International Environmental Agreements with Uncertainty, Learning and Risk Aversion

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Abstract

Uncertainty and learning play an important role for the formation of international environmental agreements (IEAs). Scientific uncertainty about climate damages and technological mitigation options is still large despite ongoing research. It has been shown in the strategic context of voluntary participation but strong free-rider incentives that learning may have a negative impact on the success of IEAs. This paper extends the model of Kolstad (2007) and Kolstad and Ulph (2008) by considering risk aversion. This seems suggestive as uncertainties in climate change are highly correlated and hence pooling risks may be limited. It is shown that the negative conclusion with respect to the role of learning derived for risk neutrality has to be qualified.

JEL-Classification: C72, D62, D80, Q54

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1. Introduction

Environmental issues such as climate change pose four key challenges for economic analysis: (i) the process of climate change is effectively irreversible; (ii) there are considerable uncertainties about the likely future costs of both abatement, but more especially environmental damages; (iii) our understanding of these uncertainties changes over time as a result of learning more about climate science, possible technological responses and behavioural responses by households, firms and governments; (iv) the problem is global, but since there is no single global agency to tackle climate change, policies need to be negotiated through international environmental agreements (IEAs).

The first three issues have been studied quite extensively in the context of a single global government, especially whether the possibility of future learning in a problem with uncertainty and irreversibility leads to more or less current abatement.[1] The precautionary principle argues for more current abatement, but the theoretical and empirical analysis is more ambiguous. There has also been an extensive literature on the fourth issue, both theoretical and empirical, but mainly in the context of certainty about the net benefits of tackling climate change.[2] The conclusions have been rather pessimistic, in the sense that while there are substantial benefits to all countries collaborating to tackle climate change, relative to countries acting non-cooperatively, if countries decide independently whether to join an IEA, the relative gains from such an agreement are small.

More recently, these two strands of literature have begun to be integrated. Ulph and Ulph (1996), Ulph and Maddison (1997) compare the fully cooperative and the non-cooperative scenarios when countries face uncertainty about damage costs. They show that the value of learning about damage costs may be negative when countries act non-cooperatively and damage costs are correlated across countries. Na and Shin (1998), Ulph (2004), Kolstad (2007), Kolstad and Ulph (2008, 2009) have considered how the

[1] See, e.g. Arrow and Fisher (1974), Epstein (1980), Kolstad (1996a,b), Gollier, Julien and Treich (2000), Ulph and Ulph (1997) as well as Narain, Fisher and Hanemann (2007).

[2] Classic papers are Barrett (1994), Carraro and Siniscalco (1993) while for instance Finus (2001, 2003) and Barrett (2003) provide surveys of the literature.

prospect of future resolution of uncertainty affects the incentives for countries to join an IEA. Again, the results have been rather pessimistic.

Kolstad and Ulph (2008) consider a model where countries face common uncertainty about the level of environmental damage costs.[3] They consider three scenarios of learning: with *full learning*, uncertainty about damage costs is resolved before countries decide whether or not to join an IEA; with *partial learning*, uncertainty is resolved after countries decide whether or not to join an IEA, but before they choose their emissions levels; with *no learning*, uncertainty is not resolved until countries have decided whether or not to join an IEA and set their emission levels. Kolstad and Ulph (2008) show that the prospect of learning, either full or partial, generally reduces the expected welfare in stable IEAs.

All these models have assumed that countries are risk neutral. However, in the climate context, risks are highly correlated and hence possibilities for risk-sharing are limited so that the assumption of risk aversion may be quite relevant. Endres and Ohl (2003) show in a two-player prisoners' dilemma that risk aversion can increase the prospects of cooperation once it reaches a certain threshold. Bramoullé and Treich (2009) integrate risk aversion in a global emission model that compares the non-cooperative with the fully cooperative solution. They show that equilibrium emissions are lower with uncertainty and this difference increase with the degree of risk aversion as part of a hedging strategy but the effect on global welfare is ambiguous. Boucher and Bramoullé (2010) use the model of Kolstad and Ulph (2008) to analyze the effect of risk aversion on coalition formation as we do in this paper. In contrast to us, they use the expected utility approach whereas we employ the mean-standard deviation approach as explained in more detail below. Our approach is simpler, which allows us to consider also the scenario of partial learning that appears to be particularly relevant in actual treaty-making. Moreover, like in Endres and Ohl (2003), we can capture a regime shift for sufficiently high levels of risk aversion, adding the aspects of coalition formation and various scenarios of learning.

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[3] By common uncertainty we mean that each country faces the same *ex-ante* distribution of possible damage costs, and when uncertainty is fully resolved they face the same *ex-post* level of damage costs, i.e. the risks they face are fully correlated across countries. Kolstad and Ulph (2009) extend this model to consider the case where the risks each country faces are uncorrelated. Uncorrelated uncertainty is also considered in a slightly different model in Finus and Pintassilgo (2009) and empirically investigated in a climate model with twelve world regions in Dellink et al. (2008).

As pointed out above, we capture risk attitudes using the mean-standard deviation (MS) decision criterion, introduced by Markowitz (1952) and Tobin (1958), which is a widely used alternative to the expected utility (EU) criterion for decision-making under uncertainty, introduced by von Neumann and Morgenstern (1944). There have been a large number of studies comparing the relative advantages of each approach, asking under which conditions are they consistent – i.e. they produce the same results. In a path-breaking article Meyers (1987) showed that under a given parameter restriction (LS – location and scale) the two approaches are consistent. This holds in particular if the payoff function is linear on the uncertain parameter, which is the case in our model (see equation 1 below). Saha (1997) argues that, despite the consistency of the two criteria, the MS is generally more flexible in representing alternative risk preferences and is simpler in terms of empirical applications. One main advantage is that it includes explicitly the two moments of the payoffs, as for a large class of preferences they contain all the relevant information of a decision problem under uncertainty. According to Saha, this explains why the MS criterion is so widely used, both in theoretical and empirical studies.

The paper proceeds as follows. In section 2, we set out the theoretical model. We first summarise the benchmark case of certainty and then we move on to introduce the case of uncertainty and risk aversion. In section 3, we present our results and section 4 summarises our main conclusions.

2. The Model

2.1 No Uncertainty

There are N identical countries, indexed $i = 1, ..., N$. Each country produces emissions x_i which we assume can take one of two values: $x_i = 1$ (pollute) or $x_i = 0$ (abate). Aggregate emissions are denoted by $X = \sum_{i=1}^{N} x_i$. Aggregate emissions cause global environmental damages. The cost of environmental damages per unit of global emissions is γ and the benefit per unit of individual emissions is normalized to 1. (Thus, γ essentially measures the cost-benefit ratio.) The payoff to country i is given by

$$\Pi_i(x_i, X) \equiv x_i - \gamma X \quad . \tag{1}$$

In order to make this model interesting, we require that the individual benefit exceeds the individual unit damage cost from pollution, i.e. $1 > \gamma$ (hence countries pollute in the Nash equilibrium) but not the global unit damage cost, i.e. $1 < \gamma N$ (hence countries abate in the social optimum), which together implies:

Assumption 1: $\quad 1/N < \gamma < 1$.

In order to study IEA formation, we shall use the two-stage model of Barrett (1994), borrowed from the literature on cartel formation (d'Aspremont et al. 1983), which is solved backwards. In the second stage, the emission game, for any arbitrary number of IEA members n, $1 \leq n \leq N$, the members of the IEA (which we denote by the symbol *c* for *c*oalition countries) and the remaining countries (which we denote by the symbol *f* for *f*ringe countries) set their emission levels as the outcome of a Nash game between the coalition and the fringe countries. That is, the coalition members together maximize the aggregate payoff to their coalition whereas fringe countries maximize their own payoff. As we assumed $1 > \gamma$, $x_i^f = 1$; coalition members will chose $x_i^c = 0$ provided $1 \leq \gamma n$, and so $\Pi_i^f(n) = 1 - \gamma(N - n)$ and $\Pi_i^c(n) = -\gamma(N - n)$; however if $1 > \gamma n$, then coalition members will also pollute, $x_i^c = 1$ and so $\Pi_i^c(n) = \Pi_i^f(n) = 1 - \gamma N$.[4]

Knowing the payoffs to coalition and fringe countries for any arbitrary number of IEA members, we then determine the equilibrium in the first stage, the membership game, again, as a Nash equilibrium: no coalition country could become better off by defecting from the coalition, and no fringe country could be made better off by joining the coalition:[5]

Internal stability: $$\forall\, i \in C : \Pi_i^c(n) \geq \Pi_i^f(n-1) \tag{2}$$

External stability: $$\forall\, i \notin C : \Pi_i^f(n) > \Pi_i^c(n+1) \quad . \tag{3}$$

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[4] It is now evident why we need Assumption 1: it avoids trivial outcomes where all countries either abate or pollute no matter whether they are coalition members or fringe countries.

[5] Without loss of generality, the strong inequality could be replaced by a weak inequality sign for external stability. Our assumption avoids knife-edge cases where a fringe country is indifferent between staying outside and joining a coalition.

Consider a coalition with n members that abates because $1 \le \gamma n$. Now if one member left the coalition and it still paid the remaining $n-1$ to abate, i.e. $1 \le \gamma(n-1)$, internal stability $\Pi_i^c(n) \ge \Pi_i^f(n-1)$ would require $0-\gamma(N-n) \ge 1-\gamma(N-n+1)$, or equivalently $\gamma \ge 1$, which violates Assumption 1. Hence, we require that it does not pay the remaining countries to abate once a member leaves, i.e. $1 > \gamma(n-1)$, and then internal stability requires $0-\gamma(N-n) \ge 1-\gamma N$ which implies that $n \ge 1/\gamma$. Thus, the internally stable coalition n^* is the smallest integer $I(\gamma)$ no less than $1/\gamma$ which, as can be easily checked, is also externally stable and hence stable. It is straightforward to see that $I(\gamma)$ is a non-increasing function of γ.[6]

Since ex-ante all countries are identical, there is no explicit process for determining which countries get selected as IEA members and which as fringe countries. We shall assume, following Kolstad and Ulph (2008) and Rubio and Ulph (2007) that there is random process for determining which countries become IEA members. Thus, we define the average or expected payoff per country by $\bar{\Pi}_i \equiv \left(n^*/N\right)\Pi_i^c + \left((N-n^*)/N\right)\Pi_i^f$ which is a strictly decreasing function of γ.[7]

Thus, this simple model provides a relationship between the unit damage cost γ and the equilibrium number of coalition members. The equilibrium is a knife-edge equilibrium with n^* countries forming the coalition, which de facto dissolves once a member leaves the coalition as no country would abate anymore. The equilibrium coalition size weakly decreases in the cost-benefit ratio from emissions γ – the larger γ the less countries are needed to make cooperation profitable.

6 Kolstad and Ulph (2008) use the approximation $I(\gamma)=1/\gamma$ which ignores the integer nature of $I(\gamma)$. Then $I(\gamma)$ can be considered a strictly decreasing and convex function of γ. However, as Karp (2009) pointed out, the original function $I(\gamma)$ is neither convex nor concave.

7 Using Π_i^c and Π_i^f from above, noting $n^* = I(\gamma)$, then $\bar{\Pi}_i = 1-\gamma N + I(\gamma)(\gamma - 1/N)$. Consider an infinitesimal variation $\Delta\gamma > 0$, such that $I(\gamma)$ does not change. Then, $\Delta\bar{\Pi}_i = \left(-N + I(\gamma)\right)\Delta\gamma < 0$, $\forall\, I(\gamma) < N$. However, if $\Delta\gamma > 0$ implies $\Delta I(\gamma) < 0$, then $\Delta\bar{\Pi}_i = \left(-N + I(\gamma)\right)\Delta\gamma + \Delta I(\gamma)(\gamma - 1/N) < 0$, which completes the proof. Using the approximation in footnote 6 (ignoring the integer nature of $I(\gamma)$), then $\bar{\Pi}_i$ is a strictly decreasing concave function of γ. See Kolstad and Ulph (2008).

2.2 Uncertainty

Now assume that the unit damage cost of global emissions is uncertain and equal for all countries, both ex-ante and ex-post. We denote the value by γ_s in the state of the world s and hence (1) becomes:

$$\Pi_{i,s}(x_i, X) \equiv x_i - \gamma_s X \ . \qquad (4)$$

For simplicity, we assume that γ_s can take one of two values: low damage costs, γ_l, with probability p, and high damage costs, γ_h with probability $(1-p)$ where $\gamma_l < \gamma_h$ and $0 \le p \le 1$. We denote by $\bar{\gamma} \equiv p\gamma_l + (1-p)\gamma_h$ the expected value of unit damage costs, and by $\sigma(\gamma_s) \equiv (\gamma_h - \gamma_l)\sqrt{p(1-p)}$ the standard deviation of unit damage costs.

To assess how countries evaluate payoffs across states of the world, we assume that each country's attitude to risk can be represented by a mean-standard deviation (MS) utility function, which is the same for all countries:

$$V_i(x_i, X) \equiv E\left[\Pi_i(x_i, X)\right] - \alpha\sigma\left[\Pi_i(x_i, X)\right] \qquad (5)$$

where $\alpha \ge 0$ is the coefficient of risk aversion[8]; i.e. the utility to a country is the expected payoff minus the standard deviation of payoffs weighted by the factor α. $\alpha = 0$ corresponds to risk neutrality.

For later purposes, it will be useful to define:

$$\hat{\gamma} \equiv \bar{\gamma} + \alpha\sigma(\gamma_s) \ge \bar{\gamma} \qquad (6)$$

as the 'risk-adjusted expected unit damage cost'.

While ex-ante countries face uncertainty about the true value of unit damage costs, we want to allow for the possibility that countries may learn information during the course of the game which changes the risk they face. We shall follow Kolstad and Ulph (2008) in considering three very simple scenarios of learning. With *N*o *L*earning (NL) countries make their decisions about membership and emissions with uncertainty about the true value of unit damage costs. With *F*ull *L*earning (FL) countries learn the true value of

[8] We could consider as in Endres and Ohl (2003) that α can be negative if players are risk-loving. However, we discard this possibility in order to keep the discussion as brief as possible: all results for risk-aversion are just reversed for risk-loving.

unit damage costs before they have to take their decisions on membership and emissions. With *P*artial *L*earning (PL) countries learn the true value of damage costs after they have made their membership decisions but before they make their emission decisions. Thus, in this simple analysis, learning takes the form of revealing perfect information.

As in the model without uncertainty, we have to introduce some parameter restrictions. Moreover, the equilibrium size of the coalition can be related to unit damage costs. We define $n_h \equiv I(\gamma_h)$, $n_l \equiv I(\gamma_l)$, $\overline{n} \equiv I(\overline{\gamma})$, $\hat{n} \equiv I(\hat{\gamma})$ and $n_N = N$. It will turn out that stable IEAs will take one of these values. For sensible results, we make the following assumption.

Assumption 2: (i) $1/N < \gamma_l < \overline{\gamma} < \gamma_h < 1$

(ii) $n_h < \overline{n} < n_l \le n_N$.

Assumption 2(i) is essentially Assumption 1 in the context of uncertainty. Assumption 2(ii) basically states that there are differences (at least 1) between the sizes of the stable IEAs under uncertainty. For the theoretical analysis, it is helpful to consider two parameter constellations, which we shall call case 1 and 2.

Cases: (i) Case 1: $\hat{\gamma} < 1 \Rightarrow 0 \le \alpha < (1-\overline{\gamma})/\sigma(\gamma_s)$ and

(ii) Case 2: $\hat{\gamma} \ge 1 \Rightarrow \alpha \ge (1-\overline{\gamma})/\sigma(\gamma_s)$

Case 1 is essentially Assumption 1 in the context of uncertainty; abatement never pays for a single country. However, now we want to allow with case 2 for the possibility that if players are sufficiently risk averse, then even a single player may decide to abate. Note that case 1 includes the case of risk neutrality ($\alpha = 0$). It will turn out that going from case 1 to case 2 leads to a regime shift. From a statistical point of view, it is clear that as long as the degree of risk aversion is sufficiently low, the restriction $\hat{\gamma} < 1$ is not really binding. Only for larger degrees of risk aversion will the likelihood of $\hat{\gamma} \ge 1$ become significant and for large enough levels of α the likelihood of $\hat{\gamma} \ge 1$ may even exceed that of $\hat{\gamma} < 1$.

Note that now with uncertainty the expected utility per country from an *ex-ante* perspective is $\overline{V}_i \equiv (\tilde{n}/N)\overline{V}_i^c + ((N-\tilde{n})/N)\overline{V}_i^f$ where $\tilde{n}$ may take on one of the values mentioned above (i.e. n_h, n_l, $\overline{n}$, $\hat{n}$ or n_N).

3. Results

3.1 Analytical Results

In this sub-section, we generalize the results of Kolstad and Ulph (2008) who assume risk neutrality ($\alpha = 0$).[9] In terms of the risk aversion parameter α, we distinguish between case 1 and case 2 as spelled out in sub-section 2.2. We start with the rather uninteresting case of *F*ull *L*earning (FL). Players know the realization of the damage parameter γ at the outset of the coalition formation game. Thus, results follow directly from what we know from a game with certainty and hence risk aversion does not play a role. However, it has to be pointed out that – even with FL – an evaluation has to take an ex-ante perspective in order to allow for a sensible comparison of coalition sizes and utility levels, across different scenarios of learning, for a given level of risk aversion.

Proposition 1: Full Learning

If state $s = l, h$ has been revealed at the outset, then in the emission game, fringe members always pollute, and coalition members abate if $n \geq n_s = I(\gamma_s)$. In the membership game, the stable IEA has n_s members; the utility to a coalition member is $V_{i,FL}^c(s) = -\gamma_s(N - n_s)$ and to a fringe country it is $V_{i,FL}^f(s) = 1 - \gamma_s(N - n_s)$. Thus, in state s, the expected utility per country is $\overline{V}_{i,FL}(s) = (N - n_s)(1/N - \gamma_s)$. From an ex-ante perspective, the expected size of an IEA is $\overline{n}_{FL} = pn_l + (1-p)n_h$ and the expected utility per country is:

$$\overline{V}_{i,FL} = p\overline{V}_{i,FL}(s = l) + (1-p)\overline{V}_{i,FL}(s = h) = (1 - N\overline{\gamma}) + pn_l(\gamma_l - 1/N) + (1-p)n_h(\gamma_h - 1/N).$$

Hence, risk aversion neither affects the coalition size nor expected utility.

With FL, the outcome in each state *s* in terms of the size of a stable IEA, the utility to coalition and fringe countries and hence the expected utility per country is obviously

[9] Because the proofs of Propositions 3 and 4 are very long, all proofs are available as a technical appendix from the authors upon request.

just the same as in an IEA game where the level of damage costs γ_s is known with certainty. Thus, by taking expectations across the two states of the world, we obtain the expected size of an IEA and the expected utility per country.

Proposition 2: No Learning

Case 1: $\boldsymbol{\hat{\gamma} < 1 \ (0 \le \alpha < (1-\bar{\gamma})/\sigma(\gamma_s) \equiv \hat{\alpha})}$

In the emission game, fringe countries always pollute, while coalition members abate if $n \ge \hat{n}$ *and pollute otherwise. In the membership game, the unique stable IEA has* $n_{NL} = \hat{n} = I(\hat{\gamma})$ *members abating and* $(N-\hat{n})$ *fringe countries polluting, with* $\hat{n} \le \bar{n}$. *The expected utility to a coalition member is* $\bar{V}_{i,NL}^{c} = -\hat{\gamma}(N-\hat{n})$ *and to a fringe country it is* $\bar{V}_{i,NL}^{f} = 1-\hat{\gamma}(N-\hat{n})$ *and hence expected utility per country is* $\bar{V}_{i,NL} = \left(N-\hat{n}\right)\left(1/N-\hat{\gamma}\right)$.

The size of the stable coalition n_{NL} *is weakly decreasing and the expected utility per country is strictly decreasing in the risk aversion parameter* α.

Case 2: $\boldsymbol{\hat{\gamma} \ge 1 \ (\alpha \ge (1-\bar{\gamma})/\sigma(\gamma_s) \equiv \hat{\alpha})}$

In the emission game, all players abate and hence $n_{NL} \in \{1,...,N\}$ *and* $\bar{V}_{i,NL} = 0$ *for all levels of risk aversion above threshold* $\hat{\alpha}$.

With respect to case 1, for $\alpha = 0$, the result displays *certainty equivalence* in the sense that the outcome is the same as would be obtained if countries faced unit damage costs $\bar{\gamma}$ with certainty and no risk. Any mean-preserving increase in risk related to the uncertain damage cost parameter has neither an effect on the expected coalition size nor on expected welfare under risk neutrality. This is different with risk aversion. i.e. $\alpha > 0$ (though $\alpha < \hat{\alpha}$): perceived unit damage cost increase with the degree of risk aversion and since the size of the stable coalition decreases in unit damage costs, risk aversion leads to smaller equilibrium coalitions. Note for *N*o *L*earning (NL), coalition size and expected coalition size are the same.

Also the impact of risk aversion on expected per country utility is negative due to two effects.[10] First for a given coalition, by assumption, expected utility of coalition members and fringe countries decreases in risk aversion, which is the direct effect. Second, expected utility per country decreases in the coalition size and – as just pointed out – risk aversion lowers the equilibrium coalition size, which may be viewed as an indirect effect.

With respect to case 2, if the degree of risk aversion reaches a threshold $\hat{\alpha}$ such that risk-adjusted unit damage cost parameter exceeds 1, $\hat{\gamma} \geq 1$, even for fringe players abatement pays. This may be interpreted as all coalitions being stable or that there is no need for cooperation as even in the non-cooperative equilibrium all players abate.

Taken together, risk-aversion has a negative impact on coalition size and expected per country utility, but once a threshold is reached, this leads to a regime shift with full cooperation.

Proposition 3: Partial Learning

There exists a stable coalition.

Case 1: $\boldsymbol{\hat{\gamma} < 1 \ (0 \leq \alpha < (1-\bar{\gamma}) / \sigma(\gamma_s) \equiv \hat{\alpha})}$

There are two possible stable IEAs: $n^1_{PL} = n_h < n_l = n^2_{PL}$.

(i) *There is a first stable IEA of size* $n^1_{PL} = n_h$ *where coalition members pollute in the low damage cost state and abate in the high damage cost state and fringe countries pollute in both states. The expected utility to coalition and fringe countries is given by:*

$$\bar{V}^c_{PL}(n_h) = -\hat{\gamma}N + p + (1-p)\gamma_h n_h - \alpha[1-\gamma_h n_h]\sqrt{p(1-p)} \text{ and}$$

$$\bar{V}^f_{PL}(n_h) = 1-\bar{\gamma}N + (1-p)\gamma_h n_h + \alpha\sqrt{p(1-p)\left[(\gamma_h-\gamma_l)N-\gamma_h n_h\right]^2}.$$

[10] Note that strictly speaking utility cannot be compared for different degrees of risk aversion. Therefore, this result will only be used later when comparing utility across different scenarios of learning for the same degree of risk aversion.

(ii) *There is a second stable IEA of size $n^2_{PL} = n_l$ in which coalition members abate in both states and fringe countries pollute in both states of the world. The expected utility to coalition and non-coalition countries is given by: $\overline{V}^c_{PL} = -\hat{\gamma}(N - n_l)$ and $\overline{V}^f_{PL} = 1 - \hat{\gamma}(N - n)$.*

(iii) *If the selected IEA has n_{PL} members, then the expected payoff per country is given by:*

$$\overline{V}_{i,PL} = \frac{n_{PL}}{N}\overline{V}^c_{PL}(n_{PL}) + \frac{(N - n_{PL})}{N}\overline{V}^f_{PL,}(n_{PL})$$

(iv) *If $\alpha = 0$, $n^1_{PL} = n_h$ is always an equilibrium whereas $n^2_{PL} = n_l$ is an equilibrium if and only if $p \geq \tilde{p}$ with $\tilde{p} \equiv \dfrac{1 - \gamma_h}{1 - \gamma_h + \varepsilon\gamma_l}$* and $\varepsilon \equiv n_l - 1/\gamma_l$. If equilibrium $n^2_{PL} = n_l$ *exists, it Pareto-dominates $n^1_{PL} = n_h$.*

(v) *If $\alpha > 0$, the likelihood of equilibrium $n^1_{PL} = n_h$ decreases, the likelihood of equilibrium $n^2_{PL} = n_l$ increases and hence the expected coalition size $\overline{n}_{PL}$ increases with the degree of risk aversion. The expected per country utility in each equilibrium decreases with the degree of risk aversion.*

Case 2: $\boldsymbol{\hat{\gamma} \geq 1 \ (\alpha \geq (1 - \overline{\gamma}) / \sigma(\gamma_s) \equiv \hat{\alpha})}$

There are two possible stable IEAs, $n^1_{PL} = n_h < n_N = n^2_{PL}$.

There may be a first equilibrium $n^1_{PL} = n_h$ with the features as described under (i) above. There is a second equilibrium, the grand coalition, $n^2_{PL} = n_N = N$, which is always an equilibrium: all countries abate and hence the expected utility per country is $\overline{V}_{PL} = 0$. The second equilibrium Pareto-dominates the first equilibrium and hence the expected coalition size is $\overline{n}_{PL} = N$.

As it appears from the results above, *P*artial *L*earning (PL) is the most complicated of the three learning scenarios. In the second stage, the emission game, the value of the damage parameter γ is revealed to the players. Hence, the emission game is like the game under FL. Importantly, and very different from NL, this implies that fringe players or single players never abate, regardless of the degree of risk aversion. Thus, the grand coalition in case 2 comes only about due to the membership game where decisions – different from FL – have to be based on expected utility. Since the grand coalition always Pareto-dominates the smaller equilibrium coalition, it seems obvious to expect full cooperation as the outcome in case 2.

In case 1, the prospects for cooperation are less bright. There are again two equilibria where the second and larger equilibrium typically Pareto-dominates the first equilibrium, though the second equilibrium does not always exists. In particular for no risk aversion, the probability of the larger second equilibrium is very low. This is evident from the definition of the threshold $\tilde{p}$ and ε, recalling that n_l is the integer value of $1/\gamma_l$ and hence ε tends to be very small. Consequently, $\tilde{p}$ is close to 1. Hence, only if the probability of the low damage cost p is close to 1 will the larger second equilibrium, $n_{PL}^2 = n_l$, materialize. This would normally be regarded as an uninteresting parameter constellation. However, once we depart from the benchmark $\alpha = 0$, with increasing α, the likelihood of $n_{PL}^2 = n_l$ increases even for values of p significantly lower than 1.

Finally, part (v) of Proposition 3 suggests in case 1 that like NL, for PL expected per country utility decreases with risk-aversion in each equilibrium, n_h and n_l.[11] This is the direct negative effect which risk has on expected per country utility. Since risk increases the likelihood of the large second equilibrium $n_{PL}^2 = n_l$, with typically higher expected per country utility than the smaller equilibrium $n_{PL}^1 = n_h$, the overall impact of risk on expected utility cannot be theoretically deduced. The simulation runs on which we report in the next sub-section show that the overall impact is negative.

We now compare the outcomes in terms of expected size of the IEA and expected utility per country across the three models of learning. In order to benchmark this with previous results, we consider under case 1 the special case of $\alpha = 0$.

Proposition 4: Comparison of Outcomes under the Three Scenarios of Learning

Case 1: $\hat{\gamma} < 1$ $(0 \le \alpha < (1-\bar{\gamma}) / \sigma(\gamma_s) \equiv \hat{\alpha})$

a) $\alpha = 0$

(i) $n_{PL}^1 = n_h < n_{NL} = \bar{n} < n_{PL}^2 = n_l$

[11] The same qualification as mentioned in footnote 9 applies.

(ii) $n^1_{PL} = n_h < \overline{n}_{FL} < n^2_{PL} = n_l$

(iii) $\overline{n}_{FL} \geq n_{NL} - 1$

(iv) $\overline{V}_{i,PL}(n_h) < \overline{V}_{i,NL}(\overline{n}) < \overline{V}_{i,PL}(n_l)$

(v) $\overline{V}_{i,PL}(n_h) < \overline{V}_{i,FL} < \overline{V}_{i,PL}(n_l)$

b) $\boldsymbol{\alpha > 0}$

(i) *There is a threshold of* α *above which* $\overline{n}_{FL} \geq n_{NL} = \hat{n}$.

(ii) $n^1_{PL} = n_h < n_l = n^2_{PL}$ *always holds. Moreover, there is a threshold of* α *above which* $n^1_{PL} = n_h \geq n_{NL} = \hat{n}$ *and hence,* $n^{min}_{PL} = \left\{ n^1_{PL}, n^2_{PL} \right\} \geq n_{NL}$.

(iii) *There is a threshold of* α *above which* $\overline{n}_{PL} \geq \overline{n}_{FL}$.

(iv) *There is a threshold of* α *above which* $\overline{V}_{i,FL} \geq \overline{V}_{i,NL}(\hat{n})$.

(v) $\overline{V}_{i,FL} \geq \overline{V}_{i,PL}(n_h)$ *always holds. Moreover, there is a threshold of* α *above which* $\overline{V}_{i,FL} \geq \overline{V}_{i,PL}(n_l)$ *and hence* $\overline{V}_{i,FL} \geq \overline{V}_{i,PL}(n^*_{PL})$ *where* $\overline{V}_{i,PL}(n^*_{PL}) = max\left\{ \overline{V}_{i,PL}(n^1_{PL}), \overline{V}_{i,PL}(n^2_{PL}) \right\}$.

(vi) $\overline{V}_{i,PL}(n_l) > \overline{V}_{i,NL}(\hat{n})$.

Case 2: $\boldsymbol{\hat{\gamma} \geq 1 \ (\alpha \geq (1 - \overline{\gamma}) / \sigma(\gamma_s) \equiv \hat{\alpha})}$

(i) $n_{PL} = n_{NL} = N > n_{FL}$

(ii) $\overline{V}_{i,PL}(N) = \overline{V}_{i,NL} > \overline{V}_{i,FL}$

In a first step, we focus on the main results for risk-neutrality (Case 1, a)). The low membership equilibrium for PL (which is always an equilibrium; see Proposition 3) has lower membership and expected utility than either NL or FL, and the opposite holds for the high membership equilibrium for PL. However, we may recall that the high membership equilibrium for PL is only an equilibrium if $p \geq \tilde{p}$ which is very unlikely.

Karp (2012) has shown that there is no general ranking of the outcomes for NL and FL that applies to any possible set of parameter values, though it is possible to exclude the outcome where FL has both smaller expected membership and higher expected utility than NL. However, for any parameter values for which the approximation in footnote 6 holds, it would be the case that FL resulted in at least as great expected membership and at least as low expected utility as with NL (see Kolstad and Ulph 2008).

In summary, with risk neutrality, if we view the parameter values $p \geq \tilde{p}$ generating $n^2_{PL} = n_l$ as being rather uninteresting (i.e. we are interested in cases where the risk of high damage costs is quite significant), then we conclude that PL yields a lower expected coalition size and utility than either NL or FL, while for the approximation in footnote 6 FL also yields lower expected utility than NL. In other words, in terms of membership, we typically expect the ranking FL>NL>PL and in terms of expected per country utility the ranking NL>FL>PL. Since the size of an agreement as such is of less importance than the welfare implication, the major conclusion from previous work is that learning can be bad in a strategic context of coalition formation.

In a second step, we consider what changes with risk-aversion, assuming that the risk-adjusted damage cost parameter is below 1 and hence no regime shift occurs (Case 1, b) in Proposition 4). Consider first membership. From Propositions 1 and 2 we know that the size of the coalition is not affected by risk aversion under FL and decreases in α under NL. From Proposition 3 we know that the coalition sizes in the two possible equilibria are unaffected by risk aversion under PL, though the likelihood of the larger equilibrium increases and the likelihood of the smaller equilibrium decreases and hence the expected coalition size increases with risk aversion. Consequently, it follows immediately, that above a threshold of risk aversion, the ranking FL>NL is always true (Case 1, b), result (i)), PL>NL with respect to the small PL-equilibrium $n^l_{PL} = n_h$ and hence with respect to any PL-equilibria (Case 1, b), result (ii)) and PL>FL holds in terms of expected membership (Case 1, b), result (iii)). Thus, increasing levels of risk aversion clearly changes the ranking in terms of membership, giving PL and FL an advantage over NL.

In terms of expected utility, we know risk aversion has not impact for FL (Proposition 1), but a negative impact for NL (Proposition 2) and on each of the two equilibria for PL (Proposition 3). Consequently, above a threshold of risk aversion, this leads to the ranking FL>NL (Case 1, b), result (iv)), FL>PL in terms of the larger PL-equilibrium and hence also if we pick the Pareto-superior PL-equilibrium in case there are two (Case

1, b), results (v)). That, is FL improves compared to NL with increasing risk aversion continuously, and is certainly superior to PL above a certain threshold. Only the relation between PL and NL is less straightforward because both are negatively influenced by risk aversion. According to result Case 1, b), (vi), the ranking established for risk neutrality for the large PL-equilibrium, $n_{PL}^{2} = n_l$, namely, PL>NL, remains valid but for the small PL-equilibrium, $n_{PL}^{1} = n_h$, NL>PL may or may not be true. Hence, overall conclusions are difficult, though our simulations in the next sub-section show that with increasing risk aversion PL>NL eventually. Hence, the main message to take away here is that the more players are risk averse, the more they learn the better it is. Putting it simply, learning is good if players are risk-averse.

Finally, in a third step, we address the possibility of a regime shift (Case 2). Above a threshold of α which leads to $\hat{\gamma} \geq 1$, NL and PL achieve the socially optimal outcome whereas this is not the case under FL. Thus, the main conclusion from step 2 above, namely that learning is good for expected utility the more risk averse players are, is now reversed once a threshold of risk-aversion has been passed. In other words, learning can be bad in a strategic context of coalition formation above a threshold of risk aversion, very much like the result obtained for risk neutrality.

3.2 Simulation Results

In this section, we present some simulation results. The Appendix describes how we conducted the Monte Carlo simulations. In a first step, we look at those few issues for which we could not establish analytical results. In a second step, we present some results which compactly summarize the overall conclusion of our paper, relating it to the question about the likelihood of case 1 and 2.

Step 1

Proposition 3 argued that, in case 1, risk aversion has a negative impact on expected per country utility in each of the two coalition equilibria under PL, but that the likelihood of the larger equilibrium with higher expected utility increases with risk aversion. Hence, it was not clear how expected utility changes with risk aversion, assuming that in case of multiple equilibria, the Pareto-superior is chosen. Table 1, column PL, shows that the overall effect of increasing risk aversion is negative.

Proposition 4 argued that, in case 1, it is not obvious how the relative ranking in terms of expected utility between PL and NL is affected by increasing risk aversion. Table 1, column PL and NL confirms that for risk neutrality NL>PL on average. However, with increasing risk aversion, this ranking is reversed.

Step 2

The analytical results distinguished between case 1 and 2. Now we ask the question how likely these cases are and what this means for overall conclusion. Table 2 illustrates that the likelihood of case 1 constantly decreases with the degree of risk aversion and the opposite is true for case 2. Hence, under PL, the relative coalition size constantly increases with risk aversion (Table 3). First because in case 1 the likelihood of the large equilibrium increases and the likelihood of the small equilibrium decreases. Second because the likelihood of case 2 increases compared to case 1, with the grand coalition being the outcome in case 2 with a regime shift. Under NL, the relative coalition size first decreases and then increases (Table 3). With increasing risk aversion, Proposition 2 showed that the coalition size decreases in case 1. However, with increasing risk aversion also the likelihood of case 2 increases with the outcome that the grand coalition forms when there is a regime shift.

In terms of expected utility, a similar pattern can be observed (Table 3). It decreases under PL and NL first because risk has a negative impact on expected utility but this is reversed for very high levels of risk aversion because the proportion of cases in which the grand coalition forms approaches finally 100%.

4. Summary and Conclusions

Kolstad and Ulph (2008) showed that with risk neutrality the possibility of learning more information about environmental damage costs in the future generally had rather pessimistic implications for the formation of IEAs. Except for a relatively small set of parameter values for which partial learning would select a high IEA membership, learning resulted in lower expected membership for partial learning and lower expected utility for both full and partial learning. Hence, in a strategic context, learning reduces expected utility for a wide range of parameter values.

This result was qualified if we take risk aversion into account. As risk aversion increases, full and partial learning improve their ranking compared to no learning in terms of the size of stable coalitions and in terms of expected utility. However, above a threshold of risk aversion, there is a regime shift, which leads to full cooperation under partial and no learning.

In terms of the role of learning, the conclusions from previous papers (e.g. Kolstad 2007, Kolstad and Ulph 2008 and Na and Shin 1998) that learning is usually bad in a strategic context of environmental treaty formation is reversed for risk aversion below some threshold, but confirmed above this threshold. In terms of the role of regime shift, the conclusion from Endres and Ohl (2003) that in a world without full information if risk aversion passes some threshold, this can have a positive impact on the success of environmental treaties is confirmed. We can show that this does not only hold for no but also partial learning and extends to an N-country prisoners' dilemma with coalition formation. However, different from them, in our model below the threshold, increasing levels of risk aversion makes things worse. This is certainly an important aspect; it suggest that the climate change problem cannot simply be solved by making governments more aware that they should be more risk averse in order to avoid disasterous climate change. As long as governments are not extremely risk averse, investment in gaining more information appears to be a more successful strategy.

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Appendix: Description of the Monte Carlo Simulations

i) The total number of simulations is chosen; 100,000 in all reported results.

ii) The level of risk aversion α is chosen, $\alpha \in \{0,0.5,1,2,5,10,100,1000,10000\}$, though not all values are reported here.

iii) For each simulation, the number of players N is generated from a discrete uniform distribution over the set {4, … , 200}.

iv) The inverse of the expected damage cost, $1/\bar{\gamma}$, is generated from a continuous uniform distribution in the range $[3, N-1]$.

v) The inverse of the high damage cost, $1/\gamma_h$, is generated from a continuous uniform distribution in the range $[2, 1/\bar{\gamma}-1]$. This ensures that $2 \le n_h \le \bar{n}-1$.

vi) The inverse of the low damage cost, $1/\gamma_l$, is generated from a continuous uniform distribution in the range $[1/\bar{\gamma}+1, N]$. This ensures that $\bar{n}+1 \le n_l \le N$.

vii) We obtain the probability of low damages from solving $p = (\gamma_h - \bar{\gamma})/(\gamma_h - \gamma_l)$. and hence get: $\hat{\gamma} = \bar{\gamma} + \alpha(\gamma_h - \gamma_l)\sqrt{p(1-p)}$.

viii) In case 1, with restriction of $\hat{\gamma}$, if $\hat{\gamma} \ge 1 \Leftrightarrow \alpha \ge (1-\bar{\gamma})/\sigma(\gamma_s) \equiv \hat{\alpha}$, then go back to step (iii), otherwise go to the next step. Without restriction of $\hat{\gamma}$, go to the next step.

ix) The coalition sizes and expected utility follow from the equations presented in section 3. In the case of multiple equilibria under partial learning the Pareto-superior equilibrium is chosen.

All numbers have been rounded to the third digit. Small differences across entries in different tables where same numbers should be expected are due to different simulation runs.

Tables

Table 1: Expected Utility in the Three Learning Scenarios in Case 1

α	FL	PL	NL
0	-2.092	-2.237	-1.977
0.5	-2.092	-3.317	-3.134
1	-2.092	-4.306	-4.329
5	-2.092	-10.145	-11.982
10	-2.092	-13.607	-17.548
100	-2.092	-17.149	-48.004

Table 2: Probability of Risk-adjusted Damage Parameter to be Larger or Smaller than 1

α	$\hat{\gamma} < 1$	$\hat{\gamma} \geq 1$
0	1	0
0.5	1	0
1	1	0
5	0.968	0.033
10	0.877	0.123
100	0.424	0.576
1000	0.051	0.949
10000	0	1

Table 3: Expected Relative Coalition Size and Utility in the Three Learning Scenarios without Restriction on $\hat{\gamma}$ *

α	$\frac{n_{FL}}{N}$	$\frac{n_{PL}}{N}$	$\frac{n_{NL}}{N}$	FL	PL	NL
0	0.646	0.309	0.531	-2.092	-2.237	-1.977
0.5	0.646	0.387	0.437	-2.092	-3.317	-3.134
1	0.646	0.442	0.379	-2.092	-4.306	-4.329
5	0.646	0.538	0.239	-2.092	-9.796	-11.572
10	0.645	0.606	0.257	-2.092	-11.863	-15.328
100	0.645	0.894	0.598	-2.092	-7.348	-20.456
1000	0.645	0.996	0.952	-2.092	-0.428	-4.407
10000	0.645	1	1	-2.092	-0.001	-0.038

In case of two equilibria under PL, the Pareto-superior is chosen.