Chapter

Ecological Engineering Measures for Ravine Slope Stabilization and its Sustainable Productive Utilization

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Abstract

The 120 countries have committed to set the UNCCD sustainable development goal on achieving the land degradation neutrality by 2030 including India. The target has to be accomplished in a synergistic and cost-effective manner in accordance with countries' specific national contexts and development priorities. Globally, the ravine landscapes are considered among the world's most degraded ecosystems. Therefore, restoring ravines is considered a high priority item in the natural resource management programs. The vegetation cover augmented with appropriate conservation measures is the most sought restoration strategy. The engineering measures are prerequisite for slope stabilization and sustainable productive utilization in ravine ecosystem. The several methods for slope stabilization are available but only few are applied in ravine land. Therefore, in this chapter, we have covered only those slope stabilization techniques which were successfully applied for the restoration of ravine land.

Keywords: ravine, soil erosion, runoff, land degradation, slope stabilization

1. Introduction

The ravine landscape is considered as one of the most degraded terrestrial ecosystems in the world. The continuous and aggravated soil erosion and subsequent anthropogenic activities leads to the formation of ravine landscapes. Ravine is intricate network of large gullies with depth ranging from 3 m or more and affected by extreme form of mass soil erosion. The high drainage density and multi-directional steep slopes are other morphological characteristics of ravines. In India, ravines occupy about 4.3 M ha along the rivers *Yamuna*, *Chambal*, *Mahi*, and *Sabarmati* [1]. The marginal lands near to gully head in ravines are dominated by agriculture land use, while pastures and open forests on the side slopes and gully bed. Generally ravine areas have 15 to 32% arable lands and 60 to 85% non-arable lands [2]. The marginal lands adjacent to ravines are under extensive cultivation without much attention to conservation measures, which leads to further extension of gullies head during rainy season. These ravine lands are under biotic stress due to uncontrolled grazing by stray and wild animals and poor vegetation cover leading to huge soil loss during rainy season. These are the worst form of land degradation formed, when the vegetal cover is not strong enough to hold and bind the soil particles together from being carried away by the runoff water. The restoration of these ecosystems through bio-engineering measures is extremely important to conserve natural resources, maintain landscape sustainability, enhance carbon sequestration, mitigate climate change, improve socio-economic conditions and ensure food and livelihood security throughout such regions [3].

Ravine is subjected to extreme hydrological events (flood and drought), high summer temperatures, high wind velocity and extreme soil erosion that make them more vulnerable to land degradation. The several anthropological activities such as improper land use, illicit mining, faulty methods of road construction, uncontrolled grazing, deforestation, increased population, overexploitation of natural resources, unplanned urbanization, unregulated industrialization, increased rural poverty, low natural resource management skill and absence of appropriate resource conservation measures etc. accelerates the erosion process, that leads to land degradation and ravine landscapes formation [4]. To reclaim and rehabilitate such unproductive ravines, soil and water conservation technologies, e.g., peripheral and contour bund, vegetative barriers, grassed waterways, terrace, trench, composite check dams, gully plugs, gully easing, afforestation, agroforestry, contour cultivation, strip cropping, intercropping, mulching, tillage, cropping system, crop scheduling, crop geometry, organic manures, conservation agriculture, and soil management techniques have been successfully tested and recommended. These soil and water conservation measures can provide a large number of tangible i.e. controlling soil erosion, improving soil properties, promoting plant growth and yield, enhancing biomass/carbon stock, and provision of various tree products and intangible benefits i.e. mitigating climate change, protection of downstream water bodies, regulating the environmental flow, biomass recycling and soil formation, capacity building, out migration mitigation, bio-diversity [5]. Therefore, we have discussed the various engineering/mechanical, afforestation, agroforestry, agronomic and soil management practices for applied for managing and stabilizing the ravine slope.

2. Extent of ravine in India

In India the ravines have mostly developed along the river systems having highly productive and deep alluvial soils. The National Commission on Agriculture estimated 3.67 M ha of ravine lands 1.12% of total geographical area of India [6]. Out of 3.67 M ha of ravine lands in India, 2.36 M ha (64%) exists in Uttar Pradesh, Madhya Pradesh, Bihar, Rajasthan, and Gujarat states of India [7]. The ravines on *Yamuna* and *Chambal* River are the largest and most severely degraded ecosystems in the country. Besides these the ravines also extends from the banks of the *Tapti*, *Narmada*, *Watrak*, *Sabarmati*, and *Mahi* River. However, some staggered patches of ravines are also found in *Chota Nagpur* plateau, *Mahanadi* river basin and upper *Sone* Valley, *Indo-Gangetic* plains, *Shiwaliks* and *Bhabar* tract, and Western Himalayas even up to the *Kashmir* Valley [7]. In unmanaged conditions rate of ravine extension ranges from 0.6 to 1.0 m per year and is much greater on sandy soil than on the clay loam soils. The average annual loss of nutrients from these ravine lands due to soil erosion has been estimated at 5.37–8.4 Mg resulting into loss of production due to non-reclamation of ravines [8].

3. Classification of ravine system

The ravine system has gullies having independent catchment along with a regular main stream. In each drainage system, it is observed that gullies occur in

Symbol	Description	Specifications
G1	Very small gullies	Depth up to 3 m. Bed width not greater than 18 m. Side slopes varies.
G2	Small gullies	Depth up to 3 m. Bed width greater than 18 meters. Side slopes varies.
G3	Medium gullies	Depth between 3 m to 9 m. Bed width not less than 18 m. Sides uniformly sloping between 8 to 15%.
G4	Deep and Narrow gullies	Depth 3 m to 9 m. Bed width less than 18 m. Side slopes varies. Depth greater than 9 m. Bed width varies. Side slopes varies. Mostly steep or even vertical with intricate and active branch of gullies.

Table 1.
Classification of gullies in ravine land.

Land capability class	Slope (%)	Distance from gully rim and land form	Recommended soil and water conservation measures
a. Land suitable for cultivation			
I (light green yellow)	0–1	Very far from gully rim	No measures necessary, except ordinary good farming practices.
II (yellow)	1–3	Beyond 60 m	(i) Contour bund in the catchment, (ii) Good agronomic measures such as contour cropping, strip cropping and cover cropping.
III (red)	0–8	Between 6 and 60 m. Table lands and wide humps between wide gullies	(i) Contour and peripheral bund, (ii) Provision of safe outlets at gully heads (pipe outlet or chute) for the discharge of excess runoff, (iii) Intense agronomic measures such as contour cropping, contour strip cropping and cover cropping.
IV (blue)	8–15	Small and medium gully sides and beds (G1, G2, and G3). Slope must be uniform and gully depth should not be more than 9 m.	(i) Peripheral control with diversion bunds and safe outlets, (ii) Clearing and minor leveling on gully sides and beds, (iii) Putting up composite check dams of earth and brick masonry across the gully bed at 4′ vertical interval or 400 m horizontal interval, (iv) Terracing on gully sides up to 15% at 3′-4′ vertical interval, (v) Good crop rotations and heavy application of manure and fertilizers for restoration of soil fertility.
b. Land not suited for cultivation			
V (dark green)	15–25	Wide humps or gully sides (minimum 120 m long and 30 m wide with no gully intrusion.	Controlled grazing after pasture development
VI (orange)	Varies	Marginal land between the gully rim and the cultivated land (Peripheral bund)	(i) Grazing strictly prohibited, (ii) Cut the grass and stall feed the cattle's, (iii) Staggered contour trenching and afforestation.

Land capability class	Slope (%)	Distance from gully rim and land form	Recommended soil and water conservation measures
VII (brown)	Varies	Gully sides and beds (G4)	(i) Staggered contour trenching for moisture conservation and afforestation, (ii) Gully plugging and easing of the rapids along the gully beds, (iii) Development of pasture and afforestation.
VIII (purple)	Varies	Gully sides and beds (G4) with rock on the surface.	Complete closure to grazing and felling of trees.

Table 2.
Land capability classification for soil and water conservation measures in ravine land.

a certain regular order with well-defined side slopes, bed width and depth. In the upper reaches of the drainage system the gullies are wide and shallow with varying side slopes. The middle part of the drainage system usually has relatively deeper, wider and has uniform side slopes normally up to about 25%. The lower portion of the drainage system usually happens very deep, has steep side slopes and associated with intricate branched gullies. The ravine management depends on extent of gully bank deformation, slope, soil quality and vegetation cover. The ravines are classified in six classes based on the extent of gully bank deformation and erosion vulnerability under varying slopes. The shallow gullies up to 3.0 m depths are classified under land capability class I and II and recommended for cultivation of seasonal crops with moderate land leveling. The land capability class III has deeper and narrow gullies and more limitations for cultivation of seasonal crops. The land capability class IV has severe limitations of soil texture, gully size, steeper side slopes, and deeper and narrower gully beds for cultivation of seasonal crops and recommended for perennial horticulture plantations. The Class V and VI lands are not recommended for high value plantations or cultivation due to limitations of seasonal backflows from an adjoining river system, waterlogging, development of soil salinity due to irrigation, or due to extreme slope of gully bank. Hence, Class V and VI lands are recommended for perennial vegetation avoiding uncontrolled grazing activities. The ravine management is location-specific and should be undertaken based on the above classification and limitations.

Several workers have classified the gullies based on their cross section, forms, gully head characteristics, length, width and depth of catchment. Classification of the gullies, evolved at the ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Vasad, Gujarat, India after critically observing ravine landscape developed along most of the river banks in Western India. The different types of gullies classified based on depth from adjacent marginal lands, width of the gully and side slopes given below in **Table 1** and the land capability classification and recommended conservation measures for ravine land is given in **Table 2** [9].

4. Measures for management of ravine land

The agricultural activity with land leveling is preferred for slope stabilization and its management in shallow ravines due to presence of deep and alluvial soil. The increased cost of land leveling operation is a major constraint and key factor in making decision for management of medium and deep ravines. The appropriate ways for management of ravines is reducing runoff intensity and safe disposal of runoff in ravines. The runoff generated from the adjacent marginal land is managed by constructing peripheral bund, checking of runoff/sediment in the interconnected gullies by earthen gully plugs/bori-bund/composite check dams at proper horizontal interval. The terracing is recommended in shallow and medium ravines slopes along with agroforestry measures for sustainable land use. The deep and very deep ravines are recommended to be kept under permanent vegetative cover along with site specific soil and water conversation measures. The medium and deep gullies having steeper slopes and economically not suitable for cultivation can be put under silvi-pasture permanent vegetation cover with protection from grazing for proper management of these lands.

4.1 Engineering measures for management of shallow ravine land

About one third of the ravine lands in the country are shallow ravines (<1 m deep) and can be easily reclaimed with simple earth moving machinery for cultivation of crops. The management of shallow ravines instigates with designing and instituting a peripheral bund along the gully head to check the runoff generated from the adjoining marginal lands. The land leveling operations across the slope and smoothening on the upstream side of the peripheral bund increases the infiltration opportunity time for the runoff generated from the crop field. The in-situ soil moisture conservation increases the water and nutrient use efficiency of the cropping systems.

4.1.1 Vegetative barrier

Vegetative barriers are used either for supplementing or substituting earthen bunds. The *Dichanthium annulatum, Cenchrus ciliaris, Vetiveria zizanioides, Eulaliopsis binata, Saccharum munja* and *Aloe barbadensis* vegetative barriers were evaluated for their effectiveness in reducing runoff, soil and nutrients losses from 2% slope of marginal shallow ravines. Vegetative barriers were grown across the slope at 45 m horizontal interval, in paired rows of 10 cm slip to slip spacing. The cultivation of pigeon pea (BDN-2) was done at 120 × 30 cm spacing in all plots. These vegetative barriers reduced the annual runoff by 19.7 to 50.1% and soil loss by 51.1 to 80.3% over the control plot [10].

The Napier, Guinea and Para fodder grasses strips of 1 m and 2 m were grown as vegetative barrier in 2% slope in shallow ravines. The lowest sediment yield was observed in 2 m width of Napier grass strip (1.43 t/ha) followed by 2 m width of Guinea and Para grass strips as compared to control (4.07 t/ha), respectively. The 2 m width of Napier grass strips has lowest nutrient loss of (N-5.64 kg/ha, P-3.1 kg/ha, K-5.4 kg/ha) followed by Guinea and Para were found almost equally efficient in reducing nutrient losses from crop field which is 28 to 30% of nutrient losses from control (N-20.01 kg/ha, P-8.3 kg/ha, K-17.00 kg/ha). The equivalent yield of 2 m width of Napier grass strip and cotton crop (1293.5 kg/ha) has highest yield followed by others. The economic analysis shows that Napier grass strips of 2 m width was found best in reducing runoff, soil loss, nutrient losses and net return from crop field [10].

4.1.2 Grassed waterway

Grassed waterways are important for preventing the scouring of channel bed in shallow ravines. The *Para* grass strips in waterways were optimized for grass cover to check runoff velocity and reduce sediment concentration in downstream water bodies. The different *Para* grass cover (0–100%) in waterways was studied at 2% slope. The different grass covers are 100%, 75%, 50%, 25% and no grass cover. These *Para* grass strips were able to produce green grass yield of 14.5 kg/m^2. The *para* grass strips in waterways is able to reduce the outflow up to 22% with 100%

grass cover. The grass filter strips is able to reduce the sediment concentration in runoff water by 5 times (from 3.6 to 0.72 g/lit). The *Para* grass filter in waterways is able to reduce the flow velocity of runoff water by converting the super critical flows into sub critical flows [10].

4.1.3 Contour and peripheral bund

The management of shallow ravine by contour and peripheral bund has shown improvement in value of land and crop yield due to soil moisture retention within the field, prevention of soil and nutrient losses from the crop field. The different cross sections of contour and peripheral bunds were tested in ravine lands of Western India [11]. The design cross sections of the bunds were fixed on the basis of the area of the catchment, slope of the land and its location. The bunds were designed on the basis of the vertical interval or horizontal spacing [11]. Usually one bund could only be located in each field approximately on contour so that it can also serve as peripheral control of gully heads. These bunds were sodded with *Dichanthium annulatum* and *Cenchrus ciliaris* grasses. In ravine lands an average cross section of 0.9 to 1.3 m^2 spaced at 0.90 to 1.20 m vertical interval was found best [11]. Grass ramps and pipe outlets were provided in the bunds for the safe disposal of excess runoff water. It is further stated that the effectiveness of the bunds would be for a longer period, as with passage of time the rate of reduction of bund height is expected to be slow and can be maintained indefinitely with good stabilized grasses [12]. It is also found that the area lost under bunds could fetch revenue from grasses, which is sufficient as comparable to production in rainfed area [12].

4.2 Engineering measures for management of medium and deep ravine land

About two third of the ravine lands in the country are deep ravines 3–9 m or more with varying width and slope and cannot be easily reclaimed with simple earth moving machinery for cultivation of crops. The management of deep ravines instigates with designing and instituting a series of composite check dams in the gully bed. The construction of gully plug at regular interval with provision for safe disposal of runoff assists in stabilization of gully bed, which can be alternatively utilized for raising crops tolerant to water logging. The easing of gully is required in deep gully to prevent caving action against steep slope due to runoff and protect the adjoining marginal land to collapse inside the gully due to unstable slope. The medium and deep gully can be reclaimed by terracing and or trenching for conservation of runoff, soil loss, associated nutrients and stabilize the steep slopes with time.

4.2.1 Composite check dam

A large number of earth cum brick masonry check dams were constructed in Mahi ravines of Western India for reclamation of medium and deep gullies in ravine [10]. These check dams were found to be very effective to check erosion, detaining the sediment and runoff water behind the structure which ultimately resulted in ground water recharge. The deposition of sediment against the check dams was measured by fixing a series of angle iron poles on concrete level of the structure. The average sedimentation from these ravine sub catchments having agricultural crop in table lands as well as in gully beds was 24.51 cu. m./ha/year during year 1961 to 1963 [10]. The average sediment deposition from watershed having agricultural crop in tablelands and natural regeneration in gully beds was 4.20 cu. m. /ha/year during year 1964 to 1977 [10]. After the siltation of these composite check dams the level terraces formed in the gully beds were stabilized and was put under cultivation but it was found to be poor in production. Therefore these reclaimed cultivated deep gully beds were subsequently planted with forest trees [10].

4.2.2 Gully plugs

Gully plugs protect the gully beds by reducing the runoff velocity, distributing the water spread, increasing infiltration opportunity time and improving the soil moisture regime for improving the vegetation cover. Gully plugs made of various materials i.e. brush wood, live hedges, earth, sandbags and brick masonry, loose boulder were evaluated in Western India [10]. The size and materials for the gully plug depends on the width, length and bed slope of the gully and anticipated runoff. In narrow gullies whose width did not exceed 3 m, live hedges consisting of Euphorbia species were planted across the gully beds in three rows spaced 90 cm apart and the stems at 90 cm in each row alternatively staggered [11]. It was found that all types of gully plugs were effective either in retaining or retarding the runoff. The earthen gully plugs were found to be the cheapest. Brick masonry gully plugs are constructed at the confluence of all gully branches of a compound gully. The gullies where no runoff is expected from the top, earthen gully plugs of 1.1 m^2 cross section with a grassed ramp of 22.5 cm below the top level and spaced at 45–60 m horizontal interval were found suitable. However, for gullies in which excess runoff from the top was expected an earthen gully plugs of 2.2 m^2 cross section with a pipe outlet was to be provided. The earthen gully plugs are required to be constructed for a life expectancy of 10 years. During these periods it is estimated that the vegetative growth of forest species will be sufficient to take care of soil erosion as well as their root system will be sufficiently developed to extract the moisture from deep soil layers [11].

4.2.3 Gully easing

Deep and vertical gully heads in association with the phenomena of under cutting or caving extending at an alarming rate endangering buildings, roads, bridges, abutments, railway tracks and costly cultivated lands. The measure which can be economically and immediately adopted to stop further progress of the gully head or cave the bottom of gully and then ease the gully for the remaining one third top portion of the vertical face. The newly formed slope of about 3:1 is stabilized by sodding with *Dichanthium annulatum* or *Cenchrus ciliaris* grasses [11]. The eased gully heads were found out to be in existence and working satisfactory even after 22 years of management. The comparison of eased gully with nearby gully under similar condition reveals that there is good vegetation on the eased gully head in comparisons to the unease gullies which are still exposed and covered with sparse annual vegetation [13].

4.2.4 Bench terracing

The impact of bench terracing on runoff, soil loss, and soil properties along with Sapota (*Achras zapota*) growth, fruit yield, biomass, and carbon stock in a degraded ravine land developed along the course of *Mahi* River in Western India were evaluated. The bench terracing in deep ravines with uniform slope of 15% resulted in significant decrease in runoff (34%) and soil erosion (25%), and enhanced tree growth, biomass and carbon stock. The cultivation of crops in between the tree plantation may induce significant soil loss (18% higher) due to tillage operations even though the runoff is not significantly affected. The findings suggested that bench terracing is the best soil and water conservation measure for restoring highly degraded ravines [3].

4.2.5 Trenching

The impact of trenching in deep ravines was evaluated ravines developed along the Mahi River in Western India. The staggered contour trenches were designed based on maximum daily rainfall. The trenching density on the ravine slopes was kept to retain 30, 50 and 80% of runoff generated from the ravine catchment. A substantial reduction in runoff was observed for treatments with higher trench densities (50% and 80%) as compared to 30%. The sediment yield in different trench densities also followed the similar trend. The soil moisture was more or less similar in different trench densities just followed by the monsoon. However, soil moisture in the 80% trench density was highest and also remains for a longer period in the lower reaches of the ravine slopes. The survival of Neem (*Azadirachta indica*) saplings planted at a spacing of 6 m × 6 m was also recorded and was also found highest in 80% trench density. In another study, the trenching of size 2 m × 0.5 m × 0.5 m at 14% uniform slope with Sapota plantation resulted in decrease in runoff by 16% and soil loss by 15% along with enhanced tree growth, biomass and carbon stock in the deep ravine slopes [11].

4.2.6 Bamboo based bio-engineering measures

The bamboo based bio-engineering measures is found as an effective means for natural resource conservation in ravines [14, 15]. The soil erosion is found comparatively less in bamboo plantations (178 kg ha^{-1}) compared with other forest plantation [16]. The significant stem flow and funneling ratio of bamboo plants provides better opportunity for rainfall absorption in degraded ravine lands [17]. Bamboo also acts as a vegetative barrier and filter for silt laden runoff flowing in gullies. The bamboo induces silt deposition and reduces the velocity of flowing water along bare river banks and deforested areas in ravines. *Dendrocalamus strictus* which occupies major area covered under bamboo plantation in India was found best for economic utilization of ravines. It is reported that annually about 4000 culms of bamboo per hectare can be harvested from ravine lands [18]. The benefit–cost ratio of 1.98 from bamboo plantation in ravines is profitable having an economic return of 19.3% over a period of 20 years [19]. The intangible benefits of carbon sequestration and prevention of soil erosion are supplementary. The ravine lands under the bamboo plantation increased the soil pH, organic carbon along with reduced runoff [20].

4.3 Forestry and agroforestry measures for management of ravines

The engineering measures are expensive and also needs technical acquaintance for proper designing and execution for management of ravines. The medium and deep gullies of ravine needs permanent vegetative cover having deep root system to bind the soil against strong forces of erosion in gullies during rainy season. The afforestation and agroforestry are relatively cheaper and affective in checking the soil erosion in medium and deep gullies. The performance of various afforestation and agroforestry system evaluated in ravine developed along the Mahi River in Western India is discussed below.

4.3.1 Afforestation

Afforestation is an important tool to mitigate land degradation due to soil erosion. Afforestation in ravine land provides ecosystem provisioning services i.e. fodder, timber, fuel, non-timber forest product, medicine and gum; regulating services i.e. nutrient cycling, controlling soil erosion, moderating climate, carbon sequestration; supporting service i.e. net primary production, soil formation and cultural services, recreation [3, 4]. The vegetation exploration in ravine shows the dominance of flora like *Azadirachta indica*, *Acacia nilotica* and *Prosopis cineraria*. In ravine gully head, there is predominance of *Prosopis cineraria*, *Acacia nilotica*, *Acacia senegal*, *Azadirachta indica*, *Holoptelia integrifolia*, *Feronia elephantum* and *Balanites roxbyrghii*. In ravine gully slope, there is equal distribution of *Acacia nilotica*, *Acacia senegal*, *Azadirachta indica* and *Prosopis cineraria*, followed by *Holoptelia integrifolia* and *Salmalia*. In bottom of ravine gully beds, there is predominance of *Holoptelia* species, *Acacia* species, *Azadirachta indica*, *Anogeissus latifolia* and *Balanites roxburghii*. Artificial regeneration results indicated the dominance of *Acacia nilotica* followed by the *Azadirachta indica*. The other dominant species were *Prosopis cineraria*, *Holoptelia integrifolia*, *Salmalia malabaricum* and *Anogiessus* species. *Acacia nilotica* attained diameter at breast height (DBH) between 19.6 cm and 28 cm in the Mahi ravines of Western India after 28 years. Semi-arid edaphically degraded soils in ravine lands are dominated by low value thorny trees and the plantation of well adapted and commercially important tree species is utmost important in such lands for obtaining higher ecological and economic benefits. In fact, the effective forest cover is less than 10%, causing shortage of fuel, fodder and timber wood in the area and further minimum 50% forest cover is required to prevent the land degradation. Therefore in such conditions maintenance of continuous canopy covers is extremely important to check soil erosion. *Eucalyptus tereticornis* and *Leuceana leucocephala* was found to be a fast growing tree species and is in much demand especially in the industries [10]. Plantation of bamboo (*Dendrocalamus strictus*) was found highly effective in enhancing vegetation cover, preventing soil erosion and stabilization of ravine slopes [21]. The uncontrolled grazing in ravines accelerates soil erosion which cannot be completely stopped. Therefore a system of restricted and rotational grazing may be helpful to some extent. In ravines, huge gap exists between the demand and supply for timber wood, and sustainable utilization of ravine land can reduce the demand–supply gap. Promotion of awareness and encouragement of tree planting on individual farm land can considerably improve the regional ecology and economy of the local people. These measures also help to improve soil carbon stock that may positively influences soil physical, chemical and biological property, improving the overall productivity of such ecosystem.

4.3.2 Agroforestry

Agroforestry is perennial and annuals plants combination that enhances landscape productivity and conserve natural resources. Agroforestry measures particularly for soil conservation have shown great potential in enhancing productivity of ravine lands [5, 22]. *Prosopis cineraria*, *Acacia leucophloea* and other regional multipurpose trees (MPT's) grown on field boundaries in Gujarat state of Western India. Sometime negative effect on crops may also occur due to competition for light, moisture and nutrients between the trees and crops. The combinations of *Dendrocalamus strictus*+*Cenchrus ciliarus* was also found successful in ravine slopes. *Dendrocalamus strictus*+*Cenchrus ciliarus* the reduced sediment yield 10–20 times less, compared to area without plantation [19]. *Moringa oleifera* and *Embilca officinalis* based agri-horticultural systems were also found effective in enhancing land productivity, conserving natural resources and improving soil health. Soil and water conservation measures (SWCM) also helps to improve agroforestry trees survival and growth due to improved soil moisture and reduced soil erosion. in an agroforestry experiment observed that Cowpea + Castor cultivation in between

Sapota trees may induce soil loss on ravine slope [3]. Supporting native or improved perennial grasses instead of crops may be a better option to reduce the soil erosion. Most researchers have concluded that incorporating trees in agriculture landscape conserve soil and water resources in ravine lands. In these conditions, extreme weather condition also affects plant growth and productivity and hence crop failure is a big problem. Tree-crop combinations system can be win-win situation in these climatically and edaphically venerable degraded agro-ecosystem. Tree and grass systems are also considered to be more resilient compared to crops during extreme weather conditions. Incorporating trees agriculture system also results in higher carbon stock and sequesters maximum carbon, compared to sole cropping systems. The CO_2 mitigation in agroforestry is approximately 11–41% higher compared to sole cropping systems. The farmers in ravine should shift from annual crops to perennial plantations to conserve soil resources, avoid risk of crop failure and mitigate climate change. Moreover, a properly managed agroforestry systems can moderate/improve climatic conditions, conserve soil and water resources, improve ecosystems services and absorb atmospheric GHG's in ravine lands. This suggested agroforestry based farming systems should be preferred globally in degraded ravine agro-ecosystems.

4.4 Agronomic measures for management of ravine

Agronomic measures are being considered as second line of defense in soil and water conservation however, these are of immense importance perhaps much more than other practices. These measures are recommended on mildly sloping lands (1–6%) for conservation of rainfall for sustainable production. They help in intercepting rain drops by decreasing the amount, intensity and the spatial distribution of the precipitation reaching the soil surface and protects the soil surface from the direct impact of raindrops which can cause a splash and sheet erosion. They also help in increasing infiltration rates and thereby reduce runoff and overland flow. These measures include contour cultivation, strip cropping, intercropping, mulching, tillage and other improved practices [23].

4.4.1 Contour cultivation

When tillage operations are carried out along the slope, the flow of generated runoff is accelerated, because each furrow serves as a rill which results in more runoff and soil erosion. Carrying out the farm operations such as plowing, seeding, planting and inter-culture operation along the contour or across the slope helps in formation of natural ridges and furrows which act as series of mini barriers and reservoirs to intercept rainwater and reduce runoff, soil and nutrient losses. In Shiwalik foothills, contour cultivation reduced runoff by 20.6%, soil loss by 43.5% and increased maize yield by 23% [24].

4.4.2 Strip cropping

It is the system of growing of erosion permitting crops (Maize, Sorghum, Pearl millet, Cotton etc.) and erosion resisting crops (Green gram, Black gram, Moth, Groundnut etc.) in alternate strips of suitable width across the slopes on contour in the same field. It helps in reducing the slope length, reducing velocity of runoff, arresting soil by provide a vegetative filter and increasing opportunity time for infiltration of rainwater into the soil profile. In Doon valley, strip cropping of Maize and Cowpea in 2:1 ratio has been reported to reduce runoff from 43 to 37% and soil loss from 21 to 11 Mg/ha [25].

4.4.3 Intercropping

The growing of low stature legumes like Groundnut, Cowpea, Green gram and Black gram in wider inter-row spaces of crops like Maize, Sorghum and Castor simultaneously on the same piece of land with a definite row-planting pattern is known as intercropping. It provides sufficient cover on the ground and thereby reduces soil erosion in shallow ravines. Intercropping offers an opportunity for profitable utilization of available space. Intercropping of Castor + Green gram (1:2) in South-Eastern Rajasthan reduced runoff by 22% and soil loss by 30% as compared to sole castor, apart from improving soil fertility status and improving crop yield. The system has been found ideal under aberrant conditions such as late onset of monsoon where it recorded only 15% reduction in productivity against 48–50% reduction in other systems [26].

4.4.4 Mulching

It is one of the most important agronomic practices which not only reduces evaporation losses, runoff, and soil erosion but also increases infiltration, improves of soil structure and regulates of soil temperature. In low rainfall areas, mulching helps in conserving moisture in the soil profile while in high rainfall areas, it reduces runoff and soil losses, in turn, are reflected in higher productivity. A study conducted at Chandigarh in Shiwalik region of Northern India indicated possibility of increasing Wheat yield by 58% by providing grass mulch during *Rabi*. In another study conducted at Dehradun, recycling of Sun hemp *in-situ* as mulch one month after sowing reduced runoff and soil loss and significantly increased yield of succeeding Wheat crop [24]. At Kanpur in Northern India, rice straw mulch increased yield of maize by 41.8% and mustard by 190%. Mulching can reduce erosion on slopes of 25–39%. In tea garden the mulching with Guatemala grass (*Tripsacum laxum*) at the rate of 37 Mg/ha reduced the soil loss from 9 Mg/ha to 7 Mg/ha [27].

4.4.5 Conservation tillage

Tillage modifies the soil physical characteristics i.e. bulk density, surface roughness, porosity and hardness of pan. The conventional tillage leaves no land unplowed and leaves no residues on the field. In the Indo-Gangetic plains of Yamuna river, where rain water cannot enter into deeper layers due to presence of impervious soil layer (*Kankar*) and is lost as runoff, deep tillage by disc plow once in three years up to 20 cm depth and one pass of cultivator every year helped in reducing runoff considerably and enhanced grain yield of pearl millet by 50%. Conservation tillage involves disturbing the soil to the minimum extent necessary and leaving crop residues on the soil surface. It ensures at least 30% coverage of the soil surface with crop residue which play a very important role in organic carbon build up and soil and moisture conservation under dry land. In Maize-Toria cropping system of the hill and mountain agro-ecosystem, Minimum Tillage + Crop residue incorporation is effective in reducing runoff by 12% and soil loss by 24% as compared to the conventional tillage besides minimizing nutrient losses [28].

4.4.6 Cropping system

Soil erosion depends on cropping system adopted on the land. The growing of crops which produce maximum cover, reduce runoff and soil loss always better for soil erosion point of view. Cowpea and Green gram are important cover crops for the rainy seasons. They provide early and dense (85%) ground cover which generally coincides with peak rate of runoff. The splash erosion loss in fallow land is 44.2 Mg/ha while it is 26.3 Mg/ha in Green gram and Black gram plots. In a study at Gujarat in Western India it was found that *Bidi* Tobacco, being a clean cultivated crop, allows higher runoff and soil loss and these losses can be reduced by introducing cover cum green manure crops during the early monsoon before Tobacco is transplanted in the field [10].

4.4.7 Crop scheduling

Sowing date and optimum seed rate are pillars for good stand and crop cover. The sowing date must be so adjusted that by the time intensive rainfall take place, there is enough of vegetation cover on the land. This can be done by advancing the date of sowing or even dry sowing in rainfed areas is always recommended. A study conducted at Dehradun in Northern India reported that sowing of Maize at the start of last week of June month produced higher and dense canopy at peak rainfall period, which in turn reduced the splash erosion considerably as compared to crop sown on first week of July. Similarly, the canopy coverage and crop yields were higher under early sowing in Maize + Cowpea intercropping system [28].

4.4.8 Crop geometry

Optimum plant population and crop geometry are equally important to have good crop cover on the land. Narrow intra-spacing (within rows) across the slope offers tolerance to runoff and ultimately reduces the soil erosion. Narrow spacing is always better for soil and water conservation, but it may cause severe competition for nutrient, water, light and space resulting in in lower yield of crops. A study carried out Chandigarh in Northern India reported that growing of Maize at 60 cm × 22.5 cm with minimum tillage reduced the runoff from 281 to 253 mm, soil loss from 5.7 to 4.4 Mg/ha as compared to conventional crop geometry [29].

4.5 Soil management measures for ravines

In order to meet the nutrient requirements of the crops in ravines, the soil fertility loss due to extreme erosion needs to be compensated accordingly as per specific site. The steep decline in soil fertility in the absence of proper measures to check erosion will cause reduction in the crop yields. This can be achieved in the following manner.

4.5.1 Judicious use of fertilizers

The soil fertility in ravine land varies from gully head to gully bed, therefore fertilizer recommendation for crops and cropping system should be site specific based on soil test. The recommended dose of fertilizers, method of application and proper scheduling is required to achieve sustainable yield from ravine lands. The nitrogen fertilizers should be applied in splits basal dose at the time of sowing and as top dressing during crop growth to the crops. The phosphate and potash fertilizers are given only as basal doses. Spraying of liquid Urea and micronutrients should be done on the standing crop, as and when deficiencies are noticed in the crop. The selection of appropriate fertilizers and their accurate combinations are necessary for maintaining the soil fertility in ravines.

4.5.2 Organic manures

Organic manures such as FYM (Farm Yard Manure), composts and green manures improve the physical condition, micro-flora of the soil and have a beneficial residual effect on succeeding crops. It is therefore necessary that organic manure should be applied to maintain soil health and sustain crop yields on a long term basis. It is generally felt that adequate amounts of these manures are many times not available. Therefore it is suggested that green manures crops may be incorporated in the prevailing cropping systems periodically.

4.5.3 Bio-fertilizers

Bio-fertilizers in the context of present day organic farming can play a key role in sustainable agriculture because of their potential to restore soil health. They are derived from the living organisms and include nitrogen fixing microorganisms i.e. *Rhizobium* spp., *Azospirillum* spp., *Bradyrhizobium* spp., *Azotobactor* spp., *Frankia* spp., Phospho-microorganisms, i.e., phosphate solubilizing bacteria, *Glonus* spp., phosphate solubilizing fungi compost inoculant i.e., *Cellolotic* or *Lignolytic* fungi etc., bio-fertilizers provide better crop yields and are ecofriendly. Bio-fertilizers can be applied through seedling treatments; tuber set treatment or oil treatment. For 10 kg of medium size seeds 483 g of culture is required for one hectare of land. In case of seedlings 1–2 kg of bio-fertilizers may be dissolved in 10 liters of water in a bucket and a suspension/slurry can be prepared for application in soil. The roots of the seedlings are dipped for 15 minutes in the slurry and then transplanted in the field. For treatment of tubers or sets slurry of 2–4 kg bio-fertilizers is prepared in 40–80 liters of water. Before sowing, tubers or sets are dipped in the slurry for 15 minutes. Soil treatment with the bio-fertilizers can also be done in the standing crop at critical stages [29].

4.5.4 Vermicomposting

Vermicomposting is technique of using different species of earthworms to convert the decomposable farm, urban and domestic waste into nutrient rich compost. It is eco-friendly, sustainable, cheaper and easy technique to obtain compost of high quality using biologically decomposable organic waste and crop residue generated from the farmers field.

4.5.5 Integrated nutrient management

The chemical fertilizers are nowadays becoming costly and may not be timely available to the farmers in remote areas. Though chemical fertilizers increase yields quickly, yet their effects on soil is visible for a short period of time and requires frequent application to maintain the soil fertility. These chemical fertilizers have a toxic and residual effect in soil, water and plants system. In order to overcome these constraints, a conjunctive use of organic and inorganic sources to maintain soil fertility has been suggested. This is generally referred to as Integrated Plant Nutrient Management (IPNM). Under this scheme, the some portions of crop nutrient requirement are met by organic manures and the remaining need is fulfilled by the chemical fertilizers. In one of the studies, 20 kg N ha^{-1} by *Azolla* (a fern) + 20 kg N by ammonium sulfate applied to rice registered a grain yield of 4435 kg ha^{-1} in comparison to 40 kg N ha^{-1} with ammonium sulfate giving a yield of 4132 kg ha^{-1} which explains the role and efficacy of nitrogen fixation in the soil and its use by rice crop. *Rhyzobium* inoculation of the seeds of legumes is being promoted for building up soil nitrogen through nitrogen fixation by increasing the efficiency of legume crop. At the farm level, domestic farm and agro-industrial wastes arising out of the food grain, crop residue and fruit processing can be diverted into the soil. This will add to soil fertility as well as biological waste management [29].

5. Conclusion

The India is one of the first countries to commit to the United Nation Convention to Combat Desertification Sustainable Development Goal to achieve the land degradation neutrality by 2030 during COP-14 held at New Delhi in September, 2019. India will restore an additional 5 M ha of degraded land by 2030, raising the land to be restored in India to 26 M ha. Therefore, ravine ecosystem can become an important milestone in achieving the food and nutritional security in coming decades through reclamation of ravine land with different site specific interventions as discussed above. There is a great opportunity for providing sustainable livelihood to the resource poor people of these areas though reclamation of the ravine with people's participation. An integrated approach with production system for bio-process industry will also generate employment opportunities for local people. In addition to this ravine reclamation is expected to mitigate climate change through carbon dioxide sequestration. Therefore, ravine reclamation should need to be on priority for the policy makers to achieve the future sustainability goals.

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