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Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture

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ABSTRACT

Agriculture accounts for approximately 11% of China's national greenhouse gas (GHG) emissions. Through adoption of region-specific best management practices, Chinese farmers can contribute to emission reduction while maintaining food security for its large population (>1300 Million). This paper presents the outcome of a bottom–up assessment to quantify technical potential of mitigation measures for Chinese agriculture using meta-analysis of data from 240 publications for cropland, 67 publications for grassland and 139 publications for livestock, and provides the reference scenario for the cost analysis of identified mitigation measures. Management options with greatest mitigation potential for rice, or rice-based cropping systems are conservation tillage, controlled irrigation; replacement of urea with ammonium sulphate, nitrogen (N) inhibitor application, reduced N fertilizer application, integrated rice-fish-duck farming and biochar application. A 15% reduction in current average synthetic N fertilizer application for rice in China i.e., 231 kg N ha^{-1}, would result in 12% decrease in direct soil nitrous oxide (N_2O) emissions. Combined application of chemical and organic fertilizer, conservation tillage, biochar application and reduced N application are possible measures that can reduce overall GHG emissions from upland cropping systems. Conventional fertilizer inputs for greenhouse vegetables are more than 2–8 times the optimal crop nutrient demand. A 20–40% reduction in N fertilizer application to vegetable crops can reduce N_2O emissions by 32–121%, while not negatively impacting the yield. One of the most important mitigation measures for agricultural grasslands could be conversion of low yielding cropland, particularly on slopes, to shrub land or grassland, which is also a promising option to decrease soil erosion. In addition, grazing exclusion and reduced grazing intensity can increase SOC sequestration and decrease overall emissions while improving the largely degraded grasslands. For livestock production, where poor quality forage is commonly fed, improving grazing management and diet quality can reduce methane (CH_4) emissions by 11% and 5%, on average. Dietary supplements can reduce CH_4 emissions further, with lipids (15% reduction) and tannins or saponins (11% reduction) showing the greatest potential. We also suggest the most economically cost-effective mitigation measures, drawing on related work on the construction of marginal abatement cost curves for the sector.

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1. Introduction

China is one of the largest current emitters of anthropogenic greenhouse gases (GHG) globally, and currently emits around 20% of global GHGs (Leggett et al., 2008). China's GHG emissions are growing rapidly and, even with policy interventions designed to reduce emissions, are expected to rise until at least 2030. Agricultural GHG emissions have been estimated at 11% of China's national emissions i.e., 820 Mt CO_2-eq, of which the emissions from rice cultivation and agricultural land uses were 374 Mt CO_2-eq, accounting for 46%, and emissions from enteric fermentation and manure management were 445 Mt CO_2-eq, accounting for 54% (National Coordination Committee on Climate Change (NCCC), 2012). China has taken a series of measures to promoting climate change adaptation in agriculture. The Chinese government has also achieved better results in reducing GHG emissions by formulating relevant laws and regulations, promoting low-emission agricultural technologies, enhancing water use and fertilization management for agriculture, upgrading farming machinery, reinforcing intensive agricultural production, and developing biogas digesters (National Coordination Committee on Climate Change (NCCC), 2012). The IPCC Fourth Assessment Report (2007) suggests a technical mitigation potential in agriculture for East Asia (a large proportion of which is covered by China) of 620 Mt CO_2-eq year^{-1} (Smith et al., 2008). Since economic potential is around 33–50% of the technical potential, depending on the carbon price, the estimated economic mitigation potential for Chinese agriculture is 200–300 Mt CO_2-eq year^{-1}. China is a very large country and the soil, climate and management practices have spatial and temporal variation, so it is essential to estimate region- and crop- specific technical mitigation potentials, and also to consider local economic conditions to assess the economic potential in China.

The 3 major GHGs affected by most agricultural activities are carbon dioxide, methane and nitrous oxide (CO_2, CH_4 and N_2O, respectively). GHGs can be mitigated by sequestrating carbon or reducing ongoing losses in the soil, by reducing N_2O emissions, by reducing CH_4 emissions or increasing CH_4 uptake in the system. Often, a management practice affects more than one gas, by more than one mechanism and sometimes in opposite ways, so the net benefits depend on the combined effects on all gases (Robertson and Grace, 2004; Koga et al., 2006). A few systematic analyses on the impact of management practices on GHGs and SOC change for croplands and grasslands of China (Rui and Zhang, 2010; Wang et al., 2011; Feng et al., 2013) have been conducted, but all of the studies estimated the impact on either SOC change or GHGs, but not on both. Globally, there is a large body of research on methods for mitigating enteric methane (CH_4) emissions from livestock production; however data specifically from Chinese production systems are scarce (Veneman et al., 2015).

In this paper, we present the outcomes of a bottom–up assessment of mitigation options in an attempt to quantify technical and economic potential of different mitigation options for Chinese agriculture. The major agricultural systems included in this study are croplands i.e., upland crops and wetland-rice, grassland and livestock system. We compiled 3 databases of GHG emissions and SOC change for cropland, grassland and livestock systems, and through statistical meta-analysis of paired datasets, the technical mitigation potential of individual management practices were estimated. Statistical meta-analysis methods have been developed for quantitative analysis of research results, from multiple independent experiments (Guo and Gifford, 2002). They have been used effectively to estimate the effect of different management practices and land use changes on soil carbon stock change and GHG emissions (Guo and Gifford, 2002; Van Groenigen et al., 2011; Linquist et al., 2012; Feng et al., 2013). These methods usually provide advantages over narrative reviews or quantitative reviews that lack sampling rigor and robust statistical methods (Johnson and Curtis, 2001).

This paper also provides estimates of feasible economic mitigation potential by constructing a bottom–up marginal abatement cost curve (MACC). Such an approach allows the mitigation potential arising from the application of a subset of cost-effective measures above a notional baseline level of activity – namely-business as usual (BAU) to be assessed.

2. Material and methods

2.1. Database collation

2.1.1. Cropland (database 1) and grassland (database 2)

Data were extracted from 53 studies on CH_4 emission, 48 studies on N_2O emission and 50 studies on SOC dynamics (Appendix A) of Chinese rice agricultural ecosystems with different management practices from literature published in both English and Chinese. For upland crops, the database included 27 studies for N_2O analysis and 62 studies for SOC change analysis (Appendix A). The grassland database consists of 8 and 41 studies on GHGs and SOC change experiments, respectively (Appendix B). The following 3 criteria were applied to select appropriate studies. (1) Studies had to report treatment plot data and control plot data. (2) Studies included in our database were only field experiments; no data were included from pot or laboratory experiments. (3) The duration of experiment to study the effect of management on SOC change had to be at least 3 years. Reporting standard deviation and number of replicates was preferable, but not essential. For SOC data where no standard deviation or standard error was reported, we assigned standard deviations that are 1/10th of means (Luo et al., 2006). If the number of replicates were not reported, the number of replicates was assumed to be 3. The database was prepared in Microsoft Access and includes detailed information on location, climate, land use, treatment, management, fertilizer date and application rate, experiment duration, soil physical and chemical character, depth wise SOC data, GHG emission data, yield data and references.

2.1.2. SOC stock calculation and missing bulk densities

SOC data were either reported as carbon concentration (Cc%), SOC stock (kg ha^{-1}) or only soil organic matter (OM%). Where SOC was reported as OM%, C% was calculated according to Eq. (1).

$$\mathrm{Cc\%} = 0.58 \times \mathrm{OM\%} \tag{1}$$

SOC stock data were either directly available or calculated according to Eq. (2).

$$\mathrm{SOC\ stock}(\mathrm{t\,ha^{-1}}) = \sum_{i=0}^{n} \mathrm{Cc\%} \times \mathrm{BD}(\mathrm{g\,cm^{-3}}) \times D(\mathrm{cm}) \tag{2}$$

where n is number of soil layers, Cc% is C concentration, BD is bulk density (g cm^{-3}) and D is the sampling depth. For the studies where soil bulk density values were missing, bulk densities were estimated by using the equations of Xie et al. (2007) for paddy surface layer, paddy subsurface layer, upland surface layer and upland subsurface layer. The estimated bulk densities for paddy soils were also checked with the bulk densities calculated using the equations of Pan et al. (2004) and BD for rice paddy calculated by both methods (Pan et al., 2004; Xie et al., 2007) showed 99% similarity. For grassland data, 36% of the cases did not report bulk density, and BD was estimated using the equation for uncultivated soil as described in Song et al. (2005).

2.1.3. Livestock (database 3)

The livestock database used for this meta-analysis has been described in detail by Veneman et al. (2015). In brief, a global search was made of relevant databases (including databases of Chinese literature) to identify published research on mitigation of CH_4 from ruminant livestock. For each paper identified, meta-data including study design, animal husbandry, diet, mitigation strategy and CH_4 emissions was collated and added to the MitiGate database. To date, the global database contains 294 papers covering in vivo mitigation data for a wide range of animals, production systems, and mitigation strategies. Although a concerted effort was made to identify studies specific to China, very few studies are available, hence a relevant subset of the global database was used for this analysis (Appendix C).

Grazing and mixed farming systems reliant on a predominantly roughage-based diet dominate Chinese ruminant livestock production (Li et al., 2008). As diet has a large impact on ruminant enteric CH_4 emissions, and therefore also on the mitigation potential of those emissions, a restricted meta-analysis was performed using only studies where the livestock were fed a mainly roughage/forage based diet (<40% concentrates included). Included in the database were only studies where emissions were reported as g CH_4 kg^{-1} DMI or where data could be transformed to the same units. In total, 139 studies were included in this analysis including 30 studies from Asia (predominantly Japan). Only 3 studies were identified from China for this analysis.

2.2. Data analysis (cropland/grassland)

2.2.1. Meta-analysis (cropland/grassland)

Selection of an appropriate effect size estimator is important when conducting metanalysis. We used two types of effect sizes for CH_4 and N_2O emission i.e., (1) the simplest measure of effect size i.e., difference between control group mean and treatment group mean (absolute effect size, ES_{abs}) (2) natural log of response ratio (RR = ln(Treatment mean/Control mean)). To account for the duration of the experiment while calculating the effect sizes for SOC changes, a time adjusted response ratio (Van Groenigen et al., 2006) was used i.e., (1) absolute effect size$_t$ (ES_{abst}) = ((Treatment − Control)/Duration of experiment), (2) RR_t = ((RR − 1)/Duration of the experiment). Results for the absolute effect size are reported as t CO_2-eq $ha^{-1}yr^{-1}$ and results for RR are reported as log response ratio (RR) or percentage change per year with management application i.e., ((RR_t − 1) × 100). The absolute effect size (ES_{abs} or ES_{abst}) was used to calculate technical potential or total climate forcing impact of each management practice, based on the effect of the management practice on SOC sequestration and GHG (CH_4 and N_2O) emission.

Many studies did not report any measure of variance for the response variables i.e., SOC, CH_4 emission and N_2O emission. For SOC data where no standard deviation or standard error was reported, we assigned standard deviations that are 1/10th of means (Luo et al., 2006). For CH_4 and N_2O emission data when variance were missing, we calculated the average coefficient of variation (CV) within each data set, and then approximated the missing variance by multiplying the reported mean by the average CV and squaring the result (Van Groenigen et al., 2011).

A weighted meta-analysis was done using Meta-Win software (Rosenberg et al., 2000). Mean effect size was calculated, with 95% confidence interval (CI). With meta-analysis, we tested the impact of management on the variables of interest i.e., CH_4, N_2O and SOC change, and we also tested whether there are significant differences in mean response ratio among various categories such as region, climate, sub-management. In a procedure analogous to the partitioning of variance in analysis of variance, the total heterogeneity for a group comparison (Q_T) is partitioned into within-class heterogeneity (Q_w) and between-class heterogeneity (Q_b), such that $Q_T = Q_w + Q_b$. The Q statistic follows a chi-square distribution, with K-1 degrees of freedom (Johnson and Curtis, 2001; Guo and Gifford, 2002)

For each management and for each variable (SOC, CH_4 and N_2O), overall mean response and CIs were calculated. Means were considered to be significantly different from one another if their 95% CIs were non-overlapping, and were significantly different from zero if the 95% CI did not overlap zero (Gurevitch and Hedges, 2001).

2.2.2. Technical potential (cropland/grassland)

To determine technical potential (all GHGs) for different agricultural management practices for rice cultivation in China, we conducted a review of literature on different management practices and their effect on SOC change (C loss or gain), CH_4 and N_2O emissions. Technical potential was calculated according to Eq. (3) and expressed in CO_2 equivalents (CO_2-eq) using 100 year global warming potentials (GWP) for CH_4 and N_2O of 23 and 298, respectively, as used in National Greenhouse Gas Inventories.

$$\text{Technical potential}_{\text{management}} = ES_{abst}SOC + ES_{abs}CH_4 + ES_{abs}N_2O \quad (3)$$

where $ES_{abs}SOC$ = absolute changes in SOC storage, $ES_{abs}CH_4$ = absolute changes in CH_4 emission and $ES_{abs}N_2O$ = absolute changes in N_2O emission, with adoption of a particular management practice.

2.3. Data analysis (livestock)

For each comparison included in the analysis, the effect size was calculated as the response ratio (mean treatment emission/mean control emission). Mean effect size and 95% confidence intervals were estimated using bootstrapping (1000). Sample variances were not available for many of the studies included; hence estimates were weighted by sample size.

2.4. Economic analysis

On top of the technical potential, an analysis of economic potential was conducted by Wang et al. (2014) to investigate the cost-effectiveness of each mitigation measure, i.e., the cost of applying the measures, as well as their likely adoption rate relative to a baseline or BAU scenario. To this end, a bottom–up MACC was constructed following the general methodological approaches used in previous studies (Beach et al., 2008; Moran et al., 2011; Schulte et al., 2012; Pellerin et al., 2013). The implementation costs/benefits of the mitigation measures for farmers as Yuan (¥)[1] per hectare (ha^{-1}) or ¥ $animal^{-1}$ in 2020 prices were estimated. The abatement rate and the implementation cost then enabled the cost-effectiveness of each individual measure to be quantified. It should be noted that meta-analysis outputs on abatement rates were adjusted to better accommodate the practical conditions, and to partially internalize interactions between measures. Finally, the uptake rate of measures under the BAU scenario, and maximum feasible adoption, were examined to deduce the overall mitigation potential. This information is reflected in a MACC graphic showing the relationship between abatement potential and cost. More details on the economic analysis are described in Wang et al. (2014).

[1] 2014 value of Yuan (¥), 1 ¥ = 0.16 US$.

3. Results

3.1. Technical potential: cropland

3.1.1. Rice

The rice database included 229 data points for SOC change, 267 data points for CH_4 emission and 204 data points for N_2O emission from soil. The change in CH_4 emission, N_2O emission and SOC was estimated for different management practices.

3.1.1.1. Impact of fertilizer management on GHG emissions from rice. With growing concern about the adverse environmental impacts of the overuse of N fertilizer (Ju et al., 2009; Peng et al., 2010), our aim was to see the effect of reduction of N fertilizer application on GHG emissions. Reducing N fertilizer application rate to an amount that would not decrease crop yield could be a potential mitigation option, not only to decrease direct N_2O emissions from soil, but also to reduce demand for N fertilizer, which would lead to less indirect GHG emissions during N fertilizer production. Soil N_2O emissions decreased by 42% when N application was reduced from 225–450 kg N ha^{-1} season^{-1} to 90–200 kg N kg N ha^{-1} season^{-1}. Fig. 1 illustrates that percentage reduction in N application rate shows a positive correlation with the percentage reduction in soil N_2O emissions (R^2 = 0.431). The regression fitting curves illustrated in Fig. 1 indicate that a 10–70% reduction in N fertilizer application could result in 8–57% reduction in soil N_2O emissions. Reducing N application rate did not show any significant effect on CH_4 emission and rate of N application did not show any significant effect on SOC sequestration, so while calculating Technical potential $_{\text{ReducedNapplication}}$, only impact of N fertilizer reduction on soil N_2O emission was taken into account. An N application reduction from 225–450 kg N ha^{-1} season^{-1} to 90–200 kg N kg N ha^{-1} season^{-1} resulted in a GHG saving of −0.42 t CO_2-eq ha^{-1}yr^{-1} (Table 1, Fig. 2). A 15% reduction in current average N application rate for rice in China i.e., 231 kg N ha^{-1} (Li et al., 2010), would result in a 12% decrease in soil N_2O emissions and mitigation potential of −0.14 t CO_2-eq ha^{-1}yr^{-1}.

Application of inhibitors i.e., urease inhibitor, nitrification inhibitor, or urease + nitrification inhibitor, decreased CH_4 and soil N_2O emissions by 21% (11–29%) and 24% (8–37%), respectively. Due to lack of data, the analysis is based on 10 data points for CH_4 and 9 data points for N_2O; however our analysis shows a significant decrease in CH_4 and soil N_2O emission with inhibitor application. Integrated mitigation effects on both CH_4 and soil N_2O emission can deliver an overall Technical potential $_{\text{Nitrogeninhibitor}}$ of −0.86 (−1.29 to −0.43) t CO_2-eq ha^{-1}yr^{-1} (Table 1, Fig. 2).

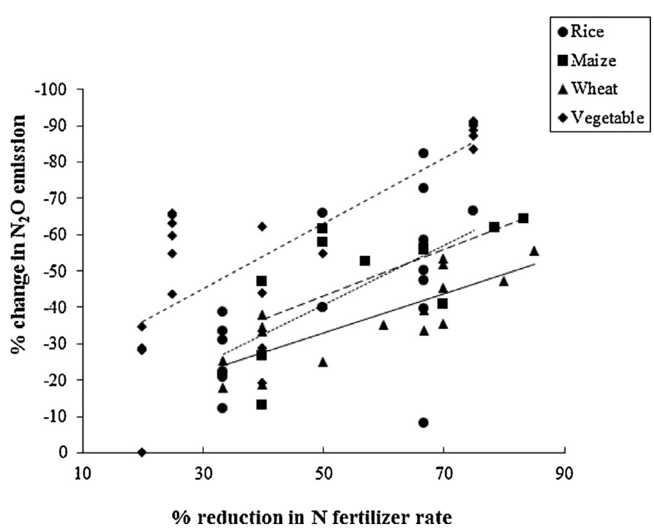

Fig. 1. Relationship between reduction percentages of N fertilizers and N_2O emissions. The equation for rice is $y = 0.8195x - 0.2158$, for wheat is $y = 0.5412x + 5.9137$, for maize is $y = 0.6365x + 11.39$, and for vegetable is $y = 0.8944 + 18.387$.

Application of straw increased CH_4 emissions by 108% compared to the control treatment i.e., with NPK addition with no straw application. In contrast to CH_4, application of straw to rice fields decreased soil N_2O emissions by 21%. SOC increased by 0.99% i.e., 200 kg CO_2-C ha^{-1} annually with straw application compared to control with only chemical fertilizer application. Taking into account of the impact of straw addition on CH_4, soil N_2O emission and SOC sequestration, Technical Potential $_{\text{Strawaddition}}$ was 1.37 t CO_2-eq ha^{-1}yr^{-1}; the positive value implies that straw application to rice field may not be an effective mitigation measure (Table 1, Fig. 2).

In our analysis, organic manure includes livestock manures, compost, fermented biogas residue and green manure. In most studies, organic manure is applied in combination with chemical fertilizer. Combined application of chemical fertilizer and livestock manure increased CH_4 emission by about 113% compared to NPK only treatment. Application of composted manure increased CH_4 emission by only 36% and in a few cases, a decrease in CH_4 emission was observed with application of aerobically composted livestock manure (Chen et al., 2011a). Maintaining intermittent irrigation with livestock manure application can decrease CH_4 emissions by 22% compared to continuously flooded rice fields with manure applied. Biogas residue, the waste generated from biogas plants, increased CH_4 emission by only 42%, while unfermented manure increased CH_4 emissions by nearly 138% when compared to inorganic NPK treatment. Application of livestock manure decreased soil N_2O emissions by about 46% from flooded rice field, while green manure increased soil N_2O emissions by 56%. Application of green manure and livestock manure increased SOC sequestration by 0.40% (−0.67 t CO_2 ha^{-1}yr^{-1}) and 0.95% (−1.37 t CO_2 ha^{-1}yr^{-1}), respectively (Table 1). With positive effects of green manure application on CH_4 and N_2O emission from rice field, the overall climate forcing of green manure application i.e., Technical potential $_{\text{Greenmanure}}$ was 2.88 t CO_2-eq ha^{-1}yr^{-1}. Livestock manure application had a significant negative effect on N_2O emissions, a positive effect on CH_4 emission and SOC sequestration and the Technical potential $_{\text{Livestockmanure}}$ was 0.72 t CO_2-eq ha^{-1}yr^{-1} (Fig. 2).

Application of biochar produced with crop straw pyrolysis increased annual C sequestration by 17% yr^{-1} (i.e., −12.54 t CO_2-eq ha^{-1}yr^{-1}, n = 10) compared to plots without biochar application; however, this value is based on very few short-term experiments and the maximum duration of experiment was 2 years. Application of biochar increased CH_4 emissions by 39% (n = 10) and decreased N_2O emissions by 35% (n = 23). Due to the lack of data on long term effect of biochar on SOC at this point, for the calculation of Technical potential $_{\text{Biochar}}$, the impact of biochar on the C component i.e., ES_{abs}SOC and $ES_{abs}CH_4$ (Eq. (1)) was not included (Table 1). Technical potential $_{\text{Biochar}}$ was estimated to be −0.18 t CO_2-eq ha^{-1}yr^{-1} when only $ES_{abs}N_2O$ was included (Fig. 2).

3.1.1.2. Impact of land management on GHG emissions from rice

Water regimes applied during the rice growing season can be broadly classified into 3 categories, i.e., continuous flooding (F), mid-season aeration with single drainage (IS), intermittent irrigation with multiple drainage (IM). Intermittent irrigation can be sub-classified as IM-F, i.e., the field is kept waterlogged after drainage, and IM-M, i.e., the field is kept moist after drainage. Mid-season aeration with single drainage decreased CH_4 emissions by 30% and increased N_2O emissions by 48%, compared to a continuously flooded rice field which is considered as the control

Table 1
Technical potential of different management options in rice agriculture in China.

Management	Sub management	Control	Treatment	ES_{abs} CH_4 (t CO_2-eq $ha^{-1}yr^{-1}$)			ESabs N_2O (t CO_2-eq $ha^{-1}yr^{-1}$)			ES_{abs} CO_2[a] (t CO_2-eq $ha^{-1}yr^{-1}$)			Technical potential (t CO_2-eq $ha^{-1}yr^{-1}$)		
				Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI
Reduced synthetic N application	All	Urea (>200 kg Nha^{-1})	Urea (<200 kg Nha^{-1}	0.02	−0.21	0.26	−0.42	−0.55	−0.28	0.00	0.00	0.00	−0.42	−0.55	−0.28
N inhibitor/slow release N fertilizer	All	Normal N fertilizer	N inhibitor or slow releasing N fertilizer	−0.35	−0.54	-0.17	−0.51	−0.75	−0.26	0.00	0.00	0.00	−0.86	−1.29	−0.43
Straw application	All	NPK	Straw, straw + NPK	2.17	1.76	2.58	−0.07	−0.12	−0.03	−0.73	−1.25	−0.22	1.37	0.4	2.33
Organic manure application	All	NPK	Manure, NPK + manure	1.23	0.86	1.59	0.1	0.01	0.19	−1.18	−0.93	−1.43	0.15	−0.06	0.36
Organic manure application	Green manure (CF)	NPK	Green manure, NPK + manure	3.48	2	4.93	0.06	0	0.12	−0.67	0.13	−1.46	2.88	2.13	3.6
Organic manure application	Livestock manure (CF)	NPK	Livestock manure, NPK + manure	2.29	1.47	3.07	−0.2	−0.37	−0.02	−1.37	−1.02	−1.73	0.72	0.08	1.32
Organic manure application	Livestock manure (IS)	NPK	Livestock manure, NPK + manure	1.15	0.35	1.96	−0.2	−0.37	−0.02	−1.37	−1.02	−1.73	−0.41	−1.04	0.21
Organic manure application	Livestock manure (IS)	NPK	Livestock manure, NPK + manure	0.65	−0.04	1.34	−0.2	−0.37	−0.02	−1.37	−1.02	−1.73	−0.92	−1.42	−0.41
Organic manure application	Biogas residue	NPK	Biogas residue, NPK + manure	0.93	−0.19	2.05	−0.1	−0.41	0.24	−1.37	−1.02	−1.73	−0.54	−1.62	0.56
Biochar	All	No biochar	Biochar	0.73	0.24	1.22	−0.18	−0.27	−0.09	−12.54	−3.57	−26.62	−0.18	−0.27	−0.09
Water management	All	Continuously flooded	IS, IM	−2.06	−2.64	−1.47	0.8	0.66	0.94	0.00	0.00	0.00	−1.25	−1.98	−0.52
Water management	IS	Continuously flooded	IS	−1.08	−2.96	0.8	0.07	−0.3	0.44	0.00	0.00	0.00	−1.01	−3.26	1.23
Water management	IM-F	Continuously flooded	IM	−2.16	−2.89	−1.43	0.61	0.34	0.87	0.00	0.00	0.00	−1.55	−2.55	−0.56
Water management	IM-M	Continuously flooded	IM	−3.1	−3.98	−2.21	1.01	0.72	1.3	0.00	0.00	0.00	−2.09	−3.27	−0.91
Conservation tillage	All	Conventional tillage	Reduced tillage	−1.14	−2.22	−0.06	0.04	−0.02	0.09	−0.78	−1.19	−0.38	−1.89	−3.43	−0.35
Integrated farming (Rice-duck, rice-fish farming)	All	Rice only	Rice-duck, rice-fish	−1.22	−1.54	−0.9	0.03	−0.02	0.08	0.00	0.00	0.00	−1.19	−1.56	−0.81

Positive values represent increase in GHG emission or decrease in c sequestration, negative value represent decrease in GHG emission or increase in c sequestration.
[a] Mitigation potentials for CO_2 represent the net change in soil carbon pools, reflecting the accumulated difference between carbon inputs to the soil after CO_2 uptake by plants, and release of CO_2 by decomposition in soil.

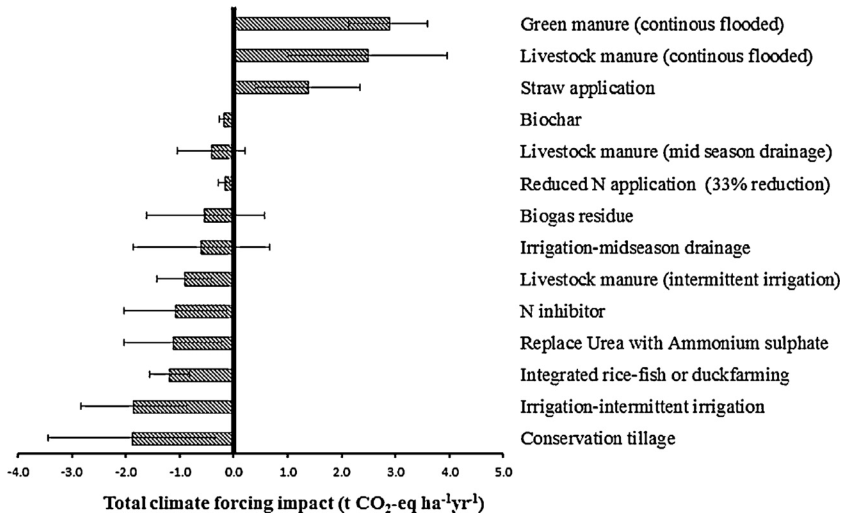

Fig. 2. Total climate forcing impact (t CO_2-eq $ha^{-1}yr^{-1}$) of different management practices in rice agriculture in China.

here. Compared to the flooded control, water regime IM-F and IM-M decreased CH_4 emissions by 46% and 73%, and increased N_2O emissions by 356% and 681%, respectively. Technical potential $_{controlledirrigation}$ was estimated to be −1.01, −1.55 and −2.09 t CO_2-eq ha^{-1} yr^{-1} (Table 1, Fig. 2) with water regime IS, IM-F, and IM-M, respectively.

Changing from conventional to conservation tillage, which aims to reduce tillage and soil disturbance in rice based cropping systems, such as rice–wheat or rice-rape systems, could sequester −0.78 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 1). CH_4 and N_2O emission from rice with reduced tillage decreased and increased by 17% and 48% compared to conventional tillage. With a total technical potential of −1.89 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 1), adoption of conservation tillage in rice-based cropping systems could be a good mitigation measure. If the change in N_2O emissions with adoption of reduced tillage from the upland crop during the non-rice growing season is included, the Technical potential $_{reducedtillage}$ from rice-based cropping systems is estimated at −1.54 t CO_2-eq $ha^{-1}yr^{-1}$.

Integrated rice-fish, rice-duck or rice-fish-duck farming reduced CH_4 emissions significantly by 23%, and increased N_2O emissions by 4% compared to the rice-only cropping system. The increase in N_2O emissions was not significant and that could be due to very few data points ($n = 8$). Technical potential $_{Rice\text{-}fish\text{-}ducksystem}$ was estimated to be −0.86 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 1, Fig. 2).

3.1.2. Upland crops

Managing upland agricultural systems to optimize soil C storage and minimize N_2O emissions can have a significant effect on future radiative forcing. The upland crop database included 330 data points for SOC change and 169 data points for N_2O emissions.

Table 2
Technical potential of different management options in Upland agriculture in China.

Management	Sub management	Control	Treatment	ES $_{abs}$ N_2O (t CO_2-eq $ha^{-1}yr^{-1}$)			ES $_{abs}$ CO_2[a] (t CO_2-eq $ha^{-1}yr^{-1}$)			Technical potential (t CO_2-eq $ha^{-1}yr^{-1}$)		
				Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI
Reduced synthetic N application	All	294 kg N ha^{-1}	113 kg N ha^{-1}	−0.54	−0.7	−0.38	0.00	0.00	0.00	−0.54	−0.7	−0.38
Reduced synthetic N application	Maize	320 kg N ha^{-1}	127 kg N ha^{-1}	−0.54	−0.77	−0.3	0.00	0.00	0.00	−0.54	−0.77	−0.3
Reduced synthetic N application	Wheat	264 kg N ha^{-1}	107 kg N ha^{-1}	-0.76	−1.08	−0.44	0.00	0.00	0.00	−0.76	−1.08	−0.44
Reduced synthetic N application	Vegetable	268 kg N ha^{-1}	158 kg N ha^{-1}	−0.92	−1.22	−0.62	0.00	0.00	0.00	−0.92	−1.22	−0.62
N inhibitor/slow release N fertilizer	Physically altered	Normal N fertilizer	Coated fertilizer	−0.01	−0.27	0.24	0.00	0.00	0.00	−0.01	−0.27	0.24
N inhibitor/slow release N fertilizer	Chemically altered	Normal N fertilizer	Urea formaldehyde	−0.52	−3.28	2.22	0.00	0.00	0.00	−0.52	−3.28	2.22
N inhibitor/slow release N fertilizer	Biochemical type	Normal N fertilizer	N inhibitor	−0.66	−1.04	−0.29	0.00	0.00	0.00	−0.66	−1.04	−0.29
Straw application	All	NPK	Straw, straw + NPK	−0.09	−0.24	0.05	−0.29	−0.16	−0.42	−0.29	−0.16	−0.42
Organic manure application	All	NPK	Manure, N + manure	0.13	0.06	0.19	−1.43	−1.65	−1.21	−1.3	−1.59	−1.01
Biochar	All	No biochar	Biochar	−0.12	−0.28	0.04	−19.3	−13.7	−23.3	−0.12	−0.28	0.04
Conservation tillage	All	Conventional tillage	Reduced tillage	0.3	0.12	0.48	−0.91	−0.55	−1.27	−0.61	−0.43	−0.79

Positive values represent increase in GHG emission or decrease in c sequestration, negative value represent decrease in GHG emission or increase in c sequestration.
[a] Mitigation potentials for CO_2 represent the net change in soil carbon pools, reflecting the accumulated difference between carbon inputs to the soil after CO_2 uptake by plants, and release of CO_2 by decomposition in soil.

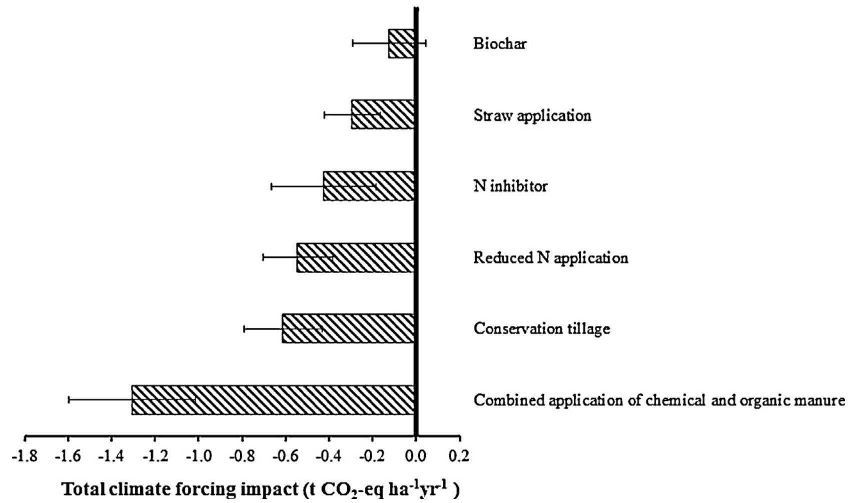

Fig. 3. Total climate forcing impact (t CO_2-eq $ha^{-1}yr^{-1}$) of different management practices in upland agriculture systems in China.

3.1.2.1. Impact of fertilizer management practices on GHG emission from upland crops. Application of 0–150, 150–300 and >300 kg N fertilizer increased N_2O emissions from upland crops by 93%, 244% and 400%, respectively, compared to control plots without any N fertilizer application (data not shown here). Fig. 1 illustrates the % reduction in N application rate, and shows a positive correlation with the % reduction in N_2O emission for wheat, maize and vegetable crops. Based on a linear regression equation for percentage reduction in N fertilizer to percentage reduction in N_2O emissions, a 10–30% reduction in N fertilizer would decrease N_2O emissions by 11–22%, 17–30% and 27–45%, in wheat, maize and vegetable crops, respectively. A 18%, 16%, 10% and 15% reduction in N fertilizer from the current national average N application rate for wheat, maize, open field vegetable and greenhouse vegetables, i.e., 229, 273, 315 and 656 kg N ha^{-1} (Li et al., 2010), will result in overall mitigation potentials of 0.16, 0.27, 0.39 and 0.94 t CO_2-eq $ha^{-1}yr^{-1}$. This analysis does not include reduction in GHG emissions due to fertilizer production, or other losses through NH_3 volatilization or NO_3 leaching. However, N loss due to NH_3 volatilization or NO_3 leaching was included in the economic analysis (Wang et al., 2014).

Use of N inhibitors such as DCD (dicyandiamide), NBPT (*N*-(*n*-butyl) thiophosphoric triamide), and HQ (hydroquinone) could decrease N_2O emissions from maize by 50% compared to urea-only treatments. Use of chemically altered SRF (slow release N fertilizer) decreased N_2O emission from maize by 44% but physically altered SRF did not decrease N_2O emissions from maize significantly. Use of N inhibitors resulted in significant reductions in N_2O emissions and the Technical potential $_{\text{Ninhibitor}}$ was −0.43 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 2, Fig. 3).

Table 3
Technical potential of different management practices of agricultural grasslands in China.

Management	Sub Management	Control	Treatment	ES_{abs} CH_4 (t CO_2-eq $ha^{-1}yr^{-1}$)			ES_{abs} N_2O (t CO_2-eq $ha^{-1}yr^{-1}$)			ES_{abs} CO_2[a] (t CO_2-eq $ha^{-1}yr^{-1}$)			Technical potential (t CO_2-eq $ha^{-1}yr^{-1}$)		
				Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI
Grazing	All	Ungrazed	Grazed	0.00	0.00	0.00	0.00	0.00	0.00	0.80	1.10	0.49	–	–	–
Reduced grazing intensity	All	Heavy	Light, moderate, winter	-0.04	-0.02	-0.06	-0.00	-0.03	0.03	−0.71	−0.78	−1.35	−0.75	−0.83	−1.38
Reduced grazing intensity	Light	Heavy	Light	-0.05	0.04	-0.15	0.00	-0.06	0.06	−0.82	0.07	−1.72	−0.87	0.05	−1.81
Reduced grazing intensity	Moderate	Heavy	Moderate	-0.03	0.04	-0.11	-0.01	-0.08	0.05	−0.66	−0.17	−1.14	−0.70	−0.21	−1.19
Reduced grazing intensity	Winter	Heavy	Winter	0.00	0.00	0.00	0.00	0.00	0.00	−0.36	–	–	−0.36	–	–
Grazing exclusion	All	Grazed	Ungrazed	0.00	0.00	0.00	0.00	0.00	0.00	−1.06	−0.78	−1.35	−1.06	−0.78	−1.35
Land use change	All	Grassland	Cropland	0.00	0.00	0.00	0.00	0.00	0.00	6.05	8.91	3.19	6.05	8.91	3.19
Land use change	All	Cropland	Other	0.00	0.00	0.00	0.00	0.00	0.00	−2.93	−1.44	−4.42	−2.93	−1.44	−4.42
Land use change	Fallow	Cropland	Abandoned field	0.00	0.00	0.00	0.00	0.00	0.00	−2.63	−0.05	−5.22	−2.63	−0.05	−5.22
Land use change	Grassland	Cropland	Grassland	0.00	0.00	0.00	0.00	0.00	0.00	−3.60	−1.64	−5.56	−3.60	−1.64	−5.56
Land use change	Shrub land	Cropland	Shrub land	0.00	0.00	0.00	0.00	0.00	0.00	−4.72	0.02	−9.47	−4.72	0.02	−9.47
Land use change	Wood land	Cropland	Wood land	0.00	0.00	0.00	0.00	0.00	0.00	−2.03	5.28	−9.34	−2.03	5.28	−9.34
Restoration of degraded grassland	All	Degraded	Restored	0.00	0.00	0.00	0.00	0.00	0.00	−4.22	−3.35	−5.08	−4.22	−3.35	−5.08
Restoration method	Reseeded	Degraded	Reseeded	0.00	0.00	0.00	0.00	0.00	0.00	−6.47	−2.19	−10.75	−6.47	−2.19	−10.75
Restoration method	Grazing exclusion	Degraded	Grazing exclusion	0.00	0.00	0.00	0.00	0.00	0.00	−1.37	−0.63	−2.11	−1.37	−0.63	−2.11
Restoration method	Forested	Degraded	Forested	0.00	0.00	0.00	0.00	0.00	0.00	−20.31	−0.29	−40.33	−20.31	−0.29	−40.33

Positive values represent increase in GHG emission or decrease in c sequestration, negative value represent decrease in GHG emission or increase in c sequestration.
[a] Mitigation potentials for CO_2 represent the net change in soil carbon pools, reflecting the accumulated difference between carbon inputs to the soil after CO_2 uptake by plants, and release of CO_2 by decomposition in soil.

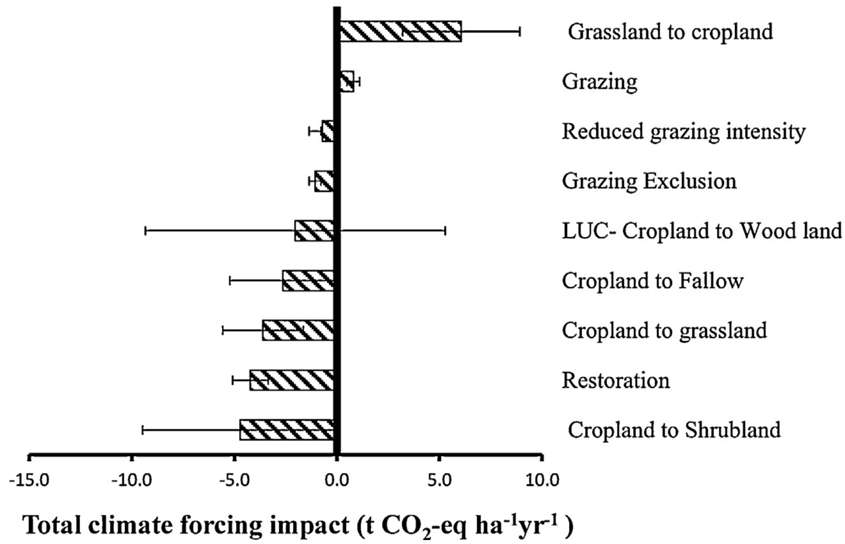

Fig. 4. Total climate forcing impact (t CO_2-eq $ha^{-1}yr^{-1}$) of different management practices grassland ecosystem systems in China.

Straw return to dry upland cropping systems increased soil C sequestration significantly by 0.73% $year^{-1}$, compared to crops with only chemical fertilizer application (NPK) and the rate of C sequestration with straw application was −0.29 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 2). Incorporation of straw during the wheat or maize growing season decreased N_2O emissions by 8%, but the effect was not significant. Technical $\text{potential}_{\text{strawaddition}}$ for upland crops was estimated at −0.29 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 2, Fig. 3).

Combined application of organic manure with N fertilizer sequestered −1.44 t CO_2-eq $ha^{-1}yr^{-1}$ and increased N_2O emission by 75% compared to NPK alone. Higher C sequestration potential neutralises the negative impact of organic manure application on N_2O emissions and gives an overall technical potential i.e., −1.31 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 2, Fig. 3), and thus could be an important mitigation option**.**

Short term studies on the effect of biochar on C sequestration potential shows addition of biochar can accumulate nearly −19.3 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 2). Application of biochar significantly decreased N_2O emissions in upland crops by 19%, and thus makes biochar addition a possible mitigation option with a technical potential of −0.12 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 2, Fig. 3). For the technical potential calculation of biochar, due to lack of long-term data on impact of biochar on SOC sequestration, only the effect on N_2O emissions was accounted for. A reduction of around 40% in the soil N_2O emission factor was realized with biochar application for wheat and maize crops.

3.1.2.2. Impact of land management on GHG emissions from upland crops. Conservation tillage practice in upland cropping systems increased soil carbon content significantly, and the rate of C sequestration was nearly −0.92 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 2). N_2O emissions with conservation tillage practice increased by 46% compared to conventional tillage. The overall technical mitigation potential was −0.61 t CO_2-eq $ha^{-1}yr^{-1}$ (Table 2, Fig. 3), so adoption of conservation tillage could be a potential mitigation option.

3.2. Technical potential: grassland

Soil organic carbon (SOC) under grasslands in China has declined by 3.56 Pg from the 1980s to the 2000s, and the major cause of this loss is increased area of degraded grassland (Xie et al., 2007). Degradation of grassland has occurred mainly due to overgrazing, change in land use (such as conversion of grassland to cropland) and various other ecosystem management strategies.

3.2.1. Impact of grazing management on GHG emission from grassland

Grazing intensity plays an important role in determining the rate of SOC loss; heavy grazing (HG) decreased SOC content significantly. Our analysis shows that effects of light (LG) to moderate grazing (MG) have no significant effect on SOC content, but when grazing intensity is reduced from heavy to light or moderate grazing, SOC contents increased by 0.77 t CO_2 ha^{-1} yr^{-1}. Conversion from HG to LG, MG and WG sequestered -0.83, -0.66, -0.36 t CO_2 ha^{-1} yr^{-1} (Table 3, Fig. 4), respectively. Reduction in grazing intensity from heavy to light or moderate intensity decreased N_2O emissions and increased CH_4 uptake.

Grazing exclusion could increase SOC content by 1.48% yr^{-1} i.e., 1.06 t CO_2 $ha^{-1}yr^{-1}$ (Table 3, Fig. 4). The amount of C sequestered depends on where the exclusion practice is being implemented; grazing exclusion in heavily grazed, degraded grasslands provides maximum benefit..

3.2.2. Impact of land management on GHG emissions from grassland

Land use plays a major role in determining the level of soil C and the direction of change in status i.e., soil as a source or sink (Smith, 2008). Conversion of grassland to cropland decreased SOC content by 1.50% yr^{-1} i.e., loss of 6.05 t CO_2 $ha^{-1}yr^{-1}$. Conversion of croplands to grassland, shrub land, and woodland sequestered −3.60, −4.72 and −2.03 t CO_2 ha^{-1} yr^{-1}, respectively (Table 3). Cropland abandonment increased SOC content by 1.60% yr^{-1} and sequestered −2.63 t CO_2 $ha^{-1}yr^{-1}$ (Table 3, Fig. 4).

Restoring degraded grassland either by grazing exclusion, reseeding or afforestation on average can sequester −4.22 t CO_2 $ha^{-1}yr^{-1}$ (Table 3, Fig. 4) or an increase in SOC content of about 10% yr^{-1}. Forestry plantations, either sparse plantations or shelter forest plantations, on degraded grassland increased SOC sequestration by 44% i.e., −20.31 t CO_2 $ha^{-1}yr^{-1}$ (Table 3). Reseeding of native species such as *Elymus natans*, *Poa crymophila* and *Festuca sinensis* increased annual SOC sequestration by 3.63% i.e., −6.47 t CO_2 ha^{-1} yr^{-1} (Table 3).

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Table 4
Technical mitigation potential of various strategies for the reduction of enteric methane emissions from livestock. Based on a meta-analysis of 139 studies in a global database. Average CO_2-eq savings calculated based on standard IPCC emission factors for sheep and cattle.

	Mitigation potential (%)			kg CO_2-eq head^{-1} year^{-1}	
	N	Mean	95% CI	Cattle	Sheep
Animal manipulations					
Breeding	6	4%	−3%, 9%	51.6	5.1
Herd management	13	11%	4%, 17%	142.7	14.1
Diet manipulations					
Improved digestibility	25	1%	−3%, 5%	11.1	1.1
Increased lipids	30	14%	11%, 18%	193.5	19.1
Addition of tannins or saponins	29	15%	11%, 20%	208.7	20.6
Nitrate supplementation	17	23%	14%, 33%	313.2	30.9
Rumen manipulations					
Probiotic supplements	12	1%	−3%, 4%	8.2	0.8
Defaunation	4	0%	−7%, 11%	0.5	0.1
Chemical inhibitors	6	22%	16%, 29%	297.3	29.3
Ionophores	16	6%	3%, 9%	78.1	7.7

3.3. Technical potential: livestock

Mitigation options for ruminants can be separated into 3 broad approaches; animal manipulations, diet manipulations and rumen manipulations.

3.3.1. Animal manipulation

Breeding for improved feed conversion rates or improved productivity did not significantly reduce CH_4 emissions (4% ± 6% mean reduction) (Table 4). Altering feeding management by increasing the total feed or energy intake, on the other hand, did reduce CH_4 emissions per head of animal by as much as 11% (Table 4). For cattle, this will mean a reduction in CH_4 emissions by 142.7 kg CO_2-eq head^{-1}year^{-1} (Table 4). Both strategies are likely to improve the CH_4 emission rate per unit product by improving the productivity of animals, though total system emissions could increase if additional feed is required.

3.3.2. Diet manipulation

Chinese ruminants are typically fed a low digestibility diet high in cellulose and hemicellulose. Improving the digestibility of such diets, through ensiling or treatment of hay with urea or enzymes does not appear to have a great effect on the direct CH_4 emissions per animal (1% ± 4% mean reduction). Changing the composition of the diet through dietary supplements to manipulate fermentation has proven to be more effective. In particular, lipid supplements significantly reduce CH_4 emissions with a predicted mean reduction of 15% ± 4%. In cattle, this would give an estimated carbon saving of 193.5 kg CO_2-eq head^{-1} year^{-1} (Table 4).

Many plant extracts have been tested for their effect on rumen fermentation. In particular tannins in general and saponins specifically, have proven very effective with a mean reduction of 15% ± 4%. This means that a dietary supplement of tea saponins, a by-product of tea production for cattle, could give a carbon saving of 208.7 kg CO_2-eq head^{-1}year^{-1} (Table 4, Fig. 5).

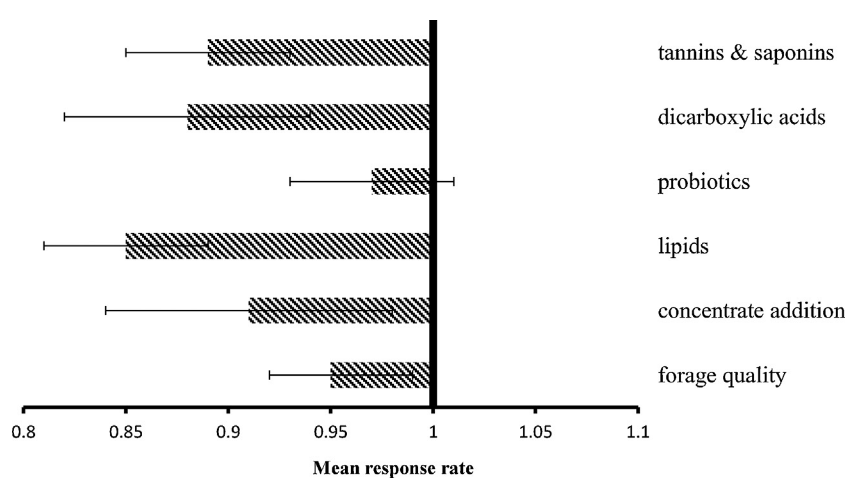

Fig. 5. Mean (±95% CI) response rate (treatment emissions as proportion of control emissions) based on a large scale meta-analysis of available data on nutritional approaches to manipulating enteric CH_4 emissions. Results for forage quality are based on 55 comparisons from 24 published papers. Results for concentration addition are based on 33 comparisons from 17 published papers. Results for lipids are based on 55 comparisons from 20 published papers. Results for probiotics are based on 11 comparisons from 5 published papers. Results for dicarboxylic acids are based on 17 comparisons from 11 published papers. Results for tannins and saponins are based on 47 comparisons from 22 published papers.

Table 5
List of mitigation measures and target crops or livestock species used for economic analysis.

No.	Measure	Target crops
C1	Fertilizer best management practices – right rate	Rice, wheat, maize, vegetable, fruit
C2	Fertilizer best management practices (wheat & maize) – right time and right placement	Wheat, maize
C3	Fertilizer and water best management in rice paddies	Rice
C4	Fertilizer best management practices (cash crops) – right product, right time and right placement	Cotton, vegetable, fruit
C5	Enhanced-efficiency fertilizers	All crops, vegetable, fruit
C6	More efficient recycling of organic manure	All crops, open field vegetable, fruit
C7	Conservation tillage for upland crops	Wheat, maize
C8	Straw addition in upland crops	Wheat, maize
C9	Biochar addition	Rice, wheat, maize
L1	Anaerobic digestion of manure	Cattle, dairy cows, sheep, goat, pigs, horse, asses, mules, poultry
L2	Animal breeding	Indoor – cattle, dairy cows, sheep, goat
L3	Ionophores addition to the diet	Indoor – cattle, dairy cows, sheep and goat
L4	Tea saponins addition to the diet	Indoor – cattle, dairy cows, sheep and goat
L5	Probiotics addition to the diet	Indoor – cattle, dairy cows, sheep and goat
L6	Lipid addition to the diet	Indoor – cattle, dairy cows, sheep and goat
L7	Grazing prohibition for 35% of grazed grasslands	Grazing – cattle, dairy cows, sheep and goats
L8	Reduction of stocking rate – medium grazing intensity	Grazing – cattle, dairy cows, sheep and goats
L9	Reduction of stocking rate – light grazing intensity	Grazing – cattle, dairy cows, sheep and goats

A range of targeted dietary supplements have also been proposed, and many of these have been proven to effectively reduce CH_4 emissions. Dicarboxylic acids include the addition of nitrates or fumarate to the diet as alternative metabolic sinks for hydrogen. This has proven to be very effective as a method of reducing CH_4 in all ruminants (23% ± 10% mean reduction). Of all methods compared in this analysis, the use of nitrates has been shown to be the most effective method, and in cattle this would mean an average reduction of 313 kg CO_2-eq head^{-1}year^{-1} (Table 4).

3.3.3. Rumen manipulation

All CH_4 mitigation strategies are aimed at changing the rumen ecosystem to some extent,but a number of methods have been proposed for manipulating the rumen microbial culture directly in an effort to alter fermentation patterns. Altering the microbial community through probiotic supplementation of yeast or bacteria, or through defaunation (i.e., removal of ciliate protozoa from the rumen ecosystem), has not proven successful in reducing CH_4 emissions (1% ± 4% and 0% ± 9% mean reduction respectively). However, specifically targeting methanogenic bacteria with halogenated analogues, such as bromochloro-CH_4 or ionophores such as monensin, is an effective method in the short term (22% ± 6% and 6% ± 3% mean reduction, respectively), with bromochloro-CH_4 being the most effective. Supplementation with this chemical can give a carbon saving of 297.3 kg CO_2-eq head^{-1}year^{-1} in cattle (Table 4).

3.4. Economic potential

3.4.1. Mitigation potential and cost-effectiveness of the mitigation measures

According to defined selection criteria, such as applicability and acceptance of the above, mitigation options were selected and aggregated for economic analysis. The defined mitigation measures and targeted crops or livestock species are presented in Table 5. Wang et al. (2013, 2014) identified that the most cost-effective measures with highest mitigation potential in the arable

Table 6
Average abatement rate, cost, CE and mitigation potential of mitigation measures.

[c]Measure codes	Abatement rate (per year)		Cost (in 2020)		Cost effectiveness (in 2020)	Additional application (in 2020)	Mitigation potential (in 2020)
	(tCO_2-eq ha^{-1})	(CO_2-eq reduction in % SU^{-1})	(¥ ha^{-1}, 2010 price)	(¥ SU^{-1}, 2010 price)[b]	(¥ tCO_2-eq^{-1}, 2010 price)	(M ha)	(MCO_2-eq)
C1	0.412		−228		−435	58.63	30.65
C2	0.201		−620		−3085	56.65	11.38
C3	1.337		464		347	17.93	23.98
C4	1.219		−2295		−1883	17.94	21.86
C5	0.271		63		231	57.23	15.54
C6	0.596		527		1576	120.11	40.19
C7	0.489		−107		−1692	22.98	1.46
C8	0.21		70		2209	30.06	0.95
C9	0.329		1804		5478	9.9	3.26
L1	2[a]		-500[a]		−32	–	58.66
L2		4.1		−47	−3393	–	4.27
L3		5.8		−53	−2033	–	1.95
L4		15.4		−3.4	−56	–	23.18
L5		0.6		−17	−7080	–	0.76
L6		14.3		109	1982	–	21.49
L7	1.067		300		281	56.98	60.78
L8	0.705		45		64	57.85	40.77
L9	0.877		283		322	57.85	50.72

[a] Per anaerobic digester.
[b] Sheep unit (SU) is a standard unit to compare different animal species. The conversion is sheep: 1, goat: 0.9, cattle: 5, dairy cow: 7. It is only an approximate simplification and normally applied in grazing systems. Hence the costs SU-1 should be interpreted with caution.
[c] See Table 5 for measure codes.

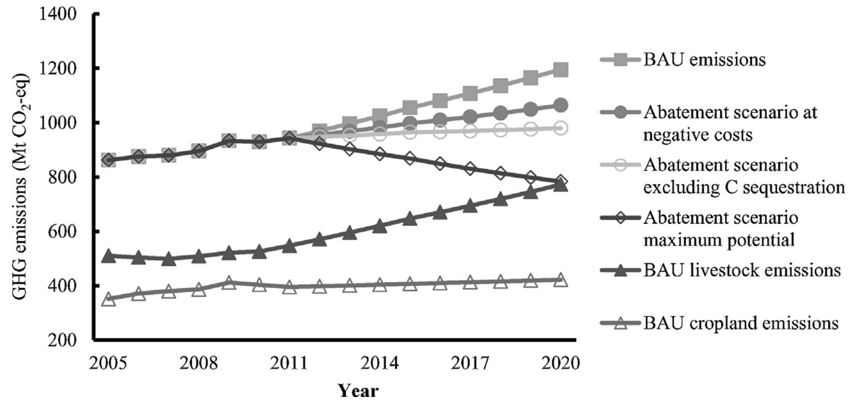

Fig. 6. Projected BAU and abatement emissions scenarios. BAU emissions are the sum of soil N_2O emissions, rice CH_4 emissions, ruminant CH_4 emissions and waste management N_2O and CH_4 emissions. Mitigation potentials at maximum feasible application, negative cost scenarios and the scenario excluding carbon sequestration were identified from data in Fig. 7 assuming a linear adoption over time.

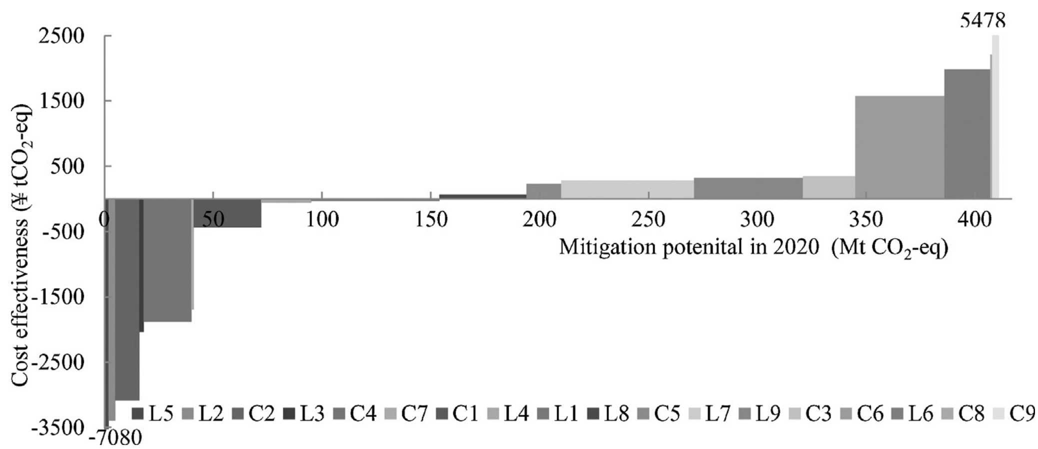

Fig. 7. MACC for China agricultural sector: maximum feasible abatement potential in 2020 (discount rate = 7%). Measures codes refer to measures in Table 1: L5- Probiotics addition to the diet; L2- Animal breeding; C2-Fertilizer best management practices (wheat & maize)- Right time and right placement; L3- Ionophores addition to the diet; C4- Fertilizer best management practices (cash crops)- Right product, right time and right placement; C7- Conservation tillage for upland crops; C1-Fertilizer best management practices- Right rate; L4- Tea saponins addition to the diet; L1- Anaerobic digestion of manure; L8-Reduction of stocking rate- medium grazing intensity; C5- Enhanced-efficiency fertilizers; L7- Grazing prohibition for 35% of grazed grasslands; L9- Reduction of stocking rate- light grazing intensity; C3- Fertilizer and water best management in rice paddies; C6- More efficient recycling of organic manure; L6- Lipid addition to the diet; C8- Straw addition in upland crops; C9- Biochar addition. Each bar represents a mitigation measure, differentiated by the implementation cost per tonne of CO_2-eq reduced (height of bar), and the quantity of emissions CO_2-eq reduced (width of bar). Measures below the *x* axis are cost negative – i.e., removing emissions and saving money.

sector are fertilizer best management practices, including best N application rate, best products, best application time and best application methods. Together they could provide over 40% of cropland abatement opportunities (Table 6). Although more efficient recycling of organic manure to croplands also offers significant potential, substantial manure fertilizer purchase costs or labor requirements for manure composting may prevent its widespread adoption. Implementation of biochar addition would be restricted by high cost at 5478 ¥ tCO_2-eq^{-1}. In contrast, the limited potential of conservation tillage and straw addition in uplands are due to high uptake of measures under the BAU scenario due to policy enforcement, leaving little scope for additional application.

For livestock, significant negative-cost measures are feeding of ionophores, probiotics and tea saponins, breeding measures, and biomass gasification; the latter generating the highest GHG reduction. In total, the negative-cost measures account for 69.8 Mt CO_2-eq GHG reduction in 2020. Medium grazing intensity also accounts for large abatement potentials available at relatively low cost of 64 ¥ tCO_2-eq^{-1}. Despite showing a large GHG reduction potential, supplementary feeding with lipids is expensive with cost effectiveness (CE) of 1982 ¥ tCO_2-eq^{-1} (Table 6).

3.4.2. MACC and abatement scenarios

The MACC (Figs. 6 and 7) shows that under the maximum technical abatement scenario for 2020, an emission reduction of 412 Mt CO_2-eq could be achieved, representing 35% of BAU emissions. 149 and 263 Mt CO_2-eq emissions could be avoided from croplands and livestock/grasslands, respectively. When only counting the measures targeting CH_4 and N_2O mitigation (and not C sequestration), the abatement potential declines to 207 Mt CO_2-eq in 2020 (Fig. 6).

4. Discussion

4.1. Cropland

4.1.1. N fertilizer management and GHG emissions

The average N fertilizer application rate for rice in China is 150–250 kg N ha^{-1} which is 67% above the global average (Peng et al., 2010). Based on a national farm survey, Li et al. (2010) found that fertilizer N rates for rice showed an increasing trend from 217 kg N ha^{-1} in 2000 to 231 kg N ha^{-1} in 2007. Lin et al. (2007) estimated the average N fertilization rate for rice in Jiangsu province at 300–350 kg N ha^{-1}. Ju et al. (2009) estimated the optimal N rate of 200 kg N ha^{-1} for rice in Taihu region while the farmer practice N level was 300 kg N ha^{-1}, and optimal N application resulted inbetter grain yield. Reducing N fertilization to an optimal level in the regions with over-application would reduce the GHG emission by reducing direct N_2O emission and indirect CO_2 emissions from N production. Application of N fertilizer at moderate level i.e., 150–200 kg N ha^{-1}, decreased CH_4 emission significantly by 44% compared to control (Feng et al., 2013). Our data analysis shows, 150–200 kg N ha^{-1} could be an ideal N rate for rice crops in China without compromising grain yield. The average N application rate for wheat and maize is nearly 60–150% higher than the recommended rate (Norse et al., 2012). The area-weighted mean rate of synthetic N application was 190 and 187 kg ha^{-1} for wheat and maize, respectively (Huang and Tang, 2010) and the over fertilization in wheat and maize was generally in central and north china. The area of N usage higher than 250 kg N ha^{-1} accounts for 23% and 21% of wheat and maize cultivated area, and at the same time the area of N rates lower than 100 kg N ha^{-1} accounts for 14% of wheat and 16% of the maize cultivated area. Use of recommended rate of N fertilizer in the North china plain i.e., 128 and 158 kg N ha^{-1} resulted in 4–5% increase in grain yield relative to farmer's rate of N i.e., 325 and 263 kg N ha^{-1} (Ju et al., 2009). Our analysis shows (Fig. 1) a 10–60% reduction in N fertilizer amount can reduce soil N_2O emission by 8–49% in rice, 11–38% in wheat, and 17–49% in maize. From 1998 to 2009, grain yields in China have increased by 10%, while consumption of N fertilizer has increased by 49%, and this suggests that large increases in fertilizer nutrient inputs did not result in a corresponding yield increase in the past decade. Improving nitrogen use efficiency (NUE) from 30% which is the current average NUE for major grain crops to 50% could cut 6.6 Tg of synthetic N use per year, accounting for 41% of the total N fertilizer used (Huang and Tang, 2010). Conventional fertilizer inputs for greenhouse vegetables are more than 2–8 times of crop nutrient uptake (Fan et al., 2010). Based on linear regression equations for % reduction in N fertilizer, to % reduction in N_2O emission, a 10–60% reduction N fertilizer amount can reduce N_2O emission by 27–72% in vegetables (Fig. 1). N_2O emissions from synthetic fertilizer accounts for about 61% of the N_2O emissions from agriculture in China (FAOSTAT, 2010). Reducing the N application rate to an optimal level where a sustainable yield can be achieved, while also delivering GHG benefits, is an important option to decrease GHG emissions from Chinese agriculture. In addition to fertilizer amount, the selection of proper fertilizer type, application mode and timing could influence N_2O emission and mitigation, but analysis was not performed here due to lack of data for meta-analysis.

Use of enhanced-efficiency fertilizer, such as those containing urease inhibitors, nitrification inhibitors and slow release fertilizer could reduce N_2O emission from rice and upland crops by 30–34% (Akiyama et al., 2010). Combined application of urease and nitrification inhibitors with N fertilizer reduced both CH_4 and N_2O emission from rice (Table 1). Akiyama et al. (2010) estimated a 30% decrease in N_2O emissions from rice soil with nitrification inhibitors, and a 24% decrease in N_2O emissions was obtained in this analysis. Our analysis shows a 44% reduction in N_2O emission from upland crops with use of N inhibitors such as DCD, DMPP(3,4-dimethyl pyrazole phosphate), NBPT, HQ while Akiyama et al. (2010) estimated a 34% reduction in N_2O emission from upland crops. Jiang et al. (2010) showed, in comparison with commercial urea, application of urea formaldehyde reduced N_2O emissions by ~42% for the wheat growing season, and 15–26% for the maize growing season, and the urea with dicyandiamide and hydroquinone treatment reduced N_2O emissions by 33–63% for the maize growing season. Application of N inhibitors not only decreases N_2O emissions, but also increases availability of soil NH_4^+ to the plants, decreases soil NO_3^- content and thus increases grain yield and decreases N loss due to leaching (Liu et al., 2013).

Increased CH_4 emissions from rice fields with straw return outweighed the benefits achieved through reduced N_2O emission and increased SOC sequestration, and overall, straw return to rice fields was not identified as a useful mitigation measure. However, integration of proper water management with straw return, such as applying intermittent irrigation with straw application could reduce the climate forcing impact (0.88–1.43 t CO_2-eq $ha^{-1}yr^{-1}$) compared to treatment with continuous flooding and straw application (3.80 t CO_2-eq $ha^{-1}yr^{-1}$). Zou et al. (2005a) estimated crop induced CH_4 as 15%, 13% and 9% of crop residue under continuous flooding, flooding-midseason drainage-frequent water logging with intermittent irrigation (F-D-F) and a dry–wet alteration (with intermittent irrigation) until a week before rice harvesting (F-D-F-M), respectively. The method of straw return such as incorporation, mulching, or burning also affected CH_4 emissions (Ma et al., 2008) and the quality of straw such as C:N ratio affected N_2O emissions from rice field with N_2O emissions negatively correlated with C:N ratio of incorporated residue (Zou et al., 2005a). With no significant effect on N_2O emissions and significant positive impacts on SOC sequestration, straw return to upland crops could be a good mitigation measure. Crop residue-induced N_2O EFs tended to decrease with increased amount of residue incorporation (Zou et al., 2005b) in a field with rice-winter wheat rotation, and Ma et al.(2008) observed a decrease in N_2O emission with incorporation of rice straw during wheat growing season but straw mulching increased N_2O emission.

Application of organic manure such as livestock manure, biogas residues, composted manures and green manures on CH_4 emission from rice fields was highly dependent on the growing season water regime (Fig. 2). Application of aerobically composted manure not only decreased CH_4 emission during the rice growing season, but also decreased the CH_4 emission with aerobic composting by 94%, compared to storage of manure in an anaerobic environment, which is a common method of storage (Chen et al., 2011a). Our analysis shows application of fermented biogas residue increased CH_4 emission by only 42% while non-composted or unfermented manure increased CH_4 emission by nearly 112–138%. With the additional carbon benefits acquired by displacement of conventional fossil fuel energy with biogas, use of biogas residue in rice fields can provide soil fertility with less CH_4 emissions. In our analysis, application of livestock manure decreased N_2O emissions from rice field, but this outcome should be treated with caution as it is based on very few data points. Yu et al. (2004) recommended keeping the field un-flooded during the rice growing season, with organic manure application as a potential measure, without decreasing rice yield. High SOC sequestration potential of organic manure application compensated the negative impact of manure application on N_2O emissions from upland crops. Recycling of nutrients thorough manure addition could be a good mitigation measure for upland agriculture. Our study on manure impact included major crops such as rice, maize and wheat, but not vegetables. Chadwick et al. (2015) (this issue) identified that manure is commonly over-applied in horticultural crops, greenhouse vegetable and fruits in China with negative environmental impacts. A judicious use of manure in different crops through proper manure nutrient management could reduce reliance on chemical fertilizers, providing benefits from reductions in indirect GHG emissions from fertilizer production, and direct N_2O emissions from soil.

The use of biochar, a more stabilized form of carbon obtained from thermal decomposition of plant derived biomass has gained increased recent attention in China. Stavi and Lal (2013) identified soil application of biochar as one of the most promising options to combat climate change with potential to efficiently sequester large amounts of carbon over long periods. Our analysis showed an increased CH_4 emissions and decreased N_2O emissions from rice fields with biochar application, with the increase in CH_4 emissions attributed to decomposition of the labile organic C pool of biochar (Zhang, 2012), particularly during the first year of application. Huang et al. (2013) did an analysis of published studies on the effect of biochar on rice yield, and concluded biochar had a positive effect on rice grain yield only when applied in conjunction with N fertilizer. With only two published studies, one on wheat and the other on maize, biochar application decreased N_2O emissions by 19% and increased grain yield by 14% in upland crops. The inhibitory effect of biochar on N_2O emissions could be due to the stimulatory activity of N_2O reductase from denitrifying micro-organisms as soil pH increased with biochar application (Yanai et al., 2007).

4.1.2. Land management and GHG emissions

CH_4 and N_2O emissions from rice fields are very sensitive to water regime management and are often affected in opposite ways. Mid-season aeration for 7–10 days with single drainage (IS) before harvesting is commonly practiced in two-thirds of Chinese rice paddies (Yan et al., 2003) to inhibit ineffective tillers, remove toxic substances and improve root activities (Zou et al., 2007). But with increasing water scarcity, water saving rice production systems such as intermittent irrigation, controlled irrigation and aerobic rice have become more prevalent and nearly 7–12% of Chinese rice fields are under intermittent irrigation (IM) water regime (Zou et al., 2009). Our analysis shows that keeping the rice field intermittently irrigated, instead of simply applying mid-season drainage, could save 0.54–1.08 t CO_2- eq $ha^{-1}yr^{-1}$ (Fig. 2). Jiang et al. (2003) reported a 60–90% decrease in GWP with intermittent irrigation compared to permanent flooding. Carbon dioxide equivalents of CH_4 and N_2O emissions from rice fields during the rice growing period under controlled irrigation were reduced by 61.4% compared, with those from flooding irrigation (Yang et al., 2012). Nie et al. (2011) estimated 9.4–13.9% higher yield of rice under intermittent irrigation than that under CF irrigation in Northeast China, and the increase in yield was mainly through significant increase in effective panicles per plant. Even though there is an increase in N_2O emissions with mid-season, single aeration or intermittent irrigation, the benefit of decreased CH_4 emission compensates the offset, and intermittent irrigation with either keeping the field water-logged or moist in between the drained period could be an effective technique to mitigate overall GHG emissions from rice fields without a significant change in yield (Cheng et al., 2014).

Rice-duck and rice-fish ecological systems are two major complex breeding and planting systems in south China and have been the major technology measure to improve rice grain quality and economic benefits (Yuan et al., 2009). With Technical potential $_{\text{Rice-fish-ducksystem}}$ of −0.86 t CO_2-eq $ha^{-1}yr^{-1}$ and numerous other advantages, such as greater yield, pest and weed control, disease resistance, increased nitrogen efficiency, integrated rice-fish or duck farming could deliver GHG benefits as well as economic benefits.

Soil C sequestration through adoption of conservation tillage methods is considered as one of the most effective ways to slow the process of global warming (Reicosky, 2003; Cheng et al., 2013) but there are site- and crop-specific limitations to where conservation tillage can be applied. More risk of fungal attack, reduced emergence and crop failure with conservation tillage could be expected in wetter areas, whereas in dry areas, productivity may improve with adoption of conservation tillage (Freibauer et al., 2004). Our meta-analysis shows a significant increase in annual SOC sequestration by 0.59% in rice based cropping systems and 0.81% in upland cropping systems. Increased N_2O emissions in rice-based systems and upland systems decreased overall mitigation potential of conservation tillage by 2% and 33%, respectively. The benefit for GHG reduction in rice-based cropping systems comes from decreased CH_4 emissions during the rice growing season. Many studies have reported an increase in grain yield by ∼1.4–9.3% for upland crops in North China (Chen et al., 2008; He et al., 2011) with adoption of conservation tillage. In the short term, conservation tillage may result in lower grain yields than conventional tillage, but such negative impacts on yield decreased with time (Brouder and Gomez-Macpherson, 2014). Xie et al. (2008) analysed the data from different field experiments and showed that, on average, crop yield was 12.5% greater under conservation tillage over that of conventional tillage by 9.0% for wheat, 6.2% for corn, and 15.9% for rice (Xie et al., 2008). Adoption of conservation tillage could be a challenge for rice paddy production because of residue and weed-related problems, but it could be a good mitigation measure particularly for upland dry crops in north China, where there is water scarcity.

4.2. Grassland

Overgrazing led to 25.2% and 12.4% loss of SOC in 0–20 cm from 1986 to 2001 in Alax, Inner Mongolia (Fu et al., 2004) and from 1956 to 1996 in a *Leymus Chinensis* steppe in the Xilin river basin, respectively (Li et al., 1998). There are conflicting reports on the effect of grazing on SOC, with few reports suggesting higher SOC in grazed land (Conant et al., 2001; Reeder et al., 2004), no significant effect (Milchunas and Lauenroth, 1993) and decreased SOC with a long history of grazing (Han et al., 2008). Our analysis shows grazing intensity plays a major role in the direction of SOC change. Heavy grazing decreased SOC storage significantly by −25% (−36% to −12%), while light and moderate grazing showed a decreasing trend in SOC, but the effect was not significant. In China, ∼1.49 Pg C was lost from the 1960s to 1990s due to overgrazing, so a reduction in grazing intensity or grazing exclusion may reverse the loss of SOC (Wang et al., 2011). In addition to increased SOC sequestration, grazing intensity reduction may increase the soil sink of atmospheric CH_4 as heavy grazing reduced annual CH_4 uptake by 24–31% compared with un-grazed steppe in a semiarid steppe of Inner Mongolia (Chen et al., 2011b). Our analysis shows a decrease in N_2O emission with GI reduction; however the analysis is based on very few data points and should be treated cautiously. Grazing induced N_2O emission reduction was observed by (Wolf et al., 2010) with a year round N_2O emission measurement from un-grazed and grazed typical steppe grasslands of Inner Mongolia.

Cultivation is one of the major causes of grassland degradation in the arid and semiarid regions of northern China (Su et al., 2004). Conversion of grassland to cropland resulted in moderate loss of SOC, with a range of −4 to 55% after 20 years of cultivation with major loss in the plough horizon i.e., 0–20 cm by 15 to 53% and relatively less loss in the plough pan horizon and underlying horizon (Liu et al., 2010). Cultivation of alpine grassland soils in China for 8, 16, and 41 years decreased SOC by 25%, 39%, and 55%, respectively (Wu and Tiessen, 2002). Our analysis showed a significant decrease in SOC with conversion from grassland to cropland, and one management option to reverse such loss processes can be by converting the croplands to grassland, shrub land or woodland. Restoration of grassland by grazing exclusion, reseeding or afforestation could increase SOC by about 6, 3 and 44% after 5–25 years of grazing exclusion, 3–7 years of reseeding and 20 years of afforestation. Wang et al. (2011) estimated an annual average increase in SOC of 5.4–6.3% with grazing exclusion and conversion of cropland to abandoned fields.

4.3. Livestock

Animal breeding is a key component in improving both the efficiency of production and quality of product produced. Comparisons of breeds, or of individual animals over time, show no clear patterns in CH_4 emissions, suggesting little genetic control over this trait (Munger and Kreuzer, 2006) though some heritability of CH_4 emission rates has recently been demonstrated (Pinares-Patiño et al., 2013). There is also some evidence that breeding for improved efficiency, for instance through improved residual feed intake, can reduce emissions both per unit product (Wall et al., 2010) and per head of animal (Alford et al., 2006). In this meta-analysis, breeding was not shown to be an effective strategy for reducing emissions per head of animal, but breeding for improved feed conversion rates, or improved productivity in general, is likely to be of benefit to Chinese livestock systems as Chinese systems may still have relatively low production efficiency. In a similar approach, herd management can give significant improvements in terms of reducing CH_4 emissions per unit product, either through reducing the number of unproductive animals on the farm, or through encouraging faster growth rates, so animals reach slaughter weight earlier, thereby reducing lifetime emissions per animal (Eckard et al., 2010).

Improving not only diet quantity, but also diet quality will have a beneficial effect on CH_4 emissions, both per unit product and per head of animal. The substrate being fermented in the rumen influences the rate of CH_4 production, with cellulose having the slowest fermentation rate and hence the highest CH_4 emission rate per unit digested. Higher quality forages are also more palatable, increasing feed intake rates. A high feed intake rate, and a faster fermentation rate, will reduce the retention time in the rumen. This in turn will in theory reduce the proportion of feed energy converted to CH_4 through fermentation. Similarly, the addition of concentrate can improve rumen fermentation efficiency, and also increase propionate production with in turn reduces the amount of H_2 available for CH_4 production (Patra, 2012). Chinese ruminants are typically fed a low digestibility diet high in cellulose and hemicellulose. Improving the digestibility of such diets, through ensiling or other means, does not appear to have a great effect on the CH_4 emissions per animal. However, reducing the amount of roughage in the diet and replacing it with some form of concentrate does seem to improve CH_4 emissions significantly (Veneman et al., 2015) though the system lifecycle effects can be significant, but are not considered here.

There are a host of different dietary supplements available, some of which have been proven to have a positive effect on CH_4 emissions and others with no demonstrated effect. Most lipid supplements reduce CH_4 emissions to some degree. The effects, however, are highly variable depending on the concentration given, the type of fatty acids included or the background diet of the animal (Eugène et al., 2008). Dicarboxylic acids such as malate or fumarates, stimulate the synthesis of propionate at the expense of CH_4, thus reducing overall CH_4 emissions (Iqbal et al., 2008). Alternatively nitrate acts as an alternative hydrogen sink during it reduction to nitrite and eventually ammonia (van Zijderveld et al., 2010). This has proven to be very effective as a method of reducing CH_4 in all ruminants, but there are some safety concerns, as a rapid or large introduction of nitrates in the diet can cause methemoglobinemia.

All dietary strategies are most likely applied to intensive production systems which account for only a small proportion of Chinese livestock production. Though effective in most cases, they are not, therefore, widely applicable in China and data specifically from Chinese systems are not available. One exception is the supplementation with tea saponins which has received a great deal of attention within the Chinese research community. China is the largest producer of tea in the world. A by-product of tea production is tea seed meal which contains a very high concentration of tea saponin (Wang et al., 2012). Tannins in general, including saponins, are assumed to reduce CH_4 production through their anti-protozoal properties (Wang et al., 2012), and have been shown to be very effective in reducing the CH_4 emissions from all groups of ruminants in this meta-analysis.

Halogenated analogues such as bromochloro CH_4 are highly effective at reducing CH_4 production, though methanogen species differ in their responsiveness (McAllister and Newbold, 2008). Though these compounds can be highly effective as we have shown, the effect of these chemicals is transitory with no significant long-term reduction in CH_4 production (McAllister and Newbold, 2008). These are also potentially highly toxic chemicals which are unlikely to be found acceptable in food production systems.

Ionophores such as monensin are antibiotic compounds which specifically target bacteria producing H_2 and formate. This reduces the amount of H_2 available for methanogenic bacteria and thereby reduces the production of CH_4 during fermentation (Russell and Strobel, 1989). Short term studies have shown that monensin is effective in decreasing CH_4 emissions, however other studies have suggest that these effects may not persist, thus whilst monensin is available and used in China (Sarmah et al., 2006) it is not considered here as a mitigation strategy.

Addition of probiotics such as yeast are assumed to reduce CH_4 production either by altering VFA profiles, reducing protozoal numbers, or promoting acetogenesis (Iqbal et al., 2008). Direct measures of the effectiveness of probiotics for reducing CH_4 are few, but probiotic supplements appear to have no beneficial effect on CH_4 production.

Defaunation of the rumen, the removal of ciliate protozoa from the rumen ecosystem, is thought to significantly alter fermentation patterns and improve nutrient use (Eugène et al., 2004). This in turn is expected to result in a reduced production of CH_4 during fermentation, although there has been no successful application of this approach to date. Research has begun into the potential for vaccines against rumen methanogens, with the aim to reduce the production of CH_4 during fermentation (Williams et al., 2009). Efforts to permanently defaunate animals or to develop a vaccine against methanogenic bacteria are still in the early stages, with research only available from sheep.

4.4. Economic potential

The MACC analysis illustrates a maximum feasible mitigation potential that could reduce total agricultural GHG emissions by 412 Mt CO_2-eq in 2020, in other words, a 35% decrease from BAU emissions. The most cost-beneficial measures are: (a) fertiliser best management techniques, (b) conservation tillage, (c) anaerobic digestion of manure, (d) breeding of livestock, (e) additive feeding of probiotics and (f) additive feeding of antibiotics. Although antibiotics are a win–win option, application is likely to face resistance from consumers (Eckard et al., 2010). Probiotics and tea saponins could offer a CE alternative application for rumen CH_4 reduction. Tea saponins are largely available in waste by products of tea production and access, and thus the cost-effectiveness of this feed additive could be improved with further research. The MACC results also highlight the importance of improved N fertilizer and manure management practices, coupled with improved irrigation systems.

5. Conclusion

Through a bottom–up approach i.e., meta-analysis of published data, both technical and economic mitigation potential of different management options was estimated. Our findings suggest that, the management options with great mitigation potential for rice paddies are controlled irrigation, replacing urea with ammonium sulphate, N inhibitor application, integrated rice fish or duck farming and reduced N fertilizer application. Combined application of chemical and organic fertilizer, conservation tillage, and reduced N application are the possible measures that can mitigate overall GHG emission from upland crops. One of the important mitigation measures for agricultural grasslands could be conversion of low yielding cropland, particularly on slopes, to shrub land or grassland and could be a promising option to decrease soil erosion. Apart from restoration of degraded grassland, grazing exclusion and reduced grazing intensity can increase SOC sequestration and decrease overall GHG emissions. There are many mitigation strategies available, with a proven effectiveness for reducing enteric CH_4 emissions from ruminants. Breeding for reduced CH_4 production may take time to develop, but appropriate feeding management can be effective either through improving feeding practice or through improving diets. Improving diet quality can have positive benefits not only on greenhouse gas emissions, but also on productivity. Dietary additives such as the ionophores and chemical inhibitors, though effective, may have safety concerns and are therefore not likely candidates for widespread adoption. Of the remaining strategies, supplementation with tea saponins is the most promising for Chinese production systems as these compounds are readily available as industry by-products with a proven effectiveness. Even though some management such as fertilizer best management practice had low abatement rate per area, the mitigation potential from such measures were still high at national level with possible applicability over a larger area. The economic analysis illustrates a maximum feasible mitigation potential of 412 Mt CO_2-eq in 2020 i.e., a 35% reduction from BAU scenario, could be mitigated in the Chinese agricultural sector as compared to baseline.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2015.04.035.

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