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Reply to comment

Climate governance as a complex adaptive system
Reply to comments on "Climate change governance, cooperation and self-organization"

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Mark Buchanan recently wrote that "*Physics is not only about Physics anymore*" [1]. We believe that the subject of our review provides a clear manifestation of this statement, and testifies for the possibility of using methods developed in the realm of theoretical physics to address problems that lie far beyond what conventional Physics thinking would conceive. It is thus rewarding (and we feel very honored) to have our manuscript commented by renowned scientists from a variety of fields.

One of the greatest legacies of Physics, which stands at the core of its enormous success as a scientific discipline, is associated with the tight interplay between theory and experiment. These often develop in parallel when investigating natural phenomena, mutually guiding each other in advancing our knowledge of them. While theoretical Physicists typically develop simple models that aim at describing, accurately, what they believe are key features of the system under study, experimental Physicists more often than not stretch our imagination and perform controlled experiments whose results are amenable to be reproduced again and again.

The problem that we address in our paper — how to cooperate in order to avoid the adverse effects of Global Warming — reveals a different stance. As Astrid Dannenberg writes [2], global warming is probably the greatest collective action problem mankind has ever faced, the "game we cannot afford to loose" [3], as Manfred Milinski quotes [4]. And yet, the theoretical and experimental tools devised to date are of limited scope. Experiments here translate into behavioral experiments, which are much more difficult to control (and thus reproduce) than, say, to cool a bunch of atoms below 10^{-9} kelvin [5]. The intrinsic complexity of the problem means that theoretical models must "*overlook*" (or "*average out*") many aspects of this complexity, focusing on the "*order parameters*" that may provide

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the clearest signal. But precisely because of this, and similar to conventional Physics problems, theory and experiment should develop hand-in-hand, guiding each-other. Here, like with the problem we address, what we want is the total to be more than the sum of its parts.

We started to develop a simple model to investigate the feasibility of achieving global cooperation in the problem of Global Warming [6,7]. At its core, our model is able to reproduce the impressive results captured in the behavioral experiments carried out both by Milinski and co-workers [8] and also by Tavoni and Dannenberg [9]: risk plays a key role in driving cooperation. At this level, theory and experiment agree, at least qualitatively.

However, as we complement our model with new features, experiments become increasingly difficult to devise. Our predictions, as pointed out by Tavoni [10] and Dannenberg [2], that local pockets of cooperation (either spontaneously formed or locally enforced) can have a catalyzing effect leading to widespread cooperation, do provide, indeed, an optimistic view which, as Milinski writes, needs "*a reality check*" to "*show whether the optimistic view is supported and whether it can help humankind to win the game*" [4]. Provocative as they may be [7], we believe that our predictions have caught the attention (and hopefully challenged) some of the experts in the field of behavioral experiments. We certainly need a lot of ingenuity to advance in this field, where time is limited.

An important feature of our evolutionary game theory approach, as pointed out by Tavoni [10] and also by Szolnoki [11], is that the model framework naturally admits the embedding of the population in a (network) structure. Our predictions state that network heterogeneity provides an additional contribution towards widespread cooperation, but the challenge posed by Szolnoki [11] is tantalizing: To which extent can interdependent networks [12,13], combined with reactive strategies [14], help coordination into global cooperation? This question is particularly relevant if one conceives an interconnected system involving multiple agreements or institutions [15]. But much can be investigated. Is there a mechanism to overcome the uncertainty about future catastrophes [6,16–18]? How is it that *i*) the diversity of the environmental resources managed, together with *ii*) the world's patent wealth inequality and *iii*) diversity of roles played by different countries [9,19,20] may influence the fate of this complex (adaptive) system [21,22]? These are important questions whose answer can be sought by extending the present model. We are doing our part, but we are very excited with the possibility that more scientists may be attracted to such an important problem by the bold simplicity of our original model. Future will tell.

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