METHODS ANNEX: METHODOLOGIES USED TO ESTIMATE TECHNICAL MITIGATION POTENTIAL

This appendix explains how mitigation potentials were calculated for this report.

Methodological overview

This analysis estimates technical greenhouse gas mitigation potential for agriculture in 2030, calculated by country and emitting sector. Technical mitigation potential is equal to the emissions reductions possible with current technologies, ignoring economic and political constraints. Because agricultural emissions is a relatively data-poor field, technical mitigation potential can be difficult to estimate precisely; one could reasonably use different data or assumptions than those employed in this report and obtain a divergent estimate of technical mitigation potential.

This analysis provides a snapshot of potential avoided emissions in the year 2030, compared to a hypothetical baseline in which no additional mitigation from production agriculture is attempted, beyond what is expected given current adoption and intensification trends. It focuses on interventions directly related to production agriculture, such as reductions in emissions from livestock, rice, and other crops, as well as carbon sequestration in agricultural systems and reductions in demand. It prioritizes interventions which are unlikely to be realized through complementary mitigation efforts in the industrial, energy, or transportation sectors.

Mitigation potential is estimated assuming that the best currently-available technologies or practices could be employed widely. Where multiple technologies or practices are possible, the most effective interventions or suite of interventions is used to estimate a mitigation potential. Estimates are based on scholarly literature, reputable datasets, and expert interviews.

In the case of enteric fermentation, manure, rice, and fertilizer emissions, mitigation potential was calculated as a percentage reduction from 2030 emissions. Our projection shows that agricultural emissions will scale from 4.67 Mt CO_2e in 2010 to 5.19 Mt CO_2e in 2030. These 2030 emissions were estimated by scaling estimates of 2010 emissions from FAOSTAT by predicted emissions growth factors, specific to sector and country. These growth factors were derived from the agricultural emissions projections provided by EPA 2012. The growth factors, shown in the table below, were generated by the IFPRI impact model, except for rice harvesting which is based on FAPRI's "U.S. and World Agricultural Outlook". For further discussion of the various global agricultural emissions inventories and why this report uses FAOSTAT for its baseline emissions analysis, see the supplementary information provided at www.agriculturalmitigation.org.

Table 1. Emissions growth factors used to estimate 2030 baseline

Projected change in emissions, 2010–2030 (based on EPA 2012).

	Globe	China	India	Brazil	USA	E.U.
Total agric. emissions	20%	15%	14%	7%	23%	3%
Ag. soils	26%	23%	24%	9%	38%	7%
Enteric	20%	18%	14%	4%	9%	-2%
Manure management	11%	12%	17%	16%	0%	-3%
Rice	-2%	-14%	8%	-3%	-3%	1%

	Indonesia	Pakistan	Argentina	Australia	Mexico	Vietnam	Horn of Africa
Total agric. emissions	26%	43%	19%	15%	23%	23%	25%
Ag. soils	42%	32%	21%	20%	32%	34%	19%
Enteric	49%	53%	17%	13%	22%	41%	26%
Manure management	34%	29%	18%	8%	7%	25%	25%
Rice	3%	7%	22%	562%	1%	10%	-14%

In the case of carbon sequestration on grazing lands and croplands, this study relies on estimates provided in existing literature as well as an analysis conducted for this study to assess the mitigation potential of biochar from a range of feedstocks. Estimates for the mitigation potential for demand-side measures also rely on existing literature.

The methodology for each sector is described further, below.

All mitigation data used in this report are rounded to the nearest 5 Mt, even if the data point is drawn from published literature in which a higher level of precision is provided.

Boundaries of this analysis

The analysis is intended to help readers understand the relative magnitude and tractability of mitigation opportunities.

- Because this report does not provide ranges or error bars in most cases, the data provides a false sense of precision. Data on agricultural greenhouse gas mitigation is complicated by uncertainty in emissions, variable testing conditions for mitigation interventions, and a range of other factors that make it very difficult to precisely estimate mitigation potential.
- No attempt was made to quantify the economic mitigation potential because of a lack of data about the economic costs and benefits of interventions across a range of geographies and production systems. Mitigation options and costs will vary significantly by region due to a number of factors including: variation in local natural resources, the maturity of local markets and distribution chains, willingness of national and local governments to subsidize, promote, and regulate mitigation practices, as well as in variation in what practices have already been implemented. Only a fraction of the technical mitigation potential shown in this report will be achievable given economic and political constraints.

- This data is not modeled. The mitigation potentials presented for different sectors may not be fully additive. However, insofar as it was possible, elements of the analysis were designed to complement each other and avoid potential double counting of mitigation opportunities. Although this report adds the mitigation potential from supply-side and demand-side interventions, these opportunities will certainly impact one another. Specifically, if demand for agricultural products decreases significantly, then the potential to reduce emissions from production will be smaller as a consequence.
- This analysis does not include specific assumptions about the pathway that would be used to get to the 2030 mitigation potential (e.g., the technology and emissions in each year from 2013–2030).

Limited data and resources prevented a robust quantitative analysis of the following issues, which in some cases are discussed narratively in the report:

- Avoided deforestation
- Biofuels
- On-farm machinery and irrigation
- Restoration of abandoned lands
- Supply chain interventions, with the exception of fertilizer production in China

Further information

Further information on individual mitigation practices can be found in the supplementary information provided at www.agriculturalmitigation.org.

2.2 Enteric fermentation

This report estimates a mitigation potential of 940 Mt CO_2e per year by 2030 from reduced emissions from enteric fermentation from ruminants. This estimate corresponds to a roughly 40 percent reduction in emissions compared with baseline emissions projections. Technically, the largest opportunities are in India (135 Mt CO_2e per year) and Brazil (105 Mt CO_2e per year), followed by China (70 Mt CO_2e per year), the Horn of Africa (65 Mt CO_2e per year), the E.U. (60 Mt CO_2e per year), and the U.S. (50 Mt CO_2e per year).

The Horn of Africa includes the following countries:
Djibouti, Kenya, Somalia, Sudan (former)/ Sudan/ South Sudan, Uganda, Ethiopia

Methodology

- Hristov et al. (2013) provides percentage reduction in CO_2e from a range of specific practices such as, improved forage, feeding of concentrates, feeding of lipids, feeding of nitrates, vaccinations, and culling practices. Other literature and expert interviews were also considered.
- We assumed that the maximum potential percentage reduction was equal to the highest estimate for any of the practices (~40 percent reduction) and did not add the practices together. The only mitigation practices for enteric fermentation that can achieve 40 percent emissions reduction is nitrates (a feed supplement). However, a combination of other practices may also achieve this level of mitigation.
- We then multiplied the emissions from each ruminant livestock category (FAO 2010) by 40 percent to determine emissions reduction potential.

Primary data source

- Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J. & Oosting, S. (2013). *Mitigation of greenhouse gas emissions in livestock production—A review of technical options for non-CO_2 emissions.* Gerber P., Henderson B., Makkar H. Rome, Italy: Food and Agriculture Organization of the United Nations.

2.3 Management of stored manure

This report estimates a mitigation potential of 260 Mt CO_2e per year by 2030 from reduced emissions from both methane and nitrous oxide emissions from stored manure. This estimate corresponds to a roughly 65 percent reduction in emissions compared with baseline emissions projections. Technically, the largest opportunities are in those countries which primarily use industrialized production for dairy, pigs and poultry: China (45 Mt CO_2e per year), the E.U. (45 Mt CO_2e per year), and the U.S. (40 Mt CO_2e per year). These animals spend most of their lives in confinement when raised in industrial systems.

Methodology

- Hristov et al. (2013) provides the percentage reduction in CO_2e from a range of specific practices such as methane digestion, composting, better timing of manure application on croplands, cooling of manure, reduced storage time, and improved animal diets. Other literature and expert interviews were also considered.
- We assumed that the maximum potential percentage reduction was equal to the highest estimate for any of the individual practices (70 percent reduction potential) and did not add the practices together. The only mitigation practices for stored manure that can achieve 70 percent emissions reduction is methane digestion. However, a combination of other practices may also achieve this level of mitigation.
- We assumed that this highpoint (70 percent reduction) could be applied to all stored manure.
- We then multiplied the emissions from each ruminant livestock category (FAO 2010) by 70 percent to determine emissions reduction potential.

Primary data source

- Hristov, (2013).

2.4 Carbon sequestration in grazing land

This report provides two estimates of mitigation potential from soil carbon sequestration in grazing lands: 170 Mt CO_2e per year and 395 Mt CO_2e per year. Since carbon sequestration in agricultural lands is not an emissions reduction, these mitigation estimates do not reflect a percentage of 2030 emissions.

The carbon sequestration potential of grazing lands is highly uncertain. The opportunity for additional carbon sequestration in grazing lands is equal to the difference between the levels of soil organic matter currently in the land and what is possible for the system given soil type and climate. Thus, to be accurate, assessments of carbon sequestration potential in grazing lands should take into account what is actually happening on the ground. However data at this level of detail is not available across the globe, or even across large regions. Therefore, most global assessments of carbon sequestration potential in grazing lands use very simple methodologies whereby they apply sequestration rates found at a range of plot experiments and apply those rates across the globe, without a sophisticated understanding of the ground-level land use. Further, most grazing land sequestration studies to not attempt to model multiple practices as once.

Methodology

The first estimate draws from a 2002 publication by Rich Conant and Keith Paustian, estimating the soil carbon sequestration potential associated with rehabilitating all of the overgrazed grasslands in the world. We have included it in this analysis because it provides a conservative and globally consistent estimate. It is conservative because it only accounts for degraded lands. Grazing lands that are not degraded can also store more carbon through changes in practices, but that potential is not covered by this paper. For example, this paper only includes 14 out of 354 Mha (~4 percent) of grazing land in North America.

The second estimate draws from a range of papers that assess the soil carbon sequestration potential in grazing lands from different countries and regions, including regional level assessments from Conant and Paustian, 2002. The limitation of this estimate is that each of these papers employs a different approach and methodology and there also may be some geographic overlap between China and Eurasia. The sum, thus, represents a cobbling together of related, but inconsistent analysis. Nevertheless, we believe this aggregation provides a useful, and more realistic, estimate of soil carbon sequestration potential in the world's grazing lands. That said, this estimate may still be conservative since several of the analyses included also only assess the potential to restore degraded pastures, rather than exploring increased carbon storage on non-degraded pastures from a range of other practices.

In the table below, Thornton and Herrero, 2010, specify 2030 as the date by which this level of annual mitigation is possible. Wang et al. 2013 specify 2020 and Smith et al., 2007 specifies 2030. In all other cases, no specific year is provided.

Table 2: Grazing land soil carbon sequestration potential

Source	Country/Region	Sequestration potential (Mt CO_2e per year)	Intervention
Conant and Paustian, 2002	Global grazing lands	168	Decreasing grazing intensity on over grazed lands.
Conant and Pasutian source used for grazing lands soil carbon sequestration potential, low estimate.			
Wang et al. 2013	China	60	Grazing land restoration, grazing ban on 35% of China's grazing lands.
Thornton and Herrero, 2010	Central and South America	53.6	Restoration of degraded pastures.
Thornton and Herrero, 2010	Sub-Saharan Africa	96.7	Restoration of degraded pastures.
Conant and Paustian, 2002	Australia/Pacific	16	Decreasing grazing intensity on over grazed lands.
Conant and Paustian, 2002	Eurasia	16	Decreasing grazing intensity on over grazed lands.
Lal et al., 2003	U.S.	47.7 to 257 (average = 152)	Improved management practices on grazing lands.
Wang et al., Thomton and Herrero, Conant and Pasutian, and Lal et al. sources summed to provide grazing lands soil carbon sequestration potential, high estimate.			
R. Lal, 2004	Global range and grasslands	36.7 to 1,100 (average = 568)	A range of practices in semi-arid and sub-humid regions.
Smith et al., 2007	Grazing land management	~1,400	Improved management practices on grazing lands.

R. Lal, and Smith et al. sources provided for comparison.

Primary data sources

- Conant and Paustian. 2002. "Potential soil carbon sequestration in overgrazed grassland ecosystems." Global Biochemical Cycles. vol. 16, no. 4.
- Wang, W., D. Moran, F. Koslowski, D. Nayak, E. Saetnan, P. Smith, A. Clare, E. Lin, L. Guo, J. Newbold, G. Pan, K. Cheng, X. Yan, L. Cardenas. (2013). *Economic potential of greenhouse gas mitigation measures in Chinese agriculture*. (Policy Brief No. 8) UK-China Sustainable Agriculture Innovation Network.
- Thornton and Herrero. (2010). Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *PNAS*, *107,* 19667-19672.
- Lal, R., R. F. Follet, J. M. Kimble. (2003). Achieving soil carbon sequestration in the United States: A challenge to policy makers. *Soil Science, 168*, *12,* 827–845.
- R. Lal. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science, 304,* 1623.
- Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko. (2007) Agriculture. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds). Cambridge, United Kingdom: Cambridge University Press.

2.5 Agroforestry

This report estimates a mitigation potential of 105 Mt CO_2e per year by 2030 from carbon sequestration associated with the adoption of agroforestry practices in mixed crop-livestock systems in humid and tropical highland areas of the developing world, specifically Central and South America, Sub-Saharan Africa, South Asia, and Southeast Asia. Adoption rates of roughly 1 percent and a per hectare sequestration potential of 38 t C (139 t CO_2) are assumed. However, this estimate is highly uncertain, particularly as agroforestry systems vary widely in type and are often cut down at varying intervals.

Primary data source

- Thornton and Herrero, (2010).

2.6 Rice management

This report estimates a mitigation potential of 120 Mt CO_2e per year by 2030 from reduced methane emissions from rice production. This estimate corresponds to a roughly 25 percent reduction in emissions compared with baseline emissions projections. Since the vast majority of rice is produced in Southeast Asia, the mitigation potential is concentrated in that geography, although spread across the many countries in that region. Countries with relatively high mitigation potential for improved rice management through methane reductions include China (25 Mt CO_2e per year), the Philippines (20 Mt CO_2e per year), India (15 Mt CO_2e per year), Indonesia (12 Mt CO_2e per year), and Vietnam (10 Mt CO_2e per year).

Rice cultivation produces methane emissions when cultivation occurs in flooded fields, as well as nitrous oxide emissions from applied nutrients. For the purposes of this analysis, all nutrient emissions for all crops, including rice, are treated in Section 2.7, below. The rice mitigation opportunity described here includes only methane emissions reductions; the total mitigation potential for rice is larger if nutrient reduction potential is also considered.

Note that because this report calculated mitigation potential based on assumed emissions reduction potential off of a projected baseline, the trajectory of the baseline has a significant influence on the size of the mitigation opportunity. The emissions growth factors used this report project negative growth for rice (see Table 1). If rice production and emissions instead grow over the coming decades, then the mitigation potential in 2030 would be larger than what is reported here.

Methodology

- To estimate mitigation potential from rice methane, we focused on straw management (e.g., off season application of rice straw) and water management (e.g., one mid-season drainage, multiple mid-season drainages, shallow flooding), the two practice categories that are most often addressed in the literature. We drew primarily from the estimates for emissions reduction provided by Yan et al. 2009.
- Based on Yan et al., we used 16 percent emissions reduction potential for both straw management and water management.
- We used FAOSTAT (scaled by EPA 2012 growth factors) to determine the applicable 2030 rice emissions for each country. Since water management and rice straw application require some type of drainage, we assumed they are only applicable on irrigated cropland. We used a data set shared by the International Rice Research Institute which provided the percentage of irrigated cropland in each rice-producing country in Asia. For the U.S., we used the applicable hectares from Eagle et al.

2001 (T-AGG, 2011). We multiplied the percent of irrigated hectares by the total rice emissions per country to estimate the applicable emissions.

- We then multiplied Yan's percentage emissions reduction estimates by the applicable rice emissions. We added the mitigation potential for rice straw and water management since they can be practiced in conjunction.

Primary data sources

- Yan, X., H. Akiyama, K. Yagi, and H. Akimoto. (2009). Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Global Biogeochemical Cycles, 23,* GB2002. doi:10.1029/2008GB003299.
- A.J. Eagle, L. Henry, L. Olander, K. Haugen-Kozyra, N. Millar, G. P. Robertson. (2011). *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature, 2nd Edition*. Durham, NC: Nicholas Institute for Environmental Policy Solutions, Duke University. http://nicholasinstitute.duke.edu/ecosystem/land/TAGGDLitRev.
- Unpublished spreadsheet shared via email by Andy Nelson (International Rice Research Institute) on August 19, 2013.

2.7 Nutrient management

This report estimates a mitigation potential of 325 Mt CO_2e per year by 2030 from reduced nitrous oxide emissions from all crops. This estimate corresponds to a roughly 30 percent reduction in emissions compared with baseline emissions projections. Technically, the largest opportunities are in China (150 Mt CO_2e per year) and India (70 Mt CO_2e per year). The mitigation potential in the U.S., E.U., and Brazil are relatively small at 20, 10, and 10 Mt CO_2e per year respectively.

This report calculates the emissions reductions associated with transitioning all of the world's crops to 55 percent nutrient use efficiency (NUE). We did not change the NUE rate for those countries that already have an average NUE rate of 55 percent or higher. A key assumption is that there is a one to one relationship between nutrients applied and nitrous oxide emissions (i.e., that a 30 percent reduction in applied nutrients corresponds to a 30 percent reduction in nitrous oxide emissions). This treatment is a simplification; in fact, the relationship between nitrogen application and N_2O emissions is almost certainly non-linear. A recent meta-analysis found that yield-scaled N_2O emissions were smallest at application rates of approximately 180–190 kg N per hectare and increased sharply after that.[1] This finding implies that as long as the nutrients can be used by the crops, emissions will be low or stable, but once nutrient application rates are in excess of what the crops can take up, emissions will spike. A further implication is that regions that are under-applying nutrients (e.g., Sub-Saharan Africa) could greatly increase their use of fertilizers without a corresponding increase in emissions.

Methodology

- Our assessment for this segment of the analysis relied heavily on data provided by Paul West, Institute on the Environment, University of Minnesota. This data included total applied nitrogen (kg) by country for the year 2000 as well as the total excess nitrogen (kg) by country for the same year.
- The nitrogen input data were derived from a few sources. Applied chemical fertilizer was compiled from application rates defined by the International Fertilizer Association, as well as country- and state-level consumption rates provided in agricultural census records and fertilizer sales data. This compilation is described in Mueller et al. 2012. Atmospheric nitrogen input data were from

Dentener et al. 2007 that were estimated and used for the IPPC AR4. Manure was calculated based on livestock density and nitrogen content in manure. Nitrogen-fixation was estimating by scaling crop-specific fixation rates by yield. Excess nitrogen was calculated using a mass balance approach to determine the delta between applied nitrogen and nitrogen used by crops.

- Based on these two data sets, we back-calculated the total amount of nitrogen used by the crops as well as an implied NUE rate. The implied global NUE rate is 38 percent. The implied NUE rates for China, India, the U.S. and the E.U. are 27, 26, 46 and 52 percent respectively.
- We then calculated what the applied nitrogen rate would have been if 55 percent NUE had been realized, based on the same level of nitrogen used by the crops. We were then able to compare the amount of excess nitrogen based on current NUE with the amount of excess nitrogen we would see if global crops achieved 55 percent NUE. We determined a percentage of applied nitrogen reduction from this delta. We selected 55 percent as a target based on Ladha et al. 2005, which found 55 percent to be the global average NUE achieved from 93 experimental plots.
- Finally, we applied these reduction potentials on a global and country-level basis to our 2030 baseline crop-related nitrous oxide emissions.

Data sources

- Unpublished spreadsheet shared via email by Paul West, Institute on the Environment, University of Minnesota (January, 2014).
- Muller, N., J. Gerber, M. Johnston, D. Ray, N. Ramankutty, J. Foley. (2012). Closing yield gaps through nutrient and water management. *Nature, 490,* 254–257.
- Dentener, F., J. Drevet, J. F. Lamarque, I. Bey, B. Eickhout, A. M. Fiore, D. Hauglustaine, L. W. Horowitz, M. Krol, U. C. Kulshrestha, M. Lawrence, C. Galy-Lacaux, S. Rast, D. Shindell, D. Stevenson, T. Van Noije, C. Atherton, N. Bell, D. Bergman, T. Butler, J. Cofala, B. Collins, R. Doherty, K. Ellingsen, J. Galloway, M, Gauss, V. Montanaro, J. F. Muller, G. Pitari, J. Rodriguez, M. Sanderson, F. Solomon, S. Strahan, M. Schultz, K. Sudo, S. Szopa, O. Wild. (2006). Nitrogen and sulfur deposition on regional and global scales: A multimodal evaluation. *Global Biogeochemical Cycles, 20.*
- Ladha, J., H. Pathak, T. Krupnik, J. Six, C. van Kessel. (2005). Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in Agronomy*, 87.

2.8 Carbon sequestration in croplands

This report provides two estimates of mitigation potential from soil carbon sequestration in crops lands: 435 Mt CO_2e per year and 1,135 Mt CO_2e per year. Both of these estimates were calculated based on an analysis built upon Woolf et al. 2010. This analysis calculates the net greenhouse gas benefits of a one-time application of 50 t C per hectare of biochar produced in a "modern" facility, based on a model of regionally available carbon feedstocks (e.g., rice straw, forest residues, bioenergy crops on abandoned lands).While the stability of the carbon in biochar depends on the conditions under which it is produced as well as the feedstock, it is more stable than the carbon in non-charred biomass and therefore can sequester the carbon for longer. This analysis assumed biochar carbon resided in two "stability" pools, a labile pool (15 percent) with a half-life of 20 years, and a recalcitrant pool (85 percent) with a half-life of 300 years. The half-life of the feedstock biomass if left in the field was assumed to be 1 year for herbaceous biomass, and 3 years for woody biomass. This analysis provides a useful estimate of the technical carbon sequestration potential in agricultural soils, by country, based on carbon sources that do not have competing uses.

That said, there are several aspects of this analysis that are probably unrealistic from a social and economic perspective. For example, this analysis assumes that all of the biochar would be produced in “modern facilities”, even though most farmers today do not have access to such facilities. Further, the analysis assumes very high (albeit one-time) rates of biochar application which may not be economically viable or practicable for most farmers. Also, while this analysis attempts to include only feedstocks which do not have competing uses, it is very difficult to determine definitively whether or not a certain feedstock actually has a competing use or what the ramifications are of changing the usage. Finally, one of the most important feedstocks for this analysis is residues from rice production. Rice hulls contain silica, which can produce a carcinogenic product if rice-based biochar is produced improperly (at high temperatures). Care needs to be taken to ensure high quality production.

Methodology

- The biochar analysis was performed as a stand-alone analysis by James Amonette, Pacific Northwest National Laboratory. It estimates the regional mitigation potential of cropland-applied biochar created from a range of feedstocks, including crop residues, bioenergy crops grown on abandoned lands, and forest residues. Assumptions about available feedstocks are intended to be conservative and employ only “waste biomass."
- The biochar is assumed to be produced in a modern production facility. Note that the mitigation potential presented includes a technology adoption function that assumes a 5-year lead time, and slow ramping of production over the next 40 years as well as a full accounting of the GHG impacts of biochar production (e.g., the energy used in the process, the avoided GHGs from feedstock decomposition, soil carbon sequestration, fossil-fuel displacement).
- The analysis also incorporates biochar’s agronomic yield benefits, which are assumed to cause GHG benefits through its land sparing effects.
- It assumed that 50 tonnes of biochar is applied only once to each hectare, with lasting effects. New hectares receive a biochar application in each year of the simulation, such that all arable land has received an application of biochar after ~70 years.
- Additional details about the methodology are available upon request.

Table 3. Global biochar feedstock assumptions and *cumulative*, net avoided GHG by 2030

Feedstock class	Pg C per year feedstock	Description of assumptions
Rice	0.31	Rice husks and 70% of paddy rice straw not used for animal feed
Manures	0.17	12.5% of cattle manure plus 50% of pig and poultry manure
Sugar cane	0.13	Waste bagasse plus 25% of field trash
Green/ wood waste	0.18	75% of low-end estimate of yard-trimmings production and wood-milling residues
Other cereals	0.094	8% of total straw and stover (assumes 25% extraction rate of crop residues minus quantity used as animal feed)
Biomass crops	0.24	50% of potential production of abandoned, degraded cropland that is not in other use
Forestry residues	0.059	44% of difference between reported fellings and extraction
Total, not including enhanced yield	1.18	

- The term "biochar" represents a large group of pyrolysis products having a range of properties, and thus is far from being a single commodity or a panacea. As a result, care must be taken in matching biochars from a particular feedstock and pyrolysis process with a soil and cropping system. While, on average, biochar amendments seem to provide mitigation and economic benefits, in some situations, biochar does not represent the best use of biomass. These trade-offs are described in Woolf et al. 2010. In addition to the potential agronomic benefits, which vary with different groupings of biochar, soil, and cropping system, the carbon-intensity of the energy being offset by biochar production strongly influences its mitigation potential relative to 100 percent bioenergy production from the same feedstock. To the extent permitted by available data, these factors were considered in the biochar analysis.

This report calculates two estimates of the mitigation potential from biochar, both based on the analysis described above.

1. **The first estimate** is the more conservative of the two, totaling 435 Mt CO_2e per year. This estimate includes only crop residue and forest residue feedstocks, omitting biomass crops and the increased soil carbon sequestration associated with enhanced yields from the agronomic benefits of biochar. Additionally, it omits all of the avoided emissions elements of the full life cycle analysis, most notably avoided methane emissions associated with the removal of rice straw from the field and fossil fuel offsets from the syngas created during the pyrolysis process. Because this report does not included bioenergy, even on degraded lands, does not include the fossil fuel offsets associated with methane digestion of stored manure, and already accounts for emissions savings associated with removal of rice straw, this lower-bound biochar estimate is consistent with the rest of the analysis.
2. **The second estimate** includes biomass crops grown on degraded lands, the benefits of enhanced yields, as well as all avoided emissions (e.g., fossil fuel offsets and avoided methane emissions from rice straw left on the field). Although this estimate is less aligned with the rest of the analysis presented in this report, we felt it was important to provide the reader with a clearer sense of the total technical mitigation potential from biochar.
3. **Neither of the estimates** include biochar produced from manure or agroforestry residues because this report treats mitigation from both of these sources separately.

Additional soil carbon sequestration potential

We recognize that biochar is not the only mitigation practice associated with soil carbon sequestration on croplands, and that there is an enormous body of scientific literature dedicated to understanding the mitigation potential from these other practices (e.g., reduced- or no- tillage, improved management of crop residues, cover crops, and perennials). Unfortunately, we were unable to find recent analyses that provide global estimates of carbon sequestration potential on croplands. While several regional analyses exist, we did not include an aggregate sum from these studies because many of them rely on improved crop residue management which overlaps (double counts) with the biochar analysis. The findings from these studies are included in the table below for comparative purposes. In most cases, no year is provided by which these sequestration potentials might be achieved. Further, though estimates for sequestration potential using no-tillage systems are provided, it is important to note that there is currently significant scientific debate about the sequestration potential of no-tillage.[2]

Table 4. Cropland soil carbon sequestration potential

Source	Country/Region	Sequestration potential (Mt CO_2e per year)	Agricultural practice
Eagle et al., 2011	United States	29 to 173 (average 101)	Reduced and no-tillage
Grace et al., 2011	Indo-Gangetic Plain	186, over 20 years	No-tillage
Cerri et al., 2010	Brazil	11.5 to 46.2 (average 28.9)	No-tillage
Freibauer et al., 2004	Europe	103	No-tillage
Eagle et al., 2011	United States	36 to 150 (average 93)	Crop residue management
Lu et al., 2009	China	126	Crop residue management
Freibauer et al., 2004	Europe	95	Crop residue management

Primary data sources

- Biochar calculations were performed using BGRAM 1.2, which has been modified by JE Amonette from BGRAM 1.1 (Woolf D, JE Amonette, FA Street-Perrott, J Lehmann, and S Joseph. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications 1*, 56.) to process national and regional data.
- A.J. Eagle, L. Henry, L. Olander, K. Haugen-Kozyra, N. Millar, G. P. Robertson. (2011). *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature, 2nd Edition*. Durham, NC: Nicholas Institute for Environmental Policy Solutions, Duke University. http://nicholasinstitute.duke.edu/ecosystem/land/TAGGDLitRev.
- Grace, P., J. Antle, P.K. Aggarwal, S. Ogle, K. Paustian, B. Basso. (2011_. Soil carbon sequestration and associated economic costs for farming systems of the Indo-Gangetic Plain: A meta-analysis. *Agriculture, Ecosystems and Environment. 146,*137–146.
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2.9 Supply chain and demand-side measures

Fertilizer production in China (160 Mt CO_2e per year)

- Emissions from Chinese fertilizer production could be reduced 160 Mt CO_2e per year below a business-as-usual scenario for (BAU) by 2030 by improving manufacturing technologies. This assumes fairly aggressive reductions in emissions from coal energy generation, which may be outside the scope of agricultural mitigation efforts.

Primary data source

- Source: Zhang, W., Z. Dou, P. He, X. Ju, D. Powlson, D. Chadwick, D. Norse, Y. Lu, Y. Zhang, L. Wu, X. Chen, K. Cassman, F. Zhang. (2013). New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *PNAS, 110.*

Reduce food waste (760 Mt CO_2e per year)

- The conclusions in this report pull from the limited existing literature on the mitigation potential from reducing food waste. This number is highly uncertain.
- Smith et al., 2013 estimate a range of 760 to 1,500 Mt CO_2e per year by 2050 from a reduction in food supply chain losses and wastes. We halved those numbers to determine mitigation potentials in 2030, assuming a linear trajectory. Thus we present 380 to 760 as a low and medium range for mitigation potential from food losses and wastes in 2030.
- For a high end, we took a different approach. A recent paper published by FAO estimates 3.3 Gt CO_2e as the annual emissions footprint of food losses and wastage across the supply chain. A recent study by Parfitt et al. 2010 (referenced in Smith et al. 2013), reports that in the UK, 64 percent of food wastage is "avoidable". Using 64 percent as the ratio for avoidable losses and wastage across the entire globe, applied to the FAO estimate of 3.3 Gt, yields a mitigation potential of 2.1 Gt per year.
- These estimates are clearly rough. Further, the actual effects of reducing food waste on food production are highly uncertain. For example, a decrease in demand might lower prices, causing producers to expand production to try to achieve profitability, or producers could transition to biofuels of alternative uses of the land which may or may not reduce emissions.

Primary data sources

- Smith, P., H. Haberl, A. Popp, K Erb, C. Lauk, R. Harper, F. Tubiello, A. Pinto, M. Jafari, S. Sohi, O. Masera, H. Bottcher, G. Berndes, M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. Elsiddig, C. Mbow, N. Ravindranath, C. Rice, C. Abad, A. Romanovskaya, F. Sperling, M. Herrero, J. House, S. Rose. (2013). How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals?" *Global Change Biology, 19*, 2285–2302.
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Change in diets (2.15 Gt CO_2e per year)

- This report provides an estimate of the reduction in agricultural and land use change emissions if the world's population ate less animal products. The low estimate (0 Gt CO_2e per year) assumes no change in production as a result of dietary shifts, the midpoint (2.15 Gt CO_2e per year) assumes the global population adopts a "healthy diet," and the high estimate assumes that the global population eats no meat at all (3.2 Gt CO_2e per year).
- This report uses the midpoint estimate. The "healthy diet" scenario prescribes daily protein intake of 90 g per day, based on guidelines by Harvard Medical School. This diet leads to higher meat intake than in the reference case for some developing countries, but much less than typical daily American diet today. The 2030 mitigation potentials were assumed to be 50 percent of the 2050 potential estimated in Stehfest et al.
- Although there are major portions of the global population that do not eat this much meat, these totals are significantly lower than the current global average and it is unrealistic to assume that the global population might reduce its meat consumption so significantly in the aggregate. We have included this calculation primarily to demonstrate the outsized impact of dietary shifts over large populations.
- Primary data source: Stehfest, E., L. Bouwman, D. van Vuuren, M. den Elzen, B. Eickhout, P. Kabat. (2009). Climate benefits of changing diet. *Climatic Change, 95,* 83–102. DOI 10.1007/s10584-008-9534-6. These scenarios were generated using an integrated assessment model (IMAGE 2.4).

Additional supply chain opportunities not included in this analysis

- Assessing the mitigation potential in the agricultural supply chain was not squarely within the scope of this report in large part because mitigation along the supply chain may be best addressed in the context of efforts focusing on the energy, building, transportation, or industrial sectors. There are, however, additional mitigation opportunities worth mentioning. Note that neither of these opportunities are addressed in this report or the aggregated analysis.
- Cold chain (250 Mt CO_2e per year) It is estimated that 50 percent of the 500 Mt CO_2e per year in cold chain GHG emissions could be reduced through technologies such as more efficient retail displays, storage methods, and transportation, based on a study of cold emissions in the UK. This estimate is probably conservative it is based off of current emissions, yet cold chain emissions are likely to grow significantly by 2030, as the developing world adopts food supply chains that increasingly rely upon refrigeration.
- Primary data source: James, SJ, C James. (2010). The Food Cold-Chain and Climate Change. *Food Research International, 23.*
- Other supply chain interventions (300–400 Mt CO_2e per year) Published estimates and our calculations suggest that other supply chain interventions might yield reductions of 300–400 Mt CO_2e per year, through efficiencies in on farm-equipment, irrigation, processing, packaging, and transport, retail, catering, and food management, and waste.
- Primary data source:
- Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko. (2007) Agriculture. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds). Cambridge, United Kingdom: Cambridge University Press.

[1] Van Groenigen, J., Velthof, G., Oenema, O., Groenigen, K., Van Kessel, C. (2010). Towards an agronomic assessment of N_2O emissions: a case study for arable crops. *European Journal of Soil Science, 61,* 903-913.

[2] There seems to be general consensus that adoption of reduced-tillage or no-tillage management practices increases soil carbon stocks within the top ten centimeters of soil. However, there is debate as to the impacts of tillage on carbon at deeper depths, with some studies indicating that if a deeper soil column is considered, carbon sequestration does not increase as a result of tillage practices. Source: Palm, C. et al. 2013.