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Reversing land degradation through grasses: a systematic meta-analysis in the Indian tropics

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Abstract. Although intensive agriculture is necessary to sustain the world's growing population, accelerated soil erosion contributes to a decrease in the environmental health of ecosystems at local, regional and global scales. Reversing the process of land degradation using vegetative measures is of utmost importance in such ecosystems. The present study critically analyzes the effect of grasses in reversing the process of land degradation using a systematic review. The collected information was segregated under three different land use and land management situations. Meta-analysis was applied to test the hypothesis that the use of grasses reduces runoff and soil erosion. The effect of grasses was deduced for grass strip and in combination with physical structures. Similarly, the effects of grasses were analyzed in degraded pasture lands. The overall result of the meta-analysis showed that infiltration capacity increased approximately 2-fold after planting grasses across the slopes in agricultural fields. Grazing land management through a cut-and-carry system increased conservation efficiencies by 42 and 63 % with respect to reduction in runoff and erosion, respectively. Considering the comprehensive performance index (CPI), it has been observed that hybrid Napier (*Pennisetum purpureum*) and sambuta (*Saccharum munja*) grass seem to posses the most desirable attributes as an effective grass barrier for the western Himalayas and Eastern Ghats, while natural grass (*Dichanthium annulatum*) and broom grass (*Thysanolaena maxima*) are found to be most promising grass species for the Konkan region of the Western Ghats and the northeastern Himalayan region, respectively. In addition to these benefits, it was also observed that soil carbon loss can be reduced by 83 % with the use of grasses. Overall, efficacy for erosion control of various grasses was more than 60 %; hence, their selection should be based on the production potential of these grasses under given edaphic and agro-ecological conditions. The present analysis also indicated that grass must be used as a vegetative strip to maintain soil quality in sloppy arable areas (8.5 Mha) of Indian hilly regions. Similarly, due attention should be paid for establishing grasses in 3 Mha of degraded pasture lands and 3.5 Mha of shifting cultivation areas in India to reverse the land degradation.

1 Introduction

Water erosion is the main cause of land degradation, affecting an area of about 2 billion ha throughout the world, with the largest part in tropics, and affecting the two most important natural resources, namely soil and water (Mandal and Sharda, 2011a; De Oliveria et al., 2010; Keesstra et al., 2014; Novara et al., 2011, 2016; Seutloali and Beckedahl, 2015). Worldwide loss of water and sediment due to soil erosion is a major environmental threat (Prosdocimi et al., 2016; Pimentel, 1993). Soil erosion is accelerated due to high rainfall intensities (Keesstra et al., 2016), steep slopes (Beskow et al., 2009) and the fragile nature of topsoil (Lal, 1998; Rodrigo Comino et al., 2016; Ochoa et al., 2016). Many parts of the tropics in India have high annual rainfall confined to only 4 to 5 months (June–September). During the 7–8-month dry period, scarcity of water causes a severe shortage of fodder in farmlands, which leads to an increase in grazing pressure on forest and community lands. Nearly a third of the fodder requirement in India is met through forest resources in the form of grazing and cut fodder (MoEF, 1999). The process of land degradation in croplands and grasslands has been ac-

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celerated mainly by inappropriate land use (Nearing et al., 2005; Mandal et al., 2010) and mismanagement (Kagabo et al., 2013).

Generally, soil conservation planning requires knowledge of soil loss tolerance values, which show the higher limit of soil erosion rate that can be allowed without long-term land degradation (Jha et al., 2009). Strategies to reverse land degradation are critical since soil is a non-renewable resource (Mandal and Sharda, 2011b; Mandal et al., 2010). Soil erosion rates more than tolerance values are considered unacceptable (Mandal and Sharda, 2013), which leads to irreversible land degradation and need to be reduced through appropriate soil conservation measures (SCMs) (Biswas et al., 2015) The physical structures to check soil erosion are proven effective but are cost-intensive. Biological methods of soil and water conservation, especially grass-based methods, have been reported to be very cost-effective and suitable for sloppy lands. Perennial grasses provide ground cover throughout the year and help in reducing runoff and soil loss when used as barriers along the contour, particularly in hill slopes (Dhruvanarayana and Rambabu, 1983). Grasses are the key component in many ecosystems of the world (Parras-Alcántara et al., 2015; Hu et al., 2016; Mekonnen et al., 2016).

Grass species, in particular, have tremendous potentialities in soil conservation as grass roots have a great binding influence on soil particles (Novara et al., 2013; Ola et al., 2015). Due to resource scarcity and multiple competing enterprises that characterize most farming situations of rural India, farmers often lack the adequate resources to invest in physical soil conservation structures. Thus, the usefulness of grasses as a vegetative barrier is an alternative to the physical soil structures. Basically, these contour vegetative barriers/grass filter strips help in reducing soil erosion by acting as porous barriers which subsequently slow down the flow of runoff (Anigma, 2002; Mutegi et al., 2008).

The hilly region of India is characterized by geological fragility, land marginality and vulnerability (Mandal and Sharda, 2013). The croplands in sloppy areas suffer from excessive soil erosion and erosion-induced nutrient depletion. Soil erosion in these areas ranges between 20 and $40\,\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ as compared to the national average of $16.35\,\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ (Dhruvanarayana and Rambabu, 1983). Such high rates of soil erosion result in considerable depletion of nutrients from the topsoil, which in turn causes poor productivity of crops. Research evidence from the land subjected to shifting cultivation reported that about 600 Mt of soil is eroded annually, which led to losses of 258 000, 73 000 and 179 000 t of N, P_2O_5 and K_2O, respectively (Kumar, 2011). Soil erosion has been pointed to as one of the important reasons for abandonment of land by many farmers in subtropical hilly areas of India (Rao and Pant, 2001).

The grasslands in the middle and lower Himalayas are generally in the most neglected state with low productivity. In this predominantly grazing region, excessive reliance on animal husbandry under a growing population has exerted great pressure on the land. In tropical India, an average of 42 animals graze on a hectare of land compared to maximum threshold level of 5 animals (Sahay, 1999). Raising and maintenance of perennial grasses on degraded soils has been suggested as a means to improve soil quality and sequester carbon in the soil. Several studies have shown that the inclusion of grasses in the agricultural landscape often improves the productivity of system while providing opportunities to create carbon (C) sinks (Ghosh et al., 2009; Cogle et al., 2011; Huang et al., 2010; Mutegi et al., 2008). Soils typically account for 70–90 % of the total carbon sequestered in a grassland ecosystem (Batjes, 2001).

In India most of the studies on the role of grasses as vegetative/filter strips have been done in isolation with fewer slope categories and with limited objectives restricted to soil erosion (Njoroge and Rao, 1994). Similarly, studies on grazing land management are also very scarce. We present here an analysis of the potential of grasses for reversing land degradations for which the meta-analysis was carried out. The objective of this study is to determine the effect of grasses in arresting soil loss; runoff, moisture conservation and carbon buildup in soils. Based on such information, conclusions regarding reversing land degradation through grasses can be drawn wherever similar land conditions are known.

2 Material and methods

Information on the usefulness of grasses in soil and water conservation was collected from published literature (Table 1a and b). Keeping in mind the role of grasses for arresting soil loss and runoff, all data were reoriented under three different categories, namely (i) the role of grasses as a vegetative barrier, (ii) the complementary role of grasses with physical soil structures and (iii) management of grazing lands. A total of 83 studies comprising 19 different sites in varied agro-climatic region were included in the data set for the analysis (Table 1a and b). Fifty-four of these studies were related to contour grass barrier (CGB), 12 were related to grazing and 17 were related to complementary role of grasses.

Meta-analysis was applied to test the hypotheses about role of grasses in reducing soil erosion by combining data from several experiments. The technique has been extensively used in natural resource management studies (Ilstect et al., 2007, Poeplau and Don, 2015; Osenberg et al., 1999).

We aim to synthesize and discuss the past scientific studies pertaining to the effect of grasses in arable and non-arable lands on one of the key determining soil processes, namely reduction in soil and water losses and enhancement of infiltration. In order to produce a combined data set, due care was given to select the studies where both reference site (bare land/fallow land) and grass treatments were present. The

Table 1. **(a)** Details of the experiments and sources of data used in the study. **(b)** Details of the experiments and sources of data used to assess relative merits of different contour grass barriers (CGBs).

(a)		With CGB		Without CGB		Soil type and climate	Source
Vegetative barrier	Name of grasses	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Runoff (%)	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Runoff (%)		
	Dichanthium annulatum	1.0	–	16.68	–	Red soil (Rhodustalfs), hot subhumid	Lal et al. (2004)
		4.2	33	10.8	48	Inceptisols, semiarid	Rao and Pande (2014)
		0.1	7.7	6.35	64.8	Red, hot subhumid	Sharma (1999)
	Tripsacum laxum	–	19	19	29	Red (laterite), warm subhumid	Madhu et al. (2004)
	Panicum maximum	2.47	20.7	8.1	40.9	Alluvial, subtropical	Sharda et al. (2002)
		5.62	34.3	20.6	48.3	Alluvial, subtropical	Ojasvi et al. (2000)
		7.54	28.6	30.9	37.9	Alluvial, subtropical	Ojasvi et al. (2000)
		7.93	17.04	15.26	22.79	Alluvial, subtropical	Khola (2000)
	Natural	2.17	35.08	5.08	54.5	Alluvial, subtropical	Aggarwal et al. (2000)
		0.5	22.7	1.05	49.6	Laterite, hot subhumid	Rao et al. (1998)
		1.37	39.9	2.16	54.8	Laterite, hot subhumid	Rao et al. (1998)
		1.02	44.1	1.72	59.1	Laterite, hot subhumid	Rao et al. (1998)
		0.59	5.87	3.12	12.08		Kale et al. (1993)
		0.76	10.2	4.4	16.95		Kale et al. (1993)
		1.36	13.36	4.84	20.1		Kale et al. (1993)
	Cenchrus ciliaris	0.6	16.25	7.05	46	Black (Inceptisol)	Nalatwadmath et al. (2000)
		0.81	21.9	1.39	29.5	Hot semiarid	Katiyar et al. (2007a)
		0.5	6.6	16.08	68.7	Red, hot subhumid	Sharma (1999)
	Vetiveria zizanioides	9.02	19.17	15.26	22.79	Alluvial, subtropical	Khola (2000)
		0.29	7.29	0.53	11.26	Red, hot subhumid	Katiyar et al. (2007b)
		1.29	25.4	6.35	64.8	Red, hot subhumid	Sharma (1999)
		0.5	8.6	0.7	20.7	Red, hot subhumid	Sharma and Bhatt (1996)
	Thysanolaena maxima (broom)	15.7	14.2	19	17	Red laterite (Alfisol)	Sahoo and Adhikari (2014)
		18.7	17.3	23.9	23.5	Hot subhumid	Sahoo and Adhikari (2014)
	Heteropogon hamata	0.59	20.8	1.39	29.5	Red laterite (Alfisol) Hot subhumid	Katiyar et al. (2007a)
Grassland management							
Grass		Grass improvement		Traditional grass		Soil type and climate	Source
	Species	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Runoff (%)	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Runoff (%)		
	Cynodon dactylon	0.06	35	3.28	54	Red, hot subhumid	Hazra and Singh (1986)
	Cenchrus ciliaris	0.13	33	3.28	28.12	Red, hot subhumid	Hazra and Singh (1986)
		2.14	16.8	3.33		Black, hot semiarid	Ilango et al. (2002)
	Panicum antidotale	0.43	36	3.28	54	Red, hot subhumid	Hazra and Singh (1986)
	Pennisetum polystachyon	0.07	27	3.28	54	Red, hot subhumid	Hazra and Singh (1986)
	Urochloa stolonifera	0.08	32	3.28	54	Red, hot subhumid	Hazra and Singh (1986)
	Cymbopogon martinii	1.08	11.32	3.33	28.12	Black, hot semiarid	Ilango et al. (2002)
	Dichanthium annulatum	1.98	12.56	3.33	28.12	Black, hot semiarid	Ilango et al. (2002)
	Vetiveria zizanioides	2.61	18.4	3.33	28.12	Black, hot semiarid	Ilango et al. (2002)

Table 1. Continued.

Grazing	Open grazing		Grazing management		Soil type and climate	Source
Treatment	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Runoff (%)	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Runoff (%)		
	2.35	27	0.85	19	Red, hot subhumid	Hazra and Singh (1986)
	3.28	22	0.58	11	Red, hot subhumid	Hazra and Singh (1986)
	–	24	–	13.9	Alluvial, hot subhumid	Bhatt et al. (2013)
	–	11.3	–	6.6	Alluvial, hot subhumid	Bhatt et al. (2013)
	1.52	21.6	1.52	10.2	Black, hot semiarid	Rao and Reddy (1996)
	3.26	29.34	0.84	15.35	Black, hot semiarid	Rao and Reddy (1996)
		20.40	1.18	9.6	Alluvial, subtropical	Khola (2004)
		33.40		19.2		Khola (2004)
		29.90		22.2		Khola (2004)

Combination

	With grass (SWC)		Without grass (SWC)		Soil type and climate	Source
	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Runoff (%)	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Runoff (%)		
Trenching + vegetative barrier	–	3.4	–	27.6	Alluvial, subtropical	Khola (2004)
	–	10.5	–	48.5	Alluvial, subtropical	Khola (2004)
	–	7.6	–	45.5		Khola (2004)
	0.84	10.2	1.53	21.6	Vertisol, hot semiarid	Rao and Reddy (1996)
	1.18	15.5	3.26	29.3	Vertisol, hot semiarid	Rao and Reddy (1996)
	0.93	8.7	1.55	17.6	Vertisol, hot semiarid	Ali et al. (2014)
	0.66	4.1	1.55	17.6		Ali et al. (2014)
	0.05	0.4	1.55	17.6	Vertisol, hot semiarid	Ali et al. (2014)
	6.4	10.8	19	17	Red laterite, hot subhumid	Sahoo and Adhikari (2014)
	14	12.7	23.9	17	Red laterite, hot subhumid	Sahoo and Adhikari (2014)
	9.9	13.4	19	23.5	Red laterite, hot subhumid	Sahoo and Adhikari (2014)
	11	15.3	23.9	23.5	Red laterite, hot subhumid	Sahoo and Adhikari (2014)

(b)
< 2 % slope

Contour grass barriers	Soil loss ($Mg\,ha^{-1}$)	Runoff (%)	Yield ($kg\,ha^{-1}$)	Crop	Soil type and climate	Source
Cynodon dactylon	3.01	18	1036	Rice	Red laterite, hot subhumid	Subudhi and Senapati (1996)
	5.51	16.83	1748	Rice		Subudhi et al. (1998)
	4.73	15.59	1759	Rice	Red laterite, hot subhumid	Subudhi et al. (1998)
	4.81	15.67	1519	Rice		Subudhi et al. (1998)
Pennisetum purpureum	2.68	17.4	1669	Rice	Red laterite, hot subhumid	Subudhi and Senapati (1996)
	3.05	18.1	1562	Rice		Subudhi and Senapati (1996)
	4.4	15.32	1828	Rice	Red laterite, hot subhumid	Subudhi et al. (1998)
	4.42	15.01	1925	Rice		Subudhi et al. (1998)
	4.41	15.17	1877	Rice		Subudhi et al. (1998)
Vetiveria zizanioides	2.22	16.6	2133	Rice	Red laterite, hot subhumid	Subudhi and Senapati (1996)
	4.23	14.83	2042	Rice		Subudhi et al. (1998)
	4.02	14.05	1976	Rice	Red laterite, hot subhumid	Subudhi et al. (1998)
	3.96	13.88	2214	Rice		Subudhi et al. (1998)
	7.1	34.63	2000	Maize	Red laterite, hot subhumid	Senapati and Sharma (2007)
	6.89	31.59	2022	Maize		Senapati and Sharma (2007)
	6.48	28.31	2053	Maize		Senapati and Sharma (2007)
	1.14	16.2	1377	Sorghum	Black soil, hot subhumid	Prasad et al. (2005)
	0.73	13.6	699	Sorghum		Prasad et al. (2005)
Eulaliopsis binata	2.37	17.5	1436	Rice	Red laterite, hot subhumid	Subudhi and Senapati (1996)
	4.82	15.87	1933	Rice		Subudhi et al. (1998)
	5.5	16.32	1812	Rice		Subudhi et al. (1998)
	5.54	16.2	1769	Rice		Subudhi et al. (1998)
Cymbopogon martinii	2.57	17.7	1911	Rice	Red laterite, hot subhumid	Subudhi and Senapati (1996)
Dichanthium annulatum	1.05	15.5	1364	Sorghum	Black soil, hot semiarid	Prasad et al. (2005)
	0.69	13.7	697	Sorghum		Prasad et al. (2005)
	0.18	7.1	808	Sunflower	Inceptisol, black subhumid	Bhanavase et al. (2007)
	0.85	40	–			Bhanavase et al. (2007)
	0.26	12.2	–		Inceptisol, black subhumid	Bhanavase et al. (2007)
	0.3	12.5	–			Bhanavase et al. (2007)
	0.52	28.14	–			Bhanavase et al. (2007)

Table 1. Continued.

(b)

< 2 % slope

Contour grass barriers	Soil loss (Mg ha^{-1})	Runoff (%)	Yield (kg ha^{-1})	Crop	Soil type and climate	Source
Cenchrus ciliaris	0.14	6.5	867	Sunflower	Inceptisol, black subhumid	Bhanavase et al. (2007)
	0.74	34.8	–			Bhanavase et al. (2007)
	0.21	11.6	–		Inceptisol, black subhumid	Bhanavase et al. (2007)
	0.22	11	–			Bhanavase et al. (2007)
	0.46	24.12	–		Black soil, hot semiarid	Bhanavase et al. (2007)
	1.01	15.8	1359	Sorghum		Prasad et al. (2005)
	0.77	13.9	697	Sorghum		Prasad et al. (2005)
Saccharum munja	0.86	16.3	1355	Sorghum	Black soil, hot semiarid	Prasad et al. (2005)
	0.7	13.4	674	Sorghum		Prasad et al. (2005)
Stylosanthes hamata	8.92	33.52	1789	Maize	Red laterite, hot subhumid	Senapati and Sharma (2007)
	8.21	33.21	1766	Maize		Senapati and Sharma (2007)
	8.13	34.41	1733	Maize	Red laterite, hot subhumid	Senapati and Sharma (2007)
	5.81	16.87	1777	Rice		Subudhi et al. (1998)
	5.85	16.92	1775	Rice		Subudhi et al. (1998)
	5.61	16.63	1803	Rice		Subudhi et al. (1998)
	2.8	18.2	1280	Rice		Subudhi and Senapati (1996)
Pennisetum pedicellatum	8.01	34.01	2011	Maize	Red laterite, hot subhumid	Senapati and Sharma (2007)
	7.01	30.98	1990	Maize		Senapati and Sharma (2007)
	6.97	31.64	1969	Maize		Senapati and Sharma (2007)
Control	3.47	21.4	1236	Rice	Red laterite, hot subhumid	Subudhi and Senapati (1996)
	10.39	19.94	1332	Rice		Subudhi et al. (1998)
	7.54	19.02	1330	Rice	Red laterite, hot subhumid	Subudhi et al. (1998)
	7.24	19.18	1508	Rice		Subudhi et al. (1998)
	8.45	40.18	1720	Maize		Senapati and Sharma (2007)
	9.22	42.32	1790	Maize	Red laterite, hot subhumid	Senapati and Sharma (2007)
	9.02	42.6	1717	Maize		Senapati and Sharma (2007)
	1.89	22	1140	Sorghum	Black soil, hot subhumid	Prasad et al. (2005)
	1.45	20.2	562	Sorghum		Prasad et al. (2005)
	0.22	10.12	618	Sunflower	Inceptisol, black subhumid	Bhanavase et al. (2007)
	1.15	53	–			Bhanavase et al. (2007)
	0.4	15.2	–		Inceptisol, black subhumid	Bhanavase et al. (2007)
	0.5	16.2	–			Bhanavase et al. (2007)
	0.8	40.2	–			Bhanavase et al. (2007)
2–4 % slope						
Vetiveria zizanioides	2.54	16.27	1075	Black gram	Red laterite, hot subhumid	Mishra and Sahu (2001)
	1.78	18.45	803	Black gram		Mishra and Sahu (2001)
	3.5	27.4	5.9	Sorghum	Alluvial soil, subhumid	Chand and Bhan (2000)
	7.2	33	1900	Maize		Bhardwaj and Sindhwal (2007)
	9.8	43	2389	Maize	Alluvial, subtropical	Bhardwaj and Sindhwal (2007)
	8.6	42	2063	Maize	Alluvial, subtropical	Bhardwaj and Sindhwal (2007)
	6.9	40	2042	Maize	Alluvial, subtropical	Bhardwaj and Sindhwal (2007)
	2.9	22	3124	Maize		Bhardwaj and Sindhwal (2007)
	5	30	3144	Maize		Bhardwaj and Sindhwal (2007)
	5.5	27	2278	Maize		Bhardwaj and Sindhwal (2007)
	6.72	35.1	2444	Maize		Bhardwaj and Sindhwal (2007)
Pennisetum purpureum	3.08	16.5	1002	Black gram	Red laterite, hot subhumid	Mishra and Sahu (2001)
	2.96	18.88	624	Black gram		Mishra and Sahu (2001)

Table 1. Continued.

Cultivated fallow	7.87	23.5		Rice	Red laterite, hot subhumid	Subudhi and Senapati (1996)
Eulaliopsis binata	3.15	18.24	836	Black gram	Red laterite, hot subhumid	Mishra and Sahu (2001)
	2.75	20.51	618	Black gram		Mishra and Sahu (2001)
	7.9	34	1869	Maize	Alluvial, subtropical	Bhardwaj and Sindhwal (2007)
	10.6	46	2333	Maize	Alluvial, subtropical	Bhardwaj and Sindhwal (2007)
	12.4	49	1833	Maize	Alluvial, subtropical	Bhardwaj and Sindhwal (2007)
	8.3	42	1961	Maize	Alluvial, subtropical	Bhardwaj and Sindhwal (2007)
	3.6	25	2941	Maize		Bhardwaj and Sindhwal (2007)
	7.3	31	2839	Maize		Bhardwaj and Sindhwal (2007)
	7.3	32	2028	Maize		Bhardwaj and Sindhwal (2007)
	8.34	37.9	2296	Maize		Bhardwaj and Sindhwal (2007)
Heteropogon contortus	0.08	5.5	523	Sorghum	Red soil, hot subhumid	Narayan et al. (2014)
	0.6	15.9	–			Narayan et al. (2014)
	0.2	4.1	–			Narayan et al. (2014)
Cenchrus ciliaris	0.9	8.37	509	Sorghum	Red soil, hot subhumid red	Narayan et al. (2014)
	0.82	19.4	–		soil, hot subhumid	Narayan et al. (2014)
	0.3	6.84	–			Narayan et al. (2014)
	4	30.2	7.2	Sorghum	Alluvial soil, subhumid	Chand and Bhan (2000)
Panicum antidotale	6.12	33.3	2460	Maize	Alluvial, subtropical	Bhardwaj and Sindhwal (2007)
	5.8	29	1911	Maize		Bhardwaj and Sindhwal (2007)
	8.1	41	2528	Maize	Alluvial, subtropical	Bhardwaj and Sindhwal (2007)
	7.6	38	2073	Maize		Bhardwaj and Sindhwal (2007)
	6.2	39	2059	Maize		Bhardwaj and Sindhwal (2007)
	2.9	23	3109	Maize		Bhardwaj and Sindhwal (2007)
	6.1	31	3089	Maize		Bhardwaj and Sindhwal (2007)
	6.8	28	2138	Maize		Bhardwaj and Sindhwal (2007)
Control	3.42	17.35	965	Black gram	Red laterite, hot subhumid	Mishra and Sahu (2001)
	3.27	20.75	603	Black gram		Mishra and Sahu (2001)
	7.5	46.5	5.3	Sorghum	Alluvial soil, subhumid	Chand and Bhan (2000)
	46.28	18.04	–	Maize		Bhardwaj and Sindhwal (2007)
	0.41	19.8	480	Sorghum	Alluvial, subtropical	Narayan et al. (2014)
	1.4	29.7	–		Red soil, hot subhumid	
	1	13.7	–			
> 4 % slope						
Thysanolaena maxima	6.92	13.85	891	Finger millet	Red laterite, hot subhumid	Sudhishri et al. (2008)
	6.02	13	1105			
	7.16	14.06	1045			
Vetiver zizanioides	4.22	8.79	1092	Finger millet	Red laterite, hot subhumid	Sudhishri et al. (2008)
	3.85	7.85	1226			
	4.06	9.88	1346			
	9.87	40.52	2180			
Saccharum munja	3.87	18.93	963	Black gram	Red laterite, hot subhumid	Mishra and Sahu (2001)
	3.07	21.04	603	Black gram		Mishra and Sahu (2001)
Saccharum munja	4.49	9.36	1045	Finger millet	Red laterite, hot subhumid	Sudhishri et al. (2008)
	4.02	8.25	1226			
	4.65	10.83	1427			
Cynodon dactylon	2.1	27.1	4355		Alluvial (Entisols) subhumid tropical	Narain et al. (1994)
Dichanthium annulatum	1.02	21.2	6805		Alluvial (Entisols) subhumid tropical	Narain et al. (1994)
	0.23	1.9				

Table 1. Continued.

Cultivated fallow	7.87	23.5		Rice	Red laterite, hot subhumid	Subudhi and Senapati (1996)
Eulaliopsis binata	0.29	5.2	16 290		Alluvial (Entisols) subhumid tropical	Narain et al. (1994)
Chrysopogon fulvus	0.3	2.5	19 170		Alluvial (Entisols) subhumid tropical	Narain et al. (1994)
Control	83.04	32.6	–	Finger millet	Alluvial (Entisols) subhumid tropical	Narain et al. (1994)
	18.45	16.2	–			Narain et al. (1994)
	92.42	71.1	–			Narain et al. (1994)
	13.9	26.02	607		Red laterite, hot subhumid	Sudhishri et al. (2008)
	13.7	24.84	676			Sudhishri et al. (2008)
	14.28	26.78	682			Sudhishri et al. (2008)

Table 2. Various attributes and normalized scores used for calculating CPI for different vegetative barriers.

	Vetiver	Hyb. Napier	*Panicum*	*Dichanthium*	Broom	*Cymbopogon*	Congo signal	*Eulaliopsis*	Sambuta
Infiltration rate ($cm\,h^{-1}$)	7.5–11.6	11.08–13.26	7.68–8.21	7.12–8.02	14.42		20.06	7.7–8.6	12.7
Score	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Soil loss ($Mg\,ha^{-1}$)	1.0–9.8	2.96–3.08	2.9–8.1	0.2–1.02	6.02–7.16	1–2.57	6.0–8.0	2.75–12.4	4.02–4.7
Score	0.5	0.8	0.5	1.0	0.5	1.0	0.5	0.8	0.8
Soil binding ($ml\,mm^{-2}$)	206–248	577–803	82–127	127–331	153–178	80–150	75–110	613–956	230–395
Score	0.2	1.0	0.2	0.2	0.2	0.2	0.2	1.0	0.5
Sod forming soil depth (cm)	60–90	40–60	80–105	50–60	60–95	80–100	30–50	30–40	35–50
Score	0.8	0.5	1.0	0.5	0.8	1.0	0.5	0.2	0.2
Fodder or commercial value	Average	Excellent	Very good	Excellent	Average	Average	Good	Very good	Average
Score	0.2	1.0	0.5	1.0	0.2	0.2	0.5	0.5	0.2
Cost of establishment (Rs.)	3500–4500	4000–6000	3000–5000	3500–4500	4000–5000	4000–6000	2500–3500	3500–5000	3000–4501
Score	0.5	0.5	0.5	0.5	0.5	0.5	0.8	0.5	0.8

reference sites were adjacent to the grass-treated field/plots within the same landscape and similar slope. Therefore, we excluded studies where the reference site was either missing or was away from the study site. The conservation use efficiency (CUE) was calculated by the following formula (Khola and Sastry, 2005):

$$\mathrm{CUE} = \frac{\text{Water/soil runoff rate before conservation measure} - \text{Water/soil runoff rate after conservationn measure}}{\text{Water/soil runoff rate before conservation measure}} \times 100. \quad (1)$$

Data were analyzed using SPSS (version 17). The analysis of variance (ANOVA) was conducted to test the significant difference between different treatments. Initially, a t test was conducted to test whether the impacts of two treatments (without grass and with grass) were significantly different. Protected least significant difference (LSD) at $P = 0.05$ was used to separate the means for all the three different categories of data (Fisher, 1935). A separate t test was also used for different slope classes to evaluate the performance of CGBs on the reduction of soil and water loss and enhancing crop yield.

Relative performance of different grasses used as CGB was evaluated by using a comprehensive performance index (CPI). The following formula was used to compute CPI values of different grasses (Sudhishri et al., 2008):

$$\mathrm{CPI} = \sum_{i=1}^{n} W_i R_i , \quad (2)$$

where CPI is comprehensive performance index of the grass species, W_i is weighting of the ith parameter, and R_i is rating (scoring) of the ith parameter based on its observed value. A total of six attributes – namely infiltration rate (IR), soil loss, root binding capacity, maximum sod forming depth, fodder/commercial value and cost of establishment (Table 2) – were used for computing CPI.

Additionally, relative reversibility of erosion/water loss and relative yield gained due to adoption of CGBs were computed by using the following formulas:

Relative reversibility of erosion/water loss:

$$\Delta\text{Erosion}/\Delta\text{Runoff} = \frac{\text{Erosion/water loss withoutCGB} - \text{Erosion/water loss with CGB}}{\text{Mean erosion/water loss}} \times 100. \quad (3)$$

Relative yield gain:

$$\Delta\text{Yield gain} = \frac{\text{Mean yield with CGB} - \text{Mean yield without CGB}}{\text{Mean yield}} \times 100. \quad (4)$$

3 Results and discussion

3.1 Contour grass barrier (CGB)

India is home to about 1225 species of grasses, the majority of which grow well in tropical and subtropical regions (Prakash et al., 1999). These grasses can be used as live bunds in arresting soil erosion. The efficacy of CGBs in increasing the opportunity time for infiltration and consequent profile recharge has also been reported by other researchers (Sharma and Bhatt, 1996; Prakash et al., 1999). In this meta-analysis, based on 25 observations, we quantified the general potential of vegetative barriers to reduce runoff and soil loss (Table 3). The overall result of the meta-analysis showed that infiltration capacity increased approximately 2-fold after planting grasses across the slopes in agricultural fields (95 % confidence level). However, it is interesting to note that the mean runoff values were statistically insignificant in the case of combined treatment of grasses along with structural measures. This may be due to very high standard deviation (SD) values obtained for vegetative barrier. These higher values indicate considerable heterogeneity in the observation which needs to be verified. Although 70 % of data showed similar variation, a few higher values were not in expected lines, which might have caused this uncertainty. In the case of the Doon Valley region, through comparing the impacts on soil wetting pattern, infiltration rate and sorptivity, it was observed that *Chrysopogon fulvus* was the most promising potential grass species. However, for this region *Panicum maximum* was identified as the most effective grass barrier with maize. Therefore, more research is required with *Chrysopogon fulvus* because the rooting pattern, soil wetting, infiltration rate and other properties of this grass show great potential to be used as a contour grass barrier in this region (Mandal and Jayaprakash, 2009). It was identified by Bhardwaj and Sindhwal (2007) that *Saccharum munja* and *Eulaliopsis binata* are the two most effective grasses for the Shivalik region of Punjab and Haryana, while hybrid Napier grass and *Panicum maximum* are very effective in humid tropical regions of the lower Himalayas.

Runoff and soil loss values in CGB plots were lower than the control plots. The data show that runoff varies between 11.26 and 62.60 % with a mean value of 37.71 % and soil loss varies between 0.53 and 30.90 Mg ha^{-1} yr^{-1} with a mean value of 9.56 Mg ha^{-1} yr^{-1} in control treatments (Table 3). With CGB, the runoff data varies between 5.87 and 44.10 % with a mean value of 20.93 % and soil loss varies between 0.50 and 18.70 Mg ha^{-1} yr^{-1} with a mean value of 3.93 Mg ha^{-1} yr^{-1}. The study revealed that, on average, the overland flow reduced by 45 % compared to control. CGB facilitated the appearance of backed-up water above the filter strips, which resulted in sedimentation and substantial reduction in soil loss. The analysis of the data indicated that as the rain proceeded, overland flow moved down slope into the grass hedges and water backed-up behind them, giving more opportunity time for the water to infiltrate the soil. Experiments conducted by Becker (2001) reported reduced soil erosion by parallel strips of stiff-stemmed grass planted along the contour lines. In addition, the amount of transported soil reduced by 59 % in the case of grass barriers than that of the control. A substantial reduction in runoff from 37.71 % in control to 20.93 % in CGB was observed. Vegetative barriers reduced the soil loss from 9.0 to 3.0 Mg ha^{-1} yr^{-1}. The CUE of vegetative barrier was found to be 44.56 and 59.04 %, for runoff and soil loss, respectively. These findings are in conformity with the results reported by Gilley et al. (2000), who showed that grass hedges have the potential to reduce runoff by 52 % and soil loss by 53 % under no-till conditions. Globally, most researchers in tropical region have used vetiver grass (*Vetiveria zizanioides*), eastern gamagrass (*Tripsacum dactyloides*) due to their special characteristics with stiff, erect and coarse stems (Rachman et al., 2004a, b, 2005; Janushaj, 2005). Such species are perennial in nature and thus give good protective cover throughout the year in warm humid topics.

In terms of soil loss, the vegetative barrier of *Panicum maximum* showed promising performance with an average rate of soil loss between 2.74 and 7.93 Mg ha^{-1} yr^{-1} in northwestern Himalayan region, which indicated that soil loss can be effectively brought below the tolerance limit by adopting such SCMs (Mandal et al., 2006). Considering the advantages of contour grass strips compared to mechanical measures, due to their lower cost and minimum removal of the fertile topsoil, many organizations are promoting this practice as an effective measure to reduce erosion (ASAE, 1981; Hudson, 1981; Mulugeta, 1988; Turkelboom et al., 1994). Moreover, CGB is comparatively simple and easy to establish (Grunder, 1988), while mechanical measures are too expensive, difficult to maintain in the long run (Rodriguez, 1997) and are time consuming (Tripathi and Singh, 1993). Additional advantages with regard to establishment and stabilization of the grass strip are that it needs very little attention to form a terrace, while mechanical measures need regular maintenance to maintain their effectiveness (Welle et al., 2006).

Table 3. Impact of grasses in arresting soil loss and runoff.

Treatment	Runoff (%)	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Number of samples (n)
Vegetative barrier			
Control (without grass)	11.26–62.40 $(37.71 \pm 18.12)^a$	0.53-30.90 $(9.56 \pm 8.79)^a$	25
With grass	5.87–44.10 $(20.93 \pm 10.76)^b$	0.5–18.7 $(3.93 \pm 5.03)^b$	25
Conservation use efficiency (CUE)	44.56	59.04	25
Along with structural conservation measures			
Control	17.0–48.5 $(25.53 \pm 10.88)^a$	1.53–3.26 $(1.88 \pm 0.77)^a$	17
Combination	0.40–15.30 $(9.37 \pm 4.76)^a$	0.05–1.18 $(0.73 \pm 0.42)^a$	17
Conservation use efficiency (CUE)	62.93	60.96	17
Grazing management			
Control (grazed)	11.30–33.4 $(24.33 \pm 6.55)^a$	1.52–3.28 $(2.58 \pm 0.73)^a$	12
Management	6.60–22.2 $(14.12 \pm 5.23)^b$	0.58–1.3 $(0.95 \pm 0.29)^b$	12
Conservation use efficiency (CUE)	42.01	63.18	12

Values in the parentheses are mean ± SD. Different letters in the same column are significantly different at $P < 0.05$.

Table 4. Site-specific suitable grasses for contour grass barrier (CGBs).

Site no.	State	Crop	Barrier
1	Andhra Pradesh	Sorghum/castor	*Cenchrus ciliaris* (buffel grass)
2	Haryana	Urd	Mixed barrier of *Vetiveria zizanioides* (vetiver) plus
		Bajra and wheat	*Eulaliopsis binata* (sabai grass)
3	Karnataka	Groundnut	*Vetiveria zizanioides* (Vetiver) on contour
		Finger millet	Combination of graded bund and *Vetiveria zizanioides* (vetiver)
		Sorghum	Compartmental bunding with *Vetiveria zizanioides* (vetiver)
4	Madhya Pradesh	Soyabean	*Cymbopogon martinii* (lemon grass/palmarosa)
5	Maharashtra	Sorghum, cotton	*Vetiveria zizanioides* (vetiver)
6	Orissa	Paddy	*Vetiveria zizanioides* (vetiver), *Cynodon dactylon* (Bermuda grass)
		Cowpea (green pod)	
7	Punjab	Maize	*Saccharum* spp.
8	Tamil Nadu	Potato	*Pennisetum purpureum* (Napier/elephant grass)
9	Uttarakhand	Corn	*Panicum maximum* (Guinea grass)

A study by Shrimali (2000) revealed that *Panicum maximum* provided 56 % of coverage after 3 years of planting. The coverage increased progressively from 23 % in the first year to 56 % in the third year. Similarly, vetiver coverage increased from 29 % in the first year to 75 % in the third year (Shrimali, 2000). Vetiver grass distinctively showed the highest reduction in annual runoff and soil loss. This was attributed to the fact that the erect and rather stiff leaves and stems of vetiver grass retarded more runoff flow and acted as a filter to retain more sediment. A similar performance level of vegetative barrier was also reported by Rao et al. (1991) and Laing and Rupenthal (1991). This is also in conformity with the results of Patil et al. (1995), who recorded 41.4 % lower runoff for vetiver over control. Similar results had been obtained by Tangtumniyom et al. (1996) for a cassava crop on a 5 % slope where vetiver was used as vegetative barrier. The effect produced by *Cenchrus ciliaris* planted at 10 m spacing was also comparable to that of vetiver at 10 m, which recorded a mean annual soil loss of 3.39 $Mg\,ha^{-1}$ (Jagannathan et al., 2000).

The conservation efficiency of CGB varies with grass types and site conditions in different regions. However, *Pen-*

nisetum purpureum, *Panicum maximum* and *Eulaliopsis binata* were very effective for the lower Himalayan and Shivalik regions. Results from different studies across the country showed that, due to the large amount of green phytomass, profuse tillering and dense rhizomatous network of roots, runoff and soil losses were significantly reduced with a barrier of *Pennisetum purpureum*. For different regions of India, including Andhra Pradesh, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Orissa, Punjab, Tamil Nadu and Uttarakhand, suitable grasses for CGB are given in Table 4. In situations where fodder requirements are high, *Pennisetum purpureum* mounted as a barrier would be beneficial, while in those areas where soil conservation is of utmost importance, *Eulaliopsis binata* or aromatic grasses such as palmarosa (*Cymbopogon martinii*) or vetiver (*Vetiveria zizanioides*) grass would be a reasonable choice.

Analysis of variance through *t* tests of soil loss, runoff and yields of crops indicated that loss of water was significantly lower in CGB-treated sites in < 2 % slopes (Table 5). The water loss provided by CGBs compared to control was 16 % vs. 27 % for the < 2 % slope. However, the similar trend was not observed in the 2–4 % slope range. Interestingly, the soil loss was significantly lower in CGB-treated sites in higher slopes (2–4 and > 4 % slopes).

Variations in soil erosion amounts paralleled to some extent those of runoff in all the slope classes except in the lower slope range (Table 5). The protective actions of various CGBs are very clearly shown by the soil loss values, which show that between 141 and 107 % reversibility in soil loss can be achieved through adoption of CGB. The relative reversibility of water loss provided by CGBs compared to control was 52.6 % for the < 2 % slope and 55.5 % for > 4 % slopes. Favorable soil conditions created by CGBs resulted in an increase of yield in all slope ranges. The significantly higher yield in CGB treated sites may be due to either better moisture regime or higher nutrients or may be depending on both the retention of runoff and deposition of fertile sediment by the CGBs. The relative yield gained by CGBs varied between 44 and 53 %, with highest value in the 2–4 % slope.

A clear picture about the relative merit of CGBs was determined through development of a CPI for different grasses (Table 6). Hybrid Napier grass (*Pennisetum purpureum*) seems to have the most desirable attributes for soil and water conservation, with the highest CPI value of 0.81. On the other hand, *Saccharum munja* had fairly good merit (0.79) in conserving soil and water and has both fodder and commercial value. Similarly, *Dichanthium annulatum*, with a CPI value of 0.77, has an edge over broom grass (0.72). However, from the point of view of farmers' adaptation, both *Saccharum munja* (0.79) and *Thysanolaena maxima* (0.72) grass are the most preferred species, especially in shifting cultivation area of the Eastern Ghats and northeastern hilly region of India.

3.2 Complementary role of grasses with physical soil structures

Grasses, shrubs and tree barriers in combination with structural measures (bioengineering measures) are known to be beneficial for soil and water conservation and have many relative advantages over structural interventions. Reinforcement by live roots which bind soil particles and underground decomposed biomass provides stability to aggregated soil. Plant detritus on the soil surface acts as a cushion for dissipating kinetic energy of rain drops. This aboveground biomass upon its subsequent decomposition also adds to the soil humus and increases infiltration, soil water-holding capacity and stability of aggregates (Prakash et al., 1999).

The data from Table 3 show that the use of grasses led to a significant decrease in runoff from 25.53 % in control to 9.37 % with structural conservation measures. Soil loss also has a significant decrease from 1.88 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ in control to 0.73 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ in structural conservation measures (Table 2). The runoff varies between 17.00 and 48.50 % with a mean value of 25.53 % and soil loss varies between 1.53 and 3.26 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ with a mean value of 1.88 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ in control. The runoff varies between 0.40 and 15.30 % with a mean value of 9.37 % in combined treatment (grass along with structural measures). The data revealed that the impact of grasses was more pronounced along with soil and water conservation measures in minimizing the losses of soil and water. In addition, the complimentary action shows water saving by 63 % and soil saving by 61 %.

Earthen bund and earthen bund with broom grass was found to be more effective in soil moisture conservation at 4 and 8 % slope as compared to other treatments (Fig. 1). The study conducted on *Pennisetum* and *Arundinella* barriers in combination with soil conservation measures revealed a substantial reduction (65–88 and 15–38 %, respectively) in overland flow compared to the control plots (Huang et al., 2010).

3.3 Management of grazing lands

In India about 12.0 Mha of area is represented by permanent pasture and grasslands, majority of which is confined to the tropical areas (Roy and Singh, 2013). Since this pasture land and grasslands are severely affected by soil erosion, special attention should be given to their management to reverse the process of degradation. Our synthesis of the meta-analysis revealed that, by managing the grassland with cut and carry system, rotational grazing and control grazing can greatly reduce the water and soil loss and helps in the reversing the land degradation process. Similar phenomena have been reported by Misri (2003) and Pathak and Dagar (2015), especially for the lower Himalayan and Shivalik grassland, where severe biotic pressure is imposed by both sedentary and migratory grazers. The grazing intensity in the country is as

Table 5. Relative merits of contour grass barrier (CGBs) in different land slopes.

Treatment	Runoff (%)	Soil loss ($Mg\,ha^{-1}\,yr^{-1}$)	Yield	Number of samples (n)
< 2 % slope				
Control (without grass)	10.12–42.60 (27.10 ± 13.58)[a]	0.22–10.39 (5.03 ± 3.92)[a]	546–1717 (1179 ± 475.32)[a]	12
With grass	13.88–16.92 (15.81 ± 1.06)[b]	3.82–5.85 (5.03 ± 0.69)[a]	1519–2214 (1843 ± 176.09)[b]	12
Relative reversibility	52.64 %	Insignificant	44 %	
2–4 % slope				
Control (without grass)	13.20–71.10 (28.36 ± 15.36)[a]	0.41–92.42 (23.46 ± 32.54)[a]	345–965 (756 ± 341.17)[a]	12
With grass	16.27–41.00 (24.65 ± 9.45)[a]	1.78–8.10 (4.24 ± 2.11)[b]	618–2528 (1257 ± 684.69)[b]	12
Relative reversibility	14.63 %	141 %	53 %	
> 4 % slope				
Control (without grass)	24.84–71.10 (36.27 ± 19.70)[a]	13.70–92.42 (43.47 ± 40.53)[a]	558–682 (638 ± 53.80)[a]	5
With grass	7.85–14.06 (11.51 ± 3.39)[b]	3.85–7.16 (5.63 ± 1.52)[b]	891–1226 (1071 ± 121.13)[b]	5
Relative reversibility	55.54 %	107 %	50.64 %	

Relative reversibility of erosion/water loss – $\Delta\text{Erosion}/\Delta\text{Runoff} = \frac{\text{Erosion/water loss without CGB} - \text{Erosion/water loss with CGB}}{\text{Mean erosion/water loss}} \times 100$.
Relative yield gain – $\Delta\text{Yield gain} = \frac{\text{Mean yield with CGB} - \text{Mean yield without CGB}}{\text{Mean yield}} \times 100$.

Table 6. Comparative comprehensive performance index of vegetative barrier.

	Vetiver	Hyb. Napier	*Panicum*	*Dichanthium*	Broom	*Cymbopogon*	Congo signal	*Eulaliopsis*	Sambuta
Infiltration rate (0.2)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Wt × score	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Soil loss (0.2)	0.5	0.8	0.5	1.0	0.5	1.0	0.5	0.8	0.8
Wt × score	0.10	0.16	0.10	0.2	0.1	0.2	0.1	0.16	0.16
Soil binding (0.1)	0.2	1.0	0.2	0.2	0.2	0.2	0.2	1.0	0.5
Wt × score	0.02	0.1	0.02	0.02	0.02	0.02	0.02	0.1	0.05
Sod forming (0.1)	0.8	0.5	1.0	0.5	0.8	1.0	0.5	0.2	0.2
Wt × score	0.08	0.05	0.1	0.05	0.08	0.1	0.05	0.02	0.02
Fodder value (0.2)	0.2	1.0	0.5	1.0	0.8	0.2	0.5	0.5	1.0
Wt × score	0.04	0.2	0.1	0.2	0.16	0.04	0.1	0.1	0.2
Cost established (0.2)	0.5	0.5	0.5	0.5	0.8	0.5	0.8	0.5	0.8
Wt × score	0.1	0.1	0.1	0.1	0.16	0.1	0.16	0.1	0.16
CPI = Σ(Wt × score)	0.54	0.81	0.62	0.77	0.72	0.63	0.68	0.68	0.79

Values in the parentheses are weights assigned to the respective attributes.

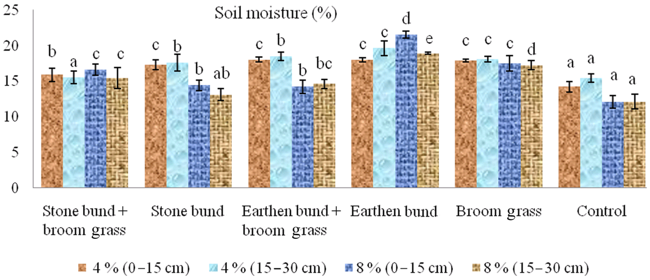

Figure 1. Complimentary role of grasses in enhancing soil profile moisture at 4 and 8 % slope.

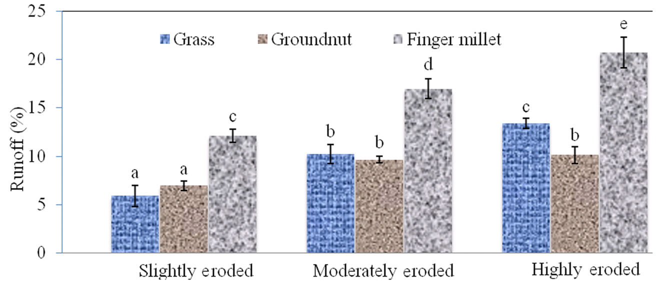

Figure 2. Impact of grasses in reducing runoff in lateritic soil.

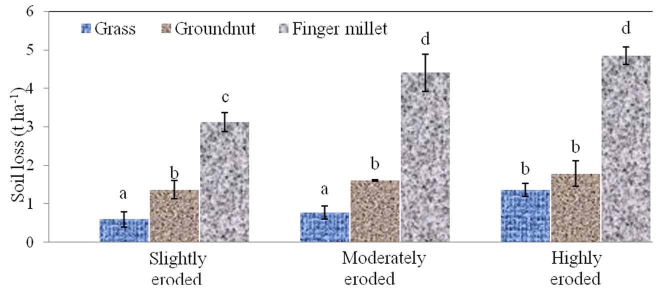

Figure 3. Impact of grasses in reducing soil loss in lateritic soil.

high as 12.6 adult cattle units per hectare (ACU ha^{-1}), compared to the carrying capacity of 0.8 ACU ha^{-1} (GOI, 2015).

The data (Table 3) show that runoff varies between 11.30 and 33.40 % with a mean value of 24.33 % and soil loss varies between 1.52 and 3.28 Mg ha^{-1} yr^{-1} with a mean value of 2.58 Mg ha^{-1} yr^{-1} in control plots (without grazing management). The management of grazing lands (cut and carry system, rotational grazing and control grazing) significantly reduced the runoff ranging between 6.60 and 22.20 % (with a mean value of 14.12 %) and soil loss ranging between 0.58 and 1.30 Mg ha^{-1} yr^{-1} (with a mean value of 0.95 Mg ha^{-1} yr^{-1}). A total of 12 studies on grazing land management revealed that the benefits of stall feeding and controlled grazing could save about 42 % water loss and 63 % soil loss in sloppy lands. The mean runoff in grazing management practices was significantly reduced from 24.33 to 14.12 %. This may be due to higher green cover and biomass production under improved management. Grazing land management of *Chrysopogon fulvus*, *Heteropogon contortus* and *Panicum maximum* have shown the potential to produce 40, 8.5 and 110 Mg ha^{-1} green biomass yields, respectively (Rana, 1998; ICAR, 2006; Ghosh et al., 2009; Pathak and Dagar, 2015). The average soil loss was significantly reduced from 2.0 to 0.95 Mg ha^{-1} yr^{-1} by the imposition of grazing and grassland practices. However, some researchers have demonstrated that grass steppes are more resistant to land degradation than shrub steppes (Palacio et al., 2014) and they contribute to increasing the biodiversity and improving the soil quality (Costa et al., 2015; Gao-Lin et al., 2016)

Dichanthium annulatum cover was found to reduce the runoff and soil loss by 35.45–51.40 and 71.90–81.08 %, respectively, in slightly to severely degraded lands in lateritic soil of the Konkan region in India (Figs. 2 and 3). In this region *Dichanthium annulatum* yielded about 25–30 Mg ha^{-1} of green biomass under improved management. The investigation further suggested that carbon loss can be reduced to the extent of 88.36–83.12 % in slightly and severely degraded lands in the same region (Fig. 4). The study also indicated that carbon sequestration rate up to 100 kg ha $^{-1}$ yr^{-1} can be achieved by the use of grass strips running across the slope, especially in laterite soils of the Konkan region (Kale et al., 1993). An about 6-fold increase in soil organic carbon (SOC) content in soil has been observed in barren lands of the Shivalik region through rehabilitation by *Arundo donax*. Grazing management typically leads to a 3 % annual increase in soil carbon (Conant et al., 2001). Duran and Rodriguez (2008) showed that grasses provide perennial protection and minimal erosion as they provide complete ground cover (Brindle, 2003). In the Mediterranean region, based on 20 paired-plot studies, Keesstra et al. (2016) reported that runoff sediment concentration was 45.5 times higher in cleaned cultivation plots compared to covered plots. They further reported that erosion rate was below the soil loss tolerance limits under surface-covered conditions. It is noticeable that the loss of vegetation cover leads to increased surface instability and poor regeneration, which in turn set a vicious cycle in motion.

In the hilly region of northeastern Himalayas, the alternative land use systems help in reducing soil erosion systems and SOC loss to a substantial extent. Higher root biomass of the grasses, particularly *Paspalum*, Congo signal, and *Panicum maximum* var. Makunia and Hamil, due to greater water transmission resulted in higher SOC in the soil profile. Following addition of organic matter through continuous root decay of these grasses, water-holding capacity of the soil increased as a result of the increased specific surface area. Additionally, these grasses helped in improving soil quality, including soil hydro-physical characteristics and biological activities. Such improvement in soil properties have a direct bearing on C sequestration (5-fold increase in SOC over con-

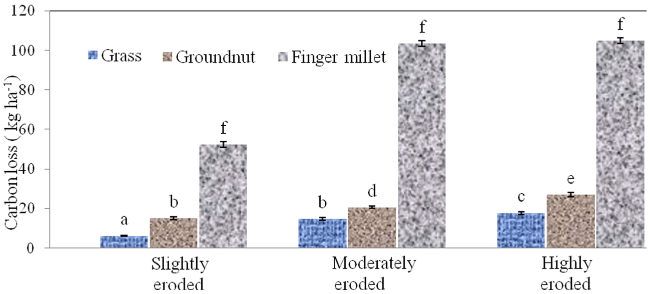

Figure 4. Impact of grasses in reducing carbon loss in lateritic soil.

trol), long-term sustainability and reducing soil erosion (2–3-fold increase in structural stability over control) in a complex, risk-prone fragile ecosystem (Ghosh et al., 2009).

4 Conclusions

Human-induced changes due to land use intensification and overgrazing have caused some severe and extreme states of land degradation that may prove to be more difficult to restore under the ongoing practices. The present meta-analysis clearly revealed that suitable conservation measures, especially the vegetative and biological practices, greatly assist in reversing the land degradation process for both cropland and grasslands.

Most soil erosion control measures implemented in cultivated fields are physical structures. However, these physical structures were reported to be less acceptable due to the high cost of their construction and maintenance. The meta-analysis clearly showed that grass barriers potentially reduce runoff and soil loss by up to 86.8 and 97.32 %, respectively. The relative yield gained of various crops through CGBs at different slopes varied between 44 and 53 %. However, the effectiveness of grass barrier, as reported by several studies, is site-specific and depends mostly on slope gradient, runoff volume and flow rate, size and density of sediment particles, grass species, density, interval and width of grass strips, underlying soil properties, and rainfall intensity and duration. According to farmers' criteria based on CPI, the study revealed that *Pennisetum purpureum* was most preferred grass, followed by *Saccharum munja* and *Dichanthium annulatum*. Considering the CPI values it is apparent that *Saccharum munja* (sambuta) and *Thysanolaena maxima* (hill broom) are two important bio-remediation options for reclamation of shifting cultivation of the northeastern hill region and Eastern Ghats of India.

The present analysis also indicated that grass must be used as a vegetative strip to maintain soil quality in sloppy arable areas (8.5 Mha) of Indian hilly regions. Special emphasis on establishing grasses should be given to about 3 Mha of degraded pasture lands and 3.5 Mha of shifting cultivation areas in India to reverse the land degradation. Overall, we conclude that the use of grass barriers alone or in combination with structural measures and grassland management was effective and efficient for decreasing soil and water loss on sloppy croplands in tropical and subtropical regions of India. Thus, these practices should be strongly recommended and used widely in similar climatic regions. Similarly, the reduction in grazing intensity needs to be advocated for about 12 Mha of permanent pasture lands.

Competing interests. The authors declare that they have no conflict of interest.

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