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Managing India's small landholder farms for food security and achieving the "4 per Thousand" target

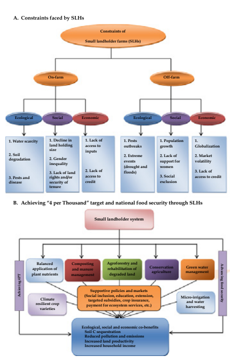
Arun Jyoti Nath [a,*], Rattan Lal [b], Gudeta Weldesemayat Sileshi [c,d], Ashesh Kumar Das [a]

[a] Department of Ecology and Environmental Science, Assam University, Silchar 788011, Assam, India
[b] Carbon Management and Sequestration Center, The Ohio State University, Columbus, OH 43210, USA
[c] Plot 1244 Ibex Hill, Lusaka, Zambia
[d] School of Agricultural, Earth and Environmental Sciences, University of Kwazulu-Natal, South Africa

HIGHLIGHTS

- SLHs in India currently contain 1370–1770 Tg C.
- Adoption of BMPs in SLHs can annually sequester 70–130 Tg CO_2e from 2020 to 50.
- Policy support for women and socially excluded groups can spur adoption of BMPs.
- Adoption of BMPs in SLHs can achieve "4 per Thousand" target and India's food security.

GRAPHICAL ABSTRACT



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ABSTRACT

The "4 per Thousand" initiative was launched at the 21st Conference of Parties (COP21) in December 2015 to address global climate change through the aspirational goal of increasing soil organic carbon (SOC) stock of the world to 40-cm depth by an average annual rate of 4%. Small landholders (SLHs), often faced with difficult biophysical and socio-economic conditions, are the principal managers of soil in India. There are 117 million SLHs representing 85% of the total operational holdings, cultivating over 72 million ha of land, and meeting 50–60% of India's food requirement. The agricultural soils of SLHs are strongly depleted of SOC and nutrient reserves. Therefore, the challenge of feeding 1.7 billion people in India by 2050 will depend on increasing the current productivity levels by restoring the depleted soils of SLHs. According to our estimates, soils of SLHs currently contain 1370–1770 Tg C and, which can be increased to 2460–2650 Tg C by 2050 through large-scale adoption of best management practices (BMPs) including balanced application of nutrients, compost, agroforestry, and conservation agriculture. A wide spread adoption of these practices can enhance C sequestration by 70–130 Tg CO_2e per annum and produce 410–440 million Mg of food grains accounting for 80–85% of the total requirement by 2050. In this paper we propose strategies for achieving the dual objectives of advancing food security, the "4 per Thousand" target and mitigating climate change in India.

1. Introduction

India is a significant contributor to global greenhouse gas (GHG) emissions (INCCA, 2010). In 2014, India was the fourth largest emitter

* Corresponding author.
E-mail address: arunjyotinath@gmail.com. (A.J. Nath).

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of carbon dioxide (CO_2) after China, USA, and the European Union (www.climateactiontracker.org). India's GHG emissions increased by an alarming 4.7% in 2016 compared to the previous year, while there was a decline in emission from the USA by 2% and China by 0.3% (www.climateactiontracker.org). The sectors with the largest contributions of GHGs are energy (58%), industry (22%), agriculture (17%) and, municipal waste (3%) (INCCA, 2010). India has agreed to reduce its emission intensity by 35% from the2005 levels by 2030. To achieve this target, India submitted its Intended Nationally Determined Contribution (INDC) in 2015 (www.climateactiontracker.org). The INDC is aimed at the followings: (i) increasing the share of non-fossil fuel based power generation capacity to 40% of installed electric power capacity, and (ii) creating an additional carbon sink of 2.5–3 $GtCO_2e$ through afforestation by 2030 (www.climateactiontracker.org). Agriculture, which is the major land use occupying 55% of the total land area of India and containing soil organic carbon (SOC) stocks estimated at 3.2 Gt (Minasny et al., 2017) was not included in the INDC. With over 162 M ha of arable land, India has considerable potential for soil carbon (C) sequestration through agricultural mitigation activities (Lal, 2004). Among agricultural mitigation options, soil C sequestration is one of the few strategies that could be applied at large scales and at lower cost (Paustian et al., 2016; Smith, 2012). Small changes in SOC stock can also have considerable impacts on the global atmospheric CO_2 concentrations (Paustian et al., 2016). In addition, soil C sequestration has inherent synergies with the Sustainable Development Goals (SDGs), including social, economic, and environmental goals (Chabbi et al., 2017; Smith et al., 2008; Soussana et al., 2017).

The “4 per Thousand” aspiration proposed during the 21st Conference of Parties (COP21) in Paris was aimed at making agriculture a solution to address climate change while also advancing food and nutritional security (Chambers et al., 2016; Lal, 2016; Le Foll, 2015; Minasny et al., 2017). While “4 per Thousand” target is not a normative target for all countries, it is intended to highlight that even small increases in SOC can play a crucial role in improving soil fertility, productivity and achieving the long-term objective of limiting global warming to 1.5 °C (http://4p1000.org). Some researchers (e.g. Baveye et al., 2018; De Vries, 2018; van Groenigen et al., 2017; White et al., 2018) have recently questioned this target on the grounds of feasibility and economics. There is also consensus that it is an important aspirational target to promotion of sustainable land management and achieving food security at the same time (Lal, 2016; Chabbi et al., 2017; Minasny et al., 2017). There is also a growing body of empirical evidence (Soussana et al., 2017) suggesting that improved agronomic practices can result in SOC increases that can exceed 0.4% per year.

Bhattacharyya et al. (2008) reported that the soils of India contain 24.04 Gt SOC in the top 1 m. Sreenivas et al. (2016) estimated the SOC stock at 22.7 ± 0.9Gt in the top 1 m, while Banger et al. (2015) estimated the SOC stock at 20.5–23.4 Gt in India, of which 47–57% is stored in forest soil. Thus, India contributes 20–25 Gt C or 1.4–1.8% of the global SOC stock estimated at 1408 Gt in the top 1 m. With an annual C emission of about 566 Tg, the required C sequestration rate for India would be about 23–28 per Thousand as opposed to the global target of “4 per Thousand” (Minasny et al., 2017). Nevertheless, opportunities exist for progressing towards the “4 per Thousand” target while also improving small landholder (SLH) agriculture in India.

The SLH agriculture in the tropics is characterized by a small farm size (0.2–2 ha) and low per capita natural resources (Lal, 2016). Indian agriculture is the home of such small and marginal farmers, which account for 80% of the total farm households (Dev, 2012). The average farm size of SLHs in India is 0.61 ha (GOI, 2014), and farmers eke out their living in the world's most ecologically and climatically vulnerable landscapes and rely on weather-dependent natural resources (IFAD, 2012; GAP, 2014). SLHs are also at the forefront of environmental degradation and its consequences as they are trapped in a vicious cycle of poverty, hunger and further degradation (Lal, 2016). Food production in India needs to be doubled in order to feed a population of 1.7 billion by 2050 (UN, 2015). Yet, increasing the productivity of SLH farmers is a viable option for advancing national food security by 2050 (Swaminathan and Bhavani, 2013). Therefore, achieving national food security will require alleviating the ecological, social and economic constraints faced by SLHs. Addressing these constraints should also be an integral part of the strategy for achieving food security and the “4 per Thousand” target. Our working hypothesis is that the "4 per Thousand" target can be achieved through application of best management practices (BMPs) and addressing the management constraints on SLH farms.The specific objective of this article is to identify BMPs that can achieve the “4 per Thousand” target and advance national food security in ways that sustain SLH farms and their environment. The broader objective is to bring the issues to the attention of policy-makers and development agencies to orient their focus towards SLH, which constitute a very large part of the world's population that manages the land and produces food.

2. Methods

A review of literature was undertaken to identify constraints under SLH, BMPs appropriate for SLHs, case studies and the evidence for enhancing soil C sequestration through BMPs in India. Journal articles, book chapters, and scientific reports were identified through a comprehensive literature search carried out using Web of Science, Scopus, Google, Google Scholar, and individual journal databases, using permutations of keywords that include: agroforestry, conservation agriculture, soil organic carbon, Indian agriculture, food security, nutrient management, tillage systems, best management practices, micro-irrigation, and grain production.

We also made projections of SOC and food production by SLHs in India at five year intervals for the period of 2015 to 2050. The SOC concentrations in most cultivated soils in India are 4–8 g kg^{-1} (Benbi and Brar, 2009; Lal, 2016; Pal et al., 2015). For improved yield under SLHs in the tropics, SOC concentration must be restored to the threshold level of ~15 g kg^{-1} in the root zone (Lal, 2014). Under the business as usual scenario (continuous cultivation), it may not be feasible to attain SOC concentration of 15 g kg^{-1}over a period of 30 yrs. on SLH (2020–2050). For the baseline years (2015), the SOC stock up to 40 cm depth was calculated using the mean SOC concentration of 4.3 g kg^{-1}, mean soil bulk density (BD) of 1.1–1.4 Mg m^{-3}, and total area of 71.8 M ha (Bhattacharyya et al., 2000; Benbi and Brar, 2009; Pal et al., 2015; Nath et al., 2016a). Large variations in SOC build up have been reported in India. For example, Bhattacharyya et al. (2007) reported change in SOC stock ranging from 30 to 395% of initial value in long-term (25 yr) fertilizer trial sites ranging from semi-arid, sub-humid and humid climates. Similar trends were projected by the RothC model under continuous management system in long term fertilizer trial sites representing sub-humid moist, sub-humid dry, and semi-arid climate in India (Bhattacharyya et al., 2011). Given this large variation, projections of SOC stock for 2050 were made using a range of baseline values (i.e. 4–7 g kg^{-1} for 2015). It was assumed that the capacity of soils to sequester carbon is time-constrained, and the rate of C accumulation slows down as the soil approaches equilibrium (Baveye et al., 2018), a phenomenon termed sink saturation which may occur after 10–100 years, depending on the BMP, soil type and climate zone (Smith, 2016), with IPCC default saturation time being 20 years. According to a global meta-analysis of SOC changes in agricultural land under different fertilizer managements showed an increase in topsoil SOC by 10–40% (Han et al., 2016). Accordingly, we projected increment of SOC concentration from the initial level by 20–30%, 12–18%, 8–10%, 4–7%, 3–5%, and 1–2% for 2015–2020, 2021–2025, 2026–2030, 2031–2035, 2035–2040, and 2041–2050, respectively. In the initial years after adopting BMPs, increased productivity of crop is expected to result in enhanced C sequestration in the surface soil layer. For example, in Punjab increased productivity of rice and wheat in BMPs resulted in enhanced C sequestration in the plough layer by 0.8 Mg C ha^{-1} per tonne of increased grain production (Benbi and Brar, 2009). However, as the soil progressively approaches sink saturation, yearly increase in SOC was set to decrease and reach 1% of its initial value in 2041–50.

Uncertainties in SOC build up are expected to lead to uncertainty in increase in food grain production. Therefore, with cumulative increase in SOC stock in SLHs, variations in increase in food grain production was compounded at the rate of 12–15%, 10–12%, 10–12%, 7–9%, 7–9%, and 5–6% from its initial production capacity in 2015–2020, 2021–2025, 2026–2030, 2031–2035, 2035–2040, and 2041–2050, respectively. A decreasing trend in food grain production from its initial production capacity over different time interval has been projected considering the saturation of soil C sink and other on-farm and off-farm constraints. Increases in SOC stock and grain yield were projected using a statistical model based on the logistic function. The 95% confidence intervals of projections were used to represent the uncertainty around projected values.

3. Constraints and opportunities for increasing SOC storage in SLH

3.1. Ecological, social and economic constraints

India has over 160 M ha of land area under agriculture spread over five distinct bioclimatic regions (Bhattacharjee et al., 1982) with varying mean annual rainfall. The regions are arid cold and hot (550 mm), semi-arid (550–1000 mm), sub-humid (1000–1500 mm), humid to per-humid (1200–3200 mm), and coastal (900–3000 mm). Principal soils of India are Inceptisols (39.4% of total land area), Entisols(23.9%), Alfisols (12.8%), Vertisols (8.1%), Aridisols (4.1%), Ultisols (2.6%) and Mollisols (0.5%) (Bhattacharyya et al., 2009a, 2009b). This diversity of bioclimatic conditions and soil types is also associated with challenges to SLHs at the farm and off-farm levels (Fig. 1).

At the farm level, the main ecological constraints include water scarcity, which is further aggravated by the projected climate challenge. About 60% of total agricultural land in India is prone to severe agronomic/pedologic drought (ICAR, 2010; IFAD, 2012), and SLHs are often severely impacted by extreme events. Major soil-related constraints include: low soil organic matter (SOM) content, high bicarbonate content in irrigation water and unbalanced application of nutrients resulting in severe losses in yield and nutritional values (Pal et al., 2000, 2015).The agricultural soils are also severely degraded; an estimated 90 M ha of land is affected by water erosion, 16 M ha by acidification, 14 M ha by flooding, 9 M ha by wind erosion, and another 6 M ha by salinity (ICAR, 2010; Bhattacharyya et al., 2015). This situation is further exacerbated by low reserves of SOC in the arid and semi-arid and dry sub-humid climatic regions, which cover nearly 50% of the total agricultural land of India (Pal et al., 2000). Most agricultural lands are characterized by low SOC (<5 g kg^{-1}) and low nutrient reserves (Lal, 2004, 2015; Pal et al., 2015). Cultivated soils containing <4 g C kg^{-1} are classified as low in soil SOC (Benbi and Brar, 2009). To maintain SOC level, at least 0.31–5.16 Mg C ha^{-1} yr^{-1}must be added to soils through crop residues or some other organic sources (Mandal, 2011).

Among the common social and economic constraints of SLHs are lack of support for women farmers, gender inequality, social exclusion, lack of land rights and/or tenure security, lack of skills and negative impacts of globalization (Dev, 2012). In much of India, gender and caste are two distinct social institutions which exhibit clearly defined norms, rules and values that have a large influence over an individual's access to resources. Recent analyses demonstrate how restrictive social environments can limit the adaptive capacity of marginalised and socially excluded groups (Jones and Boyd, 2011). The share of rural women in agriculture in India is around 83%, andagriculture is becoming increasingly feminized as men are migrating to rural non-farm sector. However, women do not have property rights and access to productive

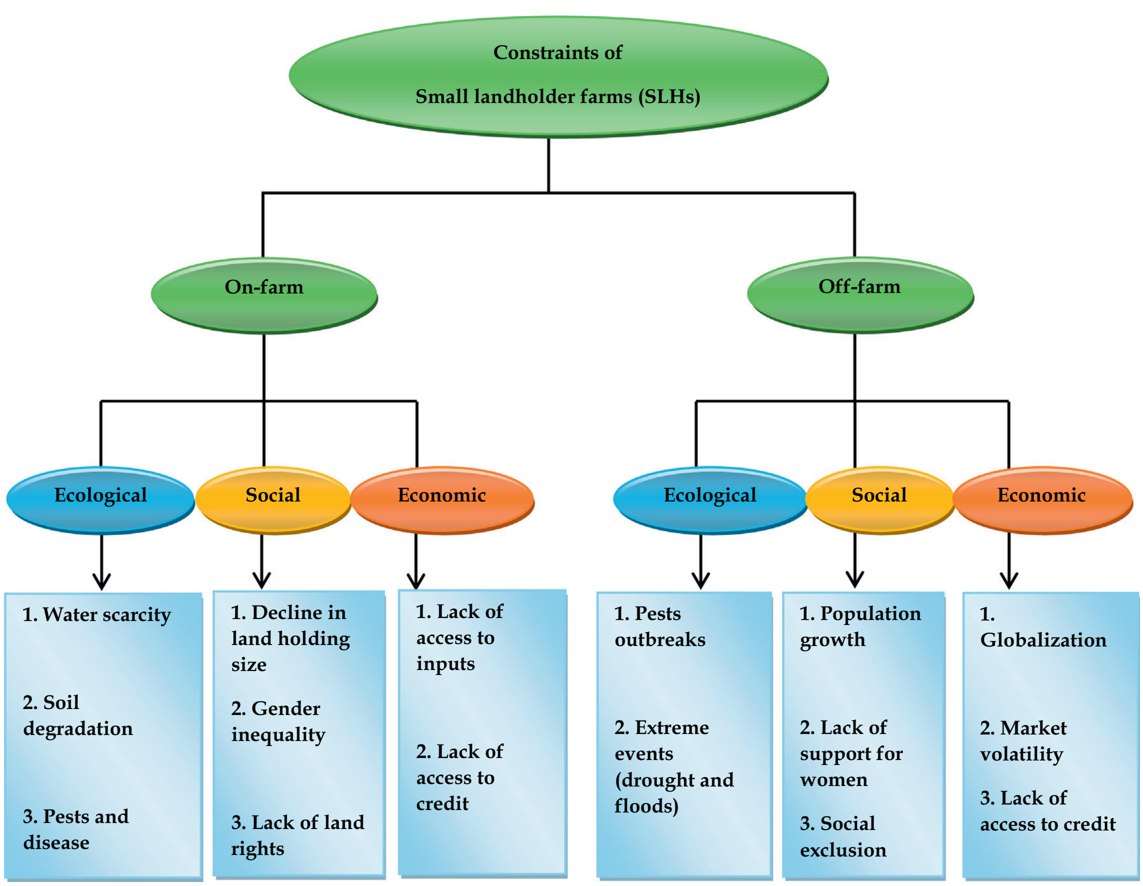

Fig. 1. Challenges and constraints faced by small landholders.

resources. Social exclusion associated with the discriminatory caste system in India is also an important factor in an individual's access to employment and economic resources (Madheswaran and Singhari, 2016). The proportion of socially disadvantaged groups such as Scheduled Castes and Scheduled Tribes is higher among marginal and small farmers than that of medium and large farmers (Dev, 2012). Access to land and the quality of land is particularly low under Scheduled Tribes. The access of such groups to information, markets, credit and publicly provided inputs and extension services is lower (NCEUS, 2008). For example, tribal cultivators and tenants face difficulties in accessing institutional credit and other facilities available to farmers with land titles (Dev, 2012).The low level of farmers' education also limits public dissemination of knowledge. For example, the literacy level among women in the marginal farmers group is only 31.2% (Dev, 2012). Therefore, sustainable management of soils on SLHs and building SOC stock requires addressing these social and economic constraints.

3.2. Opportunities

One of the greatest opportunities to achieve the "4 per Thousand" target is the existence of a large number of SLH farmers in India. Out of the total of 138 million agricultural holdings in India, 117 million (or 85%) are SLH farmers (GOI, 2014). While the total arable land area is shrinking, the contribution of SLH to total operational holding is increasing (Fig. 2). Indeed, the number of holdings under SLH are projected to approach the total land holding by 2050 albeit the large uncertainty indicated by the 95% confidence limits (Fig. 2).In accordance with the inheritance laws, farms are divided among family members, which may be considered a challenge as it leads to decline in land holding size. However, it also presents an important opportunity because in such arrangements farmers' commitment to their farm legacies is strong. On multi-generational family farms families stay committed to maintaining healthy and sustainable farms that can be passed down to the next generation (Pan et al., 2017). SLH farmers contribute 70% of the total production of vegetables, 55% of fruits, 52% of cereals and 69% of milk (Birthal et al., 2011). The crop residues from these systems are estimated at 679 Tg annually, which can add substantial amounts of C to the soil.

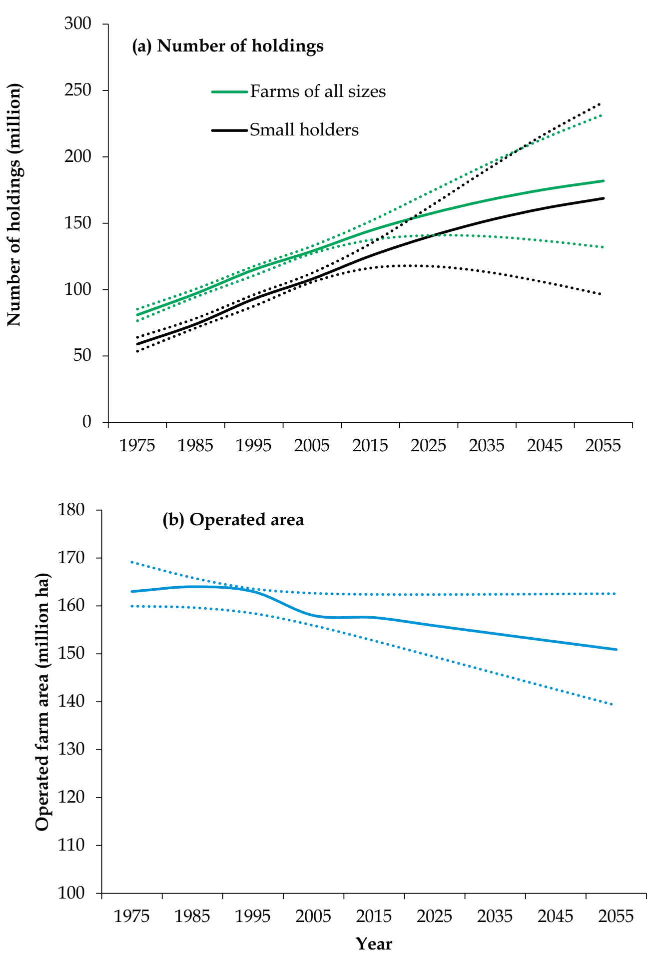

Fig. 2. Trends in actual (1975–2010) and projected (2015–2050) number of all farm sizes, number of small landholder farmsand total operated area (agricultural land) in India. The actual values were from GOI (2014). The dotted lines are upper and lower 95% confidence limits representing the uncertainty associated with the projections. Note the widening in the 95% confidence limits from 2025 onwards indicating large uncertainty in projection.

Another key opportunity is India's large human and livestock population, which produces large quantities of organic waste. India's current human population is estimated at 1.2 billion, and is projected to be 1.5 billion by 2030 and 1.7 billion by 2050 (UN, 2015). The municipal solid waste production alone is currently estimated at 64.8 Tg annually. Much of the municipal waste currently goes to landfills, where it becomes a significant source of GHG emission. The livestock population of over 500 million is estimated to produce 3000 Tg of manure annually (GOI, 2016). In order to increase productivity, the government of India has instituted the fertilizer subsidy program. Diverting part of the fertilizer subsidy to efficient use of the available crop residues and municipal solid wastes along with green manuring and suitable cropping systems may help in curbing the declining trends in SOC stock in soils of India (Minasny et al., 2018). Therefore, opportunities exist for scaling up the SOC enhancing strategies for specific conditions under SLH's. In the following sections, we will describe some of the key strategies that can be promoted for soil C sequestration while also producing other social and environmental co-benefits.

4. Strategy to achieve national food security and "4 per Thousand" through SLH

Enhancing agricultural productivity is a central component of the strategy to meet the food demands of India by 2050 (GAP, 2014). But, achieving this target will require a realistic plan. In India, any generalizations about agricultural soil management are unlikely to have wider applicability because of the diversity of soil and the factors affecting SOM dynamics (Pal et al., 2015). Therefore, in the present review, data on SOC concentration and yield were gathered from diverse agro-ecological zones. Based on these values, adoption of BMPs was projected to increase the SOC concentration from ~4.3 g kg^{-1} in 2015 to ~7.8 g kg^{-1} by 2050 (Fig. 3). Although SLH farms are depleted of their SOC stock, numerous studies applying BMPs have shown an increase in SOC concentration and crop yields (Tables 1 and 2). Reported increases in yields have been attributed to changing traditional farming systems to BMP systems, and that the yield changes cannot be ascribed to SOC only.

Data in Tables 1 and 2 further reveals that 10–30% increase in SOC concentration from its initial value can enhance grain yield by 7–40% for diverse cropping systems under different agro-ecological regions in India. Therefore, with increases in SOC concentrations, food grain production is projected to increase from 248Tg in 2015 to 415 Tg by 2050 (Fig. 3), provided that the essential inputs are made available together with extension support. The annual grain production of 410–440 Tg is 80–85% of the total food grains required to feed 1.7 billion of India's population by 2050. If implemented appropriately building up of SOC stock on SLH farms at this rate could increase C stock by 20-36Tg (~70–130 Tg CO_2e) per annum between 2020 and 2050. According to our estimates, SLHs currently contain 1370–1770 Tg C and, by 2050 that can be increased to 2460-2650Tg C through adoption of BMPs. This amount of soil C sequestration is ~13–23% of the total C emission (566 Tg) of India in 2015. In the following sections we will briefly describe some of the BMPs for sustaining and enhancing the productivity of SLH farms.

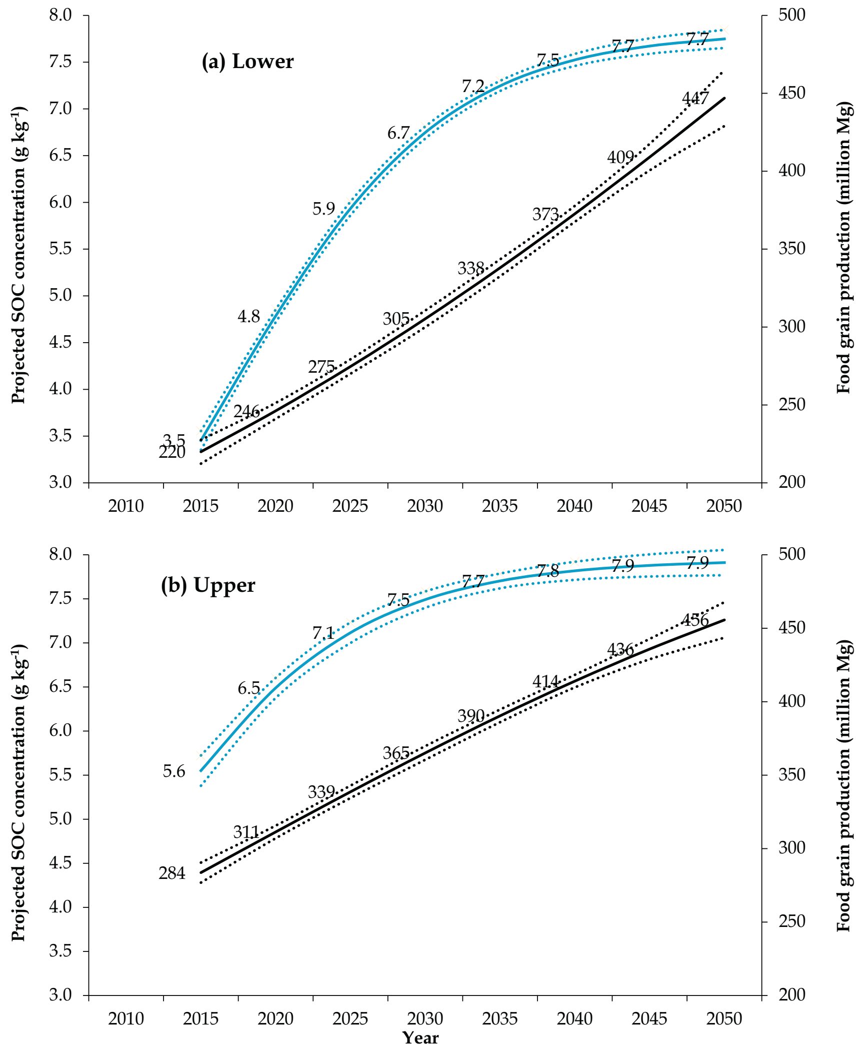

Fig. 3. Projected increases in soil organic carbon concentration (g kg^{-1} soil) and food grain production through implementation of best management practices. Projections of SOC and food grain production were made assuming a range of starting values (upper and lower). Solid blue and black lines represent SOC concentration and food grain production, respectively. The dotted blue and black lines are upper and lower 95% confidence limits representing the uncertainty associated with the projections. Note the widening in the 95% confidence limits from 2040 onwards indicating large uncertainty in projection. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1. Balanced application of plant nutrients

Over 60% of the agricultural land in India is prone to degradation due to fertilizer misuse, poor cropping practices, soil nutrient mining and deficiencies (ICAR, 2010). A surplus supply of reactive nitrogen (N) and phosphorus (P) can result in emissions of ammonia and nitrous oxides (NOx) into the air and loss of nitrate and P polluting water bodies (Sutton et al., 2017). One major cause of yield decline is the continuous nutrient mining of the soils (particularly P, K, secondary nutrients and micronutrients) resulting from unbalanced fertilizer application (IFAD, 2012).

Balanced application of NPK and sulphur (S) can substantially enhance biomass production and C sequestration as the formation and turnover of SOM depends largely on the biogeochemical processes involving C, N, P and S. It has been estimated that 39% of all soils in India are S deficient, though the level of deficiency varies among soil types, agro-ecology and cropping systems (Shukla et al., 2016). Therefore, application of inorganic sources of S (e.g. single super phosphate, gypsum, pyrites, ammonium sulphate) or organic manure (8–10 Mg ha^{-1}) can corrects S deficiency (AHBD, 2014; Fageria et al., 2002). Micro-dosing soil with correctly proportioned NPKS fertilizer could significantly increase crop yields under SLHs who are unable to afford large applications (van der Velde et al., 2012).

Long-term experiments (30 yr.) from southern parts of India have shown that high levels of grain productivity (8–12 Mg ha^{-1} yr^{-1}) can be sustained by integrating balanced fertilizer application rates with 10–15 Mg FYM ha^{-1} yr^{-1} (FAO, 2014). These experiments have established that the integrated use of fertilizers and FYM can correct nutrient deficiencies and improve soil physical and biological properties (Bhattacharyya et al., 2013). Few other long-term experiments (25–40 yr) with balanced fertilization (NPK) and 5–10 Mg ha^{-1} of organic residues have achieved a C build up rate of 0.16–0.99 Mg C ha^{-1} yr^{-1} under different cropping systems (Table 1). In addition, balanced application of nutrients has socio-economic incentives including increased nutrient use efficiency and increased land productivity (Fig. 4).

4.2. Composting municipal waste and manure management

Out of the 64.8 Tg of municipal solid waste produced in India annually, the majority is disposed in open dumps, ordinary landfills in the rural areas or sanitary landfills. The major part of municipal waste

Table 1
Influence of best management practices on soil carbon sequestration in diverse climate of India.

Management	Soil depth (cm)	Soil carbon sequestration rate (Mg C ha^{-1} yr^{-1})	Average C stocks (Mg C ha^{-1})	Period of observation (years)	Climate[b]/Reference[a]
1. Balanced application					
Rice-Rice with NPK	0–20	0.23	31.3	36	1
Rice-Rice with NPK + compost	0–20	0.41	31.3	36	1
Rice-wheat with NPK	0–60	0.66	34.4	19	2
Rice-wheat with NPK + Farm yard manure (FYM)	0–60	0.99	34.4	19	2
Rice-wheat with NPK + paddy straw	0–60	0.89	34.4	19	2
Rice-wheat with NPK + green manure	0–60	0.82	34.4	19	2
Inorganic fertilizer	0–15	0.16	13.3	32	3
Inorganic fertilizer + FYM	0–15	0.33	13.3	32	3
Finger millet with NPK + FYM	0–20	0.57	NA	27	4
Soybean with $N_{20}P_{13}$ + FYM	0–20	0.79	NA	15	5
2. Agroforestry					
Areca plantation	0–100	0.14	96.2	30	6
Rubber plantation	0–100	0.28	101.9	30	6
Piper betle agroforestry	0–100	0.74	115.9	30	6
Bamboos in agroforestry	0–30	0.29	34	20	7
Silvipastoral systems	0–100	0.91	NA	3	8
3. Restoration of degraded land					
Imperata grassland	0–100	0.14	97.8	30	6
Degraded forest	0–100	0.28	93.6	30	6
4. Conservation agriculture					
Lentil based system		0.21–0.61	24.81	6	9, 10
	0–15				
Finger millet based system	0–100	0.078	43.18	10	11
Rice-Wheat based system	0–60	1.09	28.2	7	12

NA = Not available.
[a] 1. Mandal et al. (2008); 2.Majumder et al. (2008); 3.Pathak et al. (2011); 4.Srinivasarao et al. (2012a); 5. Srinivasarao et al. (2012b); 6. Brahma et al. (2017); 7.Nath et al. (2015); 8. Mangalassery et al. (2014); 9. Bhattacharyya et al. (2012); 10.Bhattacharyya et al. (2013); 11.Prasad et al. (2016); 12.Sapkota et al. (2017).
[b] 1- Tropical sub-humid; 2-Sub-tropical; 3- sub-tropical to warm temperate; 4&5-Semi-arid; 6-Sub-tropical humid, 7- Sub-tropical humid; 8-Arid; 9 &10-Temperate; 11-Semi-arid; 12-Tropical humid.

consists of biodegradable organic materials, which undergo anaerobic decomposition in landfills generating a variety of gases collectively called landfill gas (Singh et al., 2016), which is one of the major sources of anthropogenic GHG emission. CH_4 alone constitutes about 29% of the total GHG emissions in India, which is nearly twice the worldwide average of 15% (Singh et al., 2016).

India also has a large livestock population that produces 3000 Tg of manure annually and also contributes to GHG emissions. For example, enteric fermentation from livestock alone contributes about 63% of the total emissions from the agriculture sector (INCCA, 2010). Manure management is known to be a significant source of GHGs especially methane (CH_4) and nitrous oxide (N_2O) contributing to 25% of the global CH_4 emission and 31% of the N_2O emission (Thornton and Herrero, 2010). Better management of manure may be achieved through improved storage during the curing period, composting and mixing different manures. Composting of manure and municipal waste can reduce GHG emissions by transforming them into a stable carbon sink. Thus, composting is considered to be a C-based system, similar to reforestation, agricultural management practices, or other waste management industries (Brown, 2008). Using compost also has

Table 2
Influence of best management practices (BMPs) on crop yield from diverse climate of India.

Farming type	Recommended management practices	Climate	Increase in yield (in %) over conventional system	Climate[b]/ Reference[a]
Rice (*Oryzasativa*)-Rice cropping system	NPK (60:40:40) + compost (5 Mg ha^{-1} yr^{-1})	Humid	7%	1
Mustard cropping systems	No till and residue retention (one third)	Sub tropical humid	25%	2
Rice-Wheat (*Triticum aesivum*) cropping system	NPK (120:60:60) + FYM	Humid	11% (rice) 12% (wheat)	3
Sorghum (*Sorghum bicolour*)-wheat	NPK + FYM	Semi-arid	14% (Sorghum) 5% (wheat)	3
Rice-Lentil (*Lens culinaris*)	50% NPK + 50% foliar	Dry sub-humid	45% (rice) 37% (Lentil)	4
Rice	Minimum tillage with in-situ residue management	Sub-tropical	19%	5
Mustard (*Brassica nigra*)	Zero till	Semi-arid	18%	6
Rice	Organic+inorganic	Sub tropical humid	14%	7

[a] 1. Mandal et al. (2008); 2. Ghosh et al. (2010); 3. Bhattacharyya et al. (2014); 4. Srinivasarao et al. (2012a); 5. Das et al. (2014); 6. Shekhawat et al. (2016); 7. Nath et al. (2015).
[b] 1- Tropical sub-humid; 2: Sub-tropical; 3-Sub-humid; 4-Semi-arid; 5-Temperate; 6- Semi-arid; 7-Sub-tropical humid.

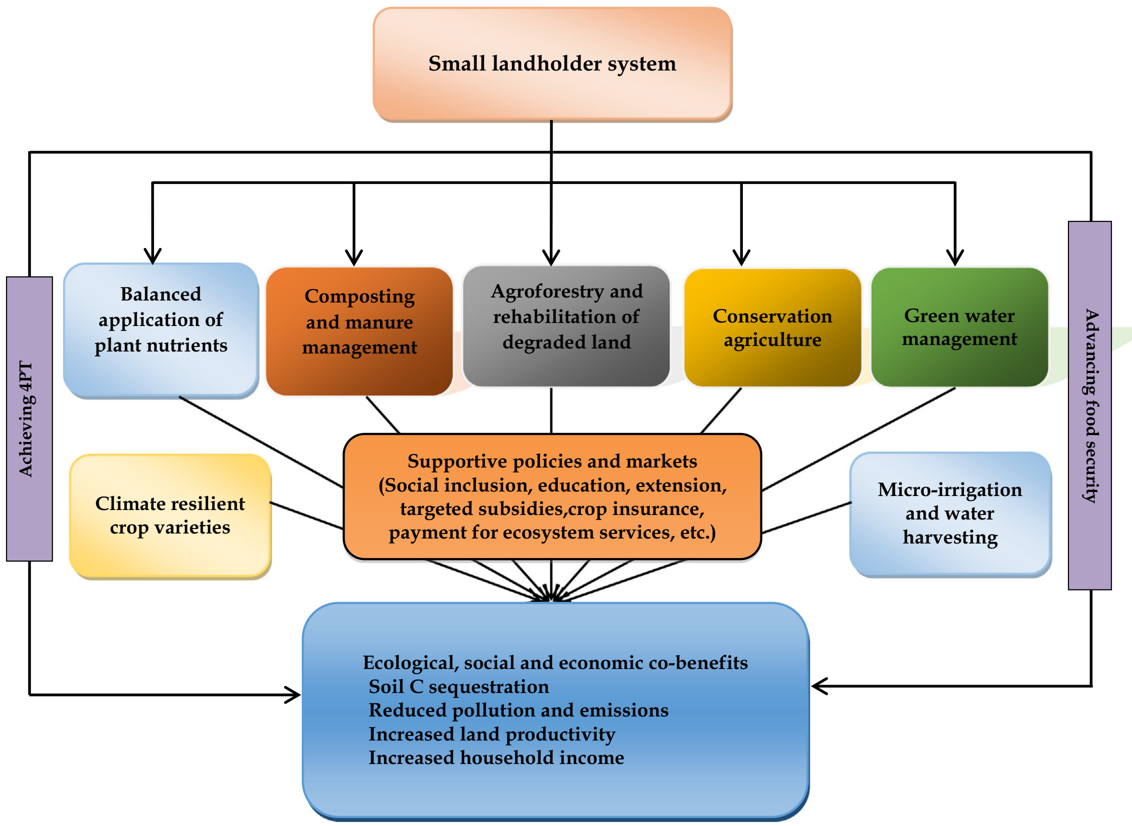

Fig. 4. Strategies for achieving"4 per Thousand" and national food security.

the potential to generate carbon credits through avoidance and sequestration of carbon. The data in Table 1 show that the use of farm yard manure (FYM) can increase C sequestration. Compared to FYM, however, composting makes manure safer (due to reduction of pathogens and weed seeds) and easier to store, transport, and apply than non-composted manure. Composting municipal waste can also reduce methane emissions besides providingsocio-economic benefits including better management of municipal waste and reduction in pollution in urban areas (Fig. 4). One strategy for promoting composting of municipal waste is through supporting start-ups in compost management and linking them with SLHs. This can also be an important income generating activity to tackle the burgeoning youth unemployment in India.

4.3. Agroforestry systems and rehabilitation of degraded land

An estimated 7.4 M ha of land is under agroforestry in India (Zomer et al., 2009), with average biomass C of 12 Mg ha^{-1} (Zomer et al., 2016). However, considering the declining land holding under SLH, some of the 147 Mha of degraded land (Maji et al., 2010) may also be immediately rehabilitated through agroforestry and other interventions. Traditional agroforestry systems such as homegardens are the predominant land use types in India. For example, in Kerala state of India, homegardens cover 1.4 M ha, which is about 36% of the total area of 3.9Mha of the state (Kumar, 2006). Another widespread system is the poplar-wheat/barley agroforestry in northern India (Zomer et al., 2009). The soil carbon sequestration potential (0.5–0.8 Mg C ha^{-1} yr^{-1}) of these systems is higher than that of agricultural systems such as rice-paddy and comparable to that of single-species tree-crop systems involving rubber, areca and coconut (Saha et al., 2009; Brahma et al., 2017). Promotion of agroforestry and plantations (e.g. rubber, bamboo, etc.) in those lands can significantly improve SOC stock. Brahma et al., (2018) reported that, rehabilitating degraded forests through *Piper betle* agroforestry increased SOC by 22.3 Mg ha^{-1}. SOC stocks in *Piper betle* agroforestry was estimated at 115.9 Mg ha^{-1} or increment of 0.74 Mg ha^{-1} yr^{-1} (Table 1). Converting degraded forest into rubber tree plantations and *Areca* agroforestry also increased SOC by 8.4 and 2.6 Mg ha^{-1}, respectively. Similarly, converting degraded *Imperata cylindrica* grassland into rubber tree plantations increased SOC by 4.1 Mg ha^{-1} in North East India (Table 1). In one study, SOC stocks increased from 106 Mg ha^{-1} under 6 yr to 130 Mg ha^{-1} under 34 yr old rubber plantations with soil C sequestration rate being 0.86 Mg ha^{-1} yr^{-1} (Nath et al., 2018). This is consistent with results from a recent global synthesis (Kim et al., 2016) where average C increments were estimated at 1.0–2.0 Mg ha^{-1} yr^{-1} in soils. Traditionally managed agroforestry systems in southern India store more or equal SOC stock to those in tropical forests (Hombegowda et al., 2016). Agroforestry practices such as the fertilizer tree (fast-growing nitrogen-fixing) and shrubs such as pigeon pea (*Cajanus cajan*) have been known to improve SOC build up in depleted soils (Sileshi et al., 2014). In horti-silvi and silvi-pastoral systems in North East India planting pineapple (*Ananas comosus*), turmeric (*Curcuma longa*) and cowpea (*Vigna sinensis*) as forage crop along with neem tree (*Azadirachta indica*) increased SOC in the surface (0-15 cm) soil (Datta and Singh, 2007). Therefore, large scale adoption of agroforestry practices with emphasis on region specific native tree species on SLH's farm can improve land productivity while enhancing SOC sequestration.

The adaptation and GHG mitigation potentials of agroforestry have also attracted significant interest in carbon credits under the Verified Carbon Standards and Reduced Emissions from Deforestation and Forest Degradation (REDD+) programs. The green bonds issued by the World Bank also offer opportunities for agroforestry interventions to benefit local people to contribute to mitigation as well as adaptation to climate change.

As indicated earlier a large proportion of the agricultural land under SLHs is severely degraded. However, C storage in these soils can be at least partly restored through agroforestry and other practices that reclaim productivity (Smith et al., 2008).The "Grain for Ecosystem Carbon Management" (GECM) approach (Nath et al., 2016b) incorporating payment for ecosystem services (PES) for land management to the hill farmers can be a good model to promote agroforestry and restoration of degraded lands in India.The ecological and socio-economic incentives for promoting agroforestry include land restoration, food security and increased household incomes through PES. However, adoption of agroforestry and investment in land rehabilitation requires land rights and security of tenure. Even modest package of land reform can dramatically improve the prospect of adoption by women and socially disadvantaged groups, who currently have limited access to land.

4.4. Conservation agriculture (CA)

Soil disturbance by tillage has been cited as the primary cause of the historical loss of SOC throughout the world, and adoption of CA has been widely recommended as a means of enhancing C sequestration in soils (Luo et al., 2010). Basic principles of CA include zero or minimum soil disturbance, maintaining permanent soil cover through retention of crop residues, mulching and growing cover crops, and adoption of crop rotation. In India, the major CA based technologies being adopted is no tillage (NT) in the rice-wheat system of the Indo-Gangetic plains (Bhan and Behera, 2014). The area under NT and CA has expanded to cover about 1.5 M ha in India (Jat et al., 2012). Adoption of NT has been a success story especially in North-western parts of India because of the followings: (a) reduction in cost of production by \$33–50 ha^{-1} (Bhan and Behera, 2014); (b) enhancement of soil quality (Jat et al., 2009; Gathala et al., 2011) through build-up of the SOM content (Saharawat et al., 2012; Bhattacharyya et al., 2013); (c) improvement of water and nutrient use efficiency (Jat et al., 2012; Saharawat et al., 2012); (d) improvement of productivity (4–10%) (Ghose et al. 2010; Gathala et al., 2011); and (e) enhancement in soil C sequestration rates (Pathak et al., 2011). Studies from north eastern India indicate that NT in rice-based system can increase SOC by 70.7%, yields by 49%, biological activity by 46.7% over conventional tillage (Ghosh et al., 2010). Similarly, under a rain-fed lentil (*Lens esculentus*)–finger millet (*Eleusine coracona*) cropping system in the Himalayas, adoption of NT improved yield by 8% and soil aggregation by 23% with greater accumulation of particulate organic matter (POM) over conventional tillage system (Bhattacharyya et al., 2013). Impacts of CA practices on C retention in the 0–15 cm layer over control site ranged 0.20 to 0.61 Mg ha^{-1} yr^{-1} (Bhattacharyya et al., 2015). A number of other studies have demonstrated improvements in SOC content due to adoption of CA (Tables 1 and 2). In addition to C sequestration, CA has socio-economic benefits including reduced rate of land degradation and increased farm productivity.

Creating incentives for such practices through PESs based on the societal value of soil C (Lal, 2014) can accelerate the adoption of CA by SLHs. Scalable models of PES already exist. For example, in the USA conversion of croplands to CA has attained general acceptance, to the extent that some farmers practicing conservation tillage now receive payments from coal-burning utilities in emissions-trading arrangements brokered through the Chicago Climate Exchange. Payments are based on the premise that CA sequesters the equivalent of about 0.3 Mg C ha^{-1} yr^{-1} (Baker et al., 2007). Adoptionof CA requires land rights and security of tenure as land ownership is important for SLHs to get access to credit and CA inputs.

4.5. Green water management

The available soil water (AWC) or "green water" is the prime determinant of sustaining high yields in rain-fed SLH farms. Soil moisture is often a scarce resource and therefore, the challenge is to enhance the availability and productivity of water for biomass production under rain-fed agriculture systems (Bhattacharyya et al., 2013). There are several ways to enhance the AWC including adoption of CA, use of compost and cover cropping, conservation of water in-situ by reducing deep drainage (IFAD, 2012), surface runoff and soil evaporation. Enhancing SOC through cover cropping can improve AWC and thus alleviate drought (Lal, 2016). However, there are numerous constraints to its adoption because of differences in soil type, cropping patterns and poor socio-economic conditions of farmers in India (Lal, 2015).

4.6. Micro-irrigation and water harvesting systems

Indian agriculture is primarily dependent on monsoons, and erratic rainfall under a changing climate (GAP, 2014). Arid, semi-arid and dry sub-humid regions in India represent ~50% of the total agricultural land, and are prone to water scarcity. Water scarcity is caused by extreme variability of rainfall rather than the amount of rainfall (Rockstrom et al., 2009). The problem is further confounded by low water use efficiency of traditional irrigation systems in India; 35–40% efficiency in surface irrigation and 65–75% efficiency when pumping groundwater (GAP, 2014). Therefore, small scale irrigation and water harvesting systems such as shallow tube wells, open wells, ponds, pipe conveyance system, open gravity and canal system and sprinkler irrigation may be preferred to large scale schemes. The latter requires high capital investment for developing infrastructure while benefitting only few (GAP, 2014). Easy adaptability of small scale irrigation makes it more relevant to a large number of farming communities (FAO, 2014). The potential of micro-irrigation in India is estimated at around 69 M ha, compared with the current coverage of merely 7.7 M ha (GAP, 2014). Benefits of micro-irrigation include increases in WUE, and savings of energy, fertilizer and water while being environmentally friendly.

Rainwater harvesting offers a critical and promising solution to replenish and recharge the groundwater in a situation where withdrawal rate of groundwater in India is twice the recharge rate (IWMI, 2002). According to Verma et al. (2008) decentralized small water harvesting structures present a major alternative to the conventional river basin water resource development models. An excellent example is the decentralized, large-scale, check dam rainwater harvesting movement in Saurashtra, Gujarat. Rainwater harvesting structures can be useful in semi-arid and dry sub-humid regions. Therefore, promotion of water harvesting systems in drought-prone agricultural land will improve agronomic yield and increase soil C sink capacity and storage.

For implementation of the interventions above, we propose a five point action plan: (i) creating a reward system; (ii) strengthening agricultural extension support; (iii) reforming the land policy; (iv) creating market linkages to ensure remunerative prices for farmers; and (v) relief measures such as those proposed in 2017 in the "*Agriculture: Doubling Farmer's Incomes*" scheme of government of India.Rewarding farmers through fair and just pricing of SOC is critical to minimizing the risks of the tragedy of commons (Lal, 2016). BMPs are knowledge-intensive and hence gaining expertise in them may not be an easy practice for many rural farmers. Therefore, it is important to strengthen extension support and improve education at all levels so that farmers are better equipped to adopt BMPs.

5. Conclusions and recommendations

Soil C sequestration confers a number of co-benefits, making it a viable option for reducing atmospheric CO_2 concentration in the short term, thus buying time for development of longer term solutions (Smith, 2012). With soil C sequestration rate of 0.2–1.0 Mg ha^{-1} yr^{-1} under BMPs, improved management of SLHs can annually sequester 70–130 Tg CO_2e in soil and produce 80–85% of food grain requirement by 2050 in India. Aggressive promotion of BMPs through PES, support to women farmers and socially disadvantaged groups and increased extension, it is possible to achieve the "4 per Thousand" target, while simultaneously advancing national food security. Developing a mechanism for PES can incentivise SLH farmers to adopt BMPs and create a much needed income stream.

Despite the importance of women and other socially disadvantaged groups in SLH, they are discriminated against and often lack property rights and access to productive resources. Therefore, improving the social status of disadvantaged groups through state and central government legislation can enhance their role in agricultural production. Deliberate policy efforts are also needed to guarantee land rights for women, Scheduled Castes and Scheduled Tribes. This will enable them to access credit, inputs and extension services to facilitate adoption of BMPs. Expanding educational opportunities for Scheduled Castes can also be an important strategy to reduce discriminatory treatment and increase their access to information, markets, credit and publicly provided inputs and extension services. Education and skills training are also important for improving farming practices, investment in land management.

Measurement and verification soil C sequestration on SLHs presents particular challenges (Smith, 2012). In this analysis we used historical data to make projections with a number of assumptions to give some ball park figures on potential C sequestration. Inevitably, some of our assumptions were made on very variable evidence, and some projected effects are expected to be associated with large uncertainties. The relationship between SOC and crop yield that we have used here is based on past climatic conditions, and such relationship may not hold the same under future temperature and precipitation changes. The C sequestration rates on individual land parcel are often low, but vast areas of land are devoted to agriculture, with SLHs numbering in hundreds of millions. Therefore, engaging a substantial number of these people is a massive undertaking in itself, and a key source of uncertainty. Most of the uncertainty in SOC build up in agricultural land is attributed to management factors including tillage and application of organic matter, and the rate of C loss. One of the key features of sustainable farming is the continuous integration of site-specific knowledge and practical experiences into future management planning and practices. Site specific studies and practical experiences are needed to be integrated into future policy formulation and implementation.

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