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Greenhouse gas mitigation in Chinese agriculture: distinguishing technical and economic potentials

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China is now the world's biggest emitter of greenhouse gases with 7467 million tons (Mt) carbon dioxide equivalent (CO_2e) in 2005, with agriculture accounting for 11% of this total. As elsewhere, agricultural emissions mitigation policy in China faces a range of challenges due to the biophysical complexity, the heterogeneity of farming systems, and social-economic barriers. Existing research has contributed to improving our understanding of the technical potential of mitigation measures in this sector (i.e. what works). But for policy purposes it is important to convert these measures into a feasible economic potential, which provides a perspective on whether agricultural emissions reduction measures are low cost relative to mitigation measures and overall potential offered by other sectors of the economy. We develop a bottom-up marginal abatement cost curve (MACC) representing the cost of mitigation measures applicable in addition to business-as-usual agricultural practices. The MACC demonstrates that while the sector can offer a maximum technical mitigation potential of 402 MtCO2e in 2020, of which a reduction of 135 MtCO2e is potentially available at zero or negative cost (i.e. a cost saving), and 176 MtCO2e (approximately 44% of the total) can be abated at a cost below a threshold carbon price of ¥ 100 (approximately €12) per tCO2e. Our findings highlight cost-effectiveness of nitrogen fertilizer and manure best management practices, and animal breeding practices. We outline the assumptions underlying MACC construction and discuss some scientific, socioeconomic and institutional barriers to realizing the indicated levels of mitigation.

Keywords: China, agriculture, climate change, greenhouse gas mitigation, marginal abatement cost curve (MACC)

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Abstract:

China is now the world's biggest emitter of greenhouse gases with 7467 million tons (Mt) carbon dioxide equivalent (CO_2e) in 2005, with agriculture accounting for 11% of this total. As elsewhere, agricultural emissions mitigation policy in China faces a range of challenges due to the biophysical complexity, the heterogeneity of farming systems, and social-economic barriers. Existing research has contributed to improving our understanding of the technical potential of mitigation measures in this sector (i.e. what works). But for policy purposes it is important to convert these measures into a feasible economic potential, which provides a perspective on whether agricultural emissions reduction measures are low cost relative to mitigation measures and overall potential offered by other sectors of the economy. We develop a bottom-up marginal abatement cost curve (MACC) representing the cost of mitigation measures applicable in addition to business-as-usual agricultural practices. The MACC demonstrates that while the sector can offer a maximum technical mitigation potential of 402 $MtCO_2e$ in 2020, of which a reduction of 135 $MtCO_2e$ is potentially available at zero or negative cost (i.e. a cost saving), and 176 $MtCO_2e$ (approximately 44% of the total) can be abated at a cost below a threshold carbon price of ¥ 100 (approximately €12) per tCO_2e. Our findings highlight cost-effectiveness of nitrogen fertilizer and manure best management practices, and animal breeding practices. We outline the assumptions underlying MACC construction and discuss some scientific, socioeconomic and institutional barriers to realizing the indicated levels of mitigation.

Keywords: China, agriculture, climate change, greenhouse gas mitigation, marginal abatement cost curve (MACC)

Research highlights

►Marginal abatement costs of greenhouse gas mitigation from Chinese agriculture are assessed.

►Technically feasible to cut emissions by about 1/3 in 2020 against baseline emissions.

►Significant potential for win-win abatement, avoiding emissions while providing financial savings.

►Analysis highlight the mitigation potential of improved N fertilizer and manure management practices and breeding practices.

►Institutional and behavioral barriers warrant further analysis to facilitate mitigation policy

1. Introduction

Greenhouse gas (GHG) emissions in China reached 7467 million tons (Mt) carbon dioxide equivalent (CO_2e) in 2005 excluding land use, land use change and forestry (NCCC, 2012), and agriculture accounted for 11% of this total, or approximately 820 MtCO_2e. Agriculture is responsible for over 70% of national nitrous oxide (N_2O) emissions and approximately 50% of methane (CH_4) emissions, arising mainly from the use of synthetic nitrogen (N) fertilizers, livestock enteric fermentation, rice cultivation and animal waste management. Between 1994 and 2005, emissions from livestock enteric fermentation (37% of 2005 total agriculture emissions) surpassed cropland (25% of the total) as the largest agricultural source of GHG emissions (only including N_2O and CH_4) (NCCC, 2004, 2012). Rice cultivation (CH_4) and livestock waste management (N_2O and CH_4) contributed around 20% and 18%, respectively (NCCC, 2012).

In China, national policy aspirations for agricultural mitigation have traditionally been eclipsed by food security ambitions, with any convergence of production and climate objectives focusing mainly on increasing productivity. But ambitious national mitigation aspirations have recently been outlined in the 12th Five-Year Plan (FYP), which targets a 17% reduction in carbon intensity (emissions) per unit of Gross Domestic Product. In response, the Ministry of Agriculture (MOA) has initiated programs to mitigate agricultural emissions by improving agricultural productivity by 2015. These include a 3% improvement in fertilizer use efficiency, enhancing irrigation water use efficiency by 6%, accelerating the development of household biodigesters, and improving degraded grasslands. The 12th FYP Plan also accommodates a significant increase (+0.45% per year) in scientific research funding.

Existing global reviews (e.g. Oenema et al., 2001; IPCC, 2007; Smith et al., 2008, 2013) suggest that agriculture offers significant technical potential to mitigate climate change through both emissions reduction and carbon sequestration in terrestrial ecosystems. Technically feasible GHG measures identified as applicable in both arable and livestock systems can be broadly grouped into increased N-use efficiency, reduced CH_4 emissions from livestock rumen and rice paddy, sequestering C into cultivated and grassland soils, and energy efficiency to reduce CO_2 emissions. Some reviews (e.g. Wreford et al., 2010) indicate that many mitigation measures can be implemented immediately using current technologies, simultaneously reducing input costs or improving productivity. Beyond such initial win-wins, some agricultural abatement options also afford co-benefits with regards to water quality, biodiversity conservation, food security, rural development and poverty alleviation, all of which have high importance in rural China.

Existing research in China has examined and quantified technical abatement potentials for specific agriculture mitigation measures (Lin et al., 2005; Lu et al., 2009; Huang and Tang, 2010; Nayak et al., 2013a, 2013b; Saetnan et al., 2013). These studies provide some insights into how mitigation potentials can be applied across the range of biophysical conditions that characterize Chinese farming systems. Beyond the farm gate, further insights have been provided by life-cycle analysis targeting the N fertilizer production and consumption chain (Zhang et al., 2013). But to date there is no synthesis estimate of overall technically feasible mitigation potential in agriculture, nor any estimate of the cost-effectiveness (CE) of abatement measures in China. Such research would consider the relative abatement cost of implementing each measure and would provide information on how agricultural abatement costs compare with both a benchmark carbon price and abatement elsewhere in the economy. This is significant, since in allocating an emissions budget to a sector, a rational mitigation policy should normally prioritize the cheapest means of abatement first and equalize marginal abatement costs across sectors. Such information is also crucial, for instance, for developing any market-based approach based on offering low cost mitigation credits to any emerging carbon market. While agriculture has been slow to graduate to such market schemes, the inception of emissions trading regimes in China is likely to lead to an increasing scrutiny of the relative cost of emissions reductions in all sectors of the economy.

This paper considers the extent of biophysical data on agricultural mitigation measures and outlines the stages in moving from a technical potential to an estimate of feasible economic mitigation potential. The methodological approach involves the use of a bottom-up or engineering marginal abatement cost curve (MACC), which allows the aggregation of the mitigation potential arising from the application of a subset of cost-effective measures above a notional baseline level of activity that we denote as business as usual (BAU). This analysis considers measures applicable within the farm gate and the direct cost and benefit implications for farmers life-cycle impacts of the measures and energy use related emissions are not within the scope of this MACC exercise. The paper covers the sections of MACC construction, presentation of key results and a discussion of data. It also reflects on the behavioral and institutional barriers to the realization of estimated mitigation potentials.

2. MACC construction

Technically feasible mitigation measures will normally be differentiated in terms of their implementation cost to farmers and their wider net environmental impacts borne by society. An economic mitigation potential considers the cost of applying the measures as well as their likely adoption rate relative to a baseline of no additional mitigation activity (BAU scenario), which may be limited by institutional and farm-scale (including behavioural) barriers.

In the first instance it is useful to rank abatement measures in order of decreasing CE; i.e. the implicit cost of each ton (t) of CO_2e mitigated were each measure fully implemented, and then to estimate the annual cumulative potential over a target time horizon offered by all cost-effective measures applied above baseline activity. MACCs offer a rational framework for combining biophysical and economic data to reflect mitigation costs. In this application we adopt the bottom-up or engineering approach to MACC construction that has been used in several previous studies (Beach et al., 2008; Moran et al., 2011; Schulte et al., 2012; Pellerin et al., 2013).

On the right hand side of Fig. 1, each bar represents a feasible abatement measure, differentiated by implementation cost per ton of CO_2e emission reduced (height of bar), and quantity of emissions they can mitigate if the measure is fully applied to its technical potential (width of bar). Measures below the x-axis are cost negative, i.e. removing emissions and saving society costs, those above incur positive cost. Therefore, the biggest financial gains and emission reductions can be seen in the longest and widest bars beneath x-axis, and conversely bars above the x-axis are the costlier measures. Policy therefore needs to focus first on the implementation of the former. An economic potential can be derived by selecting those measures that fall below a cost threshold set by a notional benchmark carbon price (horizontal dashed line). This threshold can be established with reference to traded or non-traded carbon prices and can rule out higher cost measures, and thereby define an economic potential that is less than the full technical potential.

Bottom-up MACCs are best-suited to explore and reflect the complexity and diversity of Chinese agricultural systems, specifically heterogeneity in terms of abatement potential, measure applicability and implementation costs. Overall, the aim is to derive the CE of each individual measure implemented in Chinese average conditions.

The basic steps for bottom-up MACC derivation followed the methodology by Moran et al. (2011):

1. Develop BAU or baseline emissions scenario for the target year 2020.
2. Screen mitigation measures technically applicable in Chinese agriculture.
3. Quantify the abatement rate of selected measures in terms of tCO_2e abated per hectare or per animal head, based on relevant studies or existing meta-analysis results.
4. Estimate implementation costs/benefits of mitigation measures for farmers as ¥ per hectare (ha^{-1}) or ¥ $animal^{-1}$ in 2020 prices accounting for anticipated future price rise in various

agricultural inputs. Calculate the net present value (NPV) using a discount rate and express CE in terms of ¥ tCO_2e^{-1} in the chosen benchmark year (here 2010).

5. Estimate measure uptake under the BAU scenario and maximum feasible adoption in the target year 2020 to deduce overall mitigation potential, taking into account measure interactions.
6. Draw the MACC, showing the relationship between abatement potential and cost.

2.1. Projecting BAU emissions from Chinese agriculture in 2020

Since there is no robust projection of GHG emissions from Chinese agriculture, we followed the IPCC 2006 guideline (IPCC, 2006) to compile a baseline emission inventory to 2020. We considered both direct and indirect N_2O emissions from the three major N input sources: synthetic fertilizers, organic manure and crop residues, plus CH_4 emissions from enteric fermentation, manure management and rice paddies.

Historical agriculture activity data (cropping area, production, yield, livestock numbers, selling price) were extracted from the China Rural Statistical Yearbooks (MOA, 2001-2012a) and the China Livestock Yearbooks (MOA, 2001-2012b). Future activity data for 2012 to 2020 were drawn from model projections using CAPSiM, which analyzes the impacts of policy changes and other external factors on China's agricultural production, consumption, prices and trade (Huang and Li, 2003). Model output was provided by the Center for Chinese Agricultural Policy of the Chinese Academy of Sciences (Table A.1, Table A.2). A forecast of total agricultural use of synthetic N fertilizers was based on IFADATA (IFA, 2013), assuming a 1% annual growth rate (Zhang et al., 2013) from 2012 to 2020 (Table A.3). Per hectare N application rates for different crops were collected from the China Agricultural Products Cost-Benefit Yearbooks (NDRC, 1998-2013), with linear extrapolation used to predict future trends (Table A.3). China-specific emission factors for direct and indirect N_2O emissions from cropland and manure were obtained from studies by Gao et al. (2011), Zhang et al. (2013) (Table B.1) and Wang et al. (2010). The CH4MOD model provided predicted CH_4 emissions from rice paddies; data originally compiled for the National GHG Emission Inventories (Zhang et al., 2011), and adjusted for rice cropping area in 2020. Estimated total manure production was based on regionalized manure excreta production per species derived by Wang et al. (2006), and share of liquid and solid manure reported by Hang et al. (2012). We estimated the rumen CH_4 production as well as CH_4 production from manure based on local Chinese emission factors (Fu and Yu, 2010).

An attempt to validate these data assumptions revealed a disparity between our GHG emissions estimates from enteric fermentation and manure management, and those produced for the China national inventory (NCCC, 2012). Since assumptions underlying the latter cannot be publically accessed, this study assumed a percentage increase of the baseline emissions from 2005 (stated by the national GHG inventory, NCCC, 2012) until 2020, which was observed in our estimation.

Other information required for baseline emissions compilation was selected from relevant literature and IPCC default values (Table B.2 and Table B.3) corresponding to conditions in China (Appendix B).

2.2. Screening mitigation measures

Through expert elicitation and literature review, we identified a long list of 32 technical mitigation measures applicable in Chinese conditions. The selection used the following screening criteria: (a) measures likely to reduce yields were excluded to be consistent with the national food security priority; (b) measures with limited applicability at the national level due to technical, political or obvious social barriers, were eliminated, e.g. rice-duck-fish integrated farming systems; (c) measures currently being practiced but increasing GHG emissions were removed, e.g. net emissions from direct straw return to rice paddies tend to be positive; (d) some detailed sub-sector measures were aggregated to account for measure interactions, e.g. water regimes should generally be coupled with fertilizer management practices in rice paddies. Measures selected for analysis are described in Table 1a and 1b.

2.3. Quantifying abatement rates

Based on China-specific experimental data, meta-analysis exercises were carried out to derive the annual abatement rates of some mitigation measures (Nayak et al., 2013a, 2013b; Saetnan et al., 2013). These data were further adjusted and to better accommodate additional experimental evidence outside the range of published studies and to partially internalize measure interactions (Appendix C). Abatement rates for different applicable crops/species were quantified to derive the weighted average abatement rates. Since mitigation can be achieved through both enhancing carbon sequestration in croplands/grasslands and reducing N_2O and CH_4 emissions, we evaluated the overall effects on soil organic carbon (SOC) and N_2O and CH_4 emissions from introducing each abatement measure against the baseline.

Table C.1 presents the direct N rate decrease induced abatement potential of measures C1, C2, C3 and C4, which were estimated employing emission factors (Table B.1), and the relationship between N fertilizer reduction and N_2O emissions reduction (Fig. C.1) drawn from site experiments (database from Nayak et al., 2013a). Abatement potentials of measures C1 and C2 (Table 1a) for rice, wheat and maize were aggregated from provincial level mitigation potentials (Table C.1). Abatement rates of other measures were generally countrywide estimates due to the lack of regional data. The abatement rate of measure C3 is the integrated effects of shifting from mid-season drainage (F-D-F) to an intermittent irrigation (F-D-F-M) regime and reduced N fertilizer rate. The abatement rate for C5 using enhanced efficiency fertilizers were based on global meta-analysis results (Akiyama et al., 2010). Original meta-analysis results of C6 were discounted because organic manure has already been applied to croplands in practice as opposed to the zero organic manure under controlled experiments. For measures L3-L8 we considered only the dominant ruminant and grazing species (beef cattle, dairy cow, sheep and goats), since the application of mitigation measures aiming to reduce rumen CH_4 (L3 – L5) or targeting carbon sequestration in grasslands (L6 – L8) would result in low mitigation potential for other large herbivores and non ruminants (i.e. poultry), and are therefore excluded. Since the dietary measures (L3 – L5) should be applied on a daily basis, we considered only housed animals for their application.

2.4. Measure implementation costs

Implementation costs (expressed as ¥ ha^{-1} for cropland and grassland measures and ¥ $animal^{-1}$ for livestock measures) were estimated by changes in yields, input costs (e.g. fertilizer, pesticide, seeds, feed additives), investment, labor, machinery and irrigation costs, compared to conventional practices where relevant. Costs represent direct costs to farmers in complying with a measure. Indirect and social costs/benefits are excluded from the analysis. The former include costs associated with changes in government subsidies and extension service improvement. Social costs refer to wider environmental impacts of implementing some measures (e.g. reduced water or air pollution).

A literature review and expert consultation were used to identify the on-farm implications and likely costs and benefits of mitigation practices. Typical agricultural inputs and output values for average showcase farms across China were obtained from data in the China Agricultural Products Cost-Benefit Yearbook (NDRC, 1998-2012). Yield effects of integrated nutrient management were drawn from Zhang et al. (2012a), although these were modified in this study since average yields are predicted to be higher in 2020 than in 2010 (Table A.1). Measure implementation also induces changes in agricultural inputs and production costs, which are summarized in Table 2a and 2b (See Table D.1 for detailed cost estimation and data sources). Annual growth rates of agricultural input prices for 2010-2020 are assumed to be half those over the period 2000-2010 (Table D.2) for two reasons. First, average grain sale prices to 2020 are predicted to grow at half the rate of 2000-2010 (Table A.1). Second, agricultural inputs prices are highly dependent on energy prices, which are anticipated to grow by 4-5% per year beyond 2010 compared with 10.8% during 2000-2010 (IEA, 2012). Measure lifetime costs were converted to 2010 present values using a social discount rate of 7%.

2.5. Measure adoption under BAU and abatement scenarios

Abatement scenarios to 2020 are additional to BAU or baseline activity (Fig. 1). But the actual mitigation extent depends on behavioral, political and market constraints that effect measure uptake. BAU uptake scenarios (Table D.1) were derived with reference to either relevant policy targets or historical trends; those under the abatement scenario were derived from expert judgment, scientific literature, and applicability of the specific measure.

Crop and soil measures C1, C2 and C4 are assumed to be applicable in provinces and municipalities with lower Nitrogen Partial Factor of Productivity (PFP_N) than target levels (Table C.1).

Changes in water regime patterns in rice paddies (measure C3) referred to results in Zou et al. (2009) and Zhang et al. (2011). Baseline extension areas of high-efficient irrigation systems (C4), conservation tillage (C7) and straw returning (C8) correspond to explicit targets set in the National Agricultural Water-Saving Outline (2012-2020) (State Council, 2012), the National Agriculture Mechanization Extension Plan (2011-2015) (MOA, 2011), and the Implementation Plan on the Comprehensive Use of Crop Straw during the 12th FYP Period (NDRC, 2011a).

Baseline application areas for grazing bans (L6), and reduced grazing intensity (L7 and L8) were based on historical rates of seasonal bans, rotational grazing, and prohibited grazing, stated in the Report on the State of the Environment of China (MOEP 2005 – 2011), and policy targets set out in (MOA, 2006). We assumed that the majority of Chinese grazed grasslands are under heavy grazing pressure. Medium grazing intensity and low grazing intensity refer to grassland utilization rates of 50% and 35%, respectively (Patton et al., 2007). BAU application and additional application potential for anaerobic digestion (L1) are based on MOA (2007), NDRC (2007) and Zhang et al. (2012b). The additional application potential of the dietary mitigation measures (L3 – L5) are based on literature review and expert judgment (See a detailed summary on baseline and adoption rates in Table D.3).

2.6. Measure interactions

The stand alone abatement rate and CE of one measure may change when applied in combination with others. For crop measures, interactions are addressed by assigning implementation priorities to selected mitigation options. These were determined using expert input. For example, if measure C1 and C2 allow N application rates to decrease from 300 kg ha^{-1} to 200 kg ha^{-1}, the mitigation effect of adding nitrification inhibitors (measure C5) will be based on the N rate of 200 kg ha^{-1}. The potential of adding organic manure to rice paddies (measure C6) was quantified under the intermittent water regime (F-D-F-M) realized through measure C3.

Further adjustments were also made to accommodate potential overlapping application of measures with similar effects (e.g. organic manure and biochar) or subordinating relationships (e.g. conservation tillage and straw returning). Further, the efficacy of increasing organic manure to lands will be discounted when applied jointly with conservation tillage or straw returning, all of which achieve mitigation through carbon sequestration in soils. We therefore assign an interaction factor (0.8) to the stand-alone abatement rates of the three measures on wheat and maize areas. We assume that measure interactions shall not affect the implementation costs of measures.

All three grassland (L6 – L8) and dietary mitigation options (L3 – L5) are mutually exclusive. Lacking more detailed data, we assume that grazing controls or intensities are implemented in approximately 1/3 of the total grazed grassland in China. Applications of multiple feed additives have no additive effect on emissions or productivity. Hence, multiple dietary mitigation options will not be applied simultaneously. To avoid double counting, an equal application of each of the 3 dietary mitigation options is assumed; i.e. all livestock receive only one feed additive.

2.7. MACC derivation

In the livestock, cropland and grassland sector, the CE (¥ tCO_2e^{-1}) of a measure was calculated by dividing the weighted mean cost (¥ ha^{-1} yr^{-1} or ¥ $animal^{-1}$ yr^{-1}) by the average abatement rate (tCO_2e ha^{-1} yr^{-1} or tCO_2e $animal^{-1}$ yr^{-1}), and its total mitigation potential volume was computed from per unit abatement rate and additional application area or head of population. Mitigation options were represented by bars on the plot in order of CE on the x-axis and the bar width denotes the annual mitigation potential of the specific measure. Abatement scenarios up to 2020 were drawn assuming measures adopted at a linear rate over time. This assumption initially allows us to side-step a range of potential policy scenarios and instruments incentivizing uptake.

3. Results

3.1. Baseline agricultural GHG emissions

Fig. 2 shows that GHG emissions will continue to increase from both crop fields and livestock. Baseline GHG emissions are predicted to reach 1195 MtCO_2e in 2020, a 28.6% increase from 2010 levels. Cropland GHG emissions are predicted to be 422 Mt CO_2e in 2020. N_2O emissions from croplands see significant growth by 18.5% between 2010 and 2020 driven by increasing synthetic N fertilizer application. In contrast, a declining trend is observed for CH_4 emissions from rice paddies due to improved water regimes. Livestock GHG emissions are 742 Mt CO_2e in 2020, an increase of 51% compared to 2005 levels (NCCC, 2012).

The Second National GHG Inventory reported 208 MtCO_2e emissions from cropland (N_2O) and 143 MtCO_2e from rice paddies (CH_4), excluding CH_4 emissions from winter-flooded paddy fields in 2005, using 310 and 21 as the Global Warming Potential (GWP) of N_2O and CH_4 (NCCC, 2012). Our estimates of 188 MtCO_2e N_2O emissions and 164 MtCO_2e CH_4 emissions are comparable to these data and differences can be attributed to different GWPs.

3.2. Mitigation potential and measure CE

Mitigative effects and stand-alone abatement rate of mitigation measures are summarized in Table 2 and

Table 4 (a, b). For arable land, average abatement rates range from 0.201 $tCO_2e\ ha^{-1}$ from further N rate reduction in wheat and maize fields, to 1.337 $tCO_2e\ ha^{-1}$ delivered by improved fertilization and irrigation regimes in rice paddies. High mitigation benefits can be achieved through best nutrient management practices in cash crop fields where N overuse and misuse is prevalent (Zhang et al., 2012a). For livestock, tea saponin and lipid addition show abatement rates with reduced rumen CH_4 by 15% per animal (Table 4). The abatement rates for grassland measures are large compared to cropland measures with 1.07, 0.88, and 0.71 t $CO_2e\ ha^{-1}$ for grazing ban, light grazing intensity (LGI) and medium grazing intensity (MGI), respectively (Table 4).

Implementation costs, CE and overall annual abatement potential of mitigation measures (incorporating measure interactions) for 2020 are also summarized in

Table 5. The most CE arable measures with highest mitigation potential are N fertilizer best management practices, which provide over 40% of cropland abatement potential. Although more efficient recycling of organic manure to croplands also offers significant potential, substantial commercial 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_2e^{-1}. In contrast, the relatively low potential of conservation tillage can be attributed to significant measure uptake under the BAU scenario due to policy enforcement, leaving limited scope for additional application.

Significant negative cost livestock measures are supplementary feeding of probiotics and tea saponins, breeding measures, and biomass gasification; the latter generating the highest GHG reduction. Medium grazing intensity also accounts for a large abatement potential, available at relative low cost of 64 ¥ tCO_2e^{-1}. Despite showing a large GHG reduction potential, supplementary lipid feed supplement is expensive with CE of 1950 ¥ tCO_2e^{-1} (Table 4).

3.3 Technical and economic abatement scenarios

The MACC (Fig. 2 and 3) shows that under the maximum technical abatement scenario for 2020 emission reduction amount to 402 $MtCO_2e$, representing 34% of BAU emissions. 149 and 253 $MtCO_2e$ emissions could be avoided from croplands and livestock/grasslands, respectively. Without accounting for carbon sequestration in soils, the overall mitigation potential will stand at 207 $MtCO_2e$ (Fig. 2). The results suggest that there is significant potential for win-win abatement avoiding emissions while providing financial savings. Fig. 2 and 3 illustrate that at national scale about 135 $MtCO_2e$ emissions could be abated at negative costs, equivalent to 11% of baseline emissions in 2020. If fully implemented, these win-win measures result in savings of ¥ 111 billion (2010 price) for farmers. This analysis does not account for ancillary impacts such as reduced fertilizer production, government subsidies, or reduced environmental impacts. The analysis also shows that 176 $MtCO_2e$ (approximately 44% of the total potential) emissions can be realized at a carbon price less than ¥ 100 per tCO_2e.
The most cost-beneficial measures are a) probiotics addition to the diet, b) fertilizer best management practices, c) animal breeding, and d) conservation tillage for upland crops. The MACC results highlight the importance of improved N fertilizer and manure management practices coupled with improved irrigation systems.

4. Discussion and conclusions

Estimates presented here represent the first attempt to derive a bottom-up abatement potential for the agricultural sector in China, and have been conducted using a number of necessary data, assumptions and experimental evidence that may not always reflect the real biophysical heterogeneity in Chinese systems. These include the assumptions about baseline activity projections (including input and output prices), measure abatement rates and their implementation costs. But the MACC exercise aims to make these assumptions transparent and therefore provides a basis for on-going improvement of technical and economic mitigation estimates. We also suggest that the estimates provide useful pointers for both policy and research to realize the indicated potentials.

The observation of low and negative cost potential raises several behavioural and institutional issues, some of which have been addressed in relation to mitigation studies conducted elsewhere (Moran et al., 2013; Zhang et al., 2013), some of which are specific to the structure of Chinese agriculture and its role in national policy on both food security and rural development.

Although implementation of many mitigation measures could improve farm incomes, there are several possible explanations to why these apparently unrealized savings exist. First, farmers have entrenched views on the links between inputs and yields (Wu et al., 2011) and are generally risk-averse faced with new technologies and practices. Second, given the small scale of Chinese farms, savings from rationalizing N application rates are perceived to be relatively insignificant by farmers, particularly when fertilizer prices are kept low by subsidies (Zhang et al., 2013) that serve to maintain smallholder production. Third, increasing rural labor shortages raise the perceived opportunity cost of any time required for mitigation activities. Fourth, weak agricultural infrastructure and poor rural extension services are a hindrance to measure adoption. For example, although scientifically justified fertilizer recommendations have been developed for major crops and cropping systems (Zhang et al., 2009), the absence of good extension advice hinders information dissemination to millions of smallholder farms that constitute 90% of the sector. These farms are widely distributed, with low levels of mechanization. Equally, the poor supply of artificial insemination services to livestock farmers can be attributed to large distances between farms. A solution for this would be the implementation of a tight grid of breeding farms to cover the whole country. Alternatively, the challenge of implementing more efficient and environmentally sound practices could be solved by the consolidation of agricultural land and more ambitious government investment in infrastructure.

Beyond these challenges, the MACC results also highlight the significance of livestock emissions and potential in the analysis. An observation from policy statements is that Chinese policy makers tend to ignore the role of livestock in GHG mitigation. But since the sector will continue to extend its role as largest source of GHG emissions in Chinese agriculture, it is important to focus on this sector for extensive mitigation strategies. In line with the trend of shifting from small scale and outdoor livestock production to large scale indoor systems, the focus should therefore be on biomass gasification (L1), breeding techniques and advanced feeding technologies as tea saponins (L4), which will be most applicable for housed livestock (Grainger and Beauchemin, 2011). It is expected that this trend together with application of these technologies will increase productivity/profitability significantly, and hence be part of the solution to cope with the rapidly increasing demand for livestock products in China and shifting China's role from a net importer to an exporter of livestock products (Jouany and Morgavi, 2007).

The MACC suggests other numerous research priorities in terms of tailoring practices to local biophysical conditions, thus allowing a more accurate estimate of measure CE. The Chinese government has already initiated programs to improve domestic research in the field of climate change mitigation and agriculture. For example, the ongoing research project "Integration and demonstration of key carbon sequestration and mitigation technologies in agricultural ecosystems" accredited by the Chinese Ministry of Science and Technology for the 12th FYP period, aspires to identify appropriate mitigation measures for major cropping systems, to quantify abatement rates and to model mitigation potential at the regional scale.

More broadly, the economic potential identified is timely and potentially paves the way for identifying an agricultural contribution to national GHG reduction targets, either through offsetting projects, or eventually as part of other trading arrangements. The government has designated five cities (Beijing, Tianjin, Shanghai, Chongqing, and Shenzhen) and two provinces (Guangdong and Hubei) as the pilots to test carbon emission trading in October 2011 (NDRC, 2011b), and in June 2012, the Interim Voluntary Emission Reduction (VER) Rules (NDRC, 2012) were officially published to provide basis for project-based offset markets in China. The progress of domestic trading in China remains to be seen, although some commentators suggest that successful implementation could be a highly significant development in the path towards a global carbon market. The role of agriculture in the regime has not yet been discussed, although there are well-known obstacles in terms of monitoring, reporting and verification of emissions. Despite this, the MACC provides an initial indication of priority interventions for the design of efficient policy.

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Table 1a Explanation of crops/soils mitigation measures

No.	Measure	Explanations	Target crops
C1	Fertilizer best management practices - Right rate	Reduce gross overuse of N fertilizers amount. We set regional optimal PFP_N* (Partial Factor Productivity of N fertilizer) derived from scientific fertilization recommendations (Zhang et al., 2009) as the indicator for fertilizer efficiency improvement objectives. This measure calls for a direct reduction in N fertilizer use for certain crops in targeted provinces to raise regional PFP_N to 70% of the optimal levels (Table C.1).	Rice, wheat, maize, vegetable, fruit
C2	Fertilizer best management practices (Wheat &Maize) - Right time and right placement	This strategy suggests postponing N fertilizer to a later stage of wheat and maize growth with preferably two top-dressings compared to the current one top-dressing practice, and popularizing fertilizer deep placement by using appropriate machines for maize top-dressing, in a bid to reach optimal PFP_N (or optimum N management) by increasing yield and reducing N losses and further decreasing N rate(Table C.1).	Wheat, maize
C3	Fertilizer and water best management in rice paddies	Split the total amount of N fertilizers into at least three applications for basal fertilization, early tillering, panicle initiation and heading stages; and shift from mid-season drainage (F-D-F) to intermittent irrigation (F-D-F-M).	Rice
C4	Fertilizer best management practices (cash crops) - Right products, right time and right placement	Promote fertigation (e.g. drip irrigation together with soluble fertilizers) for vegetables and cotton to save both fertilizer and irrigation inputs. As to fruits, controlling N rate and adjusting fertilization periods are essential to achieve sustainable fruit production. In addition, replacing part of ammonium-based fertilizers with nitrate-based products can also contribute to minimizing N_2O emissions and enhancing productivity.	Cotton, vegetable, fruit
C5	Enhanced-efficiency fertilizers	Use fertilizers added with nitrification inhibitors (NI) and/or urease inhibitors (UI) and slow- and controlled-fertilizers to reduce N_2O emissions.	All crops, vegetable, fruit
C6	More efficient recycling of organic manure	The general objective is to increase animal manure amendment to soils to supply 30% of crop N nutrients demand and 50% of vegetables and fruit. Efficient recycling of animal manure should be in form of composed manure or biodigester residues to replace part of synthetic N fertilizers.	All crops, open field vegetable, fruit
C7	Conservation tillage for upland crops	Conservation tillage (CT) is a series of agricultural practices aiming to reduce tillage and soil disturbance to a minimum extent with at least 30% of residues incorporated into soil to increase soil carbon content in upland cropping systems.	Wheat, maize
C8	Straw return in upland crops	Returning straw or residue back to field is considered a stand-alone farming practice in China which only involves changes in straw management compared with CT measure. This technique is an important way to improve soil fertility and soil physical properties if properly tailored to different cropping systems and local farming practices.	Wheat, maize
C9	Biochar addition	Application of biochar produced with crop straw pyrolysis can significantly decrease N_2O emissions and improve soil prosperities to enhance yields.	Rice, wheat, maize

* PFP_N -Partial Factor Productivity of N fertilizer is an indicator of N use efficiency, measured by the grain yield per N input (kg kgN^{-1})

Table 1b Explanation of livestock and grassland mitigation measures

No.	Measure	Explanations	Target species
L1	Anaerobic digestion of manure	Implementation of on farm anaerobic digesters for storing livestock manure residues and converting some of the organic content to CH_4. CH_4 can be burned to produce heat or electricity for the livestock farm or sold to other consumers.	Cattle, dairy cows, pigs, poultry
L2	Animal breeding	Breeding techniques like artificial insemination of domestic livestock with high quality semen from breeding stock will generate a trade-off between decreasing rumen CH_4 production and improved feed intake, milk production, weight gain and production efficiency. This measure does not consider cross breeding.	Indoor - cattle, dairy cows, pigs, sheep, goat
L3	Tea saponins addition to the diet	Tea saponins are plant secondary compounds that are available in highly concentrated form in waste by products of tea production. Adding tea saponins to the diet of livestock is considered to increase the productivity while reducing rumen CH_4 production.	Indoor - cattle, dairy cows, sheep and goat
L4	Probiotics addition to the diet	Probiotics are commonly used in Chinese aquaculture industry but the application is uncommon for terrestrial livestock. Adding probiotics to the diet modifies the rumen ecosystem and thereby reduce the CH_4 production as well as improve the animal productivity and immune response.	Indoor - cattle, dairy cows, sheep and goat
L5	Lipid addition to the diet	Adding polyunsaturated fatty acids to the diet of livestock can effectively reduce the CH_4 production through suppression of rumen protozoa and inhibition of methanogens in the rumen and increase the productivity of the animal.	Indoor - cattle, dairy cows, sheep and goat
L6	Grazing prohibition for 35% of grazed grasslands	Grazing ban is a common technique in grazing systems for improving degraded grasslands. This measure considers a ban of 35% of the total grazed grassland in China. While the vegetation type is recovering, the dry matter production is improving. The grass will not be cut and thus grass residues can enter the soil to improve the soil organic matter content and increase the carbon sequestration rate.	Grazing - cattle, dairy cows, sheep and goats
L7	Reduction of stocking rate - medium grazing intensity	Chinese grasslands are usually overgrazed. This measure considers a stocking rate reduction to a medium intensity. While the grassland condition is improving, the dry matter production of the grasslands would increase by 10%. The grassland utilization rate is reduced to 50% and thus the higher amount of organic material entering the soil will increase the carbon sequestration rate.	Grazing - cattle, dairy cows, sheep and goats
L8	Reduction of stocking rate - light grazing intensity	This measure considers a light grazing intensity on Chinese grasslands. As a result the grassland utilization rate is reduced to 35% and the dry matter production increases by 3%. Similar to L9, the carbon sequestration rate increases due to a higher organic matter input to the soil.	Grazing - cattle, dairy cows, sheep and goats

Table 2a Cost considerations of cropland measure implementation

Measure No.	Target crops	Cost consideration factors (2010 level per hectare per cropping season)						Incurring frequency
		Fertilizer rate* and price	Labor (mandays)	Machinery	Irrigation	Other costs	Yield	
C1	Cereal crops	N rate: rice -15% wheat- 31% maize-16%						Cropping season
	Cash crops	N rate: greenhouse veg. -15% openfield veg. -10% fruit-15%						Cropping season
C2	Wheat	N rate: -20%	+7.5				+5%	Cropping season
	Maize	N rate: -18%		¥225			+8%	Cropping season
C3	Rice	N rate: -20%	+15		-20%		+5%	Cropping season
C4	Vegetable	N rate: greenhouse -27%; openfield -24%. Nitrate-based fertilizer (10kg N) price:+60% higher	-15		-40%	Drip irrigation ¥3000; agri. film ¥1000	+10%	Cropping season
	Fruit	N rate: -30%. 17kgN price:60% higher	+45				+10%	Annual
	Cotton	N rate: -33%. 17kgN price:60% higher	-30		-40%	Drip irrigation ¥3000; agri. film¥1000; pesticide -30%	+10%	Annual
C5	All crops	N fertilizer price: 10% higher						Annual
C6	Cereal crops	N rate: rice -11% wheat- 10% maize -9%. Organic manure†: +1.6-2 t/ha at ¥500/t	+7.5					Annual
	Openfield vegetable	N rate: -7%. Organic manure:+1.52 t/ha	+7.5					
	Fruit	N rate:-11%. Organic manure:+5.16 t/ha	+15					
C7	Wheat, maize		-30%	-20%		Seed +10%; pesticide+30%		3 years or 4 years
C8	Wheat, maize	+30kg/ha		¥300		Seed +10%; pesticide+30%		Cropping season
C9	Rice, wheat, maize	20t/ha at ¥1000 /t biochar	+15				+10%	Every 5 years

* N rates in the table are those in measure target regions or balanced N application rates.
† Here the N content in typical organic manure fertilizers stands at 1.2%.

Table 3b Cost considerations of livestock measure implementation

Measure No.	Target animals	Cost consideration factors (2010 level per sheep unit per year)				Application rate
		Investment costs (year^{-1})	Administration cost	revenue	Yield increase (head^{-1})	
L1	Cattle, dairy cows, pigs, sheep, goat, , poultry	¥3250	not available	¥500/year		Every 15 years
L2	Indoor - cattle, dairy cows, pigs, sheep, goat	¥60/head	¥20/head		1%	Annual
L3	Indoor - cattle, dairy cows, pigs, sheep, goat	¥1/head	¥2/head/year		3-4%	Daily
L4	Indoor - cattle, dairy cows, sheep, goat	¥18/head	¥2/head/year		6%	Daily
L5	Indoor - cattle, dairy cows, sheep, goat	¥219/head	¥2/head/year		2-4%	Daily
L6	Grazing - cattle, dairy cows, sheep, goats	*	*		1%†	Annual
L7	Grazing - cattle, dairy cows, sheep, goats	*	*		10%†	Annual
L8	Grazing - cattle, dairy cows, sheep, goats	*	*		3%†	Annual

* We assume free grazing on pasture which is most common in Chinese grassland systems. Additionally, we do not assume construction of new warm shed since the Chinese government increases the housing capacities strongly each year. Therefore, only costs regarding additional feeding and running housing facilities are applied.
† Increase of DM production /ha based on Patton et al. (2007).

Table 4a Mitigative effects and stand-alone abatement rates of cropland mitigation measures

Measure No.	Mitigative effects			Stand alone abatement rate ($tCO_2e\ ha^{-1}$)							
	N_2O	CH_4	SOC	Rice	Wheat	Maize	Other upland crops	Greenhouse vegetable	Openfield vegetable	Fruit	Averaged
C1	-			0.075	0.351	0.406		1.225	0.505	1.266	0.412
C2	-				0.190	0.208					0.201
C3	-	-		1.337							1.337
C4	- +						0.903 (cotton)	1.376	0.829	1.827	1.219
C5	-			0.127	0.273	0.256	0.274	0.667	0.369	0.616	0.271
C6	+	+*	+	0.460	0.689	0.574	0.631		0.227	0.462	0.596
C7	+		+		0.611	0.611					0.611
C8	+		+		0.263	0.263					0.263
C9	-		+	0.187	0.364	0.342					0.329

Notes: + denotes reduced emissions or enhanced removal (positive mitigative effect);

- denotes increased emissions or suppressed removal (negative mitigative effect);

* Here CH_4 emissions increase is only applied to rice paddies.

Table 3b Mitigative effects and stand-alone abatement rates of livestock mitigation measures

Measure No.	Mitigative effects			Abatement rate (per year)							
	N_2O	CH_4	SOC	Cattle (% hd^{-1})	Dairy cow (% hd^{-1})	Pig (% hd^{-1})	Sheep (% hd^{-1})	Goat (% hd^{-1})	Average (% hd^{-1})	Grassland ($tCO_2e\ ha^{-1}$)	Anaerobic digester (tCO_2e $digester^{-1}$)
L1	+	+									2
L2		+		-11	6	4	8	8	4		
L3		+		12	15		17	17	15		
L4		+		-0.2	0.3		1	1	1		
L5		+		8	6		4	4	4		
L6	+	+	+							1.07	
L7	+	+	+							0.70	
L8	+	+	+							0.88	

Table 5 Average abatement rate, cost, CE and mitigation potential of mitigation measures

Measure No.	Abatement rate (in 2020) (tCO_2e ha^{-1})	Abatement rate (in 2020) (CO_2e reduction in % SU^{-1})	Cost (in 2020) (¥ ha^{-1}, 2010 price)	Cost (in 2020) (¥ SU^{-1}, 2010 price)†	Cost effectiveness (in 2020) (¥ tCO_2e^{-1}, 2010 price)	Additional application (in 2020) (M ha)	Mitigation potential (in 2020) (MCO_2e)
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*		-500*		-32	‡	58.66
L2		4.1		-29	-2571	‡	4.4
L3		15.4		-3.4	-56	‡	5.53
L4		0.6		-17	-7079	‡	1.09
L5		14.3		109	1950	‡	30.76
L6	1.067		300		281	56.98	60.78
L7	0.705		45		64	57.85	40.77
L8	0.877		283		322	57.85	50.72

* Per anaerobic digester

† 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, pig: 0.8. It is only an approximate simplification and normally applied in grazing systems. Hence the costs SU^{-1} should be interpreted with caution.

‡ See Annex Table A.10 for application potential

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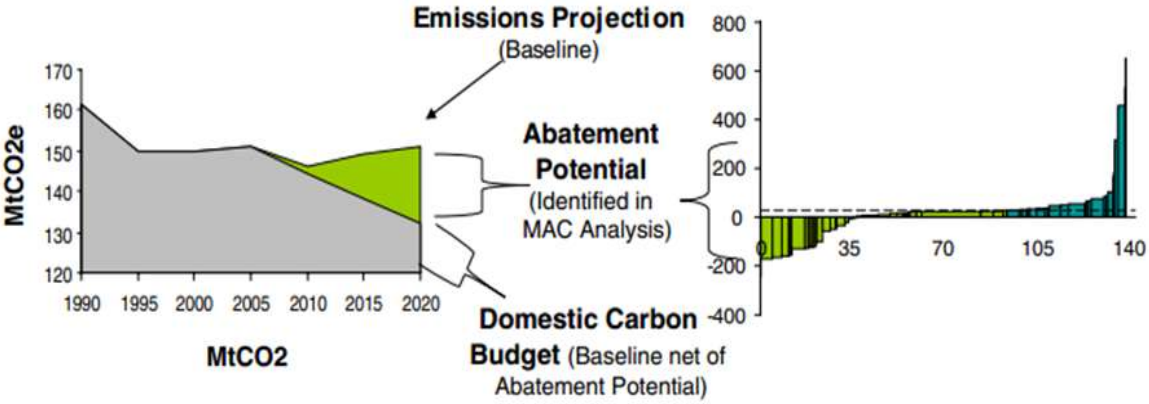

Fig.1 Illustration of the national economic abatement potential derived by the MACC exercise (left) and a “bottom-up” MACC showing its relationship to a sector carbon budget (right side). Source: Moran et al. (2011)

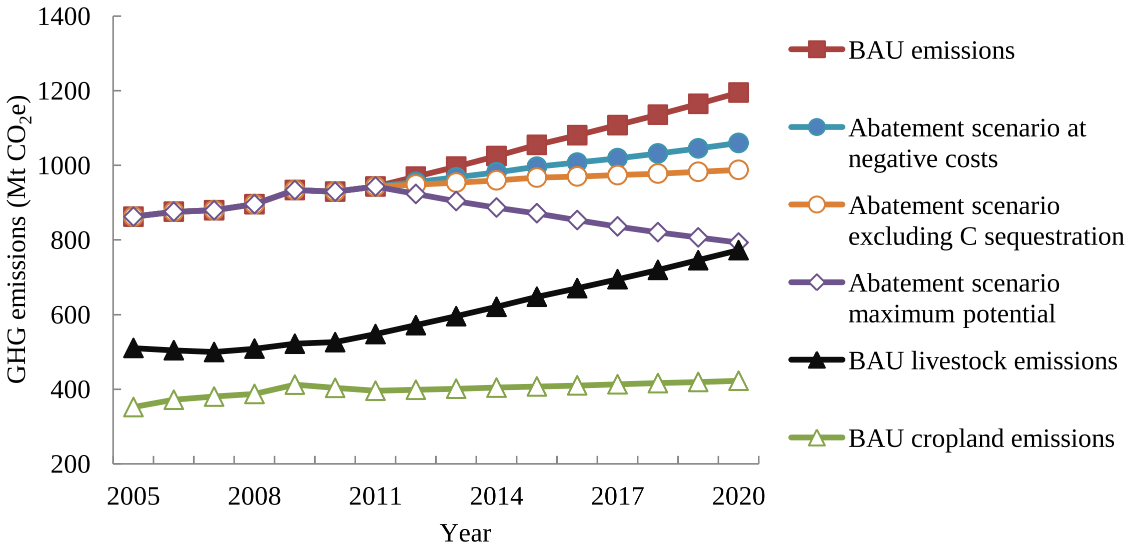

Fig. 2 Projected BAU and abatement emissions scenarios. BAU emissions are the sum of soil N_2O emissions, rice CH_4 emissions, ruminant CH_4 emissions and waste management N_2O and CH_4 emissions. Mitigation potentials at maximum feasible application, negative cost scenarios and the scenario excluding carbon sequestration were identified from data in Fig. 3 assuming a linear adoption over time.

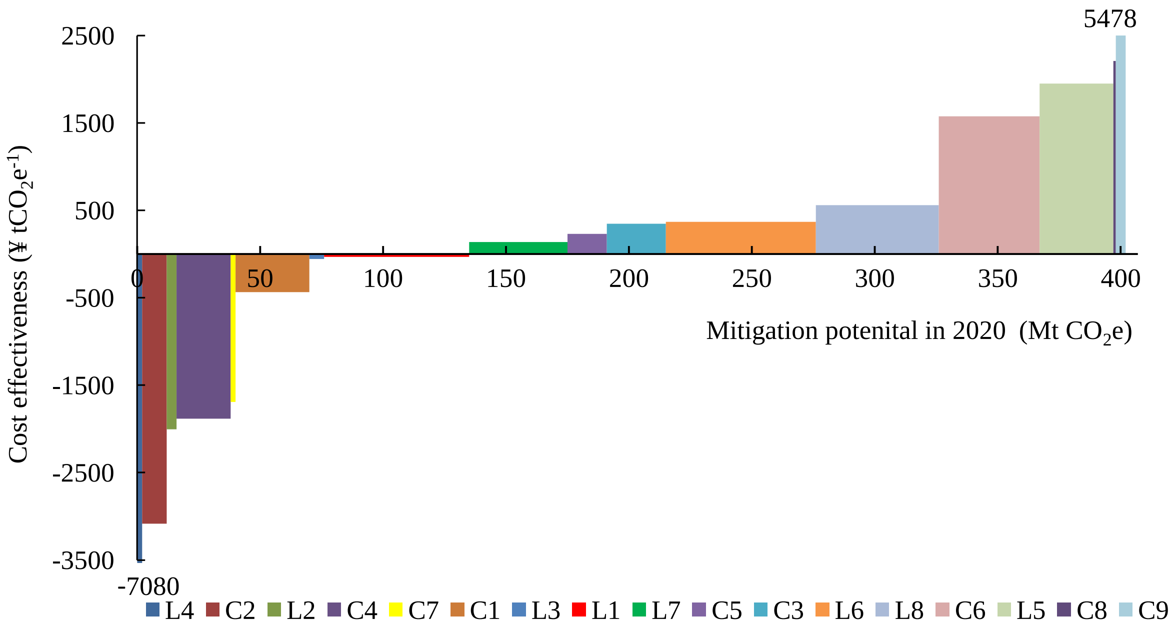

Fig. 3 MACC for China agricultural sector: maximum feasible abatement potential in 2020 (discount rate = 7%). Measures codes refer to measures in Table 1: L4- Probiotics addition to the diet; C2- Fertilizer best management practices (Wheat &Maize) - Right time and right placement; L2- Purebred breeding of livestock; 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; L3- Tea saponins addition to the diet; L1- Anaerobic digestion of manure; L7-Reduction of stocking rate - medium grazing intensity; C5- Enhanced-efficiency fertilizers; C3- Fertilizer and water best management in rice paddies; L6- Grazing prohibition for 35% of grazed grasslands; L8- Reduction of stocking rate - light grazing intensity; C6- More efficient recycling of organic manure; L5- 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_2e reduced (height of bar), and the quantity of emissions CO_2e reduced (width of bar). Measures below the x axis are cost negative – i.e. removing emissions and saving money.

Appendix A Past and Predicted future agriculture activities

Table A.6 Past and predicted future agriculture activities (crops)

Crops	Cropping area(kha)			Production (kt)			Yield (t ha^{-1})			Price (¥ kg^{-1})			
	2010	2020*	Annual change	2010	2020*	Annual change	2010	2020*	Annual change	2010	2020	Original CAPSiM annual change*	Adjusted by inflation (+2%)†
Rice	29,873	25,612	-1.5%	195,761	176,823	-1.0%	6.55	6.90	0.5%	2.36	3.02	0.7%	2.5%
Wheat	24,257	22,099	-0.9%	115,181	113,260	-0.2%	4.75	5.13	0.8%	1.98	2.46	0.4%	2.2%
Maize	32,500	35,361	0.8%	177,245	221,882	2.3%	5.45	6.27	1.4%	1.87	3.13	3.5%	5.3%
Soybean	8,516	8,223	-0.3%	15,083	16,549	0.9%	1.77	2.01	1.3%	3.87	5.46	1.7%	3.5%
Cotton	4,849	5,168	0.6%	5,961	7,503	2.3%	1.23	1.45	1.7%	24.77	26.28	-1.1%	0.6%
Oils	13,890	14,613	0.5%	7,106	8,757	2.1%	0.51	0.60	1.6%	5.25	8.50	3.1%	4.9%
Sugar	1,905	1,837	-0.4%	14,199	15,297	0.7%	7.45	8.33	1.1%	0.45	0.68	2.3%	4.1%
Total vegetable	19,000	19,040	0.0%	650,994	785,748	1.9%	34.26	41.27	1.9%	1.56	2.21	1.7%	3.5%
Greenhouse vegetable‡	3,553	3,560	0.0%	162,749	196,437	1.9%	45.81	55.17	1.9%	1.98	2.81	1.7%	3.5%
Openfield vegetable‡	15,447	15,479	0.0%	488,246	589,311	1.9%	31.61	38.07	1.9%	1.42	2.01	1.7%	3.5%
Fruit	11,544	11,668	0.1%	128,652	176,712	3.2%	11.14	15.14	3.1%	3.54	4.72	0.9%	2.9%

* Future cropping area, production, yield and agricultural price change (with variations among years) were direct modeled results of CAPSiM.

† Since inflation is not an element considered in the CAPSiM model, here we adjusted price variation rate by assumed annual inflation at +2% (+2.1% during 2001-2010).

‡ CAPSiM model gives information on total vegetable; here we split into greenhouse and openfield vegetables to facilitate subsequent mitigation potential analysis. We assume that greenhouse vegetable accounts for 18.7% and 25% of total vegetable cropping area and production, respectively, from 2005 to 2020 (Wang et al., 2010).

Table A.7 Past and predicted meat production and livestock numbers

CAPSiM results on production (kt) *			Livestock population (1000 heads) †			
	2010	2020			2010	2020
Beef	4,571	7,330	Stock population	Non-dairy cattle	92,063	147,617
Milk	37,480	60,952		Milk cows	14,201	23,095
Mutton	3,390	4,921		Sheep+goats	280,879	407,711
				Horses	6,771	6,771
				Asses	6,397	6,397
				Mules	2,697	2,697
Pork	43,877	56,137	Slaughter population‡	Pigs	666,864	853,203
Poultry	14,905	20,607		Chicken (Poultry: hens=1:1)	11,005,780	14,297,441
Eggs	19,015	23,201				
				rabbits	454,455	740,259

* Data used in the CAPSiM model are not completely in consistent with those in the China Rural Statistic Yearbooks. Population of horses, asses and mules is assumed to be stable according to historical trends and rabbit population shall grow by 5% annually.

† Predicted livestock numbers (from 2011 onwards) are calculated using relevant product growth rates assuming per head production remain constant to 2020 as in 2010.

‡ Use slaughter population for pigs, chickens and rabbits since they are alive for only part of a complete year before slaughtering.

Table A.8 Total N fertilizer use in agriculture and national average application rate

	2005	2010	2015	2020
National total N fertilizer use (kt)	29,761	32,599	35,172	36,967
N fertilizer rate(kg ha^{-1})	2005*	2010*	2015†	2020†
Rice	190	187	182	177
Wheat	189	209	219	238
Maize	186	208	211	221
Soybean	49	54	53	53
Cotton	235	246	237	237
Oils	116	125	123	123
Sugar	256	347	322	322
Total vegetable	298	368	335	336
Greenhouse vegetable‡	581	719	655	656
Openfield vegetable‡	232	288	262	262
Fruit§	357	492	507	565
% of total N consumption	2005	2010	2015	2020
Rice	18.4%	17.2%	13.8%	12.3%
Wheat	14.5%	15.6%	14.2%	14.2%
Maize	16.5%	20.7%	20.4%	21.2%
Soybean	1.6%	1.4%	1.3%	1.2%
Cotton	4.0%	3.7%	3.4%	3.3%
Oils	5.6%	5.3%	5.0%	4.9%
Sugar	1.3%	2.0%	1.6%	1.6%
Total vegetable	17.7%	21.5%	18.2%	17.3%
Fruit	11.4%	16.5%	15.9%	16.8%

* N fertilizer application rates of different crops were collected from the China Agricultural Products Cost-Benefit Yearbooks (NDRC, 1998-2013), and we adopted N fraction of 30% in the reported compound and mixed fertilizers (Sun and Huang, 2012).

† Extrapolation of future N fertilizer rates were based on 2005-2011 data for rice, wheat and maize，1998-2011 data for fruits and vegetables, and average of 2006-2011 data for other crops.

‡ According to survey results (Chadwick et al., 2013; Zhang et al., 2013), N application rate for greenhouse vegetables is generally about 2-3 times as that for openfield vegetables (here we assume 2.5 times).

§ Due to lack of data for other fruits, we used average fertilizer rate of apple, mandarin and orange to represent general fruits.

Appendix B Projections of N_2O emissions from Chinese croplands under the BAU scenario

We followed IPCC 2006 Guideline to estimate baseline N_2O emissions related to crops and soils in China in 2020. We considered both direct and indirect N_2O emissions from the three major N input sources-synthetic fertilizers, organic manure and crop residues, which are consistent with the National GHG Inventories (NCCC, 2004, 2012). The calculation was conducted following Eq. (B.1).

$$\begin{aligned}
&Emissions_{N_2O} = N_2O-N \times EF = N_2O-N \times (EF_{direct} + EF_{indirect}) \\
&N_2O-N = F_{SN} + F_{AW} + F_{CR} \\
&EF_{direct} = N_2O \times EF_1 \times 44/28 \times GWP_{N_2O} \\
&EF_{indirect} = (Frac_{GAS} \times EF_4 + Frac_{LEACH} \times EF_5) \times 44/28 \times GWP_{N_2O}
\end{aligned} \quad \text{(B.1)}$$

$Emissions_{N2O}$ is the N_2O emission from rice paddies or upland fields (Mt CO_2e). F_{SN}, F_{AW}, F_{CR} represent N inputs from synthetic fertilizers, animal manure and crop residues (Mt N). EF_1, EF_4, EF_5 are the emission factors for N_2O emissions from N inputs, N volatilization, and N leaching and runoff, respectively. GWP_{N2O} is the direct Global Warming Potential (GWP) of N_2O at the 100yr horizon, 298. $Frac_{GAS}$ and $Frac_{LEACH}$ are fractions of N that are lost through atmospheric deposition of N volatilised and leaching or runoff. Refer to Table B.1 for results of EF_{direct} and $EF_{indirect}$ and selection of EF_1, $Frac_{GAS}$, EF_4, $Frac_{LEACH}$ and EF_5.

F_{SN} for rice paddies were estimated by multiplying rice N fertilizer rate (Table A.8) by rice cropping area (

Table A.6), and we got F_{SN} for upland crops by subtracting F_{SN}-rice paddies from total synthetic N fertilizer consumption.

F_{AW} was estimated following Eq. (B.2).

$$F_{AW} = \sum_T N_T \cdot (1 - Frac_{Grazing(T)}) \cdot Nex_T \cdot (1 - Frac_{Loss(T)})$$

$$Nex_T = N_{rate(T)} \cdot \frac{TAM_T}{1000} \cdot 365 \qquad \text{(B.2)}$$

$$N_T = Days\_alive_T \cdot \frac{N_{S(T)}}{365} \quad if \quad Days\_alive_T < 365$$

N_T is annual average population of livestock T (use stock number if average breeding days is more than a complete year). $Frac_{Grazing(T)}$ is the fraction of grazing population of livestock T (%). Nex_T is annual N excretion for livestock category T (kg N animal^{-1} yr^{-1}). $Frac_{Loss(T)}$ is the amount of managed manure nitrogen for livestock category T that is lost in the manure management system S (%). $N_{rate(T)}$ is the default N excretion rate (kgN (1000 kg animal mass$)^{-1}$ day^{-1}). TAM_T denotes typical animal mass for livestock category T(kg animal^{-1}). $Days\_alive_T$ is the average growth days before slaughtering. $N_{S(T)}$ is the slaughtered number of livestock T in average. Selected default values for parameters in Eq. B.2 are summarized in

Table B.2. According to survey results (Huang and Tang, 2010; Zhang et al., 2013), we assumed that 10% of animal manure were applied to rice paddies and the rest 90% to upland fields.

F_{CR} was estimated following Eq. (B.3).

$$F_{CR} = \sum_i F_{CR\text{-}AG(i)} + F_{CR\text{-}BG(i)} = \sum_i Pdt_i \cdot R_{ST\text{-}GR(i)} \cdot N_i \cdot (R_{SR(i)} + R_{BG\text{-}AG(i)}) \qquad \text{(B.3)}$$

Where $F_{CR\text{-}AG(i)}$ and $F_{CR\text{-}BG(i)}$ represent N input from aboveground and belowground crop residues (Mt N). i denotes the crop type. Pdt is the annual crop production (Table A.1). $R_{ST\text{-}GR}$ is the ratio of straw to grain in terms of dray matter. N is residue N content (g kg^{-1}). R_{SR} is the proportion of above-ground straw returned to land (%). $R_{BG\text{-}AG}$ is the ratio of below-ground residue weight to above-ground plant weight. Values of parameters in Eq. S3 were mainly obtained from Gao et al. (2011), which are summarized in Table B.3.

Table B.1 GHG emission factors for N inputs to China's croplands

Data sources	Crop systems	Direct N_2O*			Indirect N_2O†				Total EF
		EF_1	EF(tCO_2e tN^{-1})	$Frac_{GAS}$ (%)	EF_4	$Frac_{LEACH}$ (%)	EF_5	EF(tCO_2e tN^{-1})	(tCO_2e tN^{-1})
China specific	Rice paddy	0.41	1.92	17.9	0.01	1.4	0.0075	0.89	2.81
	Upland field	1.05	4.92	12.9	0.01	9.8	0.0075	0.95	5.87
IPCC	Rice paddy	0.30	1.40	10.0	0.01	30.0	0.0075	1.52	2.93

default	Upland field	1.00	4.68	10.0	0.01	30.0	0.0075	1.52	6.20

* Direct N_2O emission factors are from a study by Gao et al. (2012) based on 456 N_2O emission measurements in China.

† Indirect N_2O emission factors are obtained from Zhang et al. (2013) based on 397 N_2O emission measurements in China.

Table B.2 Selected values for estimating N input to croplands from animal manure

	Non-dairy cattle	Milk cows	Sheep+ goats	Horses	Asses	Mules	Pigs	Chicken	Rabbits
$Frac_{Grazing}$ *	17%		35%						
N_{rate}	0.34	0.47	0.27	0.46	0.46	0.46	0.50	0.82	
TAM	319	350	29	238	130	130	28	2	0
Nex	39.6	60.0	2.9	40.0	21.8	21.8	5.1	0.5	8.1
$Frac_{Loss}$	40%	40%	67%	50%	50%	50%	35%	50%	50%
Days_alive†							158	180	105

* Proportion of grazed cattle and sheep are summarized from relevant livestock numbers in grazing areas and half-grazing areas (MOA, 2005-2012a)

† Average growth days of pigs, chicken and rabbits were cited from China Livestock Yearbook. Days_alive of chicken are weighted number of poultry (65 days) and hens (352 days).

Table B.3 Selected values for estimating N input to croplands from crop residues

	R_{ST-GR}	N	R_{SR} *				R_{BG-AG}
		g kg^{-1}	2005	2010	2015	2020	
Rice	0.9	9.1	29%	34%	35%	36%	0.13
Wheat	1.1	6.5	42%	49%	51%	52%	0.17
Maize	1.2	9.2	26%	30%	31%	32%	0.17
Potato	0.5	25.0	18%	21%	22%	22%	0.05
Soybean	1.0	21.0	45%	52%	53%	55%	0.13
Cotton	3.0	12.4	12%	14%	15%	15%	0.20
Oils	1.7	13.5	17%	20%	21%	22%	0.17
Vegetable	0.5	2.5	5%	6%	6%	6%	0.25

* Proportions of above-ground straw returned to land were cited from Gao et al. (2009) and 3% annual growth rate was employed for straw incorporation rate in the future.

Appendix C Estimation of abatement rates of mitigation measures

A meta-analysis (Nayak et al., 2013) was conducted to estimate the average technical abatement rates of mitigation measures specific to China. We made some adjustments of original meta-analysis results in this study to better accommodate actual situations and partially internalize measure interactions. Table C.1 presents the direct N rate decrease induced abatement potential of measures C1, C2, C3 and C4, which were estimated employing emission factors (Table B.1) and the relationship between N fertilizer reduction and N_2O emissions reduction drawn from site experiments (database from Nayak et al., 2013) shown in Fig. C.1. Due to lack of emission data from fruit, we used emission data from vegetable to estimate mitigation potential for fruits. We concluded from relevant literature (Ge, 2009; Jiao et al., 2010) that overuse of N fertilizer is phenomenal in nearly all greenhouse vegetable fields, and we assumed that about 50% of openfield vegetable areas receive 40% excessive N fertilizers than crop demands. Regarding orchards, survey results (Lu et al., 2008; Zhang et al., 2012) indicate that average N inputs rates were over 2.5 fold higher than fruit requirement in about 70% of orchards. Drip-irrigation has been proven to be a prominent technology in improving cotton yields and reducing fertilizer and irrigation inputs, and was therefore considered the dominant mitigation measure in cotton production. Since both high-efficiency irrigation systems and replacement of ammonia-based fertilizers with nitrate-based fertilizers are able to lower N_2O emissions by at least 50% (SAIN, 2012), i.e. halving emission factors, this part of mitigation potential was also quantified in addition to emission reduction related to direct N rate decrease.

The abatement rate of measure C3 was the integrated effects of shifting from mid-season drainage (F-D-F) to intermittent irrigation (F-D-F-M) regime (1.256 CO_2e ha^{-1}) and reduced N fertilizer rate (0.081 CO_2e ha^{-1}).

Due to limited dataset in China specific meta-analysis, estimates of abatement rate from using enhanced efficiency fertilizers were based on the global meta analysis results (Akiyama et al., 2010) suggesting NIs can reduce N_2O by 34% in upland fields and 30% in rice paddies on average, compared with those of conventional fertilizers.

Meta analysis mitigation potential of adding organic manure to croplands were discounted because organic manure have already been applied to croplands in practice opposed to the zero organic manure assumption under controlled experiments. According to Zhang et al. (2013) and Huang et al. (2010), organic manure supplied about 9%-12% of total N input for grain crops. Chadwick et al. (2013) indicated that for greenhouse vegetables >50% of the nutrients supply come from the manures, for open field vegetables and fruit, manure supply ca. 33% and 20% of the total N nutrients, respectively. Typical fertilization recommendations suggest organic manure providing 30% of N nutrients to crops and 50% to fruits and vegetables. The average abatement rate for wheat and maize were extended to other upland crops. Net emissions of adding manure to rice paddy were estimated under intermittent irrigation regime.

Meta analysis results were directly used for conservation tillage and straw returning.

Regarding biochar addition, positive effects of biochar on C sequestration were reported in literature but not included here giving uncertainty considerations constrained by limited and short-term studies. Mitigation potential from this measure sourced from decreased N_2O emissions in upland crops by 40% and rice paddies by 50% by global meta-analysis (Pan, 2012).

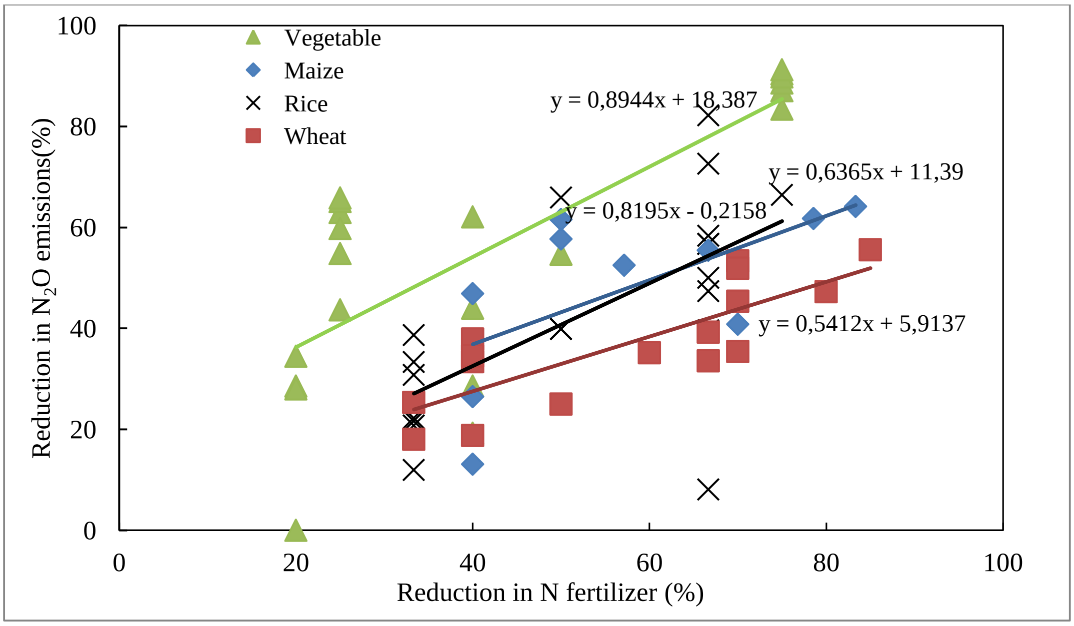

Fig. C.1 Relationship between reduction percentages of N fertilizers and N_2O emissions. The equation for rice is y=0.8195x-0.2158, for wheat is y=0.5412x+5.9137, for maize is y=0.6365x+11.39, and for vegetable is y=0.8944+18.387.

Table C.1 Mitigation potential estimates of abatement measure C1, measure C2 and measure C4

	BAU scenario*						Mitigation measure C1				Mitigation measure C2				
	N rate		Yield		PFP_N		Target PFP_N(70% of optimum)	N rate reduce	N_2O emission reduction	Mitigation potential	Optimal PFP_N†	Yield increase by	N reduce quantity	Mitigation potential	N rate objective
	2008-2010 average	2020	2008-2010 average	2020	2008-2010 average	2020									
Provinces	(kg ha^{-1})		(t ha^{-1})		(kg kg^{-1})		(kg kg^{-1})	(%)	(%)	($ktCO_2e$)	(kg kg^{-1})	(t ha^{-1})	(kt)	($ktCO_2e$)	(kg ha^{-1})
Rice												5%			
Tianjin	259	246	7.04	7.40	28.3	30.0	35.0	14.2	11.4	1.1	50.0	7.8	0.8	1.7	155
Hebei	344	328	6.79	7.14	18.7	21.8	35.0	37.8	30.7	20.1	50.0	7.5	3.8	8.8	150
Inner mengolia	221	211	7.23	7.60	33.4	36.1	35.0				50.0	8.0	4.3	9.8	160
Liaoning	235	224	7.38	7.76	31.4	34.6	52.5	34.0	27.6	100.0	75.0	8.1	22.5	51.9	109
Jilin	170	162	8.29	8.72	48.9	53.9					75.0	9.2	22.8	52.0	122
Heilongjiang	120	114	6.47	6.80	54.0	59.5					75.0	7.1	42.0	95.1	95
Shanghai	326	311	8.28	8.71	24.8	28.0	36.1	22.5	18.2	14.9	51.6	9.1	6.0	13.8	177
Jiangsu	290	277	8.03	8.45	27.7	30.5	36.1	15.4	12.4	186.7	51.6	8.9	119.9	276.1	172
Zhejiang	227	217	7.06	7.42	31.1	34.3	36.1	5.1	4.0	19.5	51.6	7.8	44.0	101.3	151
Anhui	205	195	6.22	6.54	30.4	33.5	38.9	13.9	11.2	118.9	55.6	6.9	86.1	198.4	123
Fujian	159	152	5.94	6.24	37.3	41.1					50.5	6.6	16.3	37.0	130
Jiangxi	164	156	5.71	6.00	34.9	38.5					50.5	6.3	88.8	201.9	125
Shandong	285	272	8.35	8.78	29.3	32.3	35.0	7.7	6.1	5.3	50.0	9.2	7.6	17.4	184
Henan	213	203	7.40	7.78	34.8	38.4	35.0				50.0	8.2	20.9	47.4	163
Hubei	168	160	7.73	8.12	46.1	50.9					55.0				160
Hunan	148	141	6.34	6.66	42.8	47.2					56.5	7.0	60.5	136.4	124
Guangdong	191	182	5.33	5.60	28.0	30.8	35.3	12.7	10.2	88.2	50.5	5.9	71.0	163.6	117
Guangxi	196	186	5.32	5.60	27.3	30.0	35.3	15.0	12.1	116.0	50.5	5.9	76.8	176.8	116
Hainan	144	137	4.50	4.73	31.2	34.4					50.5	5.0	10.7	24.5	98
Chongqing	143	136	7.65	8.04	53.6	59.1					50.0				136
Sichuan	201	192	7.47	7.85	37.5	41.0					50.0	8.2	47.0	106.1	165
Guizhou	134	127	6.52	6.86	48.8	53.8					50.5				127
Yunnan	229	219	6.09	6.40	26.8	29.3	35.3	17.2	13.8	75.5	50.5	6.7	42.6	98.2	133
Shanxi	180	172	6.64	6.98	37.1	40.7					50.0	7.3	2.7	6.1	147
Ningxia	283	270	8.31	8.74	29.3	32.3	35.0	7.6	6.0	3.2	55.0	9.2	5.8	13.3	167
Nation average	186	177	6.57	6.90	23.2	38.9		7.3		749.4		7.2	803.0	1837.6	133

Wheat												5%			
Beijing	239	286	4.95	5.34	20.5	18.7	24.9	24.9	19.4	18.5	35.6	5.6	3.2	10.3	158
Tianjin	233	278	4.86	5.25	20.7	18.9	24.9	24.2	19.0	31.2	35.6	5.5	5.6	17.8	155
Hebei	248	296	5.09	5.50	20.6	18.6	24.9	25.4	19.6	754.9	35.6	5.8	129.5	411.2	162
Shanxi	163	194	3.24	3.50	19.9	18.0	24.9	27.8	21.0	157.7	35.6	3.7	24.5	77.9	103
Inner mengolia	292	349	3.19	3.44	10.9	9.9	14.9	33.9	24.3	235.3	21.4	3.6	28.9	91.8	169
Heilongjiang	97	115	3.67	3.96	38.4	34.4					35.6				115
Jiangsu	238	284	4.82	5.20	20.3	18.3	27.1	32.4	23.4	747.1	38.7	5.5	97.4	309.5	141
Anhui	189	225	5.03	5.42	26.8	24.1					35.6	5.7	141.1	617.3	160
Shandong	206	246	5.77	6.23	28.1	25.3					35.6	6.5	203.1	923.5	184
Henan	183	219	5.81	6.27	32.0	28.7					35.6	6.6	163.3	886.4	185
Hubei	161	193	3.35	3.62	20.8	18.8	24.9	24.6	19.2	199.6	35.6	3.8	35.3	112.1	107
Chongqing	101	120	3.07	3.31	29.0	27.5					35.6	3.5	3.5	17.8	98
Sichuan	124	148	3.34	3.60	26.9	24.3					35.6	3.8	49.5	217.6	106
Yunnan	113	135	1.72	1.86	15.1	13.8	24.9	44.6	30.1	93.5	35.6	1.9	7.8	24.7	55
Shanxi	232	276	3.43	3.70	14.9	13.4	24.7	45.7	30.6	523.1	35.2	3.9	41.8	132.9	110
Gansu	189	226	2.84	3.07	15.0	13.6	24.7	45.0	30.2	337.5	35.2	3.2	27.7	88.1	91
Qinghai	91	108	3.82	4.12	44.0	38.1					35.2				108
Ningxia	238	284	3.28	3.54	13.8	12.5	24.7	49.4	32.7	105.6	35.2	3.7	7.4	23.4	105
Xinjiang	238	284	5.51	5.94	23.2	20.9	24.7	15.2	14.1	217.3	35.2	6.2	58.9	187.0	177
Nation average	199	238	4.75	5.13	23.9	21.5		15.2		3421.4		5.4	1030.5	4160.9	155
Maize												8%			
Beijing	213	233	5.86	6.79	25.2	29.1	32.7	11.1	18.5	42.7	46.7	7.3	8.5	31.9	157
Tianjin	201	220	5.37	6.22	26.6	28.3	32.7	13.5	20.0	48.1	46.7	6.7	8.7	32.4	144
Hebei	172	188	5.02	5.81	29.3	30.9	32.7			549.4	46.7	6.3	144.1	538.3	134
Shanxi	181	198	4.80	5.56	26.6	28.1	32.7	14.2	20.4	393.5	46.7	6.0	68.6	256.3	128
Inner mengolia	214	235	5.80	6.71	27.0	28.6	32.7	12.6	19.4	736.4	46.7	7.2	137.7	514.3	155
Liaoning	198	216	5.57	6.44	28.2	29.8	33.7	11.6	18.8	535.9	48.1	7.0	104.9	391.8	145
Jilin	178	194	6.61	7.65	37.3	39.4					48.1	8.3	76.5	724.2	172
Heilongjiang	136	149	5.06	5.85	37.1	39.2					48.1	6.3	80.7	753.3	131
Jiangsu	237	259	5.30	6.14	22.5	23.7	32.6	27.5	28.9	199.9	46.6	6.6	20.9	77.9	142
Anhui	211	230	4.11	4.76	19.6	20.7	32.6	36.7	34.7	390.3	46.6	5.1	29.6	110.5	110
Shandong	215	235	6.56	7.60	30.7	32.3					46.6	8.2	195.9	1251.9	176
Henan	183	200	5.64	6.53	30.8	32.6					46.6	7.0	160.3	1037.3	151

Hubei	256	280	4.85	5.61	19.0	20.0	32.6	38.5	35.9	336.5	46.6	6.1	23.9	89.4	130
Guangxi	247	270	4.11	4.75	16.7	17.6	32.6	46.1	40.7	381.4	46.6	5.1	21.0	78.5	110
Chongqing	232	254	5.39	6.24	23.3	24.5	32.2	23.7	26.5	205.5	45.9	6.7	24.6	92.0	147
Sichuan	254	278	4.86	5.62	19.4	20.2	32.2	37.1	35.0	865.8	45.9	6.1	64.7	241.6	132
Guizhou	177	194	5.35	6.19	30.5	31.9					46.6	6.7	43.1	272.2	143
Yunnan	295	323	4.11	4.75	13.9	14.7	31.7	53.6	45.5	1336.8	45.3	5.1	56.6	211.6	113
Shanxi	271	296	4.40	5.09	16.3	17.2	32.8	47.7	41.7	962.0	46.9	5.5	50.1	187.3	117
Gansu	274	300	4.73	5.47	17.3	18.3	32.8	44.4	39.6	540.5	46.9	5.9	31.5	117.8	126
Ningxia	279	305	7.29	8.44	26.6	27.7	32.8	15.7	21.4	93.5	46.9	9.1	15.4	57.4	194
Xinjiang	263	288	6.82	7.89	26.2	27.4	32.8	16.5	21.9	256.7	46.9	8.5	40.8	152.3	182
Nation average	202	221	5.62	5.86	26.9	28.4		15.6		7874.7		6.8	1408.0	7220.2	146

Crop ype	BAU scenario				Mitigation measure C1				Mitigation measure C4					N rate objective
	N rate 2020	Yield 2020	Area 2020	PFP_N 2020	Target PFP_N(10% or 15% increase)	N rate reduce	N_2O emission reduction	Abatement rate	Optimal PFP_N	Yield increase by 6% or 10%	Abatement rate(N reduce)	Abatement rate(EF change)	Total Abatement rate	
	(kg ha^{-1})	(t ha^{-1})	(kha)	(kg kg^{-1})	(kg kg^{-1})	(%)	(%)	(CO_2e ha^{-1})	(kg kg^{-1})	(t ha^{-1})	(CO_2e ha^{-1})	(CO_2e ha^{-1})	(CO_2e ha^{-1})	(kg ha^{-1})
Greenhouse Vegetable	656	55.2	3,560	84	97	15	31.8	1.225	160	60.7	0.936	0.440	1.376	379
Openfield vegetable	262	38.1	15,479	145										210
N overuse area	315		7,740	121	133	10	27.3	0.505	200	41.9	0.389	0.440	0.829	209
Normal area	210		7,740	181										210
Fruit	565	24.5	11,668	43										350
N overuse area	678		8,168	36	42	10	31.8	1.266	70	26.0	1.079	0.748	1.827	371
Normal area	301		3,501	81										301
Cotton	237	1.5	5,168							1.6	0.463	0.440	0.903	

[*] Baseyear data (average of 2008-2010) were obtained from the China Agricultural Products Cost-Benefit Data (N rate) and the China Rural Statistical Yearbooks (Yield), and future N rates and yields at provincial level were estimated applying the national average changing rate (Table A.1).
[†] Average optimal PFP_N were derived from recommended N fertilizer application rates under certain level of yields in various cropping regions (Zhang et al., 2009).

Appendix D Mitigation measure cost and adoption

Table D.1 Explication of and references for measure implementation cost estimation

Measure No.	Explications	Major references
C1	Reductions in N rates were based on those in target regions (see Table C.1 measure C1), which are higher than national average.	Zhang et al. (2009) Zhang et al. (2012b)
C2	More labor inputs for wheat additional topdressing. Increased machine inputs for maize fertilizer deep placement.	Zhang et al.(2009) SAIN(2012)
C3	More labor inputs for additional topdressing; irrigation costs saved due to improved irrigation regime.	Liu et al.(2006) Zhang(2012)
C4	Reductions in N fertilizer rates were based on those rates in target regions (see Table C.1 measure C4). Use Calcium Ammonium Nitrate (total nurient≥34％, total N=26%) to represent nitrate-based fertilizers, with application rate stands at 450kg/ha for vegetable and cotton and750kg/ha for fruit. High-efficient irrigation systems allow for labor savings in vegetable and cotton fields; more labors are required for fruit fertilizer split application. Subsurface drip irrigation system costs compromise ¥ 15000 initial investment and installation cost (lifespan=10years) per hectare and annual maintenance and renewal cost of smaller diameter polytube at ¥1500/ha and film input at ¥1000/ha, while labors and pesticides (cotton) and irrigation costs will be saved.Table C.1	Yang et al. (2005) Huo et al. (2011) Zhang et al. (2012b)
C5	Use NI CDC to represent additional cost of enhanced-efficiency fertilizers: in general DCD is applied at rates equivalent to 5% of N nutrient (w/w), the price of DCD is about ¥ 10000/t.	Bai et al. (2012) Liu et al. (2013)
C6	Material and labor inputs for manure composting and disposal are represented by the market price of organic manure fertilizer. More labor inputs needed for large quantity of manure application	Huang et al. (2010)
C7	Long-term no-till could lead to excessive soil surface compaction, weed spread and pest infestation. It is recommended that deep loosing should be carried out every 3-4 years. Increased seed and pesticide costs are attributed to straw returning.	He et al. (2006) Lv et al. (2010) Wang et al. (2010)
C8	Increased machine cost is for straw mulching following harvest. Additional N fertilizers should be added to accelerate fresh straw decay. Large amount of straw is likely to affect seed emerging and encourage weed growth and pest infestation.	Jiang et al. (2006) Liu et al. (2009) Tian et al. (2011)
C9	Biochar price is represented by the straw pyrolysis product from Sanli NewEnergy Company, Henan, China. More labors are required to apply large amount of biochar. Per tonne biochar price is considered constant thanks to technology improvement. Domestic experts suggest applying biochar every 5 years since single application can provide beneficial effects over several growing seasons in the field.	Major(2011) Zhang et al.(2012a) Pan(2012)
L1	The investment cost for a anaerobic digester on farm scale is about 3250 Yuan but a subsidy between 800 and 1200 Yuan is provided. The annual benefit of running a digester is estimated to be 500 Yuan. We assume that one anaerobic digester is operational for 15 years and a relative high failure rate of 8% of new constructed digesters due to immense maintenance and technological short comings	MOA (2007a) NDRC (2007) Zhang et al. (2012) Han et al. (2008)

L2	Costs for high quality genetic material, artificial insemination and administration are 20 Yuan, 40 Yuan, and 20 Yuan per animal, respectively (the costs are adjusted to current prices). Due to the low success rate more then one artificial insemination has to be done for one animal. The milk production and body weight will increase by 1% each year.	Waldron et al. (2007) Zhang and Beckman (2008) expert judgement†
L3	A sheep unit that is fed with 1g concentrated tea saponins per day shows increased milk production, body weight, and wool/cashmere production of 3%, 4%, and 4%, respectively. The feed intake increases by 2%. The costs are at ¥125/Kg.*	expert judgement†
L4	A sheep unit that is fed with 1g probiotics per day shows increased milk production and body weight of 6%. The feed intake increases by 5%. The costs are ¥50/Kg.*	Musa et al. (2009) expert judgement†
L5	A sheep unit that is fed with 40g poly unsaturated lipids per day shows increased milk production, body weight and wool/cashmere yield of 4%, 2%, and 2%, respectively. The costs are at ¥15/Kg.*	expert judgement†
L6 L7 L8	The cost assumptions for herders are based on farm surveys in Inner Mongolia. A simple model was generated that estimates the DM availability under different grazing intensities and hence the additional costs for supplementary feeding. Costs for machinery and labor input are based number of animals and area for hay making. We assume that the livestock is freely grazing. Thus, no costs a generated by grazing livestock.	Farm questionnaires by the Inner Mongolia Agricultural University.

* Additional management costs of ¥2/animal apply for purchasing, transporting, feeding the feed additives.

† Since there is a gap in Chinese Scientific literature for the required information, we consulted several Chinese experts on their judgment of impact on yields and costs. The results presented here are the mean of all assumptions.

Table D.2 Agricultural inputs in 2010 and anticipated future change (taking rice as an example)

Item	Unit	2010	Annual growth rate 2000-2010*	Assumed annual growth rate 2010-2020
Direct material and service cost/0.067ha	yuan	303.93	7%	4%
1.seed cost	yuan	39.74	8%	4%
2.fertilizer cost	yuan	110.94	7%	3%
3.organic manure cost	yuan	9.65	1%	0%
4.pesticide cost	yuan	22.39	11%	5%
5.agri. film cost	yuan	2.34	3%	1%
6.renting and operation cost	yuan	113.19	12%	6%
machine renting and operation	yuan	84.94	14%	7%
irrigation and drainage	yuan	19.08	2%	1%
water cost	yuan	6.69	0.4%	0.2%
animal power cost	yuan	9.17	-3%	-1%
7.fuel and power cost	yuan	0.68	22%	5%
8.technical service cost	yuan	0.02	-26%	-13%
9.tool and material cost	yuan	3.40	34%	17%
10.maintenance and repair cost	yuan	1.57	-0.7%	-0.4%
11.other direct cost	yuan	0.01	-43%	-22%
Human cost/0.067ha	yuan	226.90	6%	3%
1.equivalent family labor cost	yuan	206.27	6%	3%
human input days	day	6.59	-6%	-3%
labor wage	yuan/day	31.30	12%	6%
2.hiring labor cost	yuan	20.63	8%	4%
human input days	day	0.34	-4%	-2%
labor wage	yuan/day	60.67	12%	6%
Fertilizer price	yuan/kg	4.83	7%	4%
N fertilizer price	yuan/kg	3.96	6%	3%

* Growth rate of 2005-2010 was used when the rate for 2000-2010 was not available.

Table D.3 Measure adoption rates under baseline and abatement scenarios

Measure No.	Historical or current adoption	Baseline adoption in 2020	Maximum feasible adoption in 2020	References or explanation
C1		Apply to 39% rice, 44% wheat, 55% maize, 100% greenhouse veg., 50% openfield veg. and 70% fruit fields.		See Table S7 measure C1
C2		Apply to 100% wheat and maize cropping areas.		See Table C.1 measure C2
C3	Areas under F, F-D-F, F-D-F-M regimes were 16%, 77%, 7% in 1980s and 12%, 76%, 12% in 1990s.	Areas under F, F-D-F, F-D-F-M regimes are 8%, 76%, 16%.	Areas under F, F-D-F, F-D-F-M regimes are 8%, 0%, 92%	Zou et al. (2009) Zhang et al.(2011)
C4		50% of cotton, greenhouse and openfield vegetable and fruit fields. *	Apply to 100% cotton, greenhouse and openfield vegetable and fruit fields.	See Table C.1 measure C4. National Agricultural Water-Saving Outline (2012-2020)
C5	Limited	Limited	Apply to 50% rice, wheat and maize cropping areas, 30% other upland crops (excluding beans), and 30% of vegetable and fruit areas.	
C6		30% of crops receive reasonable supply of organic manure.	80% of crops (except greenhouse veg.) receive reasonable supply of organic manure.	
C7	4.30 Mha (7.6% of wheat and maize areas) in 2010	20 Mha(34.8% of wheat and maize areas)	23 Mha(40% of wheat and maize areas)	National Agriculture Mechanization Extension Plan (2011-2015)
C8	28.5Mha(about 18 Mha of wheat and maize areas, 60% of mechanized harvest areas receive straw returning)	22.5 Mha of wheat and maize areas(assuming 60% of mechanized harvest areas receive straw returning†)	30.1Mha of wheat and maize areas(assuming 80% of mechanized harvest areas receive straw returning)	National Agriculture Mechanization Extension Plan (2011-2015). Implementation Plan on the Comprehensive Use of Crop Straw during the 12th Five-year Plan Period
C9	Limited	Limited	Apply to 10% of rice, wheat and maize cropping areas.	
L1	33% of total 120 M possible farm-scale anaerobic digesters	66% of total possible farm-scale anaerobic digesters	33% of total possible farm-scale anaerobic digesters	NDRC (2007)

L2	Limited	most common for beef and cow but practically non-existent for goat farms	20% of beef and dairy cattle, 30% of sheep, 60% for goat	Waldron et al. (2007)
L3	Very limited	Very limited	10% of livestock since tea saponins are not sufficient available	Expert opinion
L4	10% of terrestrial livestock	Increasing adoption rate	50% of livestock	Wang et al. (2008) Beijing Shennong Agricultural Consultancy. (2013) Research Report on Feeding Probitics Industry in China
L5	Limited	Limited	70% of livestock	Expert opinion
L6	In 2010, 40% of Chinese grassland is under grazing ban, suspended grazing, or rotational grazing.	In 2010, 60% of Chinese grassland is under grazing ban, suspended grazing, or rotational grazing.	33% of grazing grassland	18th formal announcement of the strategic objectives of the sustainable development of Chinese grassland (in Chinese) Ministry of Environmental Protection of People's Republic of China (2005 – 2011) Report on the State of the Environment of China (in Chinese) Brown et al. (2008)
L7	Limited	Limited	33% of grazing grassland	18th formal announcement of the strategic objectives of the sustainable development of Chinese grassland (in Chinese) Ministry of Environmental Protection of People's Republic of China (2005 – 2011) Report on the State of the Environment of China (in Chinese)
L8	Limited	Limited	33% of grazing grassland	

* According to the National Agricultural Water-Saving Outline, high-efficiency irrigations shall be installed on 22.5 Mha croplands (20 Mha new areas). We estimate that approximately 30% of cash crops shall benefit from this project.

† Straw returning rate is highly dependent on crop harvesting mechanization levels, which were 64.5% for rice, 86% for wheat and 25.8% for maize in 2010, and are planned to reach 80% for rice and 45% for maize in 2015.

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