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On the Importance of Baseline Setting in Carbon Offsets Markets

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On the importance of baseline setting in carbon offsets markets

Antonio Bento, Ravi Kanbur and Benjamin Leard*

Abstract

Incorporating carbon offsets in the design of cap-and-trade programs remains a controversial issue because of its potential unintended impacts on emissions. At the heart of this discussion is the issue of crediting of emissions reductions. Projects can be correctly, over- or under-credited for their actual emissions reductions. We develop a unified framework that considers the supply of offsets within a cap-and-trade program that allows us to compare the relative impact of over-credited offsets and under-credited emissions reductions on overall emissions under different levels of baseline stringency and carbon prices. In the context of a national carbon pricing scheme that includes offsets, we find that the emissions impacts of over-credited offsets can be fully balanced out by under-credited emissions reductions without sacrificing a significant portion of the overall supply of offsets, provided emissions baselines are stringent enough. In the presence of high predicted business-as-usual (BAU) emissions uncertainty or low carbon prices, to maintain the environmental integrity of the program, baselines need to be set at stringent levels, in some cases below 50 percent of predicted BAU emissions. As predicted BAU emissions uncertainty declines or as the carbon market achieves higher equilibrium prices, however, less stringent baselines can balance out the emissions impacts of over-credited offsets and under-credited emissions reductions. These results imply that to maintain environmental integrity of offsets programs, baseline stringency should be tailored to project characteristics and market conditions that influence the proportion of over-credited offsets to under-credited emissions reductions.

Keywords: Carbon offsets, crediting, environmental integrity

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1 Introduction

Complementing cap-and-trade programs with carbon offsets supplied from uncapped sectors is recognized as a way of achieving emissions reduction targets at lower economic cost (Basu, 2009; Brown and Adger, 1994; Chameides and Oppenheimer, 2007; Lehmann, 2007; Victor, 2012). However, awarding offsets to projects requires the setting of a baseline that reflects the project's BAU emissions. Offsets are counted based on documented emissions relative to baselines. If the offsets project managers have more information on the project's BAU emissions than the regulator that assigns the project baseline, then the program may attract projects that have baselines above their BAU emissions. Managers opt these projects into the program and can claim offsets up to their baseline while not reducing emissions (Fischer, 2005; Menges, 2003; Meyers, 1999; Rentz, 1998). When these offsets are sold to firms regulated under a cap-and-trade program, overall emissions can increase (Gillenwater et al., 2007; Kintisch, 2008; Maslin, 2011; Schneider, 2009a; Zhang and Wang, 2011). Studies have documented this issue of asymmetric information in various contexts, including SO_2 tradable permit markets (Montero, 1999, 2000), incentives to reduce emissions from deforestation (Busch et al., 2012; Van Benthem and Kerr, 2013), design payments for environmental services (Ferraro, 2008) and sectoral crediting of voluntary emissions reductions (Millard-Ball, 2013). Other studies have suggested various solutions for this problem, including using multiple policy instruments (Bento et al., 2015; Calvin et al., 2015; Horowitz and Just, 2013) and contract design (Mason and Plantinga, 2013).

The issue at hand is one of crediting of emissions reductions. A program may award a project with offsets that exceed the project's emissions reductions, leading to the production of offsets that we define as *over-credited offsets*. But the crediting system may also lead to emissions reductions that do not generate offsets. This happens when an opted in project is assigned a baseline below its BAU emissions. These projects lower emissions more than the quantity of offsets they earn and can reduce aggregate emissions by the difference between the project's baseline and its predicted BAU emissions. We call the reduction in aggregate emissions *under-credited emissions reductions*.

Such reductions have been identified as a source that can counteract the emissions consequences of over-credited offsets. Schneider (2009b) suggests that setting baselines below BAU emissions can lead to an atmospheric benefit as offsets projects are credited with fewer offsets than their true emissions reductions. Gillenwater (2012a,b) correctly isolates the impact of over-crediting projects and awarding offsets to projects that are non-additional. In both cases, aggregate emissions can increase. Bento et al. (2015), Erickson et al. (2014) and Warnecke et al. (2014) model under- and over-crediting of offsets projects and find that under-crediting can play a significant role in maintaining environmental integrity of climate mitigation programs.

Even with these studies, however, little is known about the relative importance of over-credited offsets and under-credited emissions reductions and how the relative magnitudes of each quantity vary in response to key market parameters, including the carbon price, uncertainty in BAU emissions and mitigation costs. We quantify the relative magnitudes of the two emissions impacts under a wide range of market parameters by calibrating a simple model of carbon abatement in the United States that accounts for adverse selection among offsets projects (Bento et al., 2015; Bushnell, 2012). Therefore we are able to identify policies that may balance these two quantities when facing different market conditions. We find that the emissions impacts of over-credited offsets can be fully balanced out by under-credited emissions reductions without sacrificing a significant portion of the overall supply of offsets, provided emissions baselines are stringent enough. When predicted BAU emissions uncertainty is low or as the carbon market achieves high equilibrium prices, less stringent baselines are required to balance out the emissions impacts of over-credited offsets and under-credited emissions reductions. Our results suggest that to maintain environmental integrity of carbon offsets programs without sacrificing substantial cost savings from these programs, policy makers should tailor baseline stringency to project characteristics and market conditions that influence the proportion of over-credited offsets to under-credited emissions reductions.

2 Methods

Our model includes an uncapped sector that comprises heterogeneous projects and a capped sector represented by a single cost-minimizing firm. Offsets are supplied by projects in the uncapped sector. For each capped sector reduction target that we consider, we assume that a quantity of emissions permits is grandfathered to the regulated firms that equals regulated firm BAU emissions minus the reduction target. While others have pointed to other allocation methods for these types of systems (Goulder et al., 2010), whether permits are grandfathered or auctioned does not change our conclusions but instead influences the distribution of rents among firms and the regulator. The capped sector complies with the program by holding permits, reducing emissions through abatement or buying offsets. Permit and offset prices are solved endogenously so that the demand for permits and offsets by capped firms equals the supply of permits by the regulator and the supply of offsets from projects, respectively.

In equilibrium, the offsets price equals the permit price without additional distortions, such as offsets usage limits, trade ratios or offsets usage transaction costs. In some cap-and-trade programs, offsets sell for a lower price than permits, possibly due to the distortions mentioned (Braun et al., 2015; Mansanet-Bataller et al., 2011; Naegele, 2015). We do not model a gap between permits and offsets for the sake of consistency with previous analyses of Waxman-Markey (Kile, 2009). Instead, we model transaction costs on the offsets supply side, which has similar qualitative effects to a demand side transaction cost.

The Supply of Offsets

Offsets supply is derived from profit maximization behavior of offsets project managers. We model the managerial decisions of projects to supply offsets through a project-specific profit function:

$$\pi_i = \max_{s_i \leq e_i \leq u_i} \left\{ (p - t_i)(b_i - e_i) - c_i(u_i - e_i) \right\}. \tag{1}$$

Supply decisions by project managers are based on six variables: BAU emissions (u_i), sequestration potential (s_i), a marginal cost of mitigation (c_i), an assigned emissions baseline (b_i), a per unit transaction cost (t_i) and an equilibrium price of offsets that is common to all projects (p). The manager of project i knows with certainty its project's BAU emissions, while the regulator only knows predicted BAU emissions, which equal project-specific BAU emissions plus a project-specific emissions shock. Baselines are set as a function of predicted BAU emissions. Ex-post emissions are assumed to be common knowledge that the policy maker can perfectly observe. The emissions shocks are independently and identically drawn from a normal distribution.

Each manager's decision whether to opt in its project and whether to mitigate is based on equation (1). Project managers compare the profits of the difference decisions and choose the combination that solves the problem stated in equation (1). In the Supplementary Material we analytically derive optimal choices from equation (1) and divide approved projects into different categories based on project characteristics. We summarize this categorization with Figure 1. Project i's BAU emissions, u_i, is shown on the horizontal axis while its marginal costs of mitigation, c_i, is on the vertical axis.

The manager of an approved project can either commence with the project (i.e., opts into the program) or decide not to start the project (i.e., does not opt in). Approved projects that have either high marginal costs of mitigation or relatively low baselines are not profitable enough for the manager to opt in. These are designated by the purple and blue cross-hashed regions in Figure 1. There are some projects that are profitable enough for the manager to opt in and have its project perform mitigation but are under-credited because they are assigned a baseline below their BAU emissions. These are projects that fall into the green region and are characterized by marginal costs of mitigation that are sufficiently below the offsets price less transaction costs. Managers of projects that are assigned a baseline above the project's BAU emissions opt in their projects and are over-credited. These projects fall into the red region of Figure 1 and would have commenced without the program taking place. This is because these projects have marginal costs of mitigation above the offsets price less transaction costs. The orange region in Figure 1 includes projects that perform mitigation but are over-credited. These projects would not have occurred in the absence of the program, since their marginal costs of mitigation fall below the offsets price less transaction costs. However, they are awarded a greater quantity of offsets than the quantity of emissions reductions they provide. In this case, the projects earn some offsets that correspond to mitigation and some that do not correspond to mitigation (e.g., over-credited offsets). When regulated sectors under a cap-and-trade program can use offsets to meet the cap, the supply of over-credited offsets leads to overall emissions increases while under-credited emissions reductions lead to overall emissions reductions.

Managerial decisions yield offsets supply and under-credited emissions reductions, which are used to calculate the change in emissions (see Supplementary Equation 17). We exclude a supply of international offsets in our benchmark simulations because of the high level of uncertainty in existing estimates for this supply. Our sensitivity analysis, however, includes scenarios that represent a program that includes international offsets supply (see Supplementary Tables 7, 8 and 9).

While under-credited emissions reductions are affected by the price of offsets, over-credited offsets are not. As long as the offsets price less transaction cost is positive, over-credited projects are profitable and are opted in. Thus, increasing the offset price has no effect on the supply of over-credited offsets for sufficiently high price levels. In sharp contrast, the opt-in decision of an under-credited project depends on the offset price. As the offset price increases, more under-credited projects become profitable, represented by an expansion up of the lower-right green region in Figure 1. See the Supplementary Material for a graphical illustration of this effect.

The Capped Sector

Offsets are supplied to the capped sector that must comply with an emissions reduction target. We model the capped sector as a representative firm, an assumption that is consistent with prior literature (Fell et al., 2012; Fell and Morgenstern, 2010). We calibrate the abatement cost structure of the capped sector with processed simulation output from the EPA's analysis of the Waxman-Markey bill (EPA, 2009c). The capped sector emissions reduction target translates into a fixed supply of emissions permits. The capped sector must hold one emissions permit or one offset for every unit of emissions that it does not mitigate.

Equilibrium

Equilibrium is determined by equating permit supply and demand and offsets supply and demand. Permit and offset prices are determined endogenously through these market-clearing conditions. This equilibrium is static as we do not model dynamic decisions of capped sector firms or offsets projects. Dynamic cap-and-trade models, however, typically find that with unconstrained banking and borrowing and increasing reduction target stringency, equilibrium prices increase at the rate of interest over time (EPA, 2009b; Rubin, 1996). This result is consistent with how we frame our scenarios where the lowest prices emerge early in the program under low capped sector reduction targets and the highest prices come later in the program under stringent targets.

Calibration

We calibrate the model to represent a stylized federal cap-and-trade program in the United States. We assign values of the mitigation cost parameters based on estimates used in the EPA's analysis of Waxman-Markey (EPA, 2009a,c). We base our simulation on Waxman-Markey parameters because this bill is the most prominent federal legislation in the United States to include an offsets provision and therefore remains the most representative offsets policy that the United States may adopt in the future.

We calibrate the distribution of predicted BAU emissions that yields an expected quantity of over-credited offsets equal to 30 percent of total offsets supply when baselines are set to equal predicted BAU emissions in an equilibrium with a carbon price of \$25 per ton of CO_2e. We calibrate a domestic offsets supply function to data on mitigation costs from forecasts of mitigation cost curves from various offsets supply sources in the United States, including livestock management, crop management, afforestation, forest management and soil sequestration (EPA, 2009d). For full details of the model structure and calibration, see the Supplementary Material.

3 Results

We discovered that for a range of parameter values, under-credited emissions reductions exceed the supply of over-credited offsets if baselines are set stringent enough. Figure 2 shows the composition of offsets and emissions changes for a range of baselines on the horizontal axis, expressed as a proportion of predicted BAU emissions. A proportion less than one implies that every project's baseline is less than its predicted BAU emissions. The vertical axis measures offsets supply and emissions changes in terms of million metric tons of CO_2 equivalent ($\mathrm{MMTCO_2e}$).

We present outcomes under nine combinations of predicted BAU emissions uncertainty and reduction target stringency. We allow both market attributes to vary from low, to medium to high, where the medium level of each attribute is our benchmark. Our benchmark medium reduction target represents a medium-run abatement target of 2,000 $\mathrm{MMTCO_2e}$, which was scheduled under Waxman-Markey legislation to be achieved by 2026 (EPA, 2009a). The low and high cases represent short- and long-run reduction targets under the same legislation, respectively. The low and high cases for predicted BAU emissions uncertainty represent less and more uncertainty on predicting BAU emissions around the benchmark level of uncertainty, respectively.

The different curves show outcomes for the supply of over-credited offsets (OCO), aggregate change in emissions (ΔE), and under-credited emissions reductions ($UCER$). The aggregate change in emissions is relative to a program that does not include offsets. If the capped sector reduction target is high and when baselines are set to be less than about 65 percent predicted BAU emissions, under-credited emissions reductions exceed the supply of over-credited offsets for all considered levels of predicted BAU emissions uncertainty (Figure 2g,h,i). In particular, when BAU emissions uncertainty is low, baselines set below 80 percent of predicted BAU emissions achieve a similar result. Under these scenarios and for this range of baselines, emissions decrease. A high reduction target yields a higher equilibrium offsets price, which encourages greater participation by project developers as the marginal returns to mitigating emissions is higher. Therefore it is more likely for managers of projects with assigned baselines less than their BAU emissions to opt in. This increases the quantity of under-credited emissions reductions while having no effect on the supply of over-credited offsets. When the degree of uncertainty on BAU emissions is low (Figure 2g), less stringent baselines are necessary for aggregate emissions to fall. Low BAU emissions uncertainty implies that a project is more likely to receive a baseline that matches its BAU emissions. This has the effect of reducing the supply of over-credited offsets since there will be fewer projects that have baselines above their BAU emissions.

If the degree of uncertainty for predicted BAU emissions is high, it is less likely for the quantity of under-credited emissions reductions to exceed the supply of over-credited offsets (Figure 2c,f,i). A higher degree of uncertainty implies that projects have more extreme predicted BAU emissions. A project that has predicted BAU emissions that are substantially larger than its BAU emissions is more likely to receive a baseline that exceeds its BAU emissions. The manager of this project will likely opt in and earn over-credited offsets. On the other hand, a project that has predicted BAU emissions that are substantially lower than its BAU emissions is more likely to receive a baseline so low that its manager will no longer find it profitable to opt in its project. In this case, the project does not generate under-credited emissions reductions. When the capped sector reduction target is low (Figure 2c), this effect is amplified as project managers have a lower revenue incentive to opt in their project and have it mitigate emissions. In this case, project baselines must be very stringent – less than 35 percent of predicted BAU emissions – for the quantity of under-credited emissions reductions to exceed the supply of over-credited offsets. For a capped sector reduction target of 2,000 MMTCO$_2$e and the benchmark level of uncertainty (Figure 2e), the net effect on emissions of creating an offsets market is zero when baselines equal 70 percent of predicted BAU emissions.

Our analysis thus far suggests that the emissions consequences of under-credited emissions reductions can potentially cancel the emissions consequences from the supply of over-credited offsets if baselines are stringent. Setting baselines low, however, may eliminate a significant supply of offsets and lead to lost opportunities (Trexler et al., 2006). This could potentially reduce much of the cost savings from including offsets in cap-and-trade programs. To determine the relationship among baseline stringencies, offsets supply and cost savings, we simulate the model under three baseline protocols. We define the protocol denoted by “Predicted BAU Emissions” by setting baselines equal to predicted BAU emissions. We call the second protocol “Minimize Supply of Over-Credited Offsets.” This protocol sets baselines to ensure that there is no supply of over-credited offsets. The third protocol, “Maintain Environmental Integrity,” adjusts baselines to the point where the aggregate supply of over-credited offsets equals the quantity of under-credited emissions reductions. Under this protocol, the effect of including offsets in the cap-and-trade program has no net effect on emissions as the two sources of emissions changes cancel.

Table 1 reports offsets supply and emissions consequences of including offsets in the cap-and-trade program for three capped sector reduction targets. Panels (a), (b) and (c) report estimates for a low, medium and high capped sector reduction target, respectively. In general, the higher the reduction target, the higher the equilibrium price of permits and offsets. This result is illustrated by comparing the equilibrium offset prices across the three panels. When the capped sector reduction target is low, equilibrium prices range from \$7.66 to \$11.69, while with a high capped sector reduction target, equilibrium prices range from \$75.86 to \$85.85.

Table 1 highlights three key findings. First, setting baselines equal to predicted BAU emissions leads to a substantial increase in emissions. For a low capped sector reduction target (Table 1, Panel (a)), there are only 4 MMTCO$_2$e under-credited emissions reductions, compared to 144 MMTCO$_2$e over-credited offsets, leading to an aggregate increase in emissions of 140 MMTCO$_2$e. Emissions increase because projects with baselines above their BAU emissions opt in and receive over-credited offsets, while projects with baselines below their BAU emissions are not as likely to opt in and generate under-credited emissions reductions. Second, baseline protocols that attempt to fully eliminate the supply of over-credited offsets significantly reduce the supply of offsets. Across all three capped sector reduction target scenarios, we find that the minimize supply of over-credited offsets protocol has a much lower supply of offsets than the predicted BAU emissions protocol. For a capped sector reduction target of 2,000 MMTCO$_2$e, total offsets supply is about 50 percent less under the minimize supply of over-credited offsets protocol. Third, the maintain environmental integrity baseline protocol does not significantly reduce the supply of offsets as long as offset prices are high. For a capped sector reduction target of 3,500 MMTCO$_2$e, total offsets supply under the maintain environmental integrity protocol is 728 MMTCO$_2$e, which is only 10 percent less than total offsets supply under the predicted BAU emissions protocol. High offset prices encourage a greater fraction of projects with baselines set below their BAU emissions. Greater participation by these projects increases the quantity of under-credited emissions reductions. As a consequence, as the equilibrium offsets price increases, there is less need for setting stringent baselines to balance the supply of over-credited offsets and the quantity of under-credited emissions reductions. This feature is illustrated by recognizing the required baseline stringencies for the different equilibrium offset prices. While low offset prices require very stringent baselines (Table 1, Panel (a), $b_i = 0.46\tilde{u}_i$), high offset prices provide room for leeway (Table 1, Panel (c), $b_i = 0.77\tilde{u}_i$). Moving from a low reduction target of 500 MMTCO$_2$e to a medium reduction target of 2,000 MMTCO$_2$e allows the policy to relax baseline stringency by 50 percent. This suggests that for a one dollar increase in the equilibrium offsets price, baselines can be increased by between one and two percent to maintain the environmental integrity of the program.

Table 2 translates offsets supply and equilibrium prices from Table 1 into cost savings estimates from including offsets in the cap-and-trade program. We find that the protocol that minimizes the supply of over-credited offsets severely reduces the cost savings from incorporating offsets into the program. For a capped sector reduction target of 2,000 MMTCO$_2$e, cost savings are about 50 percent less relative to the predicted BAU emissions protocol (Table 2, Panel (b)). In contrast, the maintain environmental integrity protocol does not sacrifice much cost savings as long as the capped sector reduction target is sufficiently high. When the target is set to 3,500 MMTCO$_2$e, cost savings are only about 10 percent less relative to the predicted BAU emissions protocol. This result stems from the fact that more stringent reduction targets generate a supply of offsets that are only slightly less under the maintain environmental integrity protocol (Table 1). The result suggests that the trade-off between environmental integrity and compliance cost savings is insignificant under aggressive emissions reduction targets.

Sensitivity Analysis

To understand how our results depend on key market characteristics, we perform sensitivity analysis by simulating market outcomes over a wide range of parameters. We vary the tightness of offsets project baselines, from 20 percent to 100 percent of predicted BAU emissions, and analyze the pattern of offsets supply and emissions changes stemming from the quantity of under-credited emissions reductions and the supply of over-credited offsets. Sensitivity analysis around the basic assumptions including BAU emissions uncertainty, the offsets mitigation supply curve, the correlation between key variables, systematic bias in predicting BAU emissions and different measures of transaction costs is reported in the Supplementary Material. In each section of sensitivity analysis, we report the ratio of under-credited emissions reductions to over-credited offsets, offset supplies for broad ranges of the parameters and how different offsets protocols affect the cost savings from including offsets in cap-and-trade programs. Supplementary Tables 7, 8 and 9 report key model outputs for scenarios when a larger supply of offsets is allowed into the program, which represents a setting with international offsets. In these simulations we assume that the supply of mitigation function is multiplied by a constant proportion. We consider a wide range of alternative scenarios, including 25 percent (expensive mitigation opportunities) and 400 percent (cheap mitigation opportunities). Values above 100 percent represent programs that incorporate international offsets. When there are cheaper mitigation opportunities from offsets projects, there will be a greater quantity of under-credited emissions reductions created (see Supplementary Table 8), implying that baselines can be made less stringent to ensure the environmental integrity of the program. We find that transaction costs play a minor role in determining the relative magnitudes of over-credited offsets and under-credited emissions reductions (see Sections 9.7 and 9.8 of the Supplementary Material).

4 Conclusion

Our results imply two key policy recommendations, both of which involve differentiating baseline stringency. First, as the problem of over-crediting becomes less severe over time as carbon prices are expected to increase, baseline-setting stringency can be relaxed to encourage a greater supply of offsets. Therefore short-run policies that impose conservative baseline-setting measures appear justified, while they may be less justified in the future. Second, our framework serves as a guide for differentiating baseline stringency across projects based on project characteristics. In our main analysis we have shown that project types that have lower predicted BAU emissions uncertainty require a less stringent baseline to maintain environmental integrity. In the Supplementary Material, we show that projects with lower marginal costs of mitigation, higher offsets supply potential or lower transaction costs require a less stringent baseline to maintain environmental integrity. In the Supplementary Material, we categorize popular project types along these dimensions.

In addition to the significant cost reductions that offsets bring, recent arguments for including them in cap-and-trade programs point to the importance of their co-benefits. For example, offsets may be worthwhile for their ability to encourage the development of adaptation and transition toward a low-carbon world (Dargusch and Thomas, 2012). Other experience with carbon offsetting suggests that programs can prevent biodiversity loss and serve as a payment for ecosystem services projects (Green and Minchin, 2012; Jack et al., 2007; Siikamaki et al., 2012). The additional non-GHG mitigation benefits may be valuable enough to warrant incorporating offsets in cap-and-trade programs even when over-credited offsets exceed under-credited emissions reductions. Baselines calculated here can be further relaxed to account for these additional co-benefits.

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Table 1 | The effect of alternative baseline protocols on offsets supply and emissions.

(a) Capped Sector Reduction Target = 500 MMTCO$_2$e	Predicted BAU Emissions	Minimize Supply of Over-Credited Offsets	Maintain Environmental Integrity
Baselines	$b_i = \tilde{u}_i$	$b_i = 0$	$b_i = 0.46\tilde{u}_i$
Offsets Price	7.66	11.69	10.57
Percentage of Projects Opting In	51	7	23
Total Offsets Supply	202	86	127
Exact Offsets	58	86	109
Over-Credited Offsets	144	0	17
Under-Credited Emissions Reductions	4	27	17
Total Change in Emissions	140	-27	0

(b) Capped Sector Reduction Target = 2,000 MMTCO$_2$e	Predicted BAU Emissions	Minimize Supply of Over-Credited Offsets	Maintain Environmental Integrity
Baselines	$b_i = \tilde{u}_i$	$b_i = 0$	$b_i = 0.70\tilde{u}_i$
Offsets Price	38.14	47.02	40.83
Percentage of Projects Opting In	66	30	57
Total Offsets Supply	652	338	556
Exact Offsets	505	338	497
Over-Credited Offsets	147	0	59
Under-Credited Emissions Reductions	40	112	59
Total Change in Emissions	107	-112	0

(c) Capped Sector Reduction Target = 3,500 MMTCO$_2$e	Predicted BAU Emissions	Minimize Supply of Over-Credited Offsets	Maintain Environmental Integrity
Baselines	$b_i = \tilde{u}_i$	$b_i = 0$	$b_i = 0.77\tilde{u}_i$
Offsets Price	75.86	85.85	78.43
Percentage of Projects Opting In	74	39	68
Total Offsets Supply	817	436	728
Exact Offsets	672	436	653
Over-Credited Offsets	147	0	75
Under-Credited Emissions Reductions	61	152	75
Total Change in Emissions	86	-152	0

Carbon offset prices are reported in dollars per ton of CO$_2$e. Offsets supply, emissions reductions and changes in emissions are reported in MMTCO$_2$e. The percentage of projects opting in is the ratio of the quantity of projects that are opted in to the quantity of all potential projects. The Predicted BAU Emissions protocol is defined by setting project baselines equal to predicted BAU emissions. The Minimize Supply of Over-Credited Offsets protocol is defined by setting project baselines that guarantee zero supply of over-credited offsets. The Maintain Environmental Integrity protocol is defined by setting project baselines such that the expected supply of over-credited offsets equals the expected quantity of under-credited emissions reductions. This protocol keeps expected aggregate emissions fixed. Each panel shows average outcomes from 2,000 simulations. In each simulation the offsets price is endogenously determined by equating the supply and demand for offsets (see Supplementary Material).

Table 2 | The cost savings from including offsets in cap-and-trade programs under alternative baseline protocols.

(a) Capped Sector Reduction Target = 500 MMTCO$_2$e	No Offsets	Predicted BAU Emissions	Minimize Supply of Over-Credited Offsets	Maintain Environmental Integrity
Capped Sector Mitigation	500	272	413	373
Offsets Supply	0	204	86	127
Capped Sector Mitigation Costs	3,538	1,048	2,420	1,969
Uncapped Sector Mitigation Costs	0	101	314	340
Uncapped Sector Transaction Costs	0	1,019	430	636
Total Compliance Costs	3,538	2,169	3,164	2,946
Cost Savings	–	1,369	374	592

(b) Capped Sector Reduction Target = 2,000 MMTCO$_2$e	No Offsets	Predicted BAU Emissions	Minimize Supply of Over-Credited Offsets	Maintain Environmental Integrity
Capped Sector Mitigation	2,000	1,350	1,661	1,442
Offsets Supply	0	650	339	557
Capped Sector Mitigation Costs	56,600	25,784	39,020	29,419
Uncapped Sector Mitigation Costs	0	7,172	6,034	7,524
Uncapped Sector Transaction Costs	0	3,249	1,697	2,785
Total Compliance Costs	56,600	36,206	46,751	39,728
Cost Savings	–	20,394	9,849	16,872

(c) Capped Sector Reduction Target = 3,500 MMTCO$_2$e	No Offsets	Predicted BAU Emissions	Minimize Supply of Over-Credited Offsets	Maintain Environmental Integrity
Capped Sector Mitigation	3,500	2,678	3,031	2,769
Offsets Supply	0	817	434	730
Capped Sector Mitigation Costs	173,338	101,488	130,022	108,499
Uncapped Sector Mitigation Costs	0	15,036	11,507	15,115
Uncapped Sector Transaction Costs	0	4,084	2,168	3,649
Total Compliance Costs	173,338	120,608	143,698	127,263
Cost Savings	–	52,730	29,640	46,075

Capped and uncapped sector mitigation are reported in MMTCO$_2$e. Costs and cost savings estimates are reported in millions of (year 2000) dollars. The Predicted BAU Emissions protocol is defined by setting project baselines equal to predicted BAU emissions. The Minimize Supply of Over-Credited Offsets protocol is defined by setting project baselines that guarantee zero supply of over-credited offsets. The Maintain Environmental Integrity protocol is defined by setting project baselines such that the expected supply of over-credited offsets equals the expected quantity of under-credited emissions reductions. This protocol keeps expected aggregate emissions fixed. Each panel shows average outcomes from 2,000 simulations. In each simulation the offsets price is endogenously determined by equating the supply and demand for offsets (see Supplementary Material).

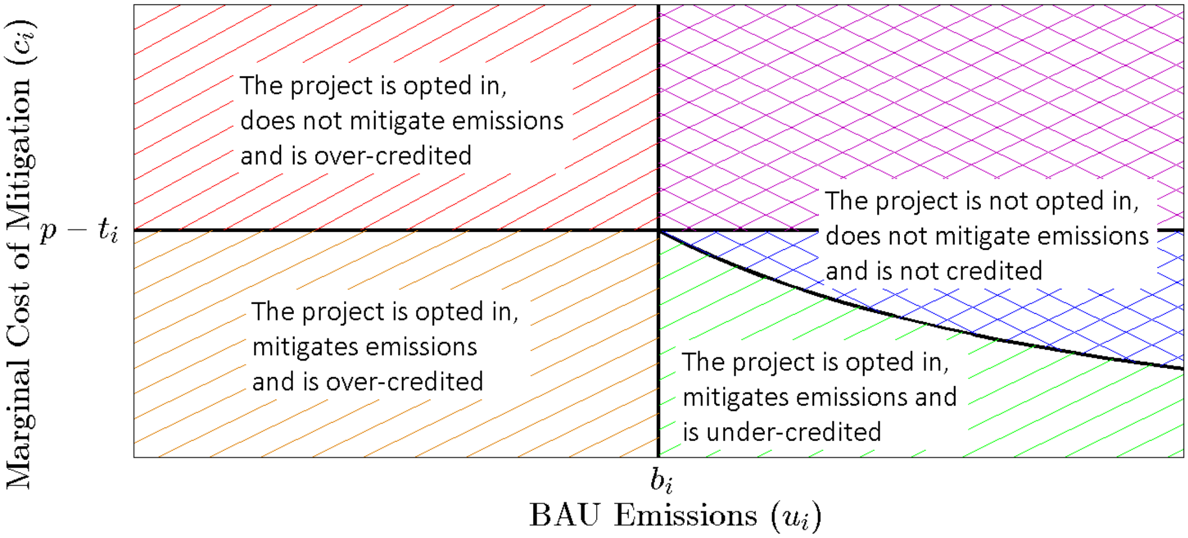

Figure 1 | Emissions and offsets supply consequences from the decisions of uncapped sector project managers. The horizontal axis denotes the ratio of a project's assigned baseline (b_i) and its BAU emissions (u_i). The vertical axis measures a project's marginal cost of mitigation (c_i), where the horizontal line $p - t_i$ represents the equilibrium price of offsets minus the project's transaction cost per ton of CO_2e. The equilibrium price of offsets is determined as an endogenous variable in our simulation model. Managers of projects that are classified in the blue and purple regions do not opt in their projects. The green region includes projects that produce under-credited emissions reductions. Projects belonging to the red and orange regions supply over-credited offsets. The curve separating the blue and green regions represents a zero-profit condition of the project profit-maximization problem (see the Supplementary Material for a formal definition and derivation).

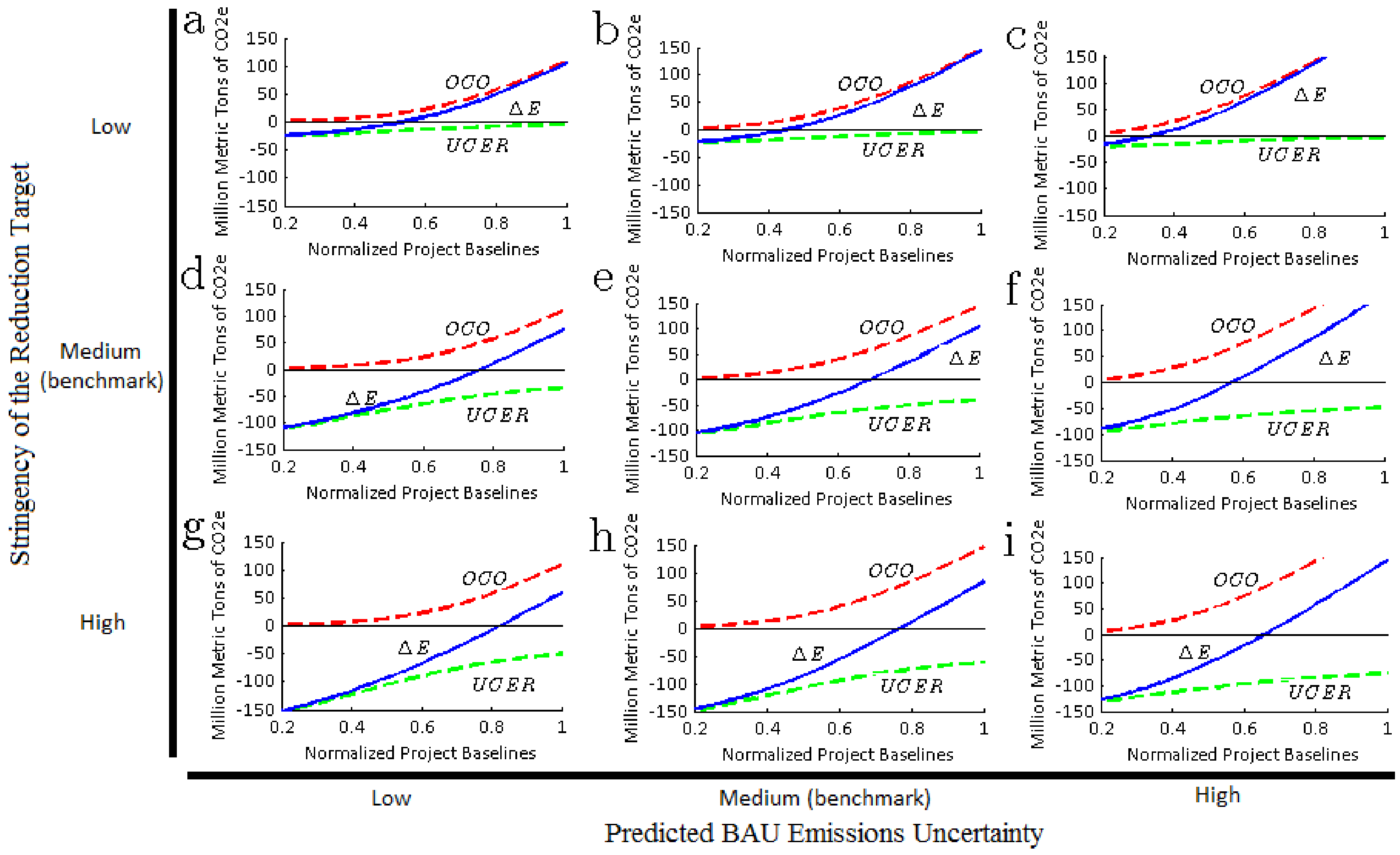

Figure 2 | The change in aggregate emissions relative to a program that does not include offsets, as a function of normalized project baselines. In each panel, the horizontal axis measures normalized project baselines, which are defined as a project's assigned baseline (b_i) divided by the project's predicted BAU emissions ($\tilde{u}_i$). The vertical axis measures million metric tons of CO_2e. The change in emissions (ΔE) is defined relative to a cap-and-trade program that does not include offsets. Its value is calculated by adding the supply of over-credited offsets (OCO) and the quantity of under-credited emissions reductions ($UCER$). Panels in the same row are simulations of programs that have a common capped sector reduction target. We consider three targets: low (500 MMTCO_2e, **a,b,c**), medium (2,000 MMTCO_2e, **d,e,f**) and high (3,500 MMTCO_2e, **g,h,i**). Panels in the same column are simulations that have the same uncertainty on predicted BAU emissions. We consider three levels of predicted BAU uncertainty that are defined by the standard deviation of emissions shocks (σ). Our benchmark simulation assumes that the standard deviation of prediction errors for BAU emissions is equal to the expected value of BAU emissions ($\sigma = E[u]$, **b,e,h**). The remaining cases have a low level of uncertainty ($\sigma = 0.75E[u]$, **a,d,g**) and high level of uncertainty ($\sigma = 1.5E[u]$, **c,f,i**). Each panel shows average outcomes from 2,000 simulations. In each simulation the offsets price is endogenously determined by equating the supply and demand for offsets (see Supplementary Material).