Ecological Economics 131 (2017) 399–406

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Performance of a cap and trade system for managing environmental impacts of shale gas surface infrastructure

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A R T I C L E   I N F O

Article history:
Received 25 March 2016
Received in revised form 9 July 2016
Accepted 15 September 2016
Available online xxxx

Keywords:
Shale energy
Shale gas infrastructure
Environmental policy
Conservation planning
Spatial optimization

A B S T R A C T

Governments across the globe are exploring ways to reduce the environmental and human health impacts created by shale energy production. In active areas, environmental regulations tend to be limited. We apply established instruments to empirically estimated environmental impact abatement cost curves for the development of 56 sites in Pennsylvania, USA. We compare the cost to industry of setting a cap on environmental impacts from land-clearing and building of surface infrastructure under two regulations: cap and trade versus a uniform, inflexible regulation. Greatest differences in cost are achieved when firm-level permits are allocated to reduce market-wide potential impacts by 36%. Cap and trade achieved this cap at a cost of 0.05% of not developing and allowed all development to proceed. The uniform, inflexible regulation cost 32% of not developing for a similar outcome and prevented 18% of firms from developing. Cap and trade's performance depended on the regulator's ability to accurately allocate firm-level permits that reflect developers' options. In extreme cases, inaccurate allocations made cap and trade perform worse than other the approach. We conclude that, where developers differ in their ability and cost of minimizing impacts, cap and trade should be explored as an inexpensive alternative to traditional approaches.

1. Introduction

In the United States, shale gas production has increased steadily over the past decades and now makes up 40% of gas production (U.S. Energy Information Administration, 2014). Concerns have been raised about the environmental (Gillen and Kiviat, 2012; Jones et al., 2014; Kiviat, 2013; Olmstead et al., 2013) and human health (Perry, 2012) effects of shale energy production. This led to consideration of how to protect society and nature from those effects (Hays et al., 2015; Howarth et al., 2011) and sometimes bans on development. Though policies and regulations in regions proceeding with development exist, new regulations can expand their environmental scope to include those of high priority that are currently unregulated.

Shale gas production progresses through many stages (Burton et al., 2014) at multiple spatial scales. We focus on the construction of surface infrastructure at the lease-hold scale. Lease-holds ("sites" hereafter) are boundaries of development that aggregate multiple gas leases to hundreds or thousands of hectares. Shale gas extraction requires belowground infrastructure, which is often the focus of environmental studies (Hays et al., 2015). However, extraction also requires significant surface infrastructure to access drilling sites, process gas, and transport it to market. We focus on well pads, access roads, and gathering pipelines, infrastructure which is common at all gas extraction sites and which has measurable environmental effects. The spatial planning of these three types of infrastructure is a complex process from a cost-minimization perspective. The cost-minimizing configuration of infrastructure relies on the simultaneous consideration of interactions among infrastructure locations. Consequently, actions that affect that configuration may not be simple to adopt.

Many environmental features are impacted by shale gas surface infrastructure (Gillen and Kiviat, 2012). Roads and pipelines fragment habitats, which increases habitat edges, produces dispersal barriers, and reduces core habitats. Construction exposes and mobilizes surface soils, potentially leading to erosion and subsequent sedimentation in water bodies. Stream-crossing infrastructure reduces freshwater connectivity by limiting upstream and downstream dispersal. These are a few of the common and pervasive environmental impacts that depend on the spatial configuration of surface infrastructure ("layout" hereafter), the regulation of which can thus help minimize impacts. For a visual representation of four different layouts produced for our case study, including resulting differences in environmental impact, see Fig. S5. Though we focus on well pads, access roads, and gathering pipelines, other parts of the gas extraction process also have negative consequences but are less dependent on infrastructure layout. For instance, faulty or poorly constructed wells can contaminate groundwater

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http://dx.doi.org/10.1016/j.ecolecon.2016.09.016

(Vengosh et al., 2014). On-site gas processing produces methane emissions (Allen et al., 2013), increasing climate forcing. In addition, the use of wells for wastewater disposal has been linked to increased seismicity in some parts of the United States (Keranen et al., 2014). These impacts negatively affect the environment and can impact human health (Adgate et al., 2014).

Current environmental regulations for shale gas surface infrastructure tend to be limited in their type, scope, and flexibility. In many places globally, there are either moratoria or outright bans on shale gas development (http://keeptapwatersafe.org/global-bans-on-fracking/, visited 23 April 2015). In other places where gas development is regulated, the most common type is uniform command-and-control, though case-by-case permitting examples exist (Richardson et al., 2013; Zirogiannis et al., 2016). Other environmental policies include unenforced performance practices that encourage voluntary adoption of lower impact development (Richardson et al., 2013). These current regulations tend to focus on water features, an important part of environmental and human health concerns but of limited scope.

Environmental, market-based instruments have increased in popularity for policymakers and scientists—evident in the payment for ecosystem services literature (Engel et al., 2008; Lapeyre et al., 2015; Lockie, 2013; Miles and Kapos, 2008; Pagiola and Platais, 2002)—at the same time that public trust in the power of markets has fallen (Sandel, 2012; Stavins, 1998). The appeal of market-based mechanisms stems in practice from their notable successes at reducing environmental impacts for low cost in other settings and in theory from their potential to achieve allocative efficiency without imposing formidable information burdens on a regulator (Conrad and Kohn, 1996; Rico, 1995; Stavins, 1998). Many of the issues surrounding purported market-based instruments point to failures in how they are structured and applied as opposed to fundamental flaws of theory (Alston and Andersson, 2011; Gómez-Baggethun and Muradian, 2015; Stavins, 1998). However, even when properly structured and applied, the theoretical performance of market-based instruments (Foster and Hahn, 1995; Goulder et al., 1999) depends on the ability of regulators to set appropriate conditions for the market (ten Brink et al., 2012; United Nations Development Program, 2011), which itself may require accurate estimates of benefits and costs (Kroeger and Casey, 2007; Salzman and Ruhl, 2000). Indeed, we find that to be the case here. Tradable permits are one type of market-based instrument that achieve environmental targets by creating a market for environmental damage. Firms with low environmental abatement costs can sell excess permits to those with higher abatement costs and in theory this equalizes the marginal cost of production across firms (Stavins, 1998). Consequently, a tradable permits system should perform best when the cost of internalizing environmental externalities varies among firms, since this is a major basis for establishing buyers, sellers, and the market price for permits. In the context of this study, such variation is produced by spatial variation of the environment. At the same time, impacts with very high spatial variance may appear homogenous across locations at the scale of infrastructure development. Alone or combined with measurement uncertainty, this could reduce the performance of a market-based instrument.

While other peer-reviewed studies have looked at the current regulatory framework for shale gas development, to our knowledge, none have quantitatively analyzed the environmental and monetary effects of implementing new regulations. Konschnik and Boling (2014) describe the current regulatory framework for shale gas in the United States and go on to propose a framework for further governance of shale gas and how that could be applied for environmental or sustainability goals. Most other studies focus on a review of current regulations (Clark et al., 2012; Rahm, 2011; Wiseman, 2014) or on the assessment of risks or damages for future regulations (Clark et al., 2012; Hays et al., 2015). In this paper, we explore the potential advantages offered by a cap and trade approach over uniform command-and-control for regulating environmental impacts from shale gas surface infrastructure. We do so using empirically driven environmental impact abatement cost curves for shale gas development in Pennsylvania. First, we explore the performance of a regulatory approach based on a uniform—ignores site characteristics—restriction on impacts. Second, we examine how tradable permits in a cap and trade system could reduce the cost of avoiding impacts compared to the former scenario. Finally, we discuss how error in the ability of the regulator to estimate impacts in the absence of an additional regulation affects the cost of cap and trade.

2. Methods and Materials

2.1. Regulatory Context

Our goal in this study is to explore cap and trade as an inexpensive approach to avoiding environmental impacts from shale gas surface infrastructure. We define a regulatory context that, while simplified from reality, reproduces enough qualities to support informative conclusions in a system that is relatively straightforward to analyze. We make seven important modeling assumptions. First, we assume the development rights at a site belong to only one developer and each developer has development rights to exactly one site. Thus, decisions about how to develop a site are site/developer-specific. Second, we assume every layout option—configuration of well pads, access roads, and gathering pipelines—for a site has the same number of wells, all wells drain the same amount of gas, and all wells cost the same to drill. Thus, layouts for a site differ only in the cost of developing surface infrastructure. Third, the construction of infrastructure produces many environmental externalities (impacts), which is the task of the regulator to internalize to the gas industry through a new regulation. Fourth, impacts incurred at a site are independent such that the aggregate impact of development of the system is just the sum of site-level impacts. Fifth, all sites are developed simultaneously such that delays in gas production do not occur and the costs and profits from developing sites are independent of the start of production. Sixth, all available leases in the regulatory region have already been acquired, such that developers are choosing how to develop rather than whether or not they will acquire leases. Finally, the regulator regulates pre-development, estimated impacts based on infrastructure layouts as opposed to post-development, measured impacts in an effort to avoid irreversible impacts. Consequently, developers may meet their cap only by choosing layouts. This is similar to the current case-by-case approval process for shale gas development in many places (Richardson et al., 2013). We recognize these are simplifying assumptions of the system which limit our ability to fully predict outcomes of different regulations and, in the Discussion, we highlight how some of these assumptions differ from current conditions. However, we feel this study is still an important first step toward understanding the implications of additional shale gas regulations.

The theoretical efficiency of cap and trade is well established, but the quantity of savings is context-specific and requires an accurate projection of abatement cost curves. As we show below, the cost of a cap and trade system depends on the overall environmental impact society is willing to bear, i.e. the overall cap, in the context of firms' impact abatement cost curves. Consequently, we show the results over the full range of caps that could be considered. Further, a key decision in establishing a cap and trade system is how to initially allocate permits across firms. Here, a permit is a unit of environmental damage (or "impact") produced by the construction of surface infrastructure. When trading is allowed, a permit may be divided into parts of any size and traded among firms. In this study, we first explore in the uniform command-and-control regulation how uniformly fixed permits affect the overall cost of the system. In the cap and trade system, the regulator attempts to benchmark the initial allocation of permits against the potential environmental damage of developing a particular site, i.e. employs a differentiated standard. In recognition of the inherent challenges for a regulator, we explore the consequences of making benchmarking errors for the performance of the cap and trade system (described more in §2.3).

Each developing firm wants to maximize the net present value of its site, which is dependent on several factors. A site contains some amount of gas, the present value of which depends on the flow rate of gas from each well, the number of wells, the price of gas, and a monetary discount rate (Supporting Information: SI §4). To get profits from the gas, the developer must construct infrastructure to access the site, extract the gas, and pipe it to the market. There are many infrastructure layouts for a site, and each layout has an associated construction cost and environmental impact. When considering tradeoffs between environmental impact and construction cost, a more expensive layout (e.g. Fig. S5) will only make sense to develop if it also results in a reduction in impact relative to other layouts. The set of layouts at a site are thus ordered by increasing cost and decreasing impact and, in aggregate, form monotonically increasing cost and decreasing impact functions, which adheres to one important Pareto-efficiency condition (Varian, 2003). We denote the discrete cost and impact functions for a site *s* by C_s and I_s, respectively, where $C_s(x)$ represents the cost of constructing layout *x* at site *s*, and $x = 0$ is the index of the layout developed without the new regulation. Cost increases and impact decreases with *x*. Because of the setup described here, a developer can maximize the net present value of its site by minimizing the cost of construction plus any additional costs from the additional regulation.

2.2. Scenarios and Solutions

We explore the two policy scenarios described above and summarized in Table 1. In *Uniform Cap without Trading* (Eq. (1)), developers minimize the cost of constructing surface infrastructure while adhering to the environmental impact permits allocated by the regulator. The regulator, in this scenario, allocates uniform permits to all developers. In *Cap and Trade* (Eq. (2)), developers minimize the combined cost of constructing infrastructure and of acquiring additional permits for exceeding their permit allotment. The right term in the developer's objective for *Cap and Trade* is the price of permits in the market times the number of permits the developer must purchase to raise its total permit allotment above the impact of the layout it chooses to develop. Accordingly, the impact constraint for *Cap and Trade* states that the impact of the chosen layout $I_s(x)$ cannot exceed the sum of the initial allotment of permits $\alpha\hat{I}_s(0)$ and any additional permits acquired on the market Φ_s. In this scenario, the regulator uses a differentiated standard to allocate permits as a proportion of the regulator's estimate of the impact that would be incurred at each site in the absence of this new regulation $\hat{I}_s(0)$.

In each scenario, we find solutions for a range of caps and record the total cost (sum of costs across all sites) and total impact (sum of impacts across all sites). The solution for *Uniform Cap without Trading* is found simply by selecting the cheapest layout at each site that meets the permit allotment *A*, which is set by the regulator. Permit allotments (*A*) have units of aggregate environmental impact, the calculation of which is described in §2.4. The choice of layout at each site in *Cap and Trade* depends on the price of permits in the market , which we found by solving for a market clearing equilibrium (see SI §1 for more details). In both scenarios, if the developer is unable to adhere to its permit allocation by choice of layout, or if the cost of purchasing permits (in *Cap and Trade*) exceeds the value of the site, the developer chooses not to develop (SI §1).

Table 1
Developer optimization problems for policy scenarios, including the objective and constraint, which is set by the regulator.

Policy	Developer objective	Impact constraint	Eq.
Uniform Cap without Trading	$\min_x \; C_s(x)$	$(I_s(x) \leq A)\,\forall s$	(1)
Cap and Trade	$\min_x \; C_s(x) + P^*(I_s(x) - \alpha\hat{I}_s(0))$	$I_s(x) \leq \alpha\hat{I}_s(0) + \max(0, \Phi_s)$	(2)

s = site/developer index
x = layout index
$C_s(x)$ = cost of developing layout x at site s
$I_s(x)$ = impact of developing layout x at site s
A = uniform firm-level permit allotment
α = proportional allotment of impacts for differentiated standard
P = price of permits in market
$\hat{I}_s(0)$ = regulator's estimate of impact of least-cost layout
Φ_s = permits bought for site s

2.3. Regulator's Error in Estimating $\hat{I}_s(0)$

The total cost and impact of the cap and trade system depends on the permit allocation across sites. To illustrate, take one site in isolation. At the extremes, permits may be so few or so many that the developer cannot develop or does not reduce potential impacts, respectively. Within the range $[I_s(x_{\max,s}), I_s(0))$—where $x_{\max,s}$ is the index of the least impacting layout where development occurs—limiting permits has some effect on the developer's choice of layout while still allowing development. In *Cap and Trade,* we assume that the regulator has some ability to estimate site-level impacts in the absence of additional regulation, ($\hat{I}_s(0)$), and uses that to proportionally allocate permits (α) across sites. This estimate has some error associated with it due to the regulator's lack of perfect information. In the case study below, we start with the case where the regulator can perfectly estimate impacts in the absence of additional regulation ($\hat{I}_s(0) = I_s(0)$) and then perform several sensitivity tests, including the regulator's estimate is (1) systematically high ($\hat{I}_s(0) > I_s(0)$), (2) systematically low ($\hat{I}_s(0) < I_s(0)$), and (3) incorrect but without bias.

2.4. Study Area

We sought to answer our questions using empirically estimated environmental abatement curves for shale gas development. To do so, we took a case study approach and applied the above regulatory context to the Marcellus shale play in Pennsylvania, where enough development has occurred and enough knowledge about the development context exists to infer with some confidence the cost of a cap and trade system. Over 9000 horizontal wells have been drilled in the Marcellus region of Pennsylvania since 2008 (according to the Pennsylvania Department of Environmental Protection's permit reporting database) and many more are likely to come. The construction of well pads, access roads, and gathering pipelines is occurring in areas of high conservation priority (Johnson et al., 2010), resulting in degradation and destruction of many environmental features including forests, wetlands, streams, and other features important for biodiversity and recreation in the area (Johnson et al., 2010).

We used a spatial planning software that we created called Bungee (Balancing Unconventional Natural Gas Extraction and the Environment) to place well pads, access roads, and gathering pipelines at 84 sites across Pennsylvania (Milt et al., 2016). Of those 84 sites, 56 sites were kept for analysis due to a necessary transformation of the impact values that resulted in some sites having non-monotonic impact functions (see SI §2). Our measure of environmental impact ($I_s(x)$), called the *Impact Score*, aggregates across several metrics of environmental impact to represent the total impact of infrastructure at a site (Milt et al., 2016, SI §2), and is further explained in the next paragraph. Those 56 sites range in size (1–14 well pads) and number of layouts (2–16). Bungee is a novel spatial planning software that optimizes infrastructure layouts to help avoid environmental impacts at fixed construction costs (Milt et al., 2016). Site boundaries were derived by overlaying production units on existing well locations in five moderately or heavily developed counties and then joining adjacent land parcels to fully contain those production units. Production units, which represent the area of gas extracted by a well pad with 6 wells, were 914 × 3353 m (3000 × 11,000 ft) rectangles rotated 27° counterclockwise to match the general direction wells bores are drilled. After accounting for access to existing road and pipeline networks and land parcel data using publicly available datasets, this process produced 84 sites. While planning infrastructure, Bungee adheres to current regulations. In Pennsylvania, these include setbacks from buildings and wetlands, and Bungee incorporates these by designating parts of the site as off-limits for infrastructure (Brannon and Shepherd, 2012; Milt et al., 2016). Other local regulations can be included, though we did not include them in this analysis. The first layout produced by Bungee is a cost-minimizing layout that ignores environmental impacts other than those already regulated. Subsequent layouts are formed by incrementally increasing the development budget by a proportion of this first layout's cost, with an objective to minimize aggregate impacts (Fig. S2). Impacts are reduced at larger budgets by reconfiguring infrastructure, i.e. by changing the routes and amounts of roads and pipelines and locations of well pads. Consequently, sequential layouts reduce impacts at increasing cost, such that no final layout is simultaneously more impacting and more costly than any other. Bungee creates layouts by iteratively proposing well pad locations in feasible envelopes within production units and then connecting well pads to existing infrastructure networks by access roads and gathering pipelines. It employs a genetic algorithm for determining the order in which infrastructure is placed—affects the spatial configuration of infrastructure—a modified form of Dijkstra's algorithm for placing roads and pipelines (Dijkstra, 1959), and constrains infrastructure by both regulatory offsets and an incrementing construction budget.

We adjusted environmental impacts and construction cost metrics to be appropriate for this analysis. Five metrics formed the *Impact Score*: (1) forest acreage lost by development of forest pixels, (2) total edge-to-area ratio of forest after construction as one measure of forest fragmentation, (3) wetland encroachment as the percentage of a buffer around wetlands occupied by infrastructure, (4) potential sedimentation in water bodies, and (5) expected impact on rare species as the expected number of known rare species occurrences impacted by infrastructure based on habitat associations across the state (Milt et al., 2016). These metrics represent common and largely unregulated impacts from surface infrastructure across the region and were decided upon in collaboration with the Pennsylvania chapter of The Nature Conservancy, a conservation organization actively working to improve the environmental performance of shale energy development. Environmental impacts were standardized to have a score per site ranging between 0 and 1. For this analysis, development costs ($C_s(x)$) include surface infrastructure construction costs and several other costs associated with determining the relative costs of developing sites (SI §3). We used those major surface infrastructure construction costs that vary with surface infrastructure locations: moving earth, clearing land, stream crossing infrastructure, and materials and labor (Triana Energy, LLC, pers. comm.). Our cost categories are based on meetings with Triana Energy, LLC, a gas company active in Pennsylvania and West Virginia, USA.

We analyzed the total cost across our 56 case study sites for various caps on impact and many sensitivity tests of the error in $\hat{I}_s(0)$. For *Uniform Cap without Trade*, we analyzed the system for 40 values of A between 0 and 5. The lower bound was chosen to show where zero impact was allowed, while the upper bound ensured that the allotment would exceed any single site's maximum impact. For *Cap and Trade*, we analyzed the system for combinations of α and error in $\hat{I}_s(0)$. We looked at 40 values of α between 0 and 1 (Table 2). Note A and α have different ranges because A has absolute units while α has relative units. This difference of allotment specification between the two regulations occurs because the regulator uses a uniform standard in *Uniform Cap without Trade*, but a relative standard—calibrated for each site—in *Cap and Trade*. To look at the scenario where $\hat{I}_s(0)$ is high or low systematically, we added or subtracted, respectively, some portion $I_s(0)$ (Table 2). When looking at the effects of random error, we changed $I_s(0)$ by a uniformly drawn random portion between $-\varepsilon$ and ε, the maximum amount of error. In other words, some sites received a positive error while others a negative error. We repeated this process 100 times for each ε and summarize the range of results. For instance, an error of $\varepsilon = 0.5$ would result in $\hat{I}_s(0) = 1.5I_s(0)$ for the systematic case and $-1.5I_s(0) \leq \hat{I}_s(0) \leq 1.5I_s(0)$ for the random case. We summarize these scenarios in Table 2.

Table 2
Analysis parameters showing various caps on impact set by the regulator as well as error in the regulator's estimate of impacts in the absence of additional regulation. Allotment is absolute and at the site-level for *Uniform Cap without Trading* and relative to total impact and site-level impact for *Cap and Trade*, respectively. Error is a proportion of the impact from the least-cost layout ($x = 0$) added to that impact.

Scenario	Allotment (A or α), $n = 40$
Uniform Cap without Trading	0, 0.13, 0.26, …, 5
Cap and Trade	0, 0.03, 0.05, …, 1

Cap and Trade error direction	Error level (ε)
Random Unbiased	(up to) ± 0.1, ± 0.25, ± 0.5, ± 0.75, ± 1
Systematic Overestimate	$+0.1$, $+0.25$, $+0.5$, $+0.75$, $+1$
Systematic Underestimate	-0.1, -0.25, -0.5, -0.75, -1

3. Results

3.1. Comparison of Uniform Cap with Cap and Trade in Perfect Information Case

Fig. 1 summarizes our results when there is no error in the regulator's estimate of a site's base level impact (estimated impact of sans regulation layout is the actual impact, $\hat{I}_s(0) = I_s(0)$). In the figure, outcomes in the lower-left corner represent the business-as-usual situation where no attempt is made to regulate additional impacts and all sites develop their least-cost, highest-impact layout. The impact cap is 100% and avoided impact is 0% while the total cost is 0.05% of the situation where no sites are developed. In the upper-right of Fig. 1 is the outcome where no impacts are allowed and as a result no sites are developed. The impact

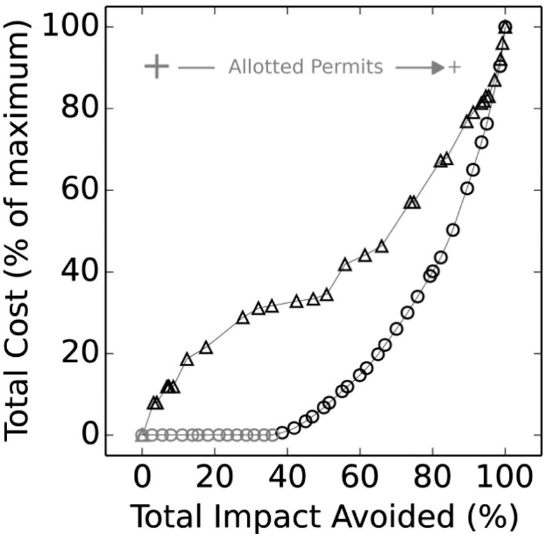

Fig. 1. Outcomes of implementing policies at various caps on impact. Triangles (△) are *Uniform Cap without Trading* and circles (○) are *Cap and Trade* in the perfect information case. Vertical axis is percent of outcome where no sites develop. Gray symbols show where all sites are developed. Black symbols show where at least one site is not developed. There are only three outcomes where all sites are developed in *Uniform Cap without Trading.*

cap is 0% and avoided impact is 100% while the total cost is the cost of foregone profits from all sites (100%). Between these extremes, developers vary the choice of layout for their site or choose not to develop, such that some (black) or all (gray) sites are developed.

There are several interesting characteristics of outcomes from implementing a *Uniform Cap without Trading* regulation. First, any choice of cap that avoids up to 35% of potential impacts would result in an impact elasticity of cost near unity (Fig. 1, triangles left of 35% total impact avoided). There is a range where choosing a lower cap would have little effect on cost. For instance, a cap that avoids 50% instead of 30% of potential impact would be only 4% more costly (Fig. 1, middle plateau of triangles). The plateau occurs because developers choose to develop more expensive layouts rather than not develop, a much more costly decision. Setting the cap to avoid >61% of potential impact would result in a relatively high impact elasticity of cost (Fig. 1). With *Uniform Cap without Trading* some sites go undeveloped for all except the lowest levels of overall cap (all triangles in the figure are black other than those on the bottom left corner).

There are important differences in the total cost of implementing different regulations. Apart from the two extremes where the two regulations necessarily converge, *Cap and Trade* is always less expensive than *Uniform Cap without Trading* as would be expected. Arguably, a more interesting question is how large the possible efficiency saving can be in this context. Depending on where the overall cap is set, this cost difference can be large; it is biggest (a difference of 32%) when the cap is set to avoid 36% of the overall environmental impact (Fig. 1). A *Cap and Trade* cap that avoids 36% of potential impacts can be implemented for only 0.05% of the maximum cost while still allowing all sites to be developed. Compare this to the *Uniform Cap without Trading* scenario, for which there are almost always some undeveloped sites. There are many more options that allow all development under the *Cap and Trade* scenario.

The distribution of outcomes along the horizontal axis in Fig. 1 is also interesting. First, *Uniform Cap without Trading* exhibits a less smooth spacing of outcomes, which is a result of the way the regulation is implemented. Outcomes that are close together are similar in that the set of sites developed does not change from one outcome to the next, but only the set of layouts chosen for development. Large jumps between clusters of outcomes are due to one or more sites being pushed out of development as fewer permits are allotted. This discontinuity in outcomes means that small regulatory adjustments may have little effect on resulting impacts and costs. With cap and trade, there is a smoother distribution of outcomes because the regulation allows more flexibility in how sites are developed.

The black open symbols in Fig. 2a show the performance of the two regulations explored here at a particular permit allotment—determined by the cap, which can be summarized by the ratio of system total absolute impact to total cost of achieving this outcome in billion USD. This metric reveals the degree to which a given cap will lead to expected impacts for a fixed investment. To plot all policy scenarios on the same horizontal axis, we transformed the permit allotment (A) for *Uniform Cap without Trading* to a relative scale by dividing by its maximum value. Outcomes that result in no impact avoidance have a performance of zero, cannot be shown on a log scale, and thus most curves start right of the 100% allotment. The two largest allotments are two of the higher performing for *Uniform Cap without Trading* because they avoid some impact while still allowing all development to proceed. With increasing permit allotments (moving to the right in the figure), *Uniform Cap without Trading* outcomes have a low performance, with a peak near (55% allotment, 0.01% impact avoided per $1B). Turning to the *Cap and Trade* policy, when many permits are allotted (Fig. 2a, leftmost black circles), *Cap and Trade* will have intermediate performance. Allotting fewer permits would have better performance up to the point where one site is pushed out of production.

In the ideal case, *Cap and Trade* is generally better performing than *Uniform Cap without Trading*. Only at the extremes (note lower convergence not revealed in Fig. 2a) do the two scenarios converge, which is a necessary result. Although both scenarios have peak performance at the smallest permit allotment where all sites are developed (highest triangle and circle in Fig. 2a), the performance of *Cap and Trade* at its peak is more than two orders of magnitude higher than *Uniform Cap without Trading* at its peak. At smaller permit allotments (Fig. 2a, right of 60%), the two scenarios have more similar performance, but *Cap and Trade's* performance is still five times higher than *Uniform Cap without Trading's* on average.

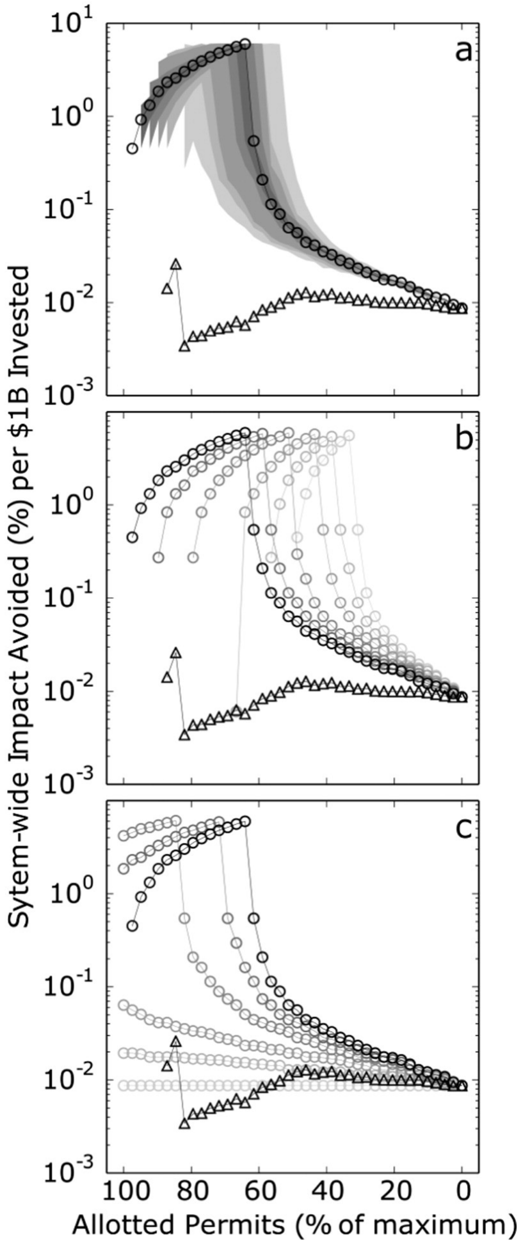

Fig. 2. Effect of error in regulator's estimate of impacts in the absence of additional regulation ($\hat{I}_i(0)$) for *Cap and Trade* when error is (a) unbiased, (b) systematically high, and (c) systematically low. Horizontal axis ranges from permits allocated at 100% of regulator's estimate of site level impact (all impact allowed) down to no 0% no permits. In all panels, outcomes from a zero-error estimate are shown in black, while increasingly lighter gray shows outcomes with increasing error. Triangles (△) are *Uniform Cap without Trading* and circles (○) are *Cap and Trade*. Error levels are summarized in Table 2. In (a) shaded regions show a range of outcomes over 100 trials of uniformly distributed error in $\hat{I}_i(0)$.

3.2. How is the performance of Cap and Trade affected by the regulator's ability to estimate $I_s(0)$?

In Fig. 2, we also summarize the results of our sensitivity tests to highlight the importance of the regulator's ability to estimate impacts in the absence of additional regulation, denoted $\hat{I}_s(0)$, benchmarking against the perfect information case (black circles and triangles are the same for each panel).

Errors in the regulator's estimate of impact in the absence of additional regulation ($\hat{I}_s(0)$) affect the outcomes of implementing *Cap and Trade*. We explored three types of error in $\hat{I}_s(0)$ (scenarios in Table 1): uniformly distributed (Fig. 2a), systematically high (Fig. 2b), and systematically low (Fig. 2c). Because outcomes are based on the choice of layouts at sites and these choices are highly discrete, error in $\hat{I}_s(0)$ serves mainly to stretch or compress the distribution of outcomes as the cap changes rather than reveal entirely different outcomes.

When error in $\hat{I}_s(0)$ is uniformly random across sites (Table 1 “Random Unbiased”), cap and trade may perform better or worse than the perfect information case at a particular allotment. For instance, when $\hat{I}_s(0)$ is up to 100% different from $I_s(0)$ (lightest gray region in Fig. 2a), allotting 70% of the no-regulation impact estimate may lead to a performance a full order of magnitude lower than if the regulator can perfectly estimate $I_s(0)$. Uniformly random error tends to decrease performance relative to the ideal case reflected by the wider range of outcomes below/left of the perfect-estimate outcomes in Fig. 2a. Higher performance relative to the ideal case is caused by permit allocation that forces developers to choose less impacting layouts but still develop.

Systematically overestimating the impact of a site's highest impacting layout ($I_s(0)$, Table 1 “Systematic Overestimate”) compresses the possible outcomes from *Cap and Trade*, which has several effects (Fig. 2b). Choosing a lax cap may not reduce impacts at all, since developers will not have to change their choice of layout to meet the impact cap (leftmost points for *Cap and Trade* in Fig. 2b). There is a range (100%–64% allotment) where the cap would be strict enough to affect developers' choices and systematic overestimate would lead to lower performance. After this, a systematic overestimate of $I_s(0)$ leads to higher performance since developers must choose layouts that are less impacting, but which still allow them to develop their sites. Again, this is due to the fact that a smaller cap is required to achieve the same outcomes as when $I_s(0) = \hat{I}_s(0)$. At larger error levels, higher performance is more likely, while many more outcomes have no effect on development.

Systematically underestimating $I_s(0)$ (Table 2 “Systematic Underestimate”) stretches the possible outcomes from *Cap and Trade*, which has several effects on performance (Fig. 2c). When error is low, allotting many permits would lead to higher performance. However, at error levels larger than 25%, any allotment will lead to lower performance. At very high error levels, the performance of *Cap and Trade* may even be lower than *Uniform Cap without Trade* (lightest gray circles are below some triangles in Fig. 2c). Since the regulator is underestimating impacts at sites, any allotment will be almost guaranteed to affect developers' choices of layouts and consequently lead to lower-impact outcomes, yet this comes with a risk of lower-efficiency outcomes and increased probability of pushing sites out of production.

4. Discussion

Ongoing shale gas development creates environmental externalities which may be internalized and reduced at reasonable costs through cap and trade. We have analyzed two policy scenarios that put a cap on environmental impacts and compared them in terms of their total resulting impact and monetary cost. We found that the policy scenario most reflective of current regulations (*Uniform Cap without Trading*), which forces developers to reduce impacts in a uniform fashion or not develop, may lead to expensive outcomes with few options to reduce impacts while still allowing all development to proceed (Fig. 1). In contrast, a cap and trade system (*Cap and Trade*) could achieve impact caps from 0 to 32 percentage points cheaper than the uniform command-and-control policy, depending on the level of impact society is willing to accept (Fig. 1). The relative costs of *Cap and Trade* versus *Uniform Cap without Trading* converge at higher or lower levels of avoidance. We also determined that the performance of cap and trade depends on the number of permits allocated to each developer, which may be affected by the regulator's ability to estimate impacts in the absence of the additional regulation. For instance, *Cap and Trade* could be totally ineffective if the regulator systematically overestimated those impacts and had a low commitment to reducing impacts (Fig. 2b). Also, the impact avoided for a $1B investment in *Cap and Trade* could be almost three orders of magnitude lower than ideal if the regulator systematically underestimated those impacts by >25% (Fig. 2c).

Our results have several implications for policy design and implementation. In our case study, cap and trade can offer large savings over a more traditional uniform and inflexible approach in line with theoretical predictions (Baumol and Oates, 1988; Goulder and Parry, 2008). Further, we find it can reduce potential impacts much more while allowing all development to proceed. At the same time, implementation efforts are not the same for the two approaches. In either scenario, the regulator needs to enable the gas industry to evaluate impacts produced by an infrastructure layout, which requires the regulator know what impacts are relevant, what priority they have, and how they are calculated. Additionally, both scenarios require the monitoring of surface development, which could be attached to current drilling permitting processes. To guarantee a high performance of cap and trade as outlined here requires that the regulator must be able to estimate impacts in the absence of the additional regulation. However, both approaches examined here would require the regulator to have some information about impacts from business-as-usual development. A more detailed method that models development could ensure higher performance in either case. Cap and trade also relies on the distribution, tracking, and enforcement of tradable permits. We expect the total cost of implementing cap and trade at intermediate levels of impact avoidance would be compensated by the long-term savings over the other inflexible approach we explored (see Fig. 1).

In our case study, the highest performance of *Cap and Trade* was achieved when the cap was set to avoid 36% of impacts (Fig. 2). This outcome is contingent on being perfectly able to estimate impacts in the absence of the cap and trade system. A more lax cap would still result in *Cap and Trade* performing better than at a more severe cap. That said, we are not suggesting that these figures should be translated directly into policy for this or other areas, but are simply using it to illustrate potential payoffs from implementing cap and trade in this context. Interestingly, the hump shape of the performance curve which leads to this outcome is due to a combination of two things. First, our estimates of the cost of developing a site is much lower than our estimates of the profits from gas extraction. As a result, not developing a site leads to large increases in the cost of the system. Second, there is large potential to avoid impacts of the system while still allowing all development to proceed (Fig. 1). Combined, large impact avoidance can be achieved without increasing costs a lot relative to profits gained from development (Fig. 1, gray circles). At more severe caps (below 64% of potential impact here), some sites are forced out of production leading to large increases in cost for relatively little change in overall impacts, which greatly reduces the performance of the system (Fig. 2: switch happens where the slope of *Cap and Trade* becomes negative).

One purpose of this study was to apply existing knowledge about the relative performance of market-based policies to inflexible uniform policies in the shale gas context. We show clearly some of the potential gains from trade created by a cap and trade system that regulates an aggregate impact metric. Other approaches may also be effective in this and other contexts. For instance, cap and trade for individual metrics (e.g. forest clearing) might increase the transparency and understanding of the market and increase support, though at an increased implementation cost due to maintaining multiple markets. In addition, a bubble-offsets approach might obviate the need for a market, especially when there is large spatial heterogeneity in the cost of reducing impacts at individual sites. A bubble policy would treat a subset of sites that are close to one another or have the same developer as a single unit ("bubble"), allocating permits to each bubble (Tietenberg, 1985) rather than to each site. Similarly, when development rights across all sites are held by just a few developers, allocating permits to each developer could be effective. This would require that each developer has development rights at sites with heterogeneous costs of impact avoidance. Many other alternatives exist. We took an approach that should be generally applicable across regions where many sites are ready for development, where developers have rights to one or a few sites, and where reducing aggregate impacts is the major goal.

More complete analyses could benefit from several adjustments to our methodology. First, we assume that each developer has rights to only one site being developed. In Pennsylvania, there are many developers, but the distribution of development is skewed towards developers with many holdings (Pennsylvania Department of Environmental Protection's permit reporting database). When combined with assumptions about market dynamics, it is likely that those developers with many sites would exert a measurable effect on the market and could compromise the effectiveness of the market (Baumol and Oates, 1988). Second, we assume all sites are to be developed simultaneously and thus enter the market simultaneously. A more complete analysis on a small market would include the staggering of development over time and adjust developer's decisions about when to develop (i.e. enter the market). Third, we assume impacts are independent across sites and thus can be combined additively. One alternative approach would be to treat nearby or adjacent sites as having dependent impacts, e.g. by combining their development boundaries to treat them as one unit when evaluating impacts. This approach would require a more complex decision process as well as stricter assumptions about the simultaneity of development across sites. Finally, we chose to focus on the direct regulation of a single aggregate metric such that trading among individual metrics could occur at the site level. This choice ignores one alternative approach to regulating multiple impacts, which is to put a cap on each individual metric. While this approach would more directly enforce local priorities for each impact, it would limit development options within sites. Further, because many impacts are positively correlated and some are negatively correlated (Milt et al., 2015), the link between an impact's cap and the resulting development choice could be confounded by choices driven by other impact caps (Bennear and Stavins, 2007), and thus presents a challenge to matching environmental goals to policy outcomes. This is a unique characteristic of regulating multiple impacts through multiple, impact-specific caps.

We have applied existing methods to the novel context of regulation of environmental impacts from shale gas surface development and found that large gains from trade are possible. As shale gas development proceeds globally, governments at multiple levels should consider the environmental implications of shale gas extraction and design policies that properly internalize environmental externalities. In regions where development rights are centrally owned or distributed, significant environmental savings can potentially be achieved without the need for additional regulations. In other regions, our findings can be used to motivate regulations that do better than traditional command-and-control approaches. As such, we see large potential to develop shale gas more conscientiously in the coming decades.

Acknowledgements

We thank Tamara Gagnolet, Daniel Phaneuf, Bill Provencher, A.W.M's dissertation committee, and the Armsworth lab for very helpful feedback. This work was conducted while a Graduate Research Assistant at the National Institute for Mathematical and Biological Synthesis, an Institute sponsored by the National Science Foundation through NSF Award #DBI-1300426, with additional support from The University of Tennessee, Knoxville and The Nature Conservancy.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2016.09.016.

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