@icar.gov.in


G. Ravindra Chary
rc.gajjala@icar.gov.in


V. Rama Murthy
ramamurthy20464@yahoo.co.in


V.K. Singh
director.crida@icar.gov.in

Name and email addresses of Contributors



K. B. Sridhar
k.sridhar@icar.gov.in



B. Bhargavi
bhargavi.bussa@icar.gov.in



Arghya Chakrabarty
arghya.chakrabarty@wi-sa.org



Ritesh Kumar
ritesh.kumar@wi-sa.org



Shailaja Punetha
shailupunetha@gmail.com



Paromita Ghosh
paroghosh@rediffmail.com



Nada Tadi
nadatadi05@gmail.com



Arun Jyoti Nath
arunjyotinath@gmail.com

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