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Risk Aversion and International Environmental Agreements

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Abstract:
We introduce uncertainty and risk aversion to the study of international environmental agreements. We consider a simple model with identical agents and linear payoffs. We show that a stable treaty with positive action always exists. While uncertainty lowers the action of signatories, we find that it may increase participation. In addition, uncertainty may generate multiple equilibria. A treaty with low action and low participation may coexist with one with high action and high participation. Overall, and despite risk aversion, the impact of uncertainty on welfare may be positive. A reduction in uncertainty may hurt international cooperation.

Keywords: International Environmental Agreements, Risk Aversion, Uncertainty

JEL Classification: D62, D80, Q54

1 Introduction

In this paper, we study how uncertainty and risk aversion affect the formation of international environmental agreements. Scientific uncertainty is a fundamental aspect of global environmental issues, climate change being a prime example. A common hope is that reductions in uncertainty about the effects of pollution through, for instance, better measurements and scientific progress, will help determine appropriate responses. While this hope is well-grounded in contexts where a single agent takes decisions, its validity in a strategic setting is less clear. Establishing and maintaining cooperation between sovereign states is difficult, as the heated debates surrounding the Kyoto protocol and what should happen after it illustrate. Does a reduction in uncertainty actually help international cooperation, or could it hinder its emergence? Through what mechanisms may uncertainty affect the incentives to join, or to quit, an international coalition trying to curb emissions? How does uncertainty affect welfare in a second-best context characterized by endogenous and partial cooperation? We seek to provide formal answers to these questions.

To do so, we extend the model of treaty formation with linear payoffs due to Barrett (1994, 2003). Agents face a n-player prisoner's dilemma and can join a coalition trying to take collective action. We introduce two new assumptions. First, pollution damages, and hence the social benefits from effort, are subject to uncertainty. Second, agents are risk-averse. We analyze how these two assumptions affect the outcomes of the game. We notably study comparative statics with respect to the levels of risk and of risk aversion, see Gollier (2001).

We find that uncertainty has strong qualitative and quantitative impacts on treaty formation. Our three main results can be summarized as follows. First, holding participation constant, uncertainty tends to reduce signatories' efforts. This negative effect is due to risk aversion. Decreasing effort allows signatory countries to reduce the variability of their payoffs. Second, and counteracting the previous effect, uncertainty may increase participation in the treaty and improve welfare in equilibirum. The decrease in effort and the increase in participation are, in fact, related. In these models, a treaty becomes stable only when a critical mass of participating countries has been reached. The effect of one country leaving on the actions of the remaining signatories must be strong and highly non-linear around the stable level. Our previous result means that this critical mass is shifted to the right under uncertainty. The increase in participation has a positive effect on welfare, which can overcome the negative effect of uncertainty. Third, uncertainty may generate multiple equilibria. We find that a treaty with low action and low participation may coexist with one with high action and high participation. Overall, we make use of both analytical results and simulations to clarify the conditions under which these results hold.

Our paper contributes to two branches of the literature. First, an active research agenda has studied international environmental agreements, see Barrett (2003). Uncertainty is mostly ignored in this literature, however, except for a few papers studying the effect of learning under risk-neutrality.[1] These papers usually contrast different timings for the resolution of uncertainty. For instance, Kolstad (2007) shows in a static framework that it may be better to negotiate after uncertainty is resolved rather than before. In contrast, Ulph (2004) finds that, in a model with two periods, the positive effects of learning may not be robust to the introduction of renegotiation between periods.[2] We do not look at learning here. Rather, we relax the assumption of risk-neutrality. We provide the first analysis of the effect of risk aversion on international environmental agreements.

Second, a growing literature examines the effect of uncertainty and risk aversion in strategic

[1] See Kolstad (2007, 2005), Ulph (2004), Ulph and Maddison (1997), Na and Shi (1998).

[2] Also, it may be easier to reach an agreement before the "veil of uncertainty" has been pierced. Kolstad (2005) and Na and Shi (1998) provide some supporting arguments, under risk-neutrality.

settings.[3] Bramoullé and Treich (2006) notably look at a model of global pollution. They find that uncertainty may decrease emissions and increase welfare in equilibrium. Our study complements their analysis. While they consider a more complicated payoff function, they assume that no cooperation is possible. In contrast, we adopt a simple, well-understood, linear formulation for the payoffs, and focus on treaty formation and on the emergence of partial cooperation. Interestingly, we also find that uncertainty may have a positive impact on welfare, although the mechanism behind this result is very different.

The applicability of our results relies on the validity of the assumption of risk aversion. In usual applications, economists tend to view countries and large organizations as risk-neutral. This view typically relies on possibilities to pool independent risks and on the law of large numbers. However, these standard arguments do not apply to the case of climate change. The magnitude of the effects involved and the global nature of the climate put strong limits on risk-sharing possibilities. Climate risks are highly correlated within and across communities.[4] Heal and Kriström (2002) defend a similar point of view, and urge economists to incorporate uncertainty and risk aversion in their analysis of climate change. In their empirical exercise, they find a relatively strong effect of risk aversion on optimal policy decisions.[5] Their analysis, however, is grounded in models with a single decision-maker and neglects the externality dimension of climate change. We take both issues seriously in this paper. We study how uncertainty and risk aversion affect the emergence of cooperation in a strategic setting.

The remainder of the paper is organized as follows. The model is set up in section II. We

[3]See e.g. Gradstein et al. (1992), Sandler and Sterbenz (1990) on the exploitation of a renewable resource, Eso and White (2004) on auctions, and White (2004) on bargaining.

[4]Opportunities to share risk within and across countries certainly exist. However, even if they are fully exploited, the remaining level of risk borne by countries and individuals will still be very high.

[5]"The point is that uncertainty, risk and our attitudes towards risk really do matter in making policy decisions. They should be taken explicitly into account in formulating policy on climate change. Our final policy analysis may be as sensitive to attitudes towards risk as to some aspects of the scientific data which we work so hard to generate. Yet we have done little to introduce these issues into the policy debate.", Heal and Kriström (2002, p.16).

study the effect of uncertainty and risk aversion on signatories' actions in section III. We analyze stable treaties in section IV, and discuss the robustness of our findings and conclude in section V.

2 The Model

In this section, we introduce uncertainty and risk aversion to the model of Barrett (2003). Consider n identical countries who face a global public good problem. Each country i exerts some costly effort q_i which benefits to all other countries. More precisely, individual payoff is equal to $b(\sum_{j=1}^{n} q_j) - cq_i$ where b represents the marginal benefit from overall effort, while c is the marginal cost from individual effort. Under global pollution, effort is identified with pollution abatement, and the benefits correspond to the reduced damages from pollution. Since payoff is linear, we assume that $q_i \in [0, q_{max}]$. The maximum level of effort $q_{\max}$ originates from economic or technological constraints. Clearly, under global pollution, $q_{\max}$ is always lower than the business as usual level of emissions.

Our main assumption is that the marginal benefit b is subject to uncertainty. For simplicity, we suppose that b can take two values. (Some of our results are valid for any distribution of the parameter). Marginal benefit b is equal to b_L with probability p and to $b_H > b_L$ with probability $1-p$. It is useful to introduce the expected marginal benefit $\bar{b} = pb_L + (1-p)b_H$. In contrast, uncertainty does not affect the marginal cost of effort c.[6]

Preferences of countries towards risk are identical, and represented by a strictly increasing and concave Von-Neumann Morgenstern utility function U. Thus, country i seeks to maximize

[6]This assumption reflects the fact that scientific uncertainty little affects private abatement costs, but is a main source of uncertainty regarding the effects of greenhouse gas emissions and climate change.

his expected utility:

$$EU(q_i, q_{-i}) = pU[b_L(\sum_{j=1}^{n} q_j) - cq_i] + (1-p)U[b_H(\sum_{j=1}^{n} q_j) - cq_i]$$

Since countries are ex-ante identical, we define social welfare W as the sum of the expected utilities of all countries. As in the model with certainty, we consider two restrictions on the parameters. First, $b_H < c$, so that playing $q_i = 0$ is a strictly dominant strategy for all countries in the game without treaty. Second, $nb_L > c$, so that the first-best outcome requires $q_i = q_{max}$ for all i. Without treaty, there is severe underprovision of the public good.

To study the formation of an international environmental agreement, we adopt the approach pioneered by Barrett (1994). Countries have to decide whether to join an international agreement before contributing to the global public good. More precisely, the game with treaty unfolds in three stages:

Stage 1 Simultaneously and independently, all countries decide to sign or not to sign the agreement. In what follows, we denote by k, the number of signatories.

Stage 2 Signatories choose their effort in order to maximize their *collective* payoff.

Stage 3 Non-signatories independently choose the effort maximizing their individual payoff.

A key feature of our approach is that uncertainty is resolved *after* stage 3. Therefore, countries are uncertain about the state of the world when deciding whether to sign the agreement. Our main objective is to study how uncertainty and risk aversion affects this decision, and hence the existence and properties of a stable treaty. We make use of the usual notion of stability.

Definition 1. *A treaty is stable when signatories have no incentive to quit and non-signatories have no incentive to join.*

Conditions for stability can be formally summarized with a unique function Δ. Given symmetry and concavity, non-signatories will play identical actions, and this holds for signatories as well. Therefore, we denote by $q^s(k)$ and $q^n(k)$ the optimal levels of effort exerted respectively by a signatory and a non-signatory country when the number of signatories is equal to k, and by $U^s(k)$ and $U^n(k)$ their expected utilities. We introduce $\Delta(k) = U^s(k) - U^n(k-1)$ which represents the net benefit to a signatory of staying in the agreement. The fact that a non-signatory country does not want to join at k^* is equivalent to the fact that a signatory country wants to quit at $k^* + 1$. Thus, a treaty is stable at $k^* \in [2, n-1]$ if and only if $\Delta(k^*) \geq 0$ and $\Delta(k^* + 1) \leq 0$.[7]

When there is no uncertainty, $b_L = b_H = \bar{b}$ and the analysis of Barrett (2003) applies. Non-signatories always play $q^n = 0$. The collective payoff of signatories is $k(k\bar{b} - c)q^s$, hence signatories play $q^s = 0$ if $k < c/\bar{b}$ and $q^s = q_{max}$ if $k > c/\bar{b}$. Signatories must reach a critical mass before action becomes worthwile. Linearity of the payoff function induces a bang-bang solution. A treaty is stable if and only if $c/\bar{b} \leq k^* \leq c/\bar{b} + 1$. This usually pins down a unique number. Social welfare in the stable treaty is $W = k^*(n\bar{b} - c)q_{\max}$ which provides a strict improvement on the equilibrium without treaty where $W = 0$. Observe that this can still be far from the optimal level where all countries play $q_i = q_{max}$ and $W = n(n\bar{b} - c)q_{\max}$. Interestingly, the analysis under certainty also covers the case where countries are risk-neutral. This justifies the introduction of risk aversion, which we assume in the remainder of the paper.

We next analyze the treaty game under uncertainty. We start with Stage 3. Since $b_L < b_H < c$, a non-signatory country always plays $q^n = 0$, no matter the number or the actions of signatories. In the next section, we study Stage 2 and the actions of signatories. This study is critical to understand when a treaty is stable. The analysis under certainty illustrates how the shape of

[7] A treaty with n signatories is stable if and only if $\Delta(n) \geq 0$. In that case, all countries are signatories, and the condition on non-signatory countries disappears.

q^s determines stability. Under certainty, q^s is a step function and k^* is the first integer situated just above the step. On the one hand, $q^s(k^*) = q_{\max}$ and $q^s(k^* - 1) = 0$. If a signatory quits, the drop in collective action is very large, hence a signatory does not want to quit. On the other hand, $q^s(k^* + 1) = q^s(k^*)$. If a non-signatory joins, the other signatories do not change what they do, which gives no incentives for non-signatories to join. The general intuition carries over to the situation with uncertainty. A signatory does not want to quit if he expects that his departure would induce a high drop in the actions of the remaining signatories. In contrast, a non-signatory does not want to join if he anticipates his decision to yield little increase, or even a decrease, in overall effort. In Section 4, we make use of our study of q^s to analyze Stage 1, and the existence and properties of stable treaties.

3 Signatories' actions

In this section, we study the actions of signatories $q^s(k)$. We have five results. First, we find that the bang-bang property which characterizes q^s under certainty partially disappears under uncertainty. Effort may take intermediate values in situations where action is desirable in one state of the world (i.e., when pollution damages are high), but not in the other (when pollution damages are low). In that case, signatories trade-off the benefit of action in one state against its cost in the other. Second, we show that the monotonicity of q^s with respect to k is ambiguous. While we expect q^s to be generally increasing, we show that it can be locally decreasing. Third, we find that uncertainty unambiguously lowers q^s. Holding k constant, an increase in uncertainty always leads to a decrease in signatories' efforts. Fourth, we show that an increase in risk aversion has a similar effect, and also lowers signatories' actions. Fifth, we derive analytical expressions for q^s for three standard classes of utility functions: quadratic, CARA, and CRRA, and study the properties of q^s in more details in these three cases.

3.1 General utility functions

Recall, signatories jointly decide how to maximize their collective welfare, defined as the sum of their expected utilities. It means that q^s is the solution of the following program:

$$\max_{0\leq q\leq q_{\max}} EU[(kb-c)q] \tag{1}$$

We first describe when the solution is at a corner. Observe that the objective function is strictly concave. Marginal expected utility is equal to $E(kb-c)U'[(kb-c)q]$. At $q=0$, this reduces to $(k\bar{b}-c)U'(0)$. Since $U'>0$, $q^s=0$ when $k\leq c/\bar{b}$. This notably covers the case where $kb_H-c\leq 0$, and signatories prefer to exert no effort in both states of the world. In contrast, when $k\geq c/b_L$, the marginal expected utility is always strictly positive. Signatories prefer to play $q_{\max}$ in both states of the world. Thus, $q_s=q_{\max}$ when $k\geq c/b_L$. When k lies between $c/\bar{b}$ and c/b_L, $kb_L-c<0$ while $kb_H-c>0$, and the solution may be interior. The first-order condition of program (1) can be written as follows:

$$p(c-kb_L)U'\left[(kb_L-c)q^s\right]=(1-p)(kb_H-c)U'\left[(kb_H-c)q^s\right] \tag{2}$$

This condition says that marginal utilities are equal in both states of the world. It expresses a trade-off between the positive marginal utility from action when $b=b_H$ and the negative marginal utility when $b=b_L$. Then, q^s is equal to the solution of this first-order condition if this solution is lower than $q_{\max}$, and to $q_{\max}$ otherwise. In any case, $q^s(k)$ is continuous over $[0,n]$ when k is allowed to take values on the real line. In summary,

Proposition 1. *The effort q^s exerted by a signatory country when k countries have signed the* *treaty is such that:*

(1) $q^s(k) = 0$ *if* $k \leq c/\bar{b}$ *and* $q^s(k) = q_{\max}$ *if* $k \geq c/b_L$.

(2) If $c/\bar{b} < k < c/b_L$, q^s *is equal to the smaller of* $q_{\max}$ *and of the solution to equation (2).*

Observe that when $b_L = \bar{b}$, there is no uncertainty and Proposition (1) reduces to the result described in the previous section.

Given that q^s varies continuously between 0 and $q^{\max}$, it is natural to ask whether q_s is increasing in k over $[c/\bar{b}, c/b_L]$. Algebraic manipulations lead to the following condition, derived in the Appendix. Let $A(\pi) = -u''(\pi)/u'(\pi)$ denote the level of absolute risk aversion. Introduce $\pi_L = (kb_L - c)q^s$ and $\pi_H = (kb_H - c)q^s > \pi_L$. Then, q^s is increasing over $[c/\bar{b}, c/b_L]$ if and only if:

$$q^s(k)\left(b_L A(\pi_L) - b_H A(\pi_H)\right) \geq \frac{-c(b_H - b_L)}{(kb_H - c)(c - kb_L)} \tag{3}$$

While the interpretation of this condition is not obvious, we can deduce from it a relatively simple sufficient condition. If $A(\pi_H) \leq (b_L/b_H)A(\pi_L)$, then condition (3) is satisfied. This means that the level of absolute risk aversion at π_H is sufficiently lower than the level of absolute risk aversion at π_L. In other words, if U is sufficiently DARA, q^s is increasing. In general, however, monotonicity of q^s with respect to k is ambiguous. We will see below that when U is CARA or CRRA, q^s can be locally decreasing in k.

We next study the effect of uncertainty on $q^s(k)$. Proposition (1) implies that $q^s(k)$ is lower under uncertainty than under certainty. Our next result shows that this property holds more generally for any increase in uncertainty in the sense of Rothschild and Stiglitz (1974). Let b and b' be two binary distributions of marginal benefit values with the same mean $\bar{b} = \bar{b}'$. Observe that b' is more risky than b if and only if $b'_L \leq b_L$ and $b'_H \geq b_H$. In the next section, we will consider separately the effects of a decrease in b_L and an increase in b_H on stable treaties.

Proposition 2. *Suppose that b' is more risky than b. Then $\forall k \in [0, n]$, $q^s(k, b') \leq q^s(k, b)$. An increase in uncertainty always reduces signatories' actions.*

The intuition behind this result can be seen by looking at the expected value and the variance of ex-post payoffs π for signatories. Here, $\bar{\pi} = (k\bar{b} - c)q^s$ and $Var(\pi) = p(1-p)(b_H - b_L)^2 k^2 (q^s)^2$. When $k \geq c/\bar{b}$, an increase in q increases the expected value and also increases the variance. One is desirable, but the other is not under risk aversion. The optimal choice of q results from a trade-off between these two motives.[8] Then, holding q and k constant, an increase in uncertainty leads to an increase in the payoff's variance while leaving its expected value unchanged. The marginal effect of a decrease in q on the variance is greater when uncertainty is greater, hence signatories' action will be lower.

This effect is confirmed by looking at an increase in risk aversion. Recall that utility function V represents more risk-averse preferences than U if there is an increasing and concave function Φ such that $V = \Phi(U)$. In our context, the effect of risk aversion is similar to the effect of uncertainty

Proposition 3. *Suppose that agents with utility V are more risk-averse than agents with utility U. Then $\forall k \in [0, n]$, $q^s(k, V) \leq q^s(k, U)$.*

For a given participation level, uncertainty and risk aversion tend to reduce signatories'actions. Signatories exert less effort in order to diminish the variability of their payoffs. While this effect may seem to be purely negative (lower level of collective action), we will see in the next section that it can have a positive indirect consequence. Lower action at all participation levels may increase the participation level that is sustainable in equilibrium. We next look at specific utility functions.

[8] In contrast, when $k < c/\bar{b}$, an increase in q decreases the expected value and increases the variance, and there is no trade-off. This provides another explanation for the fact that $q^s = 0$.

3.2 Specific utility functions

3.2.1 Quadratic utility functions

Consider first a quadratic utility function $U(\pi) = \pi - \lambda\pi^2$. We need to impose $(nb_H - c)q_{max} \leq 1/(2\lambda)$ to ensure that utility is strictly increasing over the strategy space. Signatories' action is equal to:[9]

$$q^s(k) = \frac{1}{2\lambda}\frac{k\bar{b} - c}{p(kb_L - c)^2 + (1-p)(kb_H - c)^2}$$

We show in the Appendix that q^s is always increasing in k when U is quadratic. This tells us that q^s may be increasing even when the utility function is IARA, and that the sufficient condition derived in the previous section is not necessary.

3.2.2 CARA utility functions

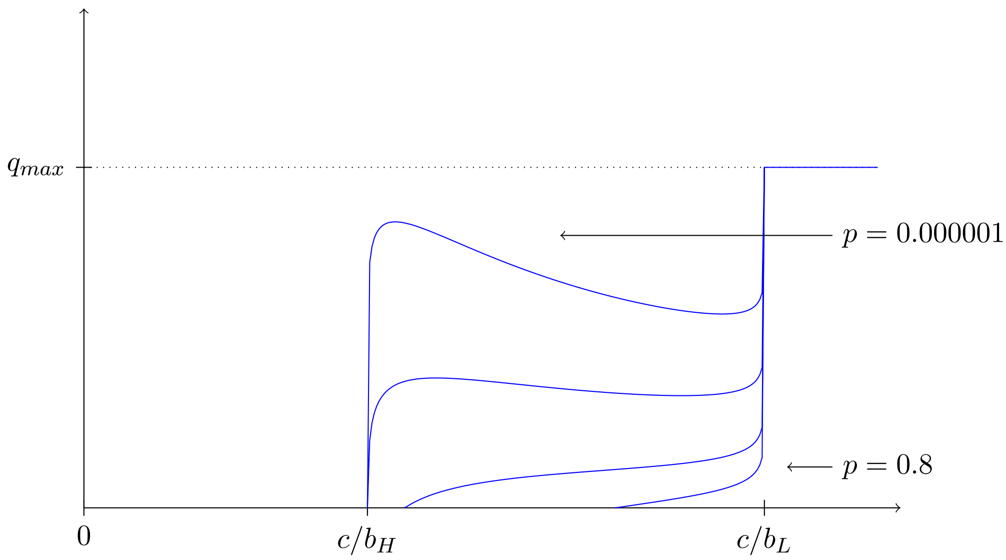
Consider next a CARA utility function $U(\pi) = -e^{-A\pi}$ where A denotes the level of absolute risk aversion. We obtain the following analytical expression for q^s (see the Appendix):

$$q^s(k) = \frac{1}{Ak(b_H - b_L)} \ln \left[\frac{(1-p)(kb_H - c)}{p(c - kb_L)}\right]$$

We also study whether q^s is increasing in k. We find that two cases appear. Either q^s is increasing, or it is first increasing, then decreasing, and again increasing over $[c/\bar{b}, c/b_L]$. Also, q^s is more likely to be increasing when p is higher. Figure 1 illustrates.

[9]More precisely, we give in this section the analytical expressions for the solution to the first-order condition (2). The precise value for q^s can then be obtained by applying Proposition 1.

Picture 1 : Effort with uncertainty, CARA function



$n = 100$, $c = 15$, $b_H = 12$, $b_L = 5$, $A = 1$, $p = \{0.000001,\ 0.001,\ 0.2,\ 0.8\}$, $q_{max} = 3.5$

3.2.3 CRRA utility function

Finally, consider a CRRA utility function $U(\pi) = \frac{1}{1-\gamma}(\pi_0 + \pi)^{1-\gamma}$ if $\gamma \neq 1$, and $\ln(\pi_0 + \pi)$ if $\gamma = 1$. Introducing a baseline payoff π_0 is necessary to ensure that ex-post payoffs are always positive. We obtain the following analytical form for $q^s(k)$:

$$q^s(k) = \pi_0 \frac{(1-p)^{1/\gamma}(kb_H - c)^{1/\gamma} - p^{1/\gamma}(c - kb_L)^{1/\gamma}}{p^{1/\gamma}(c - kb_L)^{1/\gamma}(kb_H - c) + (1-p)^{1/\gamma}(kb_H - c)^{1/\gamma}(c - kb_L)}$$

Especially, when $\gamma = 1$ this reduces to $q^s = \pi_0[\frac{1-p}{p(c-kb_L)} - \frac{p}{(1-p)(kb_H-c)}]$, which is clearly increasing in k. This may not necessarily be the case, however, when $\gamma \neq 1$. Our simulations in the next section are based on the CRRA utility functions.

4 Stable treaties

In this section, we study the existence and properties of stable treaties. We first analyze existence. We show that a stable treaty with positive action always exists. It is easy to see that in any stable treaty where some effort is sustained, $c/\bar{b} \leq k^* < c/b_L + 1$. We provide two results that give some information on the equilibrium level of participation. First, if q^s is decreasing in k over some range of values, a stable treaty always exists with participation below this range. Second, if $q_{\max}$ is large enough, there exists a stable treaty with $c/b_L \leq k^* < c/b_L + 1$. Going further analytically is difficult. Even with the specific utilities analyzed in the previous section, stability conditions yield complicated expressions without closed-form solutions.

Therefore we use simulations to investigate, in a second stage, the properties of stable treaties. We emphasize three outcomes of this analysis. First, we find that multiple equilibria may emerge. A stable treaty with low participation and low action may coexist with one with high participation and high action. To our knowledge, this is the first instance in the literature where a model of international environmental agreement generates multiple equilibria. Second, we find that uncertainty may increase participation. This is partly due to the negative effect of uncertainty on q^s. Signatories need to be in greater number to be willing to exert a high level of effort. This increases the critical number of countries above which the addition of a new signatory has little effect. And third, even though countries are risk-averse, the positive effect of uncertainty on participation may lead to an increase in welfare in equilibrium. We clarify the conditions under which uncertainty may improve overall welfare.

4.1 Existence

We first show that a stable treaty with positive action always exists.

Proposition 4. *There exists a stable treaty with k^* signatories such that $q^s(k^*) > 0$.*

Our proof relies on the study of the function Δ. Recall, $\Delta(k) = U^s(k) - U^n(k-1)$. On the one hand, $U^s = U^n = 0$ on $[0, c/\bar{b}]$. This means that $\Delta(k) = 0$ if $k \in [1, c/\bar{b}]$ and $\Delta(k) > 0$ if $k \in]c/\bar{b}, c/\bar{b}+1]$. On the other hand, $q^s = q_{\max}$ on $[c/b_L, n]$. This implies that $\Delta(k) < 0$ on $[c/b_L + 1, n]$. If we define k^* as the greatest integer such that $\Delta(k^*) > 0$, we have: $\Delta(k^*) > 0$, $\Delta(k^* + 1) \leq 0$, and $k^* > c/\bar{b}$, which means that $q^s(k^*) > 0$.

If the number of signatory countries lies just above $c/\bar{b}$, an additional country has a strictly positive incentive to join. If he does not join, signatories do no exert any effort. If he joins, all signatories start exerting positive effort. The number of signatories increases til an additional country does not want to join, at which point the treaty is stable.

Clearly, in any stable treaty with positive action, $c/\bar{b} \leq k^* < c/b_L + 1$. We next derive two further results on the participation level. First, if q^s is locally decreasing and such that for some integer k, $q^s(k) < q^s(k-1)$, we have $U^s(k) < U^n(k-1)$, hence $\Delta(k) < 0$. Applying the previous argument shows that there exists a stable treaty with $k^* \leq k$. Second, we show that an equilibrium around c/b_L is generally guaranteed if $q_{\max}$ is large enough. More precisely, let $[\pi]$ denote the smallest integer greater than or equal to π.

Proposition 5. *Suppose that either c/b_L is not an integer, or $\lim_{\pi \to +\infty} U(\pi) = +\infty$. Then, there is a $\bar{q} > 0$ such that if $q_{\max} \geq \bar{q}$, a treaty with $k^* = [c/b_L]$ is stable.*

The intuition behind this result lies in the fact that $q^s(k)$ becomes very steep when k is close to c/b_L. Recall that at c/b_L, action becomes desirable in both states of the world, hence, given linearity of the payoffs, should be as high as possible. If $q_{\max}$ is large, the drop in collective action if one country quits is large, which gives an incentive for signatories to stay in the treaty.[10]

[10]Either technical condition stated in the Proposition ensures that an arbitrarily large drop in collective action

We next discuss the possible effects of uncertainty on a stable treaty. In this model, uncertainty can affect welfare in three different ways. First, holding q^s and k fixed, it has a direct negative effect resulting from risk aversion. Second, holding only k fixed, it has an indirect negative effect through its impact on $q^s(k)$ (Proposition 2). We see these two effects in the simulations below. We also see a third, countervailing effect. Uncertainty can have a positive impact on participation, which may overcome the two other effects and lead to an increase in welfare.

4.2 Simulations

We next provide a detailed analysis of the effect of uncertainty on stable treaties through simulations. We assume in this section that the utility function satisfies Constant Relative Risk Aversion. We first look at a relatively low level of risk aversion: $\gamma = 0.5$. Baseline values for the other parameters are set as follows: $n = 100$, $c = 755$, $\bar{b} = 450$, $\pi_0 = 250$, $q_{\max} = 300$. In the baseline case, prospects for cooperation in the absence of risk are bleak: only 2 countries among 100 sign the treaty in equilibrium.

Table 1 and Picture 2 depict the effect of uncertainty on the number of signatory countries in equilibria with positive action, while Table 2 and Picture 3 report the levels of welfare in equilibrium. (A value of 100 corresponds to the level of welfare in the equilibrium under certainty). We consider separately the effects of a decrease in b_L or an increase in b_H, and adjust the probability p in order to hold $\bar{b}$ constant. Two numbers in a cell indicate the presence of two equilibria.

We observe the emergence of multiple equilibria. Participation in the low equilibrium is equal to $k = [c/\bar{b}] = 2$, as under certainty, and is much lower than participation in the high equilibrium.

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indeed translates into an incentive not to quit. The result may not hold, however, if c/b_L is an integer and U is bounded.

We can check that participation in the high equilibrium is always equal to $[c/b_L]$ in Table 1, which is the level predicted by Proposition 5. While the high equilibrium always exists, the low equilibrium emerges only when the level of risk is high enough. Welfare in the low equilibrium is much lower than under certainty. In contrast, welfare in the high equilibrium is usually higher than under certainty. More generally, changes in welfare reflect the three effects mentioned above. When participation is constant, welfare decreases. Thus, an increase in uncertainty reduces welfare in the low equilibrium. Similarly, when b_H increases or when b_L decreases without affecting participation, welfare in the high equilibrium decreases. In contrast, a decrease in b_L that increases participation always leads to an increase in welfare in Table 2.

Thus, when risk aversion is relatively low, an increase in uncertainty can strongly improve the prospects for cooperation. A decrease in b_L increases the critical mass of countries at which cooperation becomes sustainable, and this increase in participation can yield an increase in welfare.[11] This positive effect of uncertainty is mitigated by the existence of multiple equilibria. Countries can also be trapped in a low participation equilibrium, where participation is not affected by risk and welfare is much lower.

We next look at the effect of risk aversion. Table 3 and Picture 4, and Table 4 and Picture 5 replicate the previous tables and pictures for $\gamma = 1$. Other parameters are set at baseline values, and tables look at similar levels of b_L and b_H. Table 5 and Picture 6, and Table 6 and Pictures 7 and 8 do the same for $\gamma = 2.5$.[12]

Conditional on existence, participation in both equilibria is unchanged. However, risk aversion affects the existence of either equilibrium. When risk aversion is relatively high (Table 5), the

[11] Observe also that the difference between the first-best and the equilibrium levels of welfare is even more reduced, given that the first-best level of welfare decreases when uncertainty increases.

[12] When $\gamma > 1$, utility becomes negative. Welfare under certainty now corresponds to a value of -100. Picture 8 depicts variations in welfare using a logarithmic scale, which is more appropriate to examine the high equilibrium.

low equilibrium emerges more easily. On welfare, we find, not surprisingly, a reducing effect of risk aversion. When $\gamma = 1$, we now see that even when uncertainty increases participation, it can decrease welfare (e.g. Table 4, $b_H = 695$, b_L going from 15 to 10). The indirect, positive effect of participation may not be high enough to overcome the direct negative effect of uncertainty. This effect is exacerbated when risk aversion is higher, and when the initial level of risk is higher.

Overall, the three main outcomes seem to be robust to an increase in risk aversion. Risk aversion makes a positive impact of uncertainty less likely. To further study the robustness of these results, we check the properties of stable treaties for a large number of parameter values. We next report some results of this exercise.[13] Specifically, we set n, π_0 and $q_{\max}$ at baseline values, and vary γ, c, $\bar{b}$, b_L, b_H. Overall, we look at 3,970,008 admissible parameter values.[14] There are either one or two equilibria, and multiple equilibria appear in 47.35% of the cases. Risk aversion tend to increase this proportion: it ranges from 39.26% when $\gamma = 0.3$ to 53.87% when $\gamma = 3$. Among all possible equilibria, the level of participation is either $[c/\bar{b}]$ or $[c/b_L]$ in 93.94% of the cases, $[c/\bar{b}]+1$ in 5.86% of the cases, and takes a value lying between $[c/\bar{b}]+2$ and $[c/b_L]-1$ in the remaining 0.20%. We also look at the behavior of $q^s(k)$. We find that q^s is decreasing for some k only in 0.88% of the cases, and this tends to happen more when risk aversion is higher.

We look at the effect of uncertainty on welfare. Since participation appears essentially unaffected by b_H, we focus on the effect of a decrease in b_L. In all our simulations, we count the number of times where participation and welfare in the higher equilibrium increase following a marginal decrease in b_L. Overall, we make 3,860,136 such comparisons. We find that participation in the higher equilibrium stays unchanged after a decrease in b_L in 60.01% of the cases, and decreases

[13] More disaggregated results are available upon request.

[14] More precisely, γ varies between 0.3 and 3 by steps of 0.1, c between 100 and 900 by steps of 100, $\bar{b}$ between ε and $\frac{9}{10}c + \varepsilon$ by steps of $\frac{1}{10}c$, b_H between $\bar{b} + \varepsilon$ and $c - \varepsilon$ by steps of $\frac{1}{100}c$, and b_L between $\bar{b} - \varepsilon$ and ε by steps of $-\frac{1}{100}c$.

in 0.93% of the cases. Welfare decreases, of course, in either situation. In contrast, participation increases in the remaining 39.07%.[15] Conditional of having an increase in participation, welfare increases in 70.94% of the cases, and decreases otherwise. This last proportion tends to decrease with γ, ranging from 99.06% when $\gamma = 0.3$ to 57.76% when $\gamma = 3$. Overall, welfare increases following a decrease in b_L in 27.71% of the cases.

5 Conclusion

We conclude with a discussion of some limitations of our analysis, and of promising directions for future research. In this paper, we introduced uncertainty and risk aversion to a simple model of international environmental agreements. We find that uncertainty significantly affects the analysis of treaty formation. Uncertainty yields qualitative changes as well as first-order quantitative changes on the outcomes of the game.[16] This complexity provides some justification, ex-post, for the study of a simple benchmark model. It also raises the question of the robustness of our results. Three features of the model especially deserve attention: the fact that the risk is binary, linearity of the payoffs, and homogeneity of the agents.

The assumption of a binary risk may not be too problematic. Some of our results directly extend to an arbitrary risk. For instance, the argument behind Proposition 1 holds in general. If marginal benefit b is subject to an arbitrary risk with mean $\bar{b}$ and lowest value b_L, we still have that $q^s(k) = 0$ if $k \leq c/\bar{b}$ and $q^s = q_{\max}$ if $k \geq c/b_L$. Similarly, our existence results Propositions 4 and 5 hold for any risk. On the other hand, signing the effects of risk and risk aversion may be

[15] The effect of risk aversion on these proportions is slight and non-monotonic. The proportion of cases where participation increases first decreases from $\gamma = 0.3$ (40.06%) to $\gamma = 1.4$ (37.71%) and then increases til $\gamma =$ 3.(40.32%). The other two proportions follow an opposite pattern, first increasing and then decreasing, although effects are quantitatively small.

[16] Qualitative changes include the fact that signatories' actions can take intermediate values and the emergence of multiple equilibria. On quantitative changes, simulations show that participation level and welfare may be much higher under uncertainty than under certainty.

more complicated. Comparative statics may be ambiguous, and may involve conditions based on the third and higher derivatives of the utility function, see Gollier (2001).

Linearity of the payoffs is a critical assumption. Under certainty, non-linear payoffs may lead to very different equilibria, see Barrett (2003). An interest of the model with linear payoffs, however, is that it neatly captures the idea of critical mass. Collective action becomes worthwile only when enough countries have joined in, and once this threshold is reached, there is little benefit from an additional signatory. As such, studies of models with linear payoffs may be useful to understand what happens more generally. With any payoff function, stability captures a form of local critical mass. A treaty is stable when the drop in collective action if one country is high enough, and when the addition of one signatory has little effect. Thus, we conjecture that our results may also be applicable, under conditions to be determined, to models with non-linear payoffs. As soon as uncertainty lowers signatories' actions, corresponding threshold levels may increase, which may improve participation in equilibrium.

The effect of heterogeneity on international environmental agreements is not well understood yet, even under certainty.[17] Under heterogeneity, anonymity is lost. The idea of local critical mass is still relevant, but the identity of the signatories and non-signatories matters. If anything, we expect the effects of uncertainty and risk aversion to be exacerbated under heterogeneity, given that countries may differ in the risk they face and in their degree of risk aversion. Trying to understand the combined effects of arbitrary risks, general payoff functions, and heterogeneity on international environmental agreements gives matter for much future research.

[17] See Barrett (2001) for an exception.

APPENDIX

Proof of Condition 3. Condition (2) gives: $pU'_L(kb_L - c) + (1-p)U'_H(kb_H - c) = 0$ where the indices L and H stand for the function arguments $(kb_L - c)q^s$ and $(kb_H - c)q^s$. Derivating with respect to k yields:

$$pU'_L b_L + p(kb_L - c)U''_L(kb_L - c)\frac{\partial q^s}{\partial k}(k) + b_L q^s(k)]$$
$$+(1-p)U'_H b_H + (1-p)(kb_H - c)U''_H\left[(kb_H - c)\frac{\partial q^s}{\partial k}(k) + b_H q^s(k)\right] = 0$$

Rewriting using $A = -U''/U'$ shows that $q^s(k)$ is increasing if and only if:

$$pU'_L\left[-b_L + (kb_L - c)A_L b_L q^s(k)\right] + (1-p)U'_H\left[-b_H + (kb_H - c)A_H b_H q^s(k)\right] \leq 0$$

From the f.o.c., we have $\frac{U'_L}{U'_H} = \frac{(1-p)(kb_H - c)}{p(c - kb_L)}$. Substituting, the previous expression becomes:

$$q^s(k)\left(A_L b_L - A_H b_H\right) \geq \frac{-c(b_H - b_L)}{(kb_H - c)(c - kb_L)}$$

Proof of Proposition 2. Consider q^s as a function of b_L and b_H. We have $p = (b_H - \bar{b})/(b_H - b_L)$. Substituting, condition (2) becomes: $U'_L(b_H - \bar{b})(kb_L - c) + U'_H(\bar{b} - b_L)(kb_H - c) = 0$. Derivating this last expression with respect to b_H, we see that:

$$U'_L(c - kb_L) \geq k(\bar{b} - b_L)U'_H \implies \frac{\partial q^s}{\partial b_H}(k, b_H) \leq 0$$

The left-hand side holds for $k \in [c/\bar{b}, c/b_L]$. Similarly, derivating with respect to b_L, we have:

$$U'_H(kb_H - c) \leq U'_L(b_H - \bar{b})k \implies \frac{\partial q^s}{\partial b_L}(k, b_H) \geq 0$$

where the left-hand side also holds when $k \in [c/\bar{b}, c/b_L]$. Thus, holding b_H constant, q^s decreases if b_L decreases and holding b_L constant, q^s decreases if b_H increases. This means that $q^s(b'_L, b'_H) \leq q^s(b_L, b'_H) \leq q^s(b_L, b_H)$.

Proof of Proposition 3. Denote by $F(q) = EV[(kb - c)q]$ the objective function of the signatories when agents have utility V. Since $V = \Phi(U)$, we have:

$F'(q) = p\Phi'(U[(kb_L - c)q])U'[(kb_L - c)q] + (1-p)\Phi'(U[(kb_H - c)q])U'[(kb_H - c)q]$.

At $q = q^s(U)$, $pU'[(kb_L - c)q] + (1-p)U'[(kb_H - c)q] = 0$, and $F'(q^s(U)) = (1-p)U'[(kb_H - c)q](\Phi'(U[(kb_H - c)q]) - \Phi'(U[(kb_L - c)q])$. Since $(kb_H - c)q > (kb_L - c)q$, U is increasing, and Φ' is decreasing, we have. $F'(q^s(U)) \leq 0$. Since F concave, F' decreasing, and $F'(q^s(V)) = 0$, we have: $q^s(V) \leq q^s(U)$.

Computations for specific utilities.

Quadratic utility : Consider $q^s(k) = \frac{1}{2\lambda}\frac{k\bar{b}-c}{p(kb_L-c)^2+(1-p)(kb_H-c)^2}$. Introduce $\bar{b^2} = pb_L^2 + (1-p)b_H^2$. Derivating q^s with respect to k, we obtain:

$$\frac{\partial q_s(k)}{\partial k} = \frac{-k^2\bar{b}\bar{b^2} + 2k\bar{b^2}c - c^2\bar{b}}{2\lambda(k^2\bar{b^2} - 2ck\bar{b} + c^2)^2}.$$

Then, q^s is increasing iff $-k^2\bar{b}\bar{b^2} + 2k\bar{b^2}c - c^2\bar{b} \geq 0$. In $k = c/\bar{b}$, this expression becomes $c^2(b^2 - \bar{b}^2)/\bar{b}$, which is always positive. In addition, we know that $q^s(c/b_L) > q_{max}$ from proposition 1. Since the previous condition is quadratic in k, there are two cases. Either q^s is increasing over $[c/\bar{b}, c/b_L]$, or q^s is first increasing and then decreasing, and $\max_{[c/\bar{b}, c/b_L]} q^s > q_{\max}$. In either case, $\min(q^s, q_{\max})$ is increasing over $[c/\bar{b}, c/b_L]$.

CARA utility : Let $q^s(k) = \frac{1}{Ak(b_H - b_L)} \ln\left[\frac{(1-p)(kb_H-c)}{p(c-kb_L)}\right]$. Introduce the three following auxiliary functions: $f(k) = \frac{(1-p)(kb_H-c)}{p(c-kb_L)}$, $g(k) = \frac{(kb_H-c)(c-kb_L)}{k}$, and $h(k) = \ln[f(k)]g(k)$. Derivating q^s with respect to k, we obtain:

$$\frac{\partial q_s}{\partial k} = \frac{1}{A(b_H - b_L)k}\left(\frac{-\ln(f)}{k} + \frac{c(\bar{b} - b_L)}{(1-p)(kb_H - c)(c - kb_L)}\right)$$

This means that q^s is increasing iff $\frac{c(\bar{b}-b_L)}{(1-p)(kb_H-c)(c-kb_L)} \geq \frac{\ln[f(k)]}{k}$, which is equivalent to $h(k) \leq c(b_H - b_L)$. We next study the properties of h. We have : $h' = ln[f]g' + \frac{f'}{f}g$. Since $k \geq c/\bar{b}$, $f(k) \geq 1$ and $\ln[f(k)] \geq 0$. In addition, $f'(k) \geq 0$ and $g'(k) = -b_L b_H + c^2/k^2$. This means that , $h'(k) > 0$ if $k \in [0, c/\sqrt{b_L b_H}]$. Looking at the second derivative of h gives:

$$\frac{\partial^2 h}{\partial k^2}(k) = \ln[f(k)]g''(k) + \frac{c(b_H - b_L)}{k^2(c - kb_L)(kb_H - c)}\left[c(-k(b_H + b_L) + 2c)\right]$$

which is strictly negative for $k \geq c/\sqrt{b_L b_H}$. Therefore, h is increasing over $[0, c/\sqrt{b_L b_H}]$ and strictly concave over $[c/\sqrt{b_L b_H}, c/b_L]$. In addition, we know that q^s is increasing at $c/\bar{b}$ and becomes arbitrarily large when k gets close to c/b_L. This implies that q^s is either increasing over $[c/\bar{b}, c/b_L]$, or increasing, decreasing, and increasing again. Besides, $\partial h/\partial p \leq 0$, hence the whole h function shifts downwards when p increases. Suppose that $p_1 > p_2$. If q^s is increasing for p_1, then q^s increasing for p_2. If q^s is increasing, decreasing, increasing for p_1, then either q^s is increasing, or the interval on which it is decreasing is smaller.

Proof of Proposition 5. Let $[x]$ denote the smallest integer greater than or equal to x. Let $k^* = [c/b_L]$. Recall, $\Delta(k^*+1) < 0$ since $q^s(k^*) = q^s(k^*+1) = q_{\max}$. In addition, if a signatory quits at k^*, he obtains $(k^*-1)bq^s(k^*-1)$. Thus,

$\Delta(k^*) = p\left[U((k^* b_L - c)q_{max}) - U((k^*-1)b_L q^s(k^*-1)\right]$

$+(1-p)\left[U((k^* b_H - c)q_{max}) - U((k^*-1)b_H q^s(k^*-1)\right]$

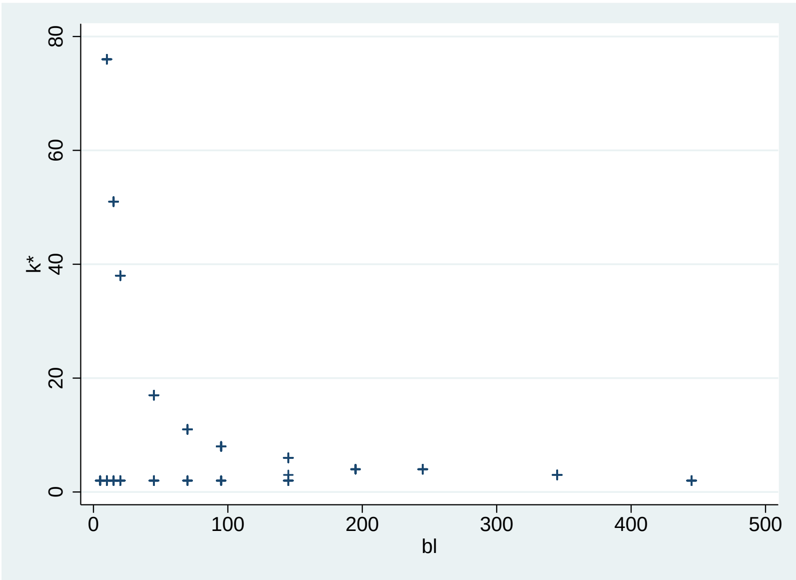
Since $q_s(k^*-1) < c/b_L$, if $q_{\max}$ is large enough, $q_s(k^*-1) < q_{\max}$. Since $k^* b_H - c > 0$, if $q_{\max}$ is large enough, $(k^* b_H - c)q_{max} > (k^*-1)b_H q^s(k^*-1)$. If $k^* \neq c/b_L$, we also have $k^* b_L - c > 0$, hence $(k^* b_L - c) q_{max} > (k^* - 1) b_L q^s (k^* - 1)$ if $q_{\max}$ is large enough. In this case, since U increasing, $\Delta(k^*) > 0$. This result also holds if $k^* = c/b_L$, and $\lim_{\pi \to \infty} U(\pi) = +\infty$.

Table 1 : Effects of Uncertainty on Participation ($\gamma = 0.5$)

$b_L \backslash b_H$	455		515		575		635		695	
445	-	2	-	2	-	2	-	2	-	2
345	-	3	-	3	-	3	-	3	-	3
245	-	4	-	4	-	4	-	4	-	4
195	-	4	-	4	-	4	-	4	-	4
145	2	6	2	6	2	6	2	6	3	6
95	2	8	2	8	2	8	2	8	2	8
70	2	11	2	11	2	11	2	11	2	11
45	2	17	2	17	2	17	2	17	2	17
20	2	38	2	38	2	38	2	38	2	38
15	2	51	2	51	2	51	2	51	2	51
10	2	76	2	76	2	76	2	76	2	76

$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 0.5$

Picture 2 : Effects of Uncertainty on Participation ($\gamma = 0.5$)



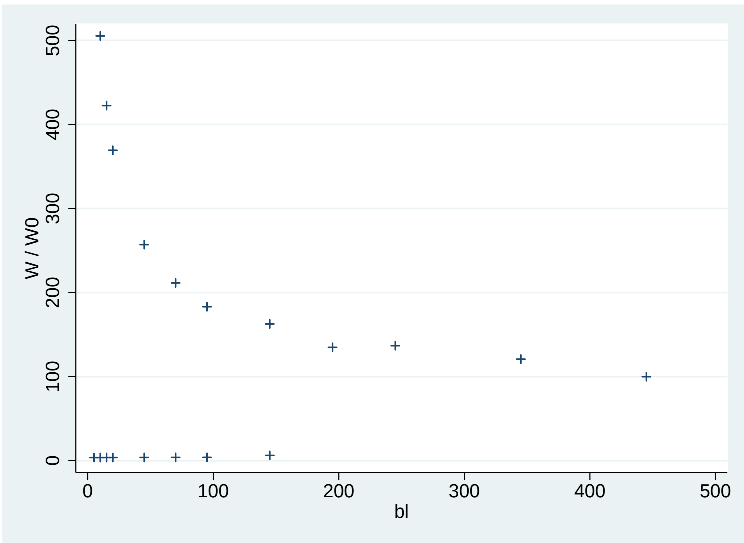
$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 0.5$

Table 2 : Effects of Uncertainty on Welfare ($\gamma = 0.5$)

$b_L \backslash b_H$	455		515		575		635		695	
445	-	100	-	99,98	-	99,96	-	99,94	-	99,93
345	-	122,64	-	122,09	-	121,61	-	121,18	-	120,8
245	-	141,61	-	140,18	-	138,93	-	137,82	-	136,84
195	-	141,55	-	139,5	-	137,74	-	136,19	-	134,82
145	5,23	173,36	4,87	170,14	4,54	167,35	4,31	164,9	6,27	162,72
95	4,92	200,08	4,59	194,9	4,31	190,46	4,1	186,58	3,95	183,15
70	4,8	234,55	4,49	227,49	4,21	221,44	4,02	216,17	3,89	211,52
45	4,69	291,45	4,39	280,83	4,14	271,78	3,96	263,93	3,83	257,03
20	4,59	435,34	4,31	414,74	4,07	397,33	3,9	382,34	3,78	369,25
15	4,58	504,19	4,3	478,63	4,06	457,07	3,89	438,56	3,77	422,42
10	4,56	615,17	4,28	580,66	4,04	551,66	3,88	526,85	3,76	505,3

$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 0.5$

Picture 3 : Effects of Uncertainty on Welfare ($\gamma = 0.5$)



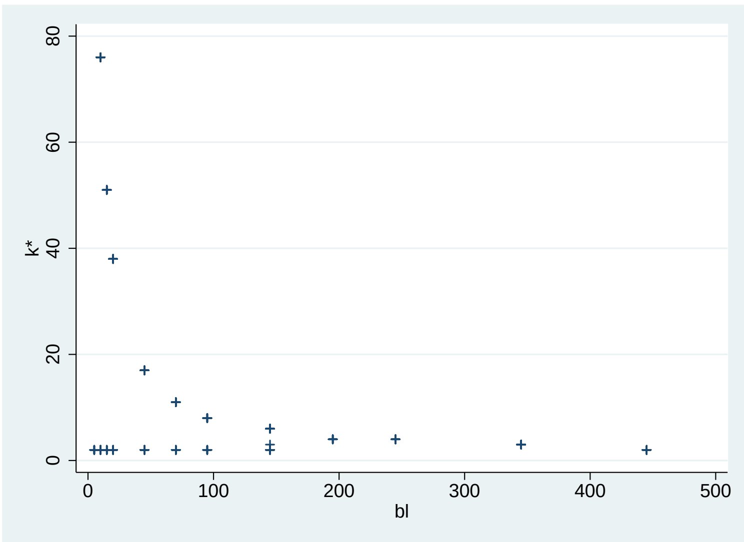
$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 0.5$

Table 3 : Effects of Uncertainty on Participation ($\gamma = 1$)

$b_L \backslash b_H$	455		515		575		635		695	
445	-	2	-	2	-	2	-	2	-	2
345	-	3	-	3	-	3	-	3	-	3
245	-	4	-	4	-	4	-	4	-	4
195	-	4	-	4	-	4	-	4	-	4
145	2	6	2	6	2	6	2	6	2	6
95	2	8	2	8	2	8	2	8	2	8
70	2	11	2	11	2	11	2	11	2	11
45	2	17	2	17	2	17	2	17	2	17
20	2	38	2	38	2	38	2	38	2	38
15	2	51	2	51	2	51	2	51	2	51
10	2	76	2	76	2	76	2	76	2	76

$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 1$

Picture 4 : Effects of Uncertainty on Participation ($\gamma = 1$)



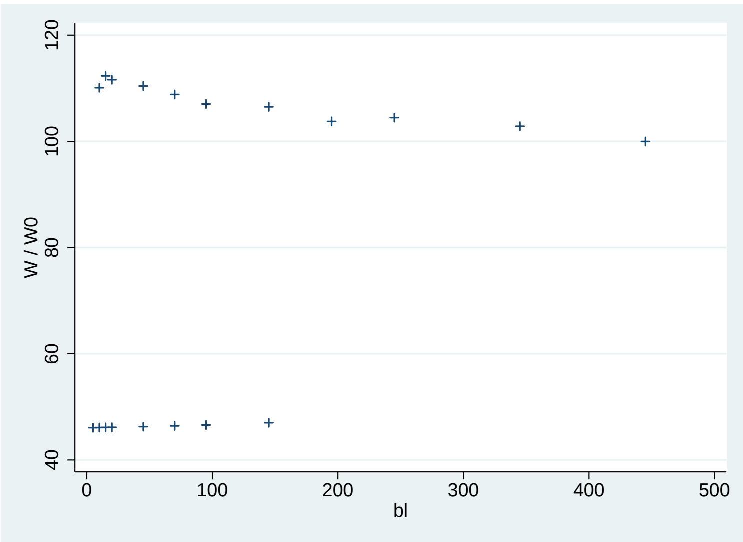
$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 1$

Table 4 : Effects of Uncertainty on Welfare ($\gamma = 1$)

$b_L \backslash b_H$	455		515		575		635		695	
445	-	100	-	99,99	-	99,98	-	99,98	-	99,98
345	-	103,33	-	103,18	-	103,05	-	102,94	-	102,84
245	-	105,64	-	105,27	-	104,96	-	104,7	-	104,48
195	-	105,62	-	105,01	-	104,52	-	104,1	-	103,75
145	52,41	108,87	49,7	108,11	48,36	107,49	47,55	106,96	47,01	106,5
95	51,46	111,13	48,96	109,79	47,76	108,71	47,06	107,81	46,59	107,04
70	51,06	113,66	48,66	112,09	47,53	110,81	46,86	109,74	46,42	108,83
45	50,71	117,1	48,4	114,92	47,32	113,14	46,69	111,67	46,28	110,42
20	50,4	123,39	48,17	119,51	47,14	116,37	46,55	113,79	46,15	111,61
15	50,34	125,7	48,13	121,28	47,11	117,73	46,52	114,79	46,13	112,33
10	50,28	128,73	48,09	122,54	47,08	117,58	46,49	113,51	46,11	110,1

$n = 100,\ c = 755,\ \bar{b} = 450,\ bh = 695,\ \pi_0 = 250,\ q_{max} = 300,\ \gamma = 1$

Picture 5 : Effects of Uncertainty on Welfare ($\gamma = 1$)



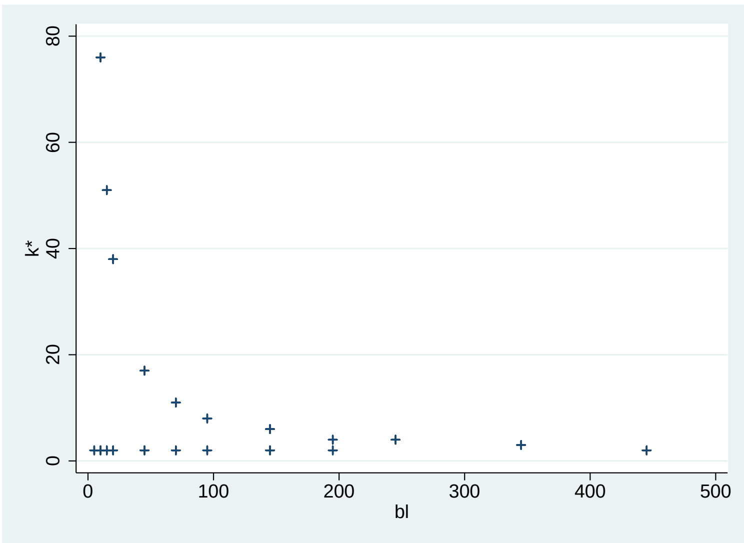
$n = 100,\ c = 755,\ \bar{b} = 450,\ bh = 695,\ \pi_0 = 250,\ q_{max} = 300,\ \gamma = 1$

Table 5 : Effects of Uncertainty on Participation ($\gamma = 2.5$)

$b_L \backslash b_H$	455		515		575		635		695	
445	-	2	-	2	-	2	-	2	-	2
345	-	3	-	3	-	3	-	3	-	3
245	-	4	-	4	-	4	-	4	-	4
195	2	4	2	4	2	4	2	4	2	4
145	2	6	2	6	2	6	2	6	2	6
95	2	8	2	8	2	8	2	8	2	8
70	2	11	2	11	2	11	2	11	2	11
45	2	17	2	17	2	17	2	17	2	17
20	2	38	2	38	2	38	2	38	2	38
15	2	51	2	51	2	51	2	51	2	51
10	2	76	2	76	2	76	2	76	2	76

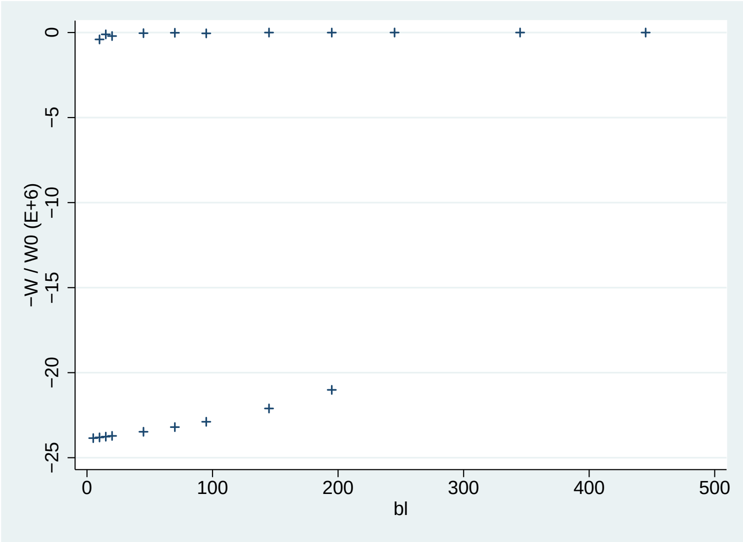
$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 2.5$

Picture 6 : Effects of Uncertainty on Participation ($\gamma = 2.5$)



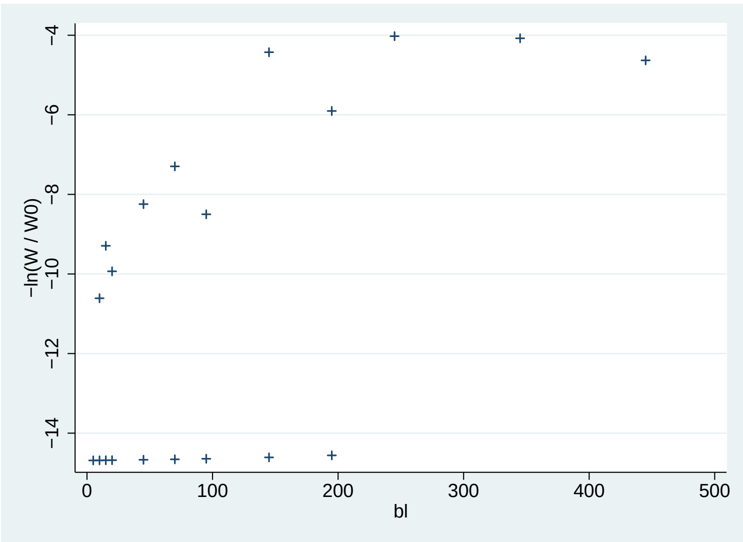
$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 2.5$

Picture 7 : Effects of Uncertainty on Welfare ($\gamma = 2.5$)



$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 2.5$

Picture 8 : Log-Effects of Uncertainty on Welfare ($\gamma = 2.5$)



$n = 100$, $c = 755$, $\bar{b} = 450$, $bh = 695$, $\pi_0 = 250$, $q_{max} = 300$, $\gamma = 2.5$

Table 6 : Effects of Uncertainty on Welfare ($\gamma = 2.5$)

$b_L \backslash b_H$	455		515		575		635		695	
445	-	-100,23	-	-101,64	-	-102,20	-	-102,52	-	-102,73
345	-	-45,91	-	-50,95	-	-54,42	-	-56,99	-	-58,97
245	-	-29,85	-	-39,48	-	-46,46	-	-51,75	-	-55,91
195	-7,11E+5	-41,91	-1,45E+6	-167,37	-1,77E+6	-254,11	-1,97E+6	-317,71	-2,10E+6	-366,36
145	-8,62E+5	-17,90	-1,61E+6	-41,65	-1,92E+6	-59,28	-2,10E+6	-72,87	-2,21E+6	-83,68
95	-9,95E+5	-176,70	-1,74E+6	-1867,23	-2,03E+6	-3135,46	-2,19E+6	-4122,07	-2,29E+6	-4911,45
70	-1,06E+6	-54,80	-1,80E+6	-552,82	-2,07E+6	-932,71	-2,22E+6	-1232,03	-2,32E+6	-1473,97
45	-1,11E+6	-126,28	-1,85E+6	-1398,78	-2,11E+6	-2383,27	-2,26E+6	-3167,59	-2,35E+6	-3807,15
20	-1,16E+6	-652,92	-1,89E+6	-7449,08	-2,15E+6	-12775,83	-2,28E+6	-17063,24	-2,37E+6	-20588,47
15	-1,17E+6	-342,59	-1,90E+6	-3912,83	-2,15E+6	-6718,03	-2,29E+6	-8980,32	-2,38E+6	-10843,38
10	-1,19E+6	-1273,87	-1,91E+6	-14589,16	-2,16E+6	-25076,47	-2,30E+6	-33550,14	-2,38E+6	-40539,53

$n = 100,\ c = 755,\ \bar{b} = 450,\ bh = 695,\ \pi_0 = 250,\ q_{max} = 300,\ \gamma = 2.5$

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