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Quantifying the Air Quality Cobenefits of the Clean Development Mechanism in China

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The Clean Development Mechanism's (CDM) contribution to sustainable development in host countries has come under criticism in recent years. Yet, there are no detailed country-wide estimates of air quality cobenefits from CDM projects. In this paper, we estimate the SO_2, $PM_{2.5}$, and NO_x cobenefit rates (tonnes per kt CO_2eq reduced) of 11 CDM project types for seven regions in China, using detailed activity data from Project Design Documents and emissions factors calculated from the GAINS-Asia model database. We forecast the CO_2eq reductions by CDM projects to 2012 and their associated contributions to air pollution reductions, and avoided health and agricultural impacts. We expect CDM projects to yield notable SO_2 reductions in the coming years (1094 kt in 2010), with more modest reductions of $PM_{2.5}$ and NO_x (79 and 270 kt in 2010, respectively). This suggests that the CDM could be making a nontrivial contribution to China's SO_2 reductions under the 11th Five-Year Plan. The monetized health and agricultural benefits from reduced PM and NO_x amount to roughly 12 billion RMB per year in 2010, roughly one-third of the market value of the associated Certified Emission Reductions.

1. Introduction

The Clean Development Mechanism (CDM) offers the opportunity for Annex I countries to make low-cost greenhouse gas-reducing investments in developing (non-Annex I) countries, which would count toward their domestic abatement obligations under the Kyoto Protocol. Along with greenhouse gas (GHG) reductions, a key motivation of the CDM is to provide sustainable development benefits to the host countries (*1*). In addition to the economic benefits of investment, it is thought that CDM projects could provide important technology transfers, and social and environmental improvements.

Air quality improvement is an example of such a contribution, and has received notable attention in the literature. The numerous synergies between climate and air quality policies are well-known, and CDM projects which install renewable energy to offset carbon energy sources, switch fuels to less carbon-intense options, or upgrade technologies are likely to reduce air pollutant emissions (*2*). This is of particular interest to a country such as China because of its large portfolio of CDM projects, and domestic air quality challenges. As of July 2009, there were 1699 registered (approved) CDM projects worldwide, 579 of which were based in China (*3*). Chinese emissions of key air pollutants have significant impacts locally and regionally (*4*).

Yet it has been suggested that the CDM has not fully lived up to initial promises of sustainable development (*5, 6*). The issue remains highly topical, and recent discussions have proposed demonstrable cobenefits be a criterion for future CDM projects (*7*). But there exists no authoritative quantitative estimate of overall air quality cobenefits of the CDM, as the Project Design Documents (PDDs), which describe the workings and expected outcomes of the individual projects, are not currently required to provide such information. Toward filling this gap, this paper estimates the total reductions of NO_x, $PM_{2.5}$ and SO_2 emissions associated with CDM activities in China to 2012. The results are presented in terms of kilotonnes of pollutant reductions, as well as monetized health and agricultural benefits, broken down into project location and type categories.

The general approach taken in this paper is as follows. The set of current active CDM projects in China, as listed in the UNEP CDM Pipeline database (*3*) is split into groups categorized by project type and geographical location. Using standard statistical techniques, we then sample a subset of projects from each group. From detailed information in the PDDs of the sampled projects and emissions factors calculated from the GAINS-Asia model (*8*), we then calculate an average coabatement rate of tonnes SO_2, $PM_{2.5}$, and NO_x per kilotonne CO_2eq (global warming potential-weighted CO_2 equivalents) reduced for each type/location grouping. We then forecast annual CO_2 reductions by all projects in each group to 2012. Combining this forecast with our coabatement rate, we estimate annual levels of ancillary pollution control from projected CDM activities to 2012, and the benefit to health and agriculture.

There are only a handful of similar CDM air quality cobenefit studies in the literature. Cosbey et al. (*9*) and Sutter and Parreño (*10*) assess sustainable development contributions (including air quality) of registered CDM projects—yet only in qualitative terms via point grading systems. Vennemo et al. (*11*) undertake a quantitative estimate of the air quality cobenefits from China's energy-related CDM projects. This paper effectively updates and extends their estimate by using new methods and data, and overcoming two key limitations of their work. First, they estimated pollution coabatement rates using a small, relatively homogeneous sample of energy-related projects. In this study we take a much larger sampling of projects, across numerous project types, to better account for the heterogeneity in the projects' characteristics. Second, their forecasts of CDM activities used literature estimates of China's aggregate CDM *potential* and was not disaggregated by project type. We are able to make a more realistic and detailed forecast using recent CDM data.

2. Pollutant Coabatement Rates in the CDM

2.1. Sampling: Type/Location Groupings and Sample Size. We seek to calculate coabatement rates for our three pollutants across existing CDM projects, which we can then apply to forecasts of CDM activity. We use statistical sampling as it allows us to calculate averages by only examining a portion of the CDM projects. However, before sampling, we split the population into smaller groupings of type and location, from which we then sample independently. The reasons are 2-fold. First, disaggregated calculations of coabatement rates offer a richer and more useful perspective

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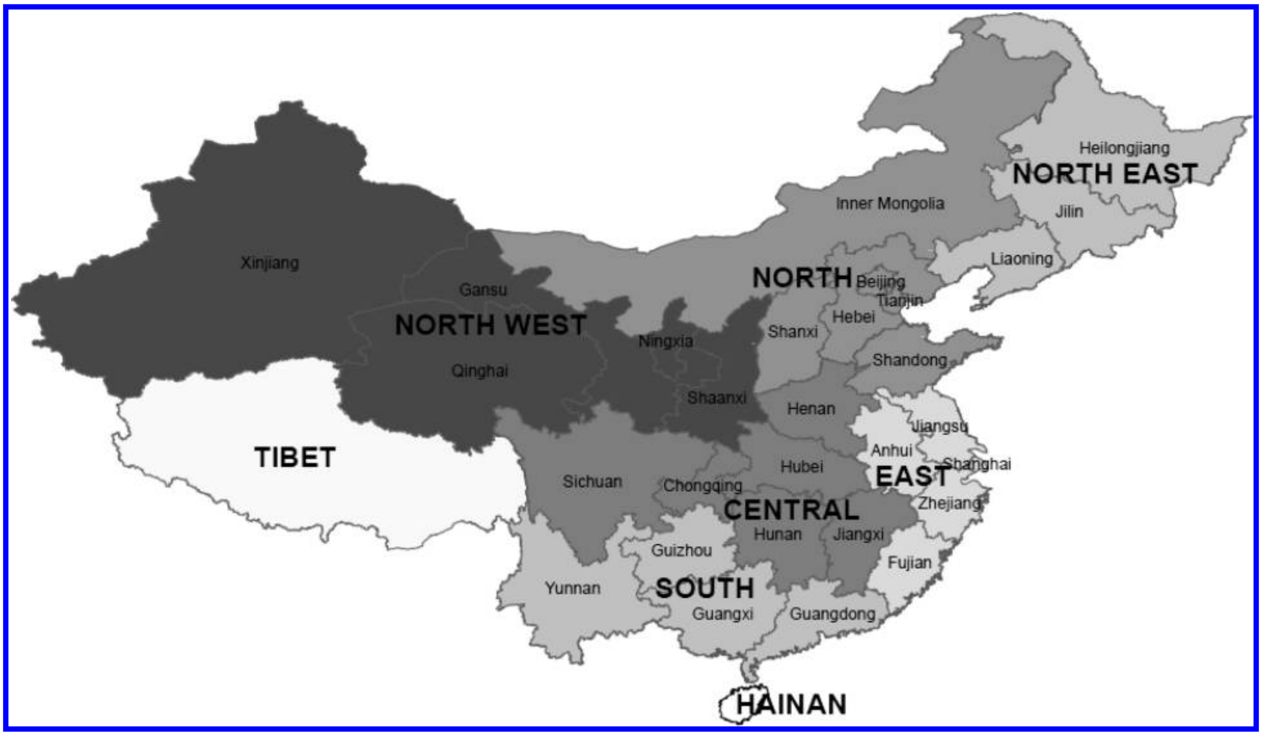

FIGURE 1. Geographical categories used in this paper and their member provinces for mainland China, based around the regional power grids. While Inner Mongolia's grid is split into the North and North East regions, PDDs typically include it in the North region. Note, there are no CDM projects in Tibet.

than a single national result, amenable to cross-region and -type comparisons. Second, project types are very heterogeneous with respect to their abating activities. If we do not categorize the projects before sampling, we risk bias in our aggregate calculation of emission offsets.

Our primary population is the set of all active CDM projects in China, based on the UNEP CDM Pipeline Database (*3*). We refer to as "active" those projects either at validation, requesting registration, or registered—the successive stages of project development (see Supporting Information (SI))—and those that could feasibly contribute to pollution offsets in future. The database is updated monthly, tracking the characteristics and progress of all projects. For this paper, we use the database updated 1 July 2009, which lists a total of active 1754 China-based CDM projects: 579 are registered, 107 are requesting registration, and 1068 are at validation. We exclude projects which are labeled "Withdrawn", "Validation terminated", "Validation negative", or "Rejected".

Each project is categorized into one of seven geographical regions, based on the location indicated in the PDD. In most of the energy-related PDDs, offsetting the use of electricity (characterized by its source grid) is a key source of Certified Emission Reduction (CER) generation. Thus, for consistency our regional boundaries are defined by the seven key power grids within China (see Figure 1). Projects are also categorized into one of eleven project types, based on the project categories found in the CDM Pipeline database. Projects within the same type category either employ the same or similar methodologies; they will be based around the same types of investments, have similar project boundaries and stipulations, and similar methods for calculating greenhouse gas offsets. The project categories, sample project descriptions, and the number of projects within each type/location group are listed in Table 1. This is a much wider range of project types than those featured in Vennemo et al. (*11*), whose sample case studies would likely fall within our Energy Efficiency (EE) Supply-side and Industry category. In SI Table S1 we list associated CDM methodologies for each project type.

We employ the standard calculation of minimum sample size for each type/location (t,l) group $(n_{t,l})$, given the standard deviation $(\sigma_{t,l})$ of the coabatement rate. This is the smallest number of samples we must take to obtain an average estimate for each category within our acceptable margin of error (e) and confidence interval (*12*).

$$n'_{t,l} = \left(\frac{T\sigma_{t,l}}{e}\right)^2 \tag{1}$$

$$n_{t,l} = \left(\frac{n'_{t,l}}{1 + \frac{n'_{t,l}}{N'_{t,l}}}\right)^2 \tag{2}$$

The margin of error (e) is set at 5%. A 95% confidence interval is applied, so the critical value T is set to 1.96. The uncorrected sample size $(n'_{t,l})$ is then adjusted to account for the population $(N_{t,l})$ in each type/location grouping, giving us the corrected minimum sample size $(n_{t,l})$. For each sampled project, we calculate its pollution coabatement rate as described in Section 2.2 below. For each location/type category, we undertake an iterative process of calculating the standard deviation of the coabatement rate and the minimum standard size, adding further samples until the two are consistent. This is described in further detail in the SI. The final sample size used for each group is shown in Table 1. In most categories we have sampled the entire project population. See the SI and sensitivity analysis in Section 6 for a discussion on sample groupings and bias.

2.2. Project Coabatement Rates. For each of the sampled projects, we extract relevant activity data from the project PDD, and use emissions factors for SO_2, $PM_{2.5}$, and NO_x to calculate its cobenefits per unit abated CO_2eq.

For consistency, we limit our cobenefit calculations to the activities within each project's "boundary", as dictated by the project's methodology. This can include the primary offsetting activity (e.g., switching from coal to biomass fuel) and any ancillary changes from the baseline activity (e.g.,

TABLE 1. Number of Active CDM Projects in China in Each Type/Location Category as of 1 July 2009, and Sample Project Descriptions[a]

Project Type/Location	Sample Project Description	Central	East	Hainan	North	North East	North West	South	Total
Zero Emission Renewables	New hydro or wind power	307 (32)	81 (13)	11 (6)	197 (24)	95 (16)	178 (23)	297 (35)	1166 (149)
Biomass	New biomass plant	22 (21)	21 (20)	0 (0)	17 (17)	12 (10)	1 (1)	1 (1)	74 (70)
Waste	Biogas recovery for power generation	19 (19)	18 (18)	0 (0)	20 (20)	9 (9)	3 (3)	14 (14)	83 (83)
FF Switch	Switch from coal to gas	3 (3)	11 (10)	0 (0)	6 (4)	1 (1)	2 (2)	7 (7)	30 (27)
Fugitive	Coal mine methane recovery for power generation	17 (16)	8 (8)	0 (0)	29 (29)	5 (5)	6 (6)	2 (2)	67 (66)
F-Gas	HFC-23 destruction	1 (0)	8 (0)	0 (0)	3 (0)	0 (0)	0 (0)	0 (0)	12 (0)
Cement	Replacement of lime in cement production	1 (1)	1 (1)	0 (0)	2 (2)	1 (1)	1 (1)	1 (1)	7 (7)
N_2O	Reduction of N_2O in nitric acid production	9 (9)	1 (1)	0 (0)	11 (11)	2 (2)	1 (1)	5 (5)	29 (29)
EE Own Generation	Waste heat for power generation	68 (67)	56 (55)	3 (3)	79 (60)	22 (22)	13 (13)	17 (17)	258 (237)
EE Supply-side and Industry	Retrofitting for improved efficiency	5 (5)	4 (4)	0 (0)	2 (2)	4 (4)	3 (3)	4 (4)	22 (22)
Forestry	Afforestation or reforestation	1 (0)	0 (0)	0 (0)	0 (0)	1 (0)	0 (0)	4 (0)	6 (0)
Total All Types		453 (173)	209 (130)	14 (9)	366 (169)	152 (70)	208 (53)	352 (86)	1754 (690)

[a] Number in parentheses is the number of projects sampled to estimate the air quality co-abatement rate. "Active" projects are those either at validation, requesting registration, or registered. FF denotes fossil fuel. Source: Fenhann (3).

increased road transport). SI Table S1 presents sample activities for each project type. These activities can contribute either positively and negatively to the net greenhouse gas reduction, with a corresponding effect on pollutants.

We use data from the GAINS-Asia model (*8*) to calculate emissions factors for the types of activities included in the CDM projects. The database offers a time series (on a five-year basis) of activity levels and emissions in each province for China. We use the data for 2010 from the GAINS-Asia *Baseline09* scenario (*13*), aggregated to our geographical regions. The GAINS-Asia data is highly detailed with respect to sectors and fuels. The scenario embodies assumptions about the characteristics of fuels and fuel use, and application and abatement rates of emissions control technologies. In particular, it captures the recent rapid deployment of desulphurisation technologies in the electricity sector.

Attempting to match them as closely as possible with descriptions of the sectors/activities in GAINS database, we calculate emissions factors for the activities described in the PDDs (see SI Table S1): grid electricity production, point source industrial combustion of coal/diesel/biomass/gas, and road transport. The full set of emissions factors used in our base calculations is included in the SI, along with a more detailed discussion of the methods and assumptions used. Acknowledging the importance of these emissions factors to our final results, we undertake a sensitivity analysis (see Section 6) using different assumptions. Of course, our GAINS-derived emissions factors represent region-wide averages, rather the particular characteristics of the sampled CDM projects. It would be impossible to obtain the individual project data in a study such as this, and as such our results should be seen as indicative estimates.

We have excluded two project types from our calculations: the Forestry and F-Gas projects. Based on the pipeline database, only approximately 0.15 and 0.04% of baseline emissions (in CO_2eq terms) in these respective project types are relevant to air quality cobenefits, and we assume their coabatement rates to be zero.

From the results of our sampled projects, we calculate weighted mean coabatement rates (and standard deviations) for each location/type category, weighted by the annual expected CERs from the sampled projects. Detailed results are presented in Tables S3–5 in the SI. In Table 2, we present the national average results (by project type), which are calculated from the disaggregated mean coabatement rates, and weighted by each location/type category's expected annual CERs in 2012. The weighted average cobenefit rate over all projects (including forestry and F-gas projects) is approximately 3.7 $tSO_2/ktCO_2eq$, 0.26 $tPM_{2.5}/ktCO_2eq$, and 0.88 $tNO_x/ktCO_2eq$, and approximately 4.9 tSO2/$ktCO_2eq$, 0.35 $tPM_{2.5}/ktCO_2eq$, and 1.2 $tNO_x/ktCO_2eq$ over energy-related projects (excluding Forestry, N_2O, Cement, and F-Gas).

We can categorize pollution reduction in each project into one of three key modes: grid electricity offsets, point source offsets, and transport offsets. Reductions in grid electricity use are the primary source of the CDM's pollution offsets; they are the sole source in Zero Emission Renewable and EE Own Generation projects. Generally, we find the point source and transport offsets to be small. Biomass projects tend to have negative point-source offsets (increased emissions) because they take agricultural waste that is only partially open burned in the baseline, and fully combust it in their project. These offsets are discussed in the SI, where we also we present a sample breakdown of $PM_{2.5}$ offsets (SI Table S6).

Comparing coabatement rates across project types, we see that the energy-related projects offer notably higher reductions than the projects with little or no energy component (e.g., N_2O and Cement, which may see an increase due to additional energy use). The differences highlight the importance of sampling from categorized subpopulations. Across the energy-related projects, there is great variation, on account of the differing activities within projects. Fossil Fuel (FF) Switch projects, for example, offer comparably high SO_2 reductions per unit CO_2eq reduced as they tend to substitute gas for coal; the drop in SO_2 emissions from this switch is virtually 100%, whereas the drop in CO_2 is only about 40% (*8*). Similarly, the comparably small estimate of offsets of NO_x from the other natural gas-related projects (e.g., Fugitive, Waste, FF Switch) is due to the expectation that this new gas combustion will itself involve new NO_x emissions.

Regional variation (seen in SI) is partly due to the energy sector and environmental control characteristics of the region. This is seen, for example, in the higher SO_2 coabatement averages for the North, Central, and North East regions, owing to higher SO_2 intensity of grid electricity production. When it comes to the averages, however, the results also depend on the project makeup in each region. The East region has a high SO_2 coabatement rate across energy-related projects owing to a predominance of FF Switch projects.

TABLE 2. All-China Weighted Average Co-Abatement Rates and Monetized Benefits from CDM Activities[a]

All-China Weighted Averages	Co-Abatement Rates			Avoided Deaths from PM (RMB/tCO2)	Avoided Crop Loss from NOx (RMB/tCO2)
	$tSO_2/ktCO_2$	$tPM_{2.5}/ktCO_2$	$tNO_x/ktCO_2$		
Zero Emission Renewables	4.5	0.31	1.5	20	38
Biomass	5.6	0.74	1.5	50	38
Waste	0.79	0.042	0.082	2	2
FF Switch	12	0.79	0.12	55	3
Fugitive	1	0.06	0.22	4	6
F-Gas					
Cement	0.062	-0.0019	-0.022	0	0
N2O	0.0019	0.00013	0.0019	0	0
EE Own Generation	4.9	0.35	1.5	23	38
EE Supply-side and Industry	6.9	0.39	3.3	53	72
Forestry					
Energy-Related Weighted Average	4.9	0.35	1.2	24	30
All-Project Weighted Average	3.7	0.26	0.88	18	22

[a] Calculated from sample mean co-abatement rate for each type/location category, using the expected annual CER generation to 2012 reported in CDM Pipeline Database (3) for each type/location category as the weighting factor. The energy-related grouping excludes the Forestry, N_2O, Cement, and F-Gas project types. See SI for results disaggregated by project type and location. RMB in 2005 terms.

We can compare our SO_2 and PM results with the case studies surveyed in the Vennemo et al. (*11*) study, which would likely fall within our EE Supply-side and Industry category. Our national EE Supply-side and Industry averages (6.9 $tSO_2/ktCO_2$ and 0.39 $tPM_{2.5}/ktCO_2$) fit into the 15−85% intervals (5.7−11.4 $tSO_2/ktCO_2$ and 0.3 to 1.4 $tPM_{2.5}/ktCO_2$) for all projects surveyed. (We use a 0.12 $tPM_{2.5}/tTSP$ ratio to compare PM results.) We expect our estimate to be on the low side of these ranges, given improvements in pollution control in recent years. These results lend confidence to our result, given the similar bottom-up approach taken in the studies surveyed.

We can make a rough comparison of our NO_x results with a computable general equilibrium (CGE) study by Vennemo et al. (*14*). From their alternative national carbon tax scenarios in China for 2020, we calculate an implied economy-wide cobenefit rate of 1.0−1.3 $tNO_x/ktCO_2$, comparable to our all-project average of 1.2 $tNO_x/ktCO_2$. However, this does not necessarily confirm our result, as we have used significantly different methods.

3. Forecasting CDM Activity to 2012

We forecast CDM activity in China for the first crediting period to 2012. Our approach borrows from a similar forecasting exercise in the UNEP CDM Pipeline Database.

3.1. Currently Active CDM Projects. Forecasting CER generation from the active (as of July 2009) CDM projects simply uses the annual CER data provided by the PDDs. We first forecast the *expected* CER generation from all the individual active projects listed in the CDM Pipeline database. The start time for each project's CER generation is assumed to be the "Credit Start" date listed on the project PDDs, which is the start point of abatement activities. This means we forecast when CERs are being *generated* (i.e., when abatement is actually taking place), rather than when the CER credits are subsequently *issued*. By tracking the time of CER generation, we can track when associated cobenefits are actually occurring. This is particularly important because the effects of air pollution reduction come on very short time scales. The *expected* generation in each year must be adjusted to account for the expected validation, registration, and issuance success rates at each point in the CDM project cycle. This yields the forecasted *actual* CER generation; abatement that actually will take place and be credited. This is detailed further in the SI. We can then sum up the annual forecasted CER generation for each location/type grouping.

3.2. New Projects. For each type/location grouping we also forecast CER generation from new projects - those that become active after 1 July 2009 (the cutoff date of the CDM database we use). We first do this by tracking the rate at which projects in each location/type category have been added in the 12 months running up to 1 July 2009. We extrapolate these additions forward to 2012, and forecasting the annual *actual* reductions in each category. Doing so, we are effectively assuming little change in criteria for project validation or crediting going forward. Ongoing negotiations could yield a change in the way projects are accepted in future. However, we keep our forecast simple for convenience, and only to 2012. In addition, we focus on the results for 2010, during which the new projects play only a small role. See the SI for further details.

The aggregate forecasts from current and new projects are summarized in Table 3. Annual abatement from CDM projects is forecasted at 319 $MtCO_2eq/yr$ in 2010, rising to 560 $MtCO_2eq/yr$ in 2012. Not all credits will be available for trading within the Kyoto Protocol period due to the issuance delay.

Our forecasts are broken down by project type and status in SI Figures S1 and S2. They suggest that the largest contribution until 2009 has come from Zero Emission Renewable projects, and these projects will continue to dominate going forward. While there are no new hydrof-lourocarbon (F-Gas) projects being developed, the remaining are still expected to contribute a sizable portion of GHG reductions going forward. Other notable project types are the EE Own Generation, Fugitive, and Biomass projects. Our forecast suggests new projects could make up half of total CER generation in 2012.

4. Pollution Reduction Cobenefits to 2012

Combining the coabatement rates from Section 2 and the CER forecast from Section 3, we forecast the pollution reduction cobenefit of each type/location grouping to 2012. A China-wide summary of the estimated cobenefits is presented alongside CER generation forecast in Table 3. The results for 2010 are broken down by project status, type, and location in Table 4.

TABLE 3. Forecasted Actual CERs Generated from CDM Activities in China, and Accompanying Offsets of SO_2, PM, and NO_x[a]

Year	CER Generation (MtCO2eq)	SO_2 Offsets ($ktSO_2$)	PM Offsets ($ktPM_{2.5}$)	NO_x Offsets ($ktNO_x$)
2003	0.0	0.2	0.0	0.1
2004	0.4	0.7	0.1	0.2
2005	0.8	1.5	0.1	0.5
2006	5.8	5.4	0.4	1.7
2007	62	52	3.9	14
2008	126	235	17	52
2009	236	745	53	165
2010	319	1094	79	270
2011	430	1536	114	417
2012	560	2049	155	588
Cumulative 2006-2010 (11th Five-Year Plan)	749	2132	153	504
Cumulative 2008-2012 (Kyoto Period)	1671	5659	417	1494

[a] CER generation refers to when the abatement takes place, rather than when the CERs are issued.

TABLE 4. Forecasted Actual CER Generation and Accompanying Offsets and Monetized Benefits of SO_2, $PM_{2.5}$, and NO_x in 2010, Broken Down by Status, Project Type, and Location. RMB in 2005 Terms

	Annual Reductions from CDM in China in 2010	CER Generation (MtCO2/yr)	Air Pollution Offsets			Avoided Deaths from PM (million RMB/yr)	Avoided Crop Loss from NO_x (million RMB/yr)
			SO_2 ($ktSO_2$/yr)	PM ($ktPM_{2.5}$/yr)	NO_x ($ktNO_x$/yr)		
	National Total	319	1094	79	270	5359	6895
	Share of Total (%)						
By Status	At Validation (as of July 2009)	32 %	43 %	43 %	49 %		
	Req. Registration (as of July 2009)	4 %	8 %	8 %	5 %		
	Registered (as of July 2009)	53 %	36 %	35 %	28 %		
	New (from July 2009)	11 %	13 %	14 %	18 %		
By Type	Zero Emission Renewables	37 %	48 %	47 %	64 %	43 %	65 %
	Biomass	4 %	7 %	12 %	7 %	12 %	7 %
	Waste	1 %	0 %	0 %	0 %	0 %	0 %
	FF Switch	7 %	23 %	21 %	1 %	22 %	1 %
	Fugitive	8 %	2 %	2 %	2 %	2 %	2 %
	F-Gas	21 %	0 %	0 %	0 %	0 %	0 %
	Cement	1 %	0 %	0 %	0 %	0 %	0 %
	N2O	9 %	0 %	0 %	0 %	0 %	0 %
	EE Own Generation	12 %	17 %	16 %	20 %	16 %	21 %
	EE Supply-side and Industry	2 %	2 %	2 %	6 %	6 %	4 %
	Forestry	0 %	0 %	0 %	0 %	0 %	0 %
By Location	Central	18 %	25 %	22 %	24 %	28 %	25 %
	East	25 %	19 %	21 %	10 %	23 %	10 %
	Hainan	0 %	0 %	0 %	0 %	0 %	0 %
	North	25 %	24 %	24 %	29 %	20 %	29 %
	North East	11 %	8 %	11 %	13 %	9 %	13 %
	North West	8 %	9 %	8 %	11 %	6 %	10 %
	South	12 %	15 %	14 %	13 %	13 %	13 %

We see that that nationwide total reduction from CDM activities is forecasted at 1094 $ktSO_2$, 79 $ktPM_{2.5}$, and 270 $ktNO_x$ in 2010. Applying coabatement rates at one standard deviation above and below the mean values for each location/type category (SI Tables S3−S5), our China-wide offset estimate range is 882−1305 $ktSO_2$, 65−93 $ktPM_{2.5}$, and 199−341 $ktNO_x$ for 2010. These cobenefits will come predominantly from the Zero Emission Renewables, FF Switch, and EE Own Generation projects. The results for the Zero Emission Renewables and EE Own Generation projects is unsurprising, owing to their large share in total GHG reduction. Interestingly, the FF Switch project type is only forecasted to contribute 7% of total CDM GHG reductions, but due to its high coabatement rates contributes 23% and 20% of SO_2 and $PM_{2.5}$ reductions, respectively. Location-wise, we can see that the GHG reductions are most heavily located in four regions: the Central, East, North, and South regions. The cobenefits are similarly distributed, although it is worth noting that the share of total NO_x cobenefits occurring in the East is notably smaller than its GHG reductions, owing to a predominance of FF Switch projects.

To put these emission reductions in context, we compare them with prevailing emissions levels. Inventories by Zhang et al. (*15*) put China's national emissions at 31020 $ktSO_2$, 13266 $ktPM_{2.5}$, and 20830 $ktNO_x$ in 2006, while an updated projection (used by this study for emission factors) by Klimont et al. (*13*) for 2010 puts emissions at 35609 $ktSO_2$, 14162 $ktPM_{2.5}$, and 20782 $ktNO_x$. Comparing our forecasted offsets in 2010 with these levels, we see that the SO_2 offset is the most important cobenefit (approximately 3.5 and 3.1% of the 2006 and 2010 estimates, respectively), followed by relatively modest contributions to $PM_{2.5}$ and NO_x reductions (approximately 0.6 and 1.3%, respectively, for both estimates). A likely explanation for the differences in relative reduction is the share of these pollutants coming from the power sector. According Zhang et al. the power sector contributed 60% of China's total SO_2 emissions in 2006, but only 11 and 44% of its $PM_{2.5}$ and NO_x emissions. Because many of the CDM GHG reductions come from grid electricity offsets, the CDM's SO_2 cobenefits will be more significant. The CDM's low NO_x offsets, however, can likely be explained by the use of natural gas in many projects, which (based on the GAINS data) are likely to release NO_x with little or no control.

We can also compare our results to 11th Five Year Plan, under which China seeks to reduce national SO_2 emissions by 10% during the period 2005−2010. The GAINS-Asia *Baseline09* data suggest that had SO_2 emission factors not improved in this period, China's national emissions in 2010 would have been around 44000 $ktSO_2$. Comparison to their above projected level suggests that the desulphurization policy yields a reduction of 8400 $ktSO_2$ in 2010. A similar number is found by a U.S.-China Joint Economic Study (*16*). With a different model and assumptions, they suggest that the required reduction from the 2010 business as usual level to meet the 11th Five Year Plan goal is 8000 $ktSO_2$. Our forecasted CDM offsets of SO_2 in 2010 are, respectively, 13 and 14% of these reductions, suggesting the CDM is making a nontrivial contribution to China's SO_2 reduction targets. These figures are summarized in SI Table S8.

5. Benefits to Health and Agriculture

We make a rough, illustrative assessment of the avoided deaths from reduced PM emissions and avoided crop loss from reduced NO_x emissions associated with the CDM. We estimate the monetized avoided damages per unit CO_2eq abated for each CDM project type/location grouping and apply them to our forecasts of CER generation.

5.1. Avoided Premature Deaths per $ktCO_2$ Reduced. To estimate avoided premature deaths associated with reduced PM emissions from CDM projects, we rely on data from a number of literature sources. Vennemo et al. (*11*) compile research on health cobenefits from energy related CO_2 mitigation in different parts of the world, from which we derive an estimate of 0.10 avoided deaths per $tPM_{2.5}$ reduced for energy-related CDM type projects in China. However, this refers primarily to industrial point sources. The CDM projects we have covered include offsets from grid electricity, transport, as well as point sources, which contribute to population exposure at different rates. As such, we weight the relative health impact of the three offset categories based on intake fractions (iF) from Ho and Nielsen (*17*). We further weight the health impact of offsets in each region on the basis of relative urban population density. Combining these with the coabatement rates in Section 2, and using a Value of Statistical Life of 1 million RMB (in 2005 terms) per avoided premature death (see Vennemo et al. (*11*)), we calculate the CDM health benefit in terms of RMB/tCO_2eq. The China-wide average estimates are presented in Table 2. The disaggregated results are presented in SI Table S8, alongside additional details of the calculations.

5.2. Avoided Crop Loss Per $ktCO_2$ Reduced. Emissions of NO_x lead to formation of ozone, which is a photo-oxidant affecting plant growth as well as human health. For our calculations, we take average avoided crop loss per tNO_x loss estimates from Vennemo et al. (*14*). These should be taken as very rough approximations as they are dependent on the model parameters and assumptions, and geographical differences in ozone formation were not fully accounted for by Vennemo et al. We use an average value for China at 0.026 million RMB (2005) avoided crop loss per tNO_x reduced. Combining this estimate with the coabatement rates from Section 2, we calculate a monetized agricultural benefit rate for each project location/type category. The China-wide average estimates are presented in Table 2. The disaggregated results are presented in SI Table S9, alongside additional details of the calculations.

5.3. Absolute Health and Agricultural Benefits for 2010. The benefit rates are combined with our forecasts of CER generation from Section 3 to estimate absolute benefits from the CDM. These are presented below in Table 4. We find that the benefits from both avoided deaths and crop loss are approximately 12 billion RMB (in 2005 terms) in 2010, over 50% of which occurs in the North and Central regions. While these benefits are minute compared to China's GDP, we can undertake a rough cost-benefit calculation by comparing them to the CER price of 12 €/tCO_2 (www.pointcarbon.com, accessed March 2010). If we divide these annual benefits by the forecasted number of permits for 2010, we get a CER benefit of 38 RMB/tCO_2eq, or 4 €/tCO_2eq at current exchange rates. While only a rough estimate (and ignoring inflation), this suggests that on average, one-third of the current market value of CERs is reaped by China in the form of benefits to health and agriculture alone.

6. Sensitivity Analysis

All our results are heavily dependent on external data sources and key assumptions about CDM activities and their impacts. First, we have chosen to use the GAINS-Asia database for 2010 to generate emissions factors, and in doing so, have adopted the underlying methods and assumptions therein. Of course, choosing a different data source would yield different results. However, even with the GAINS model, there is some ambiguity in choosing data to calculate emissions factors, in particular for the point sources. In our sensitivity analysis, we thus apply alternative high and low assumptions. Second, our health and agricultural cobenefit calculations are particularly uncertain, given our reliance on literature estimates that do not exactly match our regional and activity aggregations. As such, we explore the effects of alternative intake fraction and population density weighting assumptions. Third, as is always the case with sampling, we risk bias to our aggregate result. One weakness of our sampling approach is that we include projects which are currently active but could still feasibly be canceled (e.g., at validation, or requesting registration). As such, the risk of bias is higher if these projects rejected at a high rate and their characteristics are notably different than the registered projects. We thus undertake a sensitivity analysis wherein we break down our type/location categories into further registered and nonregistered groupings, from which we sample. Details of the sensitivity analyses are presented in the SI.

We find that alternative assumptions on point source removal efficiencies can have large impacts on the result. These relate to the removal efficiencies of the CDM installations themselves, and when set to zero, PM emissions actually increase. While our default assumptions are arguably reasonable and consistent with strict standards on new build plants (*13*), this highlights the importance of using advanced environmental control technologies in CDM projects. The monetized benefit calculations are similarly dependent on our assumptions, particularly with regards to intake fractions from the different sources. This data is particularly uncertain, and depends on the technical and geographical characteristics of the projects. Finally, we find that splitting the categories into registered and nonregistered projects results in considerable change in the calculations for certain project types, such as Waste, Cement, and Fugitive, due to high variance in their coabatement rates. However, these types generally have only few projects; while improvement can always be made, switching to this sampling approach has little effect on the regional and national results, giving us confidence in the approach we have taken.

7. Discussion

In this paper, we undertake an updated estimate of SO_2, NO_x, and $PM_{2.5}$ offsets from CDM projects in China, categorized by type and location, using detailed data from project PDDs and emissions factors calculated from the GAINS-Asia model. Our results suggest that the CDM projects are likely to make a notable contribution to SO_2 reductions in the coming years (1094 kt in 2010, approximately 3.1% of projected total Chinese SO_2 emissions in 2010), with a more modest contribution to offsets of $PM_{2.5}$ and NO_x (79 and 270 kt in 2010, respectively, approximately 0.6 and 1.3% of projected 2010 levels, respectively). The higher SO_2 reductions are important given they are a national priority under the 11th Five Year Plan; the CDM SO_2 offsets make up approximately 13−14% of the reductions (from business as usual level) in 2010. Our rough estimate of the monetized health and agricultural benefits from the reduced PM and NO_x is 12 billion RMB (2005) in 2010, approximately one-third of the current market value of the associated CERs.

These results are highly relevant to the ongoing discussions of a post-2012 climate agreement and the role of the CDM therein. There have been a number of proposals for incentivizing cobenefits of CDM projects (*5, 18*), and a recent AWG-KP nonpaper included the proposal that demonstrable cobenefits be a requirement for project acceptance (*7*). The methodologies presented here may be used by project developers generate pollution cobenefit estimates for their PDDs.

Furthermore, our results could inform the way in which host designated national authorities (DNAs) approve projects, helping to orient the CDM toward existing national environmental goals. China's DNA already heavily taxes F-Gas and N_2O projects—seen to contribute little to sustainable development—and prioritizes the energy efficiency and renewable projects. Based on our results, these prioritisations would be supported on the grounds of pollution cobenefits, as would be Biomass and FF Switch projects. It should be noted that while such estimates are of interest to other countries, given the heterogeneous coabatement rates found even within China, simple extrapolations to other countries would likely be insufficient.

Finally, as a disclaimer, it should be noted there is still considerable debate on the issues of additionality, project boundaries, leakage, and CER calculation. Our results should be interpreted accordingly. First, that CDM projects would not have taken place in the absence of CERs is often difficult to assess, and questions have arisen over whether certain (even registered) projects should indeed have been deemed additional (*19*). We are well aware of the implications for our results; the nonadditional offets should simply be treated as business as usual. But assessing additionality is beyond the scope of this paper, and our calculations effectively trust the current project approvals with respect to additionality. Third party surveys of nonadditionality (see Schneider (*19*)) could be used to downscale our results. Second, the CDM project boundary is of course artificial and limited. As such, the CER (and cobenefit) calculation may not be capturing the true leakage (both positive and negative) in emissions. This weakness has prompted suggestions toward sector and programmatic CDM (*20*). While we acknowledge such critiques, for consistency with the calculation of CERs, we follow the PDDs' assumptions.

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Supporting Information Available

Detailed discussion of methodologies and disaggregated results. This material is available free of charge via the Internet at http://pubs.acs.org.

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