



Climate change mitigation options among farmers in South Asia

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Abstract

Agriculture in South Asia is highly vulnerable to climate change due to increasing variability in rainfall and rising temperatures leading to the incidence of extreme climatic events such as floods, droughts, heat/cold waves, and storms. Agriculture sector also contributes to the causes of climate change through the emission of greenhouse gasses (GHGs). Hence, adaptation-led mitigation measures are required to sustain agricultural productivity, farm income and reduce GHG emissions wherever possible. This study presents a systematic review of agriculture emission reduction opportunities with a particular focus on agricultural production systems in South Asia. Our review indicates that the adoption of better soil, water, nutrient management practices, and technologies has enormous potential to reduce GHG emissions from agriculture, thereby contributing to the mitigation of climate change. Many existing practices and technologies have the potential to improve both adaptation and mitigation in agriculture which can significantly contribute to complying with nationally determined contributions (NDCs) of South Asian countries. However, barriers to the adoption of GHG mitigating agricultural practices, mainly the financial and institutional barriers, need to be appropriately addressed to achieve the desired level of mitigation.

Keywords Climate change · Greenhouse gas mitigation · Agriculture · South Asia

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1 Introduction

The nationally determined contributions (NDCs) of all South Asian countries proposed their contribution to climate change mitigation efforts and local adaptation actions with individual country's national priorities. According to the recent report of the Intergovernmental Panel on Climate Change (IPCC), the current level of emissions of greenhouse gases (GHG) needs to be reduced considerably to limit the temperature rise to below 2 °C (UNFCCC 2015). Although contribution from the agriculture sector to global emissions is lower than industrial, energy, and other sectors, it has substantial potential to contribute to global emission mitigation supplemented by appropriate adaptation options.

Issues on agriculture for climate action were in the agenda under the UNFCCC's Subsidiary Body for Scientific and Technological Advice (SBSTA) in COP17 in Durban, but it did not define the way forward. The COP21 in Paris placed the agriculture sector under priority for climate action but the major stride on this was not observed until COP 23 (UNFCCC 2017). The COP23 in Bonn took a major step to prioritize agriculture in climate action and established the Koronivia joint work on agriculture to design and realize new strategies for adaptation and mitigation in the agriculture sector to reduce emissions.

A wide range of mitigation options in agriculture have been proposed based on the evaluation of practices and technologies in different agricultural production systems in South Asia. Changes in soil, water, and nutrient management practices and adoption of climate-smart technologies can significantly reduce GHG emissions from croplands (Ahmad et al. 2013; Aryal et al. 2015a, b; Sapkota et al. 2015a, b; Singh et al. 2010). Similarly, feed inputs and manure management have enormous potential to reduce emissions from the livestock sector (Gerber et al. 2013a, b; Vetter et al. 2017). Despite substantial potential for GHG mitigation from the agriculture sector, national and subnational governments in the region do not prioritize agricultural mitigation options in their NDCs. Nevertheless, their priorities on adaptation initiatives such as water and crop, crop management, value chain interventions, and landscape-level actions have substantial potential for generating mitigation co-benefits.

Given the increasing emphasis on climate-change mitigation, an important research gap is that mitigation options in agriculture have not been assessed and presented to the key stakeholders of adaptation and mitigation in agriculture. We systematically reviewed all available literature on agriculture mitigation options and their potential contributions to reducing GHG emissions. This study provides rich information about the potential of GHG emission reduction through the application of different practices and technologies in crop and livestock production systems in South Asia.

2 Agricultural emissions

Agriculture, forestry, and other land use (AFOLU) account for 24% of anthropogenic GHG emissions globally (about 9–12 GtCO₂e year⁻¹), mainly from deforestation and agricultural emissions (Smith et al. 2014). The livestock sector alone contributes to 14.5% of the total human-induced GHG emissions (IPCC 2014; Gerber et al. 2013a, b). GHG emissions from the AFOLU sector differ among the South Asian countries. For instance, the AFOLU sector as a whole accounts for more than 80% of the total GHG emissions in Nepal (Pradhan et al. 2017). Methane from enteric fermentation and rice cultivation and nitrous oxide,

mainly from soil and fertilizer application, are major contributors to agricultural GHG emissions. For the period 1970–2010, the emission of methane increased by 20%, whereas emissions of nitrous oxide increased by 45–75%, mostly in Asia (Smith et al. 2014). Within Asia, South Asia has the largest share of methane emissions. The livestock sector and paddy production are the primary sources of methane emissions, whereas the application of manures and fertilizers is the largest source of nitrous oxide emissions. From rice cultivation only, South Asia emits almost 4900 Gg methane per year, which is the third-highest level of methane from rice cultivation globally (IRRI 2018).

We noted that in South Asia, the emission of nitrous oxide from agriculture has increased over time due to the increased application of fertilizer. For instance, between 2003 and 2010, the fertilizer application in India increased from 105 to 179 kg ha⁻¹, in Pakistan from 106 to 217 kg ha⁻¹, in Bangladesh from 160 to 184 kg ha⁻¹, in Sri Lanka from 231 to 259 kg ha⁻¹, and in Nepal from 5 to 23 kg ha⁻¹ (World Bank 2013a). GHG emission from agriculture is more likely to increase in South Asia due to the need for producing more food to satisfy the food demand of the increasing population. In addition, higher mechanization and the use of groundwater irrigation could increase energy consumption from the agriculture sector and hence substantially increase GHG emissions. Against the backdrop of global warming, rapid climate change, the substantial contribution of agriculture to global warming, and the vulnerability of agriculture to climate change, the objective of the current paper is to review these inter-linkages. As South Asia consists mainly of agrarian countries which are highly vulnerable to climate change, the current paper focuses exclusively on South Asia.

Figure 1 (upper section) exhibits an increase in methane emissions in South Asian countries in 2010 compared to 1990. The share of agricultural emissions in total methane emissions ranges between 70 and 80% in all countries under study. If methane emissions from agriculture between 1990 and 2010 are compared, the largest increase is found in Pakistan (47.1%), whereas a decline in methane emission was observed in Sri Lanka. Figure 1 (lower section) indicates a sharp increase in nitrous oxide emissions over the last two decades. Between 1990 and 2010, the percentage increase in total emissions of nitrous oxide was largest in Bangladesh (72.7%), followed by Pakistan (62.9%) and India (46.8%). From 1990 to 2010, the percentage increase in nitrous oxide emissions from agriculture was found to be highest in Bangladesh (about 80%) and lowest in Sri Lanka (9%). As shown in Fig. 1, the share of individual countries in South Asia in total emission of nitrous oxide in 2010, India remained on top with a share of 77%.

Unlike CH₄ and N₂O, CO₂ is cycled in large amounts through agricultural production systems. Plants consume a large amount of CO₂ through the process of photosynthesis, but most of the plant products, including grains, fruit, residue, and root biomass, are eventually converted back to CO₂ when consumed or when they decompose. Considering the total pool cycling in the system, the net emission of CO₂ is small in agriculture and, therefore, not presented in detail. However, energy use on farms and emissions due to the production and transport of agricultural inputs constitute a substantial portion of CO₂ emissions.

Figure 2 shows the GHG (methane) emissions from livestock for meat and milk. GHG emissions from livestock meat in six South Asian countries (Bangladesh, Bhutan, India, Nepal, Pakistan, and Sri Lanka) increased by 24%, from 338,413 gigagrams (Gg) in 1990 to 419,549 Gg in 2014, and GHG emissions from livestock milk increased by 69%, from 125,312 Gg to 211,291 Gg (FAOSTAT 2017).

The GHG emissions from livestock meat is highest for India, which is about 300,995 Gg, followed by Pakistan (81,899 Gg), Bangladesh (21,381 Gg), Nepal (14,034 Gg), Sri Lanka (1103 Gg), and Bhutan (137 Gg). The GHG emission from

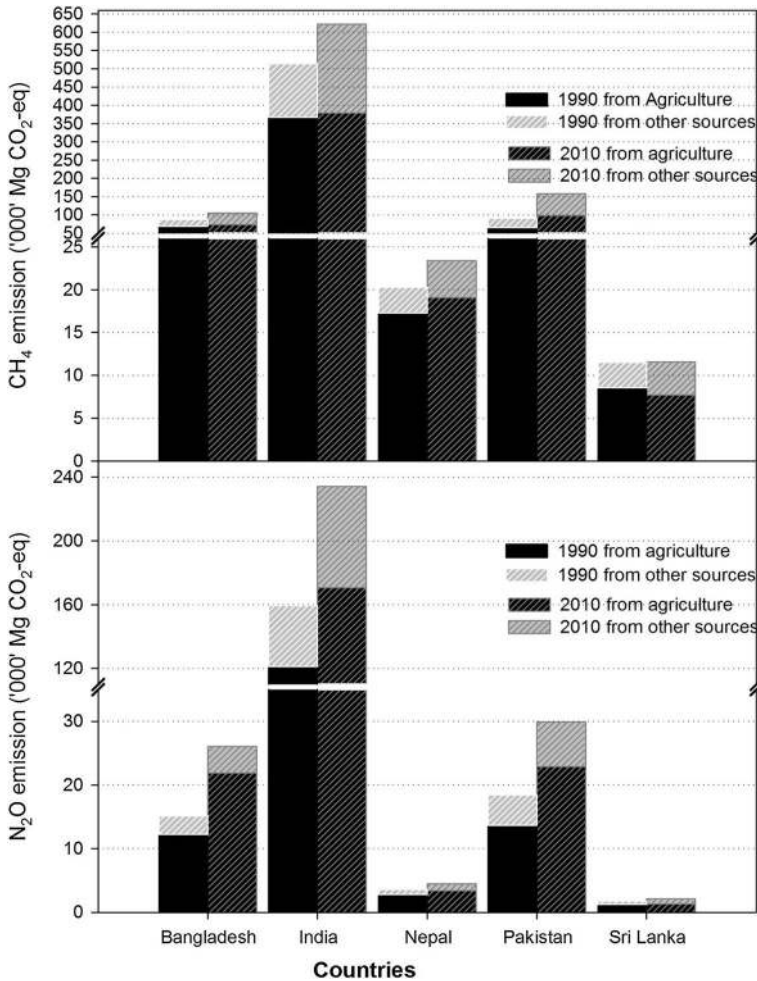


Fig. 1 Share of methane and nitrous oxide emissions from agriculture. Data source: World Bank (2013a)

livestock milk is the highest for India, which is about 141,534 Gg, followed by Pakistan (50,562 Gg), Bangladesh (14,196 Gg), Nepal (4126 Gg), Sri Lanka (656 Gg), and Bhutan (217 Gg). The GHG emissions from Bhutan and Sri Lanka are small compared to other South Asian countries; the share of GHG emissions from livestock from Bhutan is less than 1%, while it is about 70% for India and 20% for Pakistan.

The GHG emissions from livestock (meat and milk) increased substantially in 2014 compared to 1990 for all South Asian countries except Bhutan and Sri Lanka. During the same period, the GHG emissions from livestock (meat) decreased by 34% in Bhutan and 54% in Sri Lanka, while the GHG emissions from livestock (milk) decreased by 8% in Bhutan and 18% in Sri Lanka.

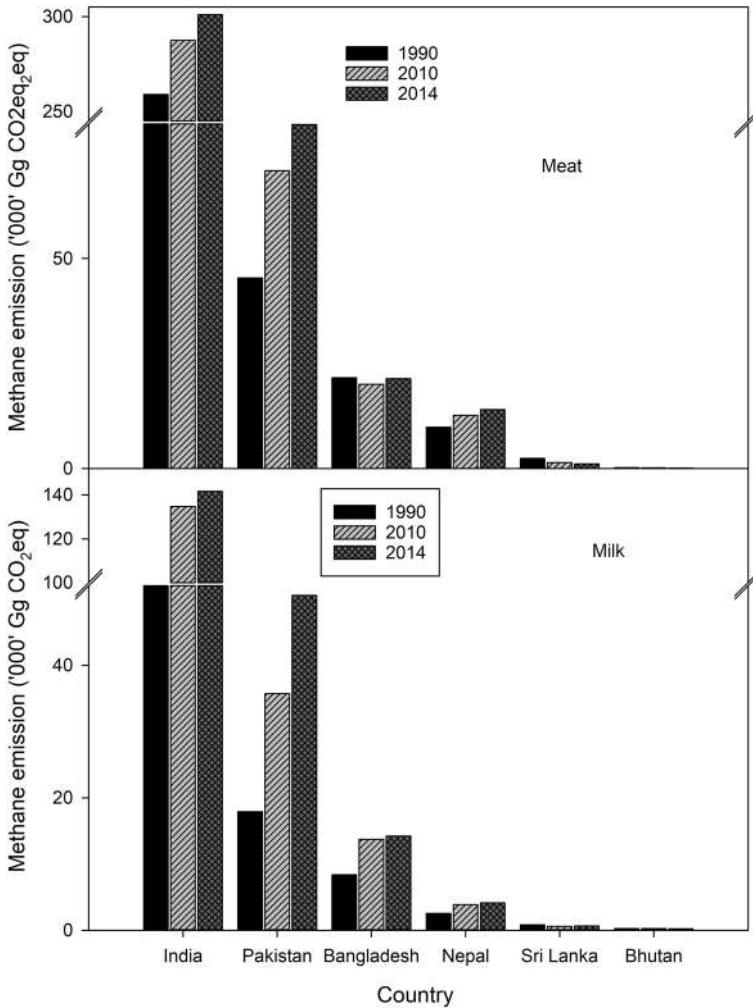


Fig. 2 Share of methane emission from livestock products. Data source: FAOSTAT (2017)

3 Greenhouse gas mitigation options in the agricultural sector and their abatement potential

Improving the efficiency of production through the adoption of better agricultural practices not only reduces emissions of GHGs from agro-ecosystems but also sequesters atmospheric carbon into terrestrial ecosystems (Sapkota et al. 2017a, b). Globally, agriculture accounts for about 14% of the annual increase in anthropogenic GHG emissions, mainly through methane and nitrous oxide (Smith et al. 2008). Therefore, mitigation efforts in agriculture could significantly reduce GHG emissions (Nelson 2009). Mitigating GHG is possible either by the sequestration of CO₂ or the reduction in CH₄ and N₂O emissions. Livestock has the potential to contribute to climate change mitigation either by reducing greenhouse gas emissions or through increasing soil carbon sequestration (Mottet

et al. 2017). Agriculture, forestry, and other land use (AFOLU) contribute to about 24% (approximately 10–12 GtCO₂e year⁻¹) of anthropogenic GHG emissions, primarily from deforestation and agricultural emissions from livestock, soil, and nutrient management (IPCC 2014). The annual GHG emissions from agricultural production from 2000 to 2010 were estimated at 5.0–5.8 GtCO₂e year⁻¹ (IPCC 2014). The IPCC (2014) estimates that the economic mitigation potential of supply side measures in the AFOLU sector will be 0.49–10.60 GtCO₂e year⁻¹ by 2030 for mitigation efforts consistent with carbon prices up to USD100 per tCO₂e. Estimates from the agricultural sector only range from 0.3 to 4.6 GtCO₂e year⁻¹ at prices up to USD100 per tCO₂e, and estimates from the forestry sector only range from 0.2 to 13.8 GtCO₂e year⁻¹ at prices up to USD100 per tCO₂e.

Table 1 presents that sustainable land management (SLM) practices help mitigate GHG emission from agriculture irrespective of the climate zone. In cool–moist, warm–moist, and warm climatic zones, improved agronomic practices more efficiently reduce GHG emissions from agriculture. Cover crops and fallow rotation suits warm and moist climates the best, annually mitigating 0.98 tCO₂e ha⁻¹ (tons of carbon dioxide per hectare), while nutrient management performs the best in cool-to-warm and moist climates. In cool–dry climatic zones, agroforestry is the most effective method, as it reduces GHG emissions by 1.17 tCO₂e ha⁻¹ year⁻¹. Irrespective of the climatic zone, better water management, including irrigation, contour farming, bunds, and water harvesting, can mitigate GHGs 1.14 tCO₂e ha⁻¹ year⁻¹.

The following sections present a summary of the mitigation options in the agricultural sector together with their mitigation potentials with a particular focus on South Asia.

3.1 Conservation agriculture

Conservation agriculture (CA) refers to agricultural practices that are based on three principles: minimal soil disturbance, permanent soil cover, and crop rotation (Kassam et al. 2009). CA is an important management strategy to address multiple challenges of sustainable food production, climate change adaptation, and mitigation (Gupta and Seth 2007). For example, zero tillage (ZT) is reported to increase soil organic carbon SOC and improve several other soil-quality parameters compared to conventional tillage (CT) systems (Gathala et al. 2011). Plow-based agriculture exacerbates the problems of accelerated soil erosion by water and wind, oxidation of soil organic matter and disrupts soil aggregation (Lal 2015), all leading to the loss of SOC from agro-ecosystems. ZT, on the other hand, helps in accumulating SOC by reducing net mineralization of soil organic matter and by promoting soil aggregation (Sapkota 2012). In a long-term experiment, (Gil et al. 2009) found a 10% higher organic-matter concentration and a 55% higher total N in ZT than in the moldboard plow-based system mainly in surface 0.05 m depth. However, the literature on the influence of ZT on SOC concentration still remains inconsistent, as many other researchers (Baker et al. 2007; Halvorson et al. 2002; Thomas et al. 2007; West and Post 2002) reported no significant increase in SOC between ZT and CT. Variation in crops, climate, and soils is probably the primary reasons for such inconsistencies in the findings. By analyzing the tropical dataset, Powlson et al. (2014, 2016) argued that the rate of SOC increase in ZT systems in the Indo-Gangetic Plains (IGP) could be around 0.3 Mg C ha⁻¹ year⁻¹ in a 0–0.3 m soil layer. Similarly, Grace et al. (2003) estimated that CO₂ equivalent emissions from conventionally tilled cropping systems (rice–wheat system) would be about 29 MgCO₂ year⁻¹ if applied to one million hectares of the Indo-Gangetic Plains, while this is lowered to 14 MgCO₂ year⁻¹ if a ZT system with residue retention is applied to the same.

Table 1 Annual mitigation potential of different sustainable land management practices. Source: IPCC (2007)

SLM practices	Climate zones						
	Dry	Cool-Dry	Cool-Moist	Warm-dry	Warm-moist	Warm	
Agromony (Use of cover crops, improve crop or fallow rotation, crop varieties and use of legumes)	0.39	0.39	0.98	0.39	0.98	0.98	
Nutrient Management (Use of organic fertilizers like bio fuels made of animal and plant manure, efficient use of nitrogen fertilizers)	0.33	0.33	0.62	0.33	0.62	0.62	
Tillage and Residue Management (Use of crop residues, minimum tillage of the land)	0.35	0.17	0.53	0.35	0.72	0.72	
Water Management (Irrigation facilities, bunds, terrace or contour farming, water harvesting)	1.14	1.14	1.14	1.14	1.14	1.14	
Agroforestry (Trees as barriers, for example eucalyptus and populus, trees in the field)	0.72	1.17	0.53	0.35	0.72	0.72	

All figures are in $\text{tCO}_2\text{e ha}^{-1}\text{ year}^{-1}$ (tons of carbon dioxide per hectare per year)

Another study (Grace et al. 2012) shows that the rice–wheat system of India has the potential to sequester 44,100 Gg C over 20 years if it is converted to ZT. This study estimated that adopting ZT in maize–wheat and cotton–wheat systems in India can sequester 6600Gg C during the same period. A study by (Aryal et al. 2015b) shows that shifting from CT to ZT based on wheat production reduces GHG emissions by 1.5 MgCO₂-eq ha⁻¹ year⁻¹. Recently, Sapkota et al. (2017a, b) reported soil carbon increases by 4.7 Mg C ha⁻¹ after seven years of CA (ZT with partial residue retention) in the rice–wheat systems of the Eastern Indo-Gangetic Plains of India.

Conventional puddle transplanted rice (TPR) is a major source of methane emissions. Adoption of direct-seeded rice (DSR), which does not require puddling of the field during transplanting, is thus a feasible alternative to mitigate GHG emissions from agriculture (Sapkota et al. 2015a, b). This saves water and labor requirements for planting. A study in Punjab state of India (Pathak et al. 2013) showed that the total global warming potential of TPR ranged from 2.0 to 4.6 tCO₂e ha⁻¹, while it ranged from 1.3 to 2.9 tCO₂e ha⁻¹ in the DSR. Their study claimed that if the entire area under TPR in Punjab state is converted to DSR, the global warming potential from paddy cultivation can be reduced by 33% of the current emissions. Another way to reduce methane emissions is to incorporate organic manure in the alternate seasons (Xu et al. 2000; Cai and Xu 2004).

Crop residue management is one of the major components of CA, and thus, it reduces the burning of crop residue. This means it also reduces the emission of N₂O and CH₄ as each ton of crop residue emits 40 g of N₂O (equivalent to 12.4 kg of CO₂) and 2.3 kg of CH₄ (equivalent to 48.3 kg of CO₂) (Grace et al. 2003).

3.2 Laser land leveling

Laser land leveling helps reduce GHG emissions from several farm operations, especially by reducing the demand for irrigation water and the resultant reduction in energy requirements for pumping it. In addition, it reduces 10–15% in the operating time of agricultural machinery in the field, thereby saving a considerable amount of energy use for farming operations (Rickman 2002). Compared to the traditionally leveled field, in the laser-leveled fields of Punjab and Haryana, irrigation time in the rice–wheat (RW) system is reduced by almost 70 h ha⁻¹ rotation⁻¹ (Aryal et al. 2015a). As a result, the RW system in a hectare of laser-leveled field required almost 754 kWh less electricity for irrigation per year compared to a traditionally leveled field (Aryal et al. 2015a). Gill (2014) estimates that under the existing system of electricity generation in India, the use of laser land leveling reduces about 0.15 Mg of CO₂ eq year⁻¹ ha⁻¹ due to the decreased pumping time of water for irrigation and decreased cultivation time. In general, each liter of diesel consumed emits approximately 2.6 kg of CO₂ (Grace et al. 2003). Besides, the LLL technology saves irrigation water and increases productivity (Ali et al. 2018).

3.3 Site-specific nutrient management (SSNM)

Fertilizers are a crucial input-driving food production, second to crop varieties. However, the intensified use of synthetic fertilizer has led to significant direct and diffuse environmental problems with over 60% of nitrogen pollution estimated to have originated from crop production alone (Sapkota et al. 2016). Recent reports by the IPCC and FAO revealed that synthetic fertilizers contribute 12–14% of the total global GHG emissions from agriculture (680–725 TgCO₂-eq year⁻¹ in 2010/2011). Fertilizer-use efficiency in South Asia

is very low, i.e., 30–40% (Farnworth et al. 2017; Tewatia et al. 2017). If we can increase fertilizer-use efficiency by 5–10%, it will increase yield, reduce N_2O emissions, and reduce the cost of production considerably, thereby providing higher profits to farmers (Majumdar et al. 2000). Precision agriculture, contrary to some views, is an approach that can be applied not only to large-scale mechanized farms but also to the management of inputs on smallholder farms in the tropics. Precision nutrient management aims to improve the efficiency of fertilizer use through ensuring that nutrients are applied in the right form, in the right amount, at the right time of plant uptake, and in the right place. These principles of good fertilizer management are applicable to fields over 1000 ha or less than 0.5 ha. All that changes are the tools. For example, leaf chlorophyll content can be linked with leaf N content and, therefore, measurement of leaf greenness by using a chlorophyll meter, leaf color chart, or optical sensors (e.g., GreenSeeker) can be used as the basis of in-season nitrogen management (Bijay-Singh et al. 2011, 2015). Similarly, computer/android phone-based decision support systems (e.g., Nutrient Expert, Crop Manager) are nowadays progressively being used to facilitate the application of improved nutrient-management practices in farmers' fields (Pampolino et al. 2012). Such tools have become increasingly important in geographies such as South Asia where blanket fertilizer recommendations prevail. Through on-farm comparison in over 4000 farmers' fields across the Indo-Gangetic plains of India, International Maize and Wheat Improvement Center (CIMMYT) found that 'nutrient expert'-based nutrient management reduced the GHG intensity of rice, wheat, and maize production by 5–35% (average 13%) over farmers' fertilizer practices.

3.4 Water management in rice

Globally, flooded rice emits approximately 20,000–40,000 Gg of CH_4 year⁻¹, i.e., about 12% of anthropogenic emissions from the agriculture sector. India alone contributes around 5% of global CH_4 emissions (Richards and Sander 2014; Wassmann et al. 2009). At the same time, rice production needs to be increased to meet the food demand of Asia's growing population. Given these challenges, developing technologies that enhance the yield yet render less harm to the environment is essential. Alternate wetting and drying (AWD) is a water management technique in rice that was developed in the 1970s to address the problem of increasing water scarcity in agriculture (Bouman and Tuong 2001). Under this system, rice fields are irrigated to the desired depth only and then re-irrigated after some time, when the water dissipates (Lampayan et al. 2015). IPCC (2006) Guidelines for National Greenhouse Gas Inventories claims a 48% reduction in methane emissions under AWD practices, whereas on-farm experiments on AWD shows 20–70% reduction in methane emissions (Richards and Sander 2014). A study by LaHue et al. (2016) showed that AWD reduced growing-season methane emissions by 60–87% and maintained low annual nitrous oxide emissions. Upriety et al. (2012) also projected that AWD leads to a 60% decline in methane emissions.

Besides reduced CH_4 emissions, AWD also makes rice production possible when water resources are scarce. Rice production with an AWD approach of water management saves 25–30% of water compared to the conventional flooding (CF) system (Richards and Sander 2014; Siopongco et al. 2013). For instance, AWD required five fewer irrigations in 2010 and three fewer irrigations in 2011 compared to conventional flooding of rice fields. This accounted for a saving of 41.8% and 28% of water, respectively (Ye et al. 2013). AWD is believed to increase rice yield, although the results in yield are inconsistent (Bouman and

Tuong 2001; Zhang et al. 2012). On the one hand, AWD is estimated to increase yield by 10% relative to CF (Yang et al. 2009; Zhang et al. 2009), while on the other hand, some studies refute this and claim no change or a slight decline in the yield (Yadav et al. 2012; Yao et al. 2012). Gathala et al. (2013) show that adopting AWD can save 30% irrigation water in puddled transplanted rice, thereby reducing GHG emissions due to reduced energy used for pumping irrigation water. AWD reduces irrigation water input in rice fields by up to 38% without any reductions in rice yield (Lampayan et al. 2015). Therefore, AWD serves the twin purpose of mitigating GHG emissions by reducing methane and adapting to water stress.

3.5 Improved livestock management

Livestock contributes about 18% of global anthropogenic GHG emissions (Steinfeld et al. 2006). Total global emission from livestock between 1995 and 2005 was between 5.6 and 7.5 PgCO₂e year⁻¹ (Herrero et al. 2016). Of the total emissions from livestock systems, CO₂ emitted from land use, its changes (including feed production and deforestation associated with it) accounts for 32%, N₂O emitted from manure and slurry management occupies 31%, and CH₄ produced through enteric fermentation of ruminants accounts for 25% (Thornton and Herrero 2010). Adopting improved pastures, intensifying ruminants' diets, changing land-use practices, and changing breeds of ruminants can largely contribute to GHG mitigation from the livestock sector. Applying all these mitigation measures, the total mitigation potential becomes 417,000 Gg CO₂e, which is about 12% of the global livestock-related CH₄ and CO₂ emissions associated primarily with extensive livestock systems (Thornton and Herrero 2010; Steinfeld et al. 2006).

Table 2 presents options to reduce methane emission from the livestock sector. Mitigation options in the livestock sector include a range of diet and other management interventions that improve the efficiency of feed conversion, increase livestock productivity, and reduce emissions. In the context of smallholder production systems in South Asia, improved feed digestibility through the provision of highly digestible fodder (e.g., green fodder), and the inclusion of energy-dense food (i.e., increased concentrate feed), have considerable potential for mitigating GHG emissions from the livestock sector. For example, green fodder supplements and increased concentrate in the rations of ruminants in India would have the potential to mitigate ca. 3.4 TgCO₂e year⁻¹ (Sapkota et al. 2019). Similarly, improved manure management through the establishment of large biogas plants has the potential to save ca. 9.3 TgCO₂e year⁻¹ in India.

Mitigation practices, however, cannot be generalized, and thus, each practice needs to be evaluated for an individual agricultural system based on the climatic, edaphic, social, and historical pattern of land use and management (Smith et al. 2007a, b). In addition,

Table 2 Potential of reducing methane emissions from the livestock sector through better management. Source: Smith et al. (2007a, b)

Mitigation potential	Dairy cows	Beef cattle	Sheep	Dairy buffalo	Non-diary buffalo
Improved feeding practice	0.04	0.02	0.02	0.04	0.02
Dietary additives	0.01	0.01	0.0005	0.01	0.002
Animal breeding	0.01	0.01	0.001	0.01	0.02

All the figures are in (MgCO₂e head⁻¹ year⁻¹)

several non-climatic factors can influence climate change mitigation through its impact on farmer technology adoption.

3.6 Agroforestry

In the current climate-change scenario, agroforestry systems have attracted special attention in climate change mitigation and food security (Feliciano et al. 2018; Makundi and Sathaye 2004). Agroforestry systems yield multiple benefits, such as sustainable production, supporting household requirements through diversified productions, resource conservation, groundwater recharge, and environmental improvements. Agroforestry contributes to climate-change mitigation by storing carbon above ground in the form of biomass and below ground in the soil carbon. Soil organic carbon can be enhanced by planting trees and grasses in degraded lands (Kar et al. 2009). Agroforestry provides a solution to tillage, burning of leaf litter, deforestation, wildfires, and soil disturbance by storing carbon or minimizing emissions into the atmosphere. On average, carbon storage by agroforestry systems has been estimated to be around 9, 21, 50, and 63 Mg C ha⁻¹ in semiarid, subhumid, humid, and temperate regions, respectively (Jat et al. 2016). Globally, there is the potential to establish agroforestry systems on 585–1275 × 10⁶ ha land, and this could store 12–228 (median 95) Mg C ha⁻¹ under current climate and edaphic conditions (Dixon 1995). Sathaye and Ravindranath (1998) projected that the mitigation potential of agroforestry systems in India is 25.4 Mg C ha⁻¹ and 29.7 Mg C ha⁻¹ in Pakistan.

4 Synergies and trade-offs between adaptation and mitigation options in agriculture

Most of the adaptation options in agriculture have GHG mitigating co-benefits, although this might differ across spatial and geographical characteristics. Valin et al. (2013) showed that closing yield gaps by 50% for crops and 25% for livestock by 2050 would decrease agriculture and land-use change emissions by 8%. Improvement in crop yields would bring the largest food provision benefits, whereas livestock productivity gains would allow the greatest reductions in GHG emissions. Combining productivity increases in the two sectors appears to be the most efficient way to exploit mitigation and food security co-benefits (Valin et al. 2013).

In the agricultural sector, cropland adaptation options that also contribute to mitigation are: soil management practices that reduce fertilizer use and increase crop diversification; promotion of legumes in crop rotations, increasing biodiversity, the availability of quality seeds and integrated crop/livestock systems, promotion of low-energy production systems; avoiding burning of crop residues; and promoting efficient energy use by commercial agriculture and agro-industries (Smith et al. 2014). For example, site-specific nutrient management that is practiced as adaptation measures against declining yields due to climatic variability and enhances nutrient use efficiency also reduces N₂O emissions from agriculture (Sapkota et al. 2014). Mitigation benefits of some adaptation measures in the agricultural sector, such as the adoption of heat and water-stress seed varieties are not clear. For example, *Sahbhagidhan* used in India and the *Sookhadhan* varieties in Nepal have the advantage of over 0.8–1.2 tons per hectare under drought and contribute immensely to climate change adaptation. However, its mitigation benefits are not yet clear. Similarly, agroforestry

is an example of mitigation-adaptation synergy in the agriculture sector, since trees planted sequester carbon and tree products provide livelihoods to communities, particularly during drought years (Verchot et al. 2007).

Synergies and trade-offs also depend on technology type and the stage of its adoption. For example, in the case of direct seeding rice, in the initial years of adoption, it is found to have only GHG mitigation benefits (reduced methane emission and reduced CO₂ due to reduced energy use for pumping water and land preparation), even though the adaptation benefits are not observed during the initial 3–4 years of adoption (measured as gain benefits over conventional transplantation methods) (Jat et al. 2014).

Farmers usually adopt farming technologies such as laser land leveling, zero tillage, and direct-seeded rice as measures for climate change adaptation, i.e., as a response to increasing water stress and/or rainfall variability. Some of these measures lead to substantial reductions in GHG emissions, i.e., mitigation of climate change (Aryal et al. 2015a; Sapkota et al. 2017a, b). In semiarid and arid regions such as Haryana and Punjab states of India, where more than 80% of agriculture is based on irrigation and increasingly relies on groundwater for irrigation, the use of laser land leveling not only increases crop yields but also reduces the environmental footprint (Aryal et al. 2015a; Jat et al. 2015). Zero tillage, mainly a mitigation strategy, not only sequesters carbon in the soil but also prevents soil degradation, maintains the nutrient level of the soil, improves soil quality, and ultimately enhances crop productivity and yield (Lal 2004). A recent study in India shows that conservation agriculture-based wheat production systems cope better with rainfall variability compared to the conventional tillage-based system (Aryal et al. 2016a, b). Similarly, rice management (direct-seeded rice) can be used to overcome a water crisis, but with high labor costs (Farooq et al. 2011). This will enrich water quality and control weeding which forms a part of the adaptation to climate change. At the same time, this conserves energy resources and sequesters carbon, thereby lowering GHG emission levels. Alternate wetting and drying is another way to adapt to increasing water stress (Gathala et al. 2013).

There are trade-offs between adaptation and mitigation options in some cases. Farmers may use more water for irrigation to cope with rising temperatures. Recent studies show that water demand for irrigation in semiarid and arid regions could increase by 10% with a degree Celsius rise in temperature. To cope with such heat/temperature stress, farmers have to use more water for irrigation. Given that farmers in IGP are increasingly using groundwater for irrigation, they now require more energy for pumping irrigation water, which ultimately leads to more GHG emissions (Gill 2014). Farmers sometimes use fertilizers as a measure of adapting to declining soil fertility; however, this can lead to more N₂O emissions (Celikkol Erbas and Guven Solakoglu 2017). This could also happen in the case of zero tillage (ZT) with residue retention, primarily due to immobilization (Sapkota et al. 2015a, b).

As per capita meat consumption in South Asia, mainly in India, is increasing, livestock production has become a profitable portfolio within agriculture. Still, livestock management is traditional, and feed management for GHG reduction is beyond the capacity of the majority of farmers in South Asia. The livestock sector emits higher levels of CH₄, a gas with more potential to global warming. Improving feed practices and dietary patterns of livestock is a short-term measure which reduces the amount of CH₄ released through enteric fermentation in ruminant animals. In the long run, structural and management changes along with animal breeding will have positive mitigation effects on CH₄ and N₂O.

In Table 3, we provide a brief overview of the synergies and trade-offs between climate change adaptation and mitigation measures in the agricultural sector in South Asian countries, which is briefly described above.

Table 3 Synergies and trade-offs between adaptation and mitigation measures to climate change in agriculture

Practices	Adaptation	GHG mitigation	Synergy/trade-off
Tillage and residue management	Zero tillage (ZT)-based wheat production requires less irrigation and hence helps adapt water stress (Aryal et al. 2015b)	Shifting from conventional technology (CT) to ZT-based wheat production reduces GHG emission by 1.5 MgCO ₂ -eq ha ⁻¹ season ⁻¹ (Aryal et al. 2015b)	Synergy
	Direct seeding of rice (DSR) saves water and helps adapt to water-stress conditions (Pathak et al. 2013)	Reduce methane emission (Pathak et al. 2013)	Synergy
	ZT with residue management help adapt rainfall variability (Aryal et al. 2016a, b)	Increased soil carbon in the soil (Dixon 1995)	Synergy
	ZT help adapt water stress (Grace et al. 2003, 2012)	Reduced GHG emission (Grace et al. 2003, 2012)	Synergy
Water management	Laser land leveling (LLL) helps adapt to water stress especially due to rapidly declining groundwater (Aryal et al. 2015a; Jat et al. 2015)	Reduce emission through reduced use of energy used for irrigation (Aryal et al. 2015a; Gill 2014)	Synergy
	Expansion of irrigation helps adapt to rainfall variability (Rothausen and Conway 2011)	Expansion of irrigation may increase GHG emission due to increased energy use for irrigation (Rothausen and Conway 2011)	Trade-offs
Agroforestry	Adapt to climate risks such as extreme rainfall, reduce soil erosion, and enhance food security (Sathaye and Ravindranath 1998; Makundi and Sathaye 2004; Feliciano et al. 2018)	Carbon sequestration the form of biomass above and below ground (Sathaye and Ravindranath 1998; Makundi and Sathaye 2004; Feliciano et al. 2018)	Synergy
	Address water stress, 30% reduction in water use (Gathala et al. 2013)	Reduce GHG emission due to reduced energy use for water pumping (Gathala et al. 2013)	Synergy
Alternate wetting and drying (AWD)	Adopt to water scarcity (IPCC 2006)	Reduce GHG emission by 38% (IPCC 2006)	Synergy
	Adapt to declining soil fertility (Sapkota et al. 2014)	Less N ₂ O emission (Sapkota et al. 2014)	Synergy
Baira farming system (hanging garden)	Adapt to waterlogging, and salinity problems (Deb and Haque 2017)	May emit more N ₂ O if farmers use more fertilizer to compensate soil fertility	Trade-off
	Adapt to water stress (Lin 2011)	Reduce GHG emission by reduced energy use for irrigation (Lin 2011)	Synergy
Crop diversification to less water-intensive crops such as maize	Improved adaptation to climate shocks (Smith et al. 2014; Mottet et al. 2017)	Reduce methane emission, soil carbon sequestration (Smith et al. 2014; Mottet et al. 2017)	Synergy
Improved livestock management			

5 Barriers to the adoption of mitigation measures in South Asia

Croplands in South Asia are intensively managed and offer many opportunities to impose practices that reduce GHG emissions. All the crops, soil, and livestock management practices aimed toward increasing efficient use of water, nutrients, energy, and other production inputs, and those which increase crop/livestock production/productivity, lead to GHG mitigation. A bottom-up analysis in India, which can be generalized for South Asia, suggests that about 80% of the total technical mitigation potential (67.5 out of 85.5 TgCO₂e year⁻¹) in agriculture can be obtained by adopting cost-beneficial mitigation options (Sapkota et al. 2019). Cost-beneficial mitigation measures in South Asia that can be implemented through proper policy and programs include zero tillage, site-specific nutrient management, alternate wetting and drying in rice, provision of highly digestible fodder and inclusion of energy-dense food for livestock, and improved manure management. Many farmers are already adopting these measures. Still, adoption at scale is not taking place, indicating that there are barriers to overcome (Bustamante et al. 2014).

Despite the availability of a number of adaptation and mitigation measures to climate change in agriculture, many farmers still continue with conventional methods. Hence, a careful examination of factors that inhibit the adoption of such measures is direly needed. It should be noted, however, that farmers' adoption of any practice is difficult to project and largely depends on the sociopolitical environment under which the farmer operates. A better understanding of the sociopolitical environment and farmers' behaviors in relation to the adoption of these cost-beneficial GHG mitigation measures would help in designing appropriate policies, consistent with food security and sustainable development goals. Inaction is often justified on the ground of its uncertainty and also the conflicting scientific evidence. On the one hand, there is a need to increase farmer's knowledge on climate-smart agricultural practices (Aryal et al. 2018a), and on the other hand, the scientific community needs to ensure that the CSAPs are both cost-effective and user-friendly to the farmers (Aryal et al. 2019; Khatri-Chhetri et al. 2016). Other aspects of serious concern are a lack of immediate benefits of adopting such measures and the overall adaptive capacity of the concerned society.

Although farmers receive benefits from new technologies, shifting from the traditional to modern technologies has transaction costs in terms of knowledge accumulation, information gathering, and access to inputs required. Knowledge networks play a crucial role in enhancing farmers' understanding of CSAPs. Such networks help them to understand the trade-offs between the short-term costs and long-term benefits of CSAPs (Steenwerth et al. 2014). Most of the technologies may reap benefits after a critical scale of adoption. Agricultural technology adoption may benefit farmers equally, but whether the number of benefits is significantly higher to the individual farmer or not is a different issue. In the study of ZT wheat in Haryana, (Aryal et al. 2015b) found that though ZT wheat is more profitable to farmers in general, the total benefit is much smaller in the case of small and marginal farmers. This may be one of the reasons why small and marginal farmers do not adopt new technology or revert to the traditional methods once the project support is over.

5.1 Financial barriers

The financial capacity of South Asian farmers can hinder the adoption of GHG mitigating agricultural practices. Given the limited safety nets to cope with climate change, farmers

may use less costly locally available adaptation measures that may not have mitigation co-benefits. The financial barrier is more likely to constrain GHG mitigation measures in agriculture sector of South Asia because farmers usually prioritize adaptation and the national mechanisms to finance GHG mitigating agricultural practices such as climate-smart agriculture is yet to develop (Patra and Babu 2017). Moreover, climate finance mechanism for GHG mitigation from agriculture sector lags behind other sectors (Buchner et al. 2017).

5.2 Social and cultural barriers

Aryal et al. (2014) found social and cultural issue such as gender is an important social barrier to having access to information. Women farmers in South Asia usually need assistances from their male relatives or neighbors to hire machineries required to apply climate-smart agriculture such as laser land leveling, Turbo Happy Seeder, etc. If there is no adult male member in the family, a general conceptual lock-in is observed in these societies, and still, women are not considered full-time farmers. Social and cultural barriers influence the adoption of new climate-smart agricultural practices that have both climate change adaptation and GHG mitigation benefits (Sapkota et al. 2015a, b). The social system defines the belief system of farmers, which is integral to decision making in the adoption of GHG mitigation measures in agriculture. The structure of the land tenure system and lack of clearly defined property rights may restrict farmers' adoption of CSAPs that have short-term costs but long-term benefits. Dual ownership patterns, for example, a land-to-the-tiller provision in some South Asian countries discouraged both landlord and tenant from investing in land management (Aryal and Holden 2013), which may serve both adaptation and mitigation benefits. In Bangladesh, almost 40% of the land is under the owner–tenant pattern, and this reduces the incentives to the tenant to apply land-conserving practices. In Andhra Pradesh, India, nearly 1.9 million (almost 42%) of all rural low-caste and tribal households operate on insecure land rights (Landesa 2012). Such insecurities make the people more concerned with the short-term profits rather than the long-term sustainable use of land. Short-term tenants are less likely to invest in land conservation measures that have long-term mitigation benefits (Aryal and Holden 2013).

5.3 Permanence

Carbon sequestration is a proxy solution to reduce the effects of GHG emissions. To completely remove the carbon from the ecosystem, it may take decades and is contingent upon management practices (Smith et al. 2007a, b). For instance, shifting from conventional tillage (CT) to ZT may definitely result in sequestering $57 \pm 14 \text{ g C m}^{-2}$, but on the wheat-fallow system, a change from CT to NT may not result in the desired amount of sequestration as a permanent solution (West and Post 2002). Therefore, what is needed is a permanent solution. Since carbon sequestration is time-bound, afforestation and biofuels are long-term permanent measures to counterbalance GHG emissions (McCarl and Sands 2007).

5.4 Institutional/policy barriers

Lack of institutional support is one of the major reasons behind the low adoption of climate-change adaptation and mitigation measures by farmers. Studies have noted the lack of institutional support as the main reason for low adoption of climate-smart agriculture, which helps simultaneous achievement of GHG mitigation and climate change adaptation in agriculture (Aryal et al. 2018a, b, c, 2019; Sapkota et al. 2015a, b, 2019). Without the strong institutional setup and support, it is very unlikely that small farm households will adopt GHG mitigation measures. Investment on GHG mitigating measures in agriculture by South Asian farmers is low due to: (i) lack of awareness about climate change and its consequences; (ii) lack of knowledge about the adaptation and mitigation mechanisms and their benefits; (iii) lack of knowledge in implementing such methods and ability of poor farmers to invest in those tools and techniques; and iv) lack of financial support from government. In South Asia, the institutions at the local level are weak and do not have the capacity to assist in enhancing the adoption of climate-change adaptation and mitigation measures at the farm level. Thus, institutional support in the form of extension support, providing technological information, and subsidies can play major roles in scaling up GHG mitigation measures in agriculture sector in South Asia.

Lack of a clear policy, guidelines, and coordination between policies at different levels is also a major barrier for scaling up the adoption of climate-risk adaptation and mitigating strategies at the farm level. Climate change adaptation and mitigation policies for the agricultural sectors should start from the local level on up, and the national-level policy should be based on the local-level adaptation plan (Choudhary et al. 2002). In the South Asian context, such adaptation and mitigation policies could also be integrated at the regional level to have a greater impact on the region. The problem of low adoption of these measures arising from uncoordinated policies is further aggravated due to the presence of multiple stakeholders, as this sometimes leads to a dilution of responsibility.

Governance at different institutions related to formulation and implementation of policies at various levels is poor and lacks coordination, leading to duplication of efforts and, at times, gaps. Hence, the governance structure of the institutions working on climate-risk mitigation and adaptation scaling out should be coordinated. Vested interests and political agents have long opposed political or regulatory action in response to climate change by appealing to scientific uncertainty. Here, we examine the effect of such contrarian talking points on the scientific community itself (Lewandowsky et al. 2015).

Overall, the uncertainty of climate change has often been one of the major reasons for inaction. Contradictory and conflicting scientific evidence further add to this. While adopting mitigation measures, the public nature of its benefits and the problem of 'free riders' can also minimize its adoption. Existing institutional and policy structures especially the traditional extension services can further aggravate the problem. Therefore, institutional policies that address local issues and bridge the gaps between national, regional, and local climate change challenges are required (Aryal et al. 2016a, b).

6 Conclusions

When focusing on climate change mitigation in agriculture, an assessment of potential options for adaptation and mitigation, their synergies and trade-offs, and key barriers for scaling out are essential. To this end, this detailed review of mitigation options in agriculture finds that there are many practices and technologies, which have low to high potential in reducing GHG emissions from agricultural production systems in South Asia. Our review of scientific studies indicates that simple changes in agronomic practices, such as tillage methods, water application, and nutrient management, can significantly reduce GHG emissions from agricultural lands. Furthermore, modification and promotion of traditional agroforestry systems and implementation of improved livestock management in the livestock-crop mixed-farming system also reduce large amounts of GHG emissions without reducing agricultural production. Many adaptation options have climate change mitigation co-benefits, which are mostly preferred by adaptation policy makers in South Asia. One of the primary objectives of a large number of smallholder farmers in the region is to improve farm productivity and income under climate change and variability. Therefore, promotion of adaptation options in agriculture that can improve farm productivity, income, and reduce climatic risks together with GHG mitigation benefits should be the main focus of national and subnational governments. This study also highlights that, despite mitigation requirements and farmers' interest in implementing adaptation and mitigation options, their lack of investment capacity, cultural and social behaviors, and lack of provision of incentives through policies and programs limit the adoption of GHG mitigation practices and technologies in agriculture.

This assessment of mitigation options provides critical evidence that can be incorporated into the national, subnational, and local-level adaptation and mitigation plans/programs such as the National Action Plan for Climate Change (NAPCC), National Adaptation Programme of Action (NAPA), and the Local Adaptation Plans of Action (LAPA) including the implementation of the nationally determined contributions (NDCs) of all South Asian countries. Scaling up and scaling out of the adaptation and mitigation options considered in this study can largely enhance the mitigation potential of the agriculture sector in South Asia as well as the ambition of achieving a goal of the Paris Agreement.

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