Multilevel Governance and Risk Diversification*

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Abstract

In this paper we study decisionmaking concerning risks. We investigate the circumstances under which a centralized or decentralized decisionmaking process concerning risk regulation is most desirable. While the topic of federalism has been variously analyzed by previous studies, the relative desirability of different levels of governance in the specific field of risk law has escaped scholarly attention. Our paper contributes to previous literature by showing how the decision about the level of governance can function as a risk management strategy. In particular we focus on two idiosyncratic features of risk regulation: the role of experts committees in the decisionmaking process and the nature of the regulated object, i.e. risk. We thereby build a model that allows us to study the optimal level of governance for risk law, which builds on and integrates the Condorcet Jury Theorem (CJT) and portfolio theories. To assess the relative desirability of (de-)centralization, the model relies on two parameters: expected returns and risk diversification. Further, we identify three typologies of risks, namely weakest-link risks, best-shot risks and independent risks; relying on the mentioned parameters we compare the cases under which centralization is superior to decentralization and vice versa. We conclude by discussing the relevance of our results for policymaking.

Keywords: globalization, risk, decentralization, harmonization, Condorcet Jury Theorem
JEL classification: D72, D74, F02, K34..

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1 Introduction

The discourse on risk regulation has largely focused on the tragic trade-offs between levels of safety and technological developments; in other words, on how much risk regulation is needed, an undoubtedly crucial issue for contemporary industrial societies. Little attention, however, has been paid to the question of which level of governance in the specific context of risk regulation may be most desirable in welfare terms.

This paper aims at filling this gap by studying the optimal levels of governance in the specific field of risk law–environmental, health and safety regulation. It accordingly singles out the issues idiosyncratic to risk law and identifies the circumstances under which it is more desirable to rely on a centralized or decentralized decisionmaking process. Our analysis offers the insight that decentralization, implying the possibility that different jurisdictions take different decisions, works as a risk-diversification device, thereby limiting society's exposure to risk. We discuss the validity of our argument in the light of a possible disadvantage of decentralization: decentralization may adversely impact the quality of the decisions as resources devoted to decisionmaking are dispersed in several independent agencies instead of being concentrated in a single one. To make our point stronger, we consider the case in which this effect is most relevant and later discuss reasons why this may not be the case when there are some inherent informational advantages in going local.

We frame the problem as follows. We begin by postulating that there is a "right" decision, one that most benefits society. For some issues, mankind share a common goal. In these cases, the decision that better serves such common goal can be readily defined as the right one. This framework is subject to two important qualifications. On the one hand, the right decision is generally not known ex ante; this is the problem we address in this paper. On the other hand, even ex post, when all relevant information becomes known, the definition of the right decision might be problematic, because individuals may differ in their goals. In such instances, unanimous consent cannot be reached. Consequently, the definition of the right decision necessarily rests on a previous choice of a social welfare function that aggregates individual preferences. This is a well-known problem in welfare economics, which we do not address here. Thereby, our analysis rests on the assumption that society's goal has been set.[1]

Most decisions concerning the environment, health and safety are based on the work of expert committees. For instance, in Europe the approval of genetically modified organisms (GMO) greatly relies on the opinion of the GMO Panel within the European Food and Safety Authority (EFSA). Such committees of experts are called upon because they possess better information than laymen and politicians and are more likely to pick the right decision. We model the quality of available expertise as an expert's probability to pick the right decision and the resources invested in the decisionmaking process as the total

[1] Miller (1986) tackles this problem by considering as correct the alternative that would receive a majority of votes ex post, when all information is available. See also Ladha (1992, p. 620).

number of experts. Given these two parameters, the question is whether experts should be pooled together in a centralized regulatory agency taking global decisions or spread in several independent agencies with local jurisdiction. We ask this question in the face of two potentially conflicting aspects of the decisionmaking process at different levels of governance: its accuracy versus its riskiness.[2]

Using a well-known result–the *Condorcet Jury Theorem*–we show that agencies with more experts are more accurate than agencies with fewer experts. Thus, centralization has an advantage over decentralization in that, by pooling experts together, entrusts decisions to a global agency of larger size than any of the regional agencies; hence, centralization yields the right decision more often than decentralization. In contrast, using insights from portfolio theory, we argue that decentralizing decisions allows for risk diversification, thus casting a vote for decentralization. It might be objected that a centralized agency may also diversify its decisions, for instance, by allowing a product in some regions and banning it in others in order to diversify risk. This solution might however encounter political opposition as, in fact, it implies exposing a portion of the population to a choice that is known to be less likely to be right than its alternative. We do not deny that this route might in some cases be feasible but rather focus on a different means to achieve risk diversification, namely, decentralization.

In the analysis, we first focus on approval, yes-or-no decisions, such as those concerning the marketing of specific GMOs. We analyze different risk scenarios. First, we consider *independent risks*, such as local pollution problems, where local policies are not affected by each other and, hence, the global outcome is simply a weighted average of the local outcomes. In this case, failure or success are purely local and there are no externalities between different regions. The analysis shows that the choice between centralization and decentralization crucially depends on the level of scientific expertise available. If advanced expertise is available, centralization guarantees both more accurate decisions and less risk. Decentralization only becomes desirable with poor expertise, if the degree of risk aversion is sufficiently large. The number of available experts affects this balance by lowering the critical threshold for the expertise and making centralization desirable at lower levels of expertise.

Further, we test these results in the case of *interdependent risks*, considering three different cases. With weakest-link risks, such as the risk of a viral epidemic, local policies are strict complements for the achievement of the global policy and, hence, local failure results in global failure.[3] In the opposite situation of best-shot risks, such as the risk that an endangered species will become extinct, local policies are perfect substitutes in the achievement of the global policy and, thus, success at the local level results in success at the global level. In the intermediate case, which we call majority risks, success or failure result depending on what the majority of the local agencies decide. In each of these cases, we will examine

[2] In the analysis, we disregard strategic aspects of the decisionmaking process. We comment on how our results could be affected by them in section ___.

[3] This case is similar to the collapse of bank loan re-payment systems. quote____

the determinants of the decisions concerning the optimal level of governance.

The paper is organized as follows. After making reference to other strands of literature discussing questions similar to ours, in section 2 we present a formal model of approval decisions. We tackle the question *whether* the decisionmaking should be centralized or completely decentralized. In section 3, we ask *how much* decentralization is desirable, allowing for intermediate levels of decentralization between the two extremes of centralized and completely decentralized decisionmaking. In section 4 we extend the model in several directions. Most notably, we provide a framework for the analysis of decisions concerning standards, where the choice is not of a yes-or-no type but rather over a continuum. This part can be also seen as an extension of the Condorcet Jury Theorem to the case of choices over a continuum. We further relax several assumptions of the model, examining the robustness of our results. In section 5, we discuss several applications of the model, its limits, and its implications for global governance. In section 6, we show that there exists a body of law governing risks at a global level and how our theory applies to it. In section 7, we conclude.

1.1 Related literature

To be added___

2 The basic model of approval decisions

In this section, we introduce a model of approval decisions, where we analyze binary yes-or-no decisions, such as the decision whether to ban an allegedly hazardous product. The wrong decision–banning a product that should not be banned or failing to ban a product that should be banned–yields a (normalized) payoff equal to zero, while the right decision–banning or failing to ban appropriately–yields a payoff of $G > 0$.[4] Such payoffs are aggregate ones, referring to the global effects of decisions on a planetary scale. The question we address is whether those decisions should be taken at a centralized level by one regulatory agency with global jurisdiction over the entire planet or at a decentralized level by N different agencies, each having local jurisdiction in one of N (identical) regions in which the planet is divided. It is instructive to begin by posing the problem in such dichotomous terms; in section 3, we will account for intermediate levels of decentralization.

Lack of information prevents society from taking good decisions all of the time. This gives rise to two different problems. One is to maximize the expected return to the decision; the other is to reduce the risk due to the variance of the outcome. This trade-off can be expressed by the following simple formulation of society's welfare: $W = R - \alpha V$, where R is the expected return of a decision, V is its variance, and the risk-aversion index $\alpha > 0$ measures society's willing-

[4] This formulation is equivalent to assuming that type I and type II errors occur with the same probability and trigger the same costs.

ness to accept lower returns in exchange for less risk.[5] The balance between expected returns and riskiness of decisions will be shown to depend on the level of governance at which those decisions are taken.

Regulatory agencies rely on the opinion of committees of experts. For the purpose of the analysis, we assume that agencies always follow the advice of their committees and, hence, we use the words committee and agency interchangeably. Reliance on expert committees is justified by the technical nature of the decisions. Laymen and politicians do not possess the necessary knowledge to come to an assessment: their choices would be a 50% guess. However, as it is often the case, the state of the art is such that not even experts are able to pick the right outcome with certainty. Each expert $i \in \{1, \ldots, N\}$ identifies the good decision with a probability $p_i = p > 50\%$, which indicates the quality of the scientific knowledge available and suggests that experts have identical expertise.[6] The number N of available experts is a resource constraint imposed on the decisionmaking process.[7]

Within an agency, decisions are taken by a simple majority rule,[8] where individual experts vote independently of each other.[9] Accordingly, the probability $P_n(p)$ that a committee of n experts with expertise p takes the good decision can be calculated as follows:[10]

$$P_n(p) = \sum_{i=\frac{n+1}{2}}^{n} \binom{n}{i} p^i (1-p)^{n-i}$$

where the right-hand side is simply the probability that more than half of the experts vote for the right decision, given the probability p that an expert votes for the right decision and the probability $(1-p)$ that an expert votes

[5] Issues of fairness and distribution will be discussed in section ___.

[6] The assumption that $p > 50\%$ is justified by the observation that, if experts were correct in less than 50% of the cases, society would be better-off taking a random pick rather than delegating the decision to them. See Owen, Grofman and Feld (1983) for the case of heterogeneous expertise.

[7] The Moore-Shannon theorem shows that by using a sufficiently large number of components a system can be designed in such a way that it is perfecly reliable. This result carries over to our framework suggesting that with a sufficiently large number of experts, global governance could be designed to always achieve the right decision. The problem becomes interesting precisely when the number of experts is limited or else when resources devoted to taking decisions are taken away from other valuable tasks and hence will not be unlimited. See Sah (1991, p. 68) on this issue. Later on in the analysis we discuss what effect relaxing the resource constraint has on our results.

[8] Note that, under our assumptions, the simple majority rule is the optimal committee decision rule (Nitzan and Paroush, 1984). That simple majority is optimal means that $P_n(p)$ is maximized by the simple majority rule. Qualified majority rules emerge as efficient when there is a status quo bias, which is absent in our model. Ben-Yashar and Nitzan (1997) employ a setting in which expertise, payoffs, and priors depend on the state of nature. Fey (2003) employs a framework in which three outcomes are possible (instead of two as usual): the status quo and two alternative options.

[9] LIT on dependent decisions___

[10] This formulation refers to n odd. If n is even, there is an easy transformation rule to bring the analysis back to n odd: $P_n(p) = P_{n-1}(p)$ (Miller, 1996, p. 175). The same applies to other variables used in the analysis.

for the wrong one. The standard result, known as *Condorcet Jury Theorem* (Miller, 1986),[11] henceforth CJT, is that $P_n(p) > p$, that is, the probability that a committee takes the good decision is greater than the probability that a single expert takes the good decision. From the CJT it also follows that $P_n(p)$ increases at a decreasing rate both in n and in p and asymptotically approaches 1 as n grows to infinity or p approaches 1. This means that the agency's decision improves if more resources are devoted to the decisionmaking process, in terms of number of experts n, or if their expertise p improves.

2.1 The benchmark case: centralization

When decisionmaking is centralized, all of the N experts are pooled together in one agency. The probability that they take the right decision is $P_N(p)$, which is as good as it gets, given N and p. The expected return and the variance of centralized decisions are easily calculated as follows:

$$\begin{aligned} R_1 &= P_N(p)\,G \\ V_1 &= P_N(p)\,(1 - P_N(p))\,G^2 \end{aligned}$$

The optimal level of governance depends on the variables introduced so far and on the nature of the risks involved. The latter issue does not play a role in centralized decisionmaking but becomes important when discussing decentralization. It is instructive first to discuss the case of independent risks and then analyze risks that are dependent on each other. Risks are said to be independent when a decision taken by a regional agency has no impact on other regions. Risks are interdependent if the opposite holds true. Note, however, that local outcomes may be dependent on each other also for another reason; even if risks are independent, local agencies might influence each other's decisions and hence the outcomes will be correlated. We will examine this type of dependency due to mutual influence later on. For now, let us keep the assumption that agencies decide independently.

2.2 Decentralization with independent risks

Decentralized decisionmaking employs N agencies consisting of one expert each. In this scenario, the probability that the agency takes the right decision is trivially the same as the probability that the expert decides correctly, $P_1(p) = p$. Because local outcomes are independent of each other, expected return and variance of the decision are simple sums over the N local expected returns and variances. Moreover, since each region is $\frac{1}{N}$ of the planet, the local payoff $\frac{G}{N}$. Accordingly, expected return and variance are as follows:[12]

[11] See also Black (1958), NOTE ON USE OF CJT IN THE L&E LIT. . . . Berend and Sapir (2005).

[12] The formulas in the text follow from simplifying the following expressions: $R_N = \sum_{j=1}^{N} P_1(p)\frac{G}{N}$ and $V_N = \sum_{j=1}^{N}\left[P_1(p)\left(\frac{G}{N} - \frac{R_N}{N}\right)^2 + (1 - P_1(p))\left(0 - \frac{R_N}{N}\right)^2\right]$.

$$
\begin{aligned}
R_N &= pG \\
V_N &= \frac{1}{N} p\,(1-p)\,G^2
\end{aligned}
$$

Centralization has a clear advantage over decentralization: it yields larger expected returns ($R_1 > R_N$) since decisions are more accurate. This is true for any level of expertise but is more pronounced for interior values of p. In fact, when p approaches $\frac{1}{2}$ (complete lack of expertise) or 1 (very accurate expertise), $P_N(p)$ approaches p and hence the returns to centralized and decentralized decisions are the same.

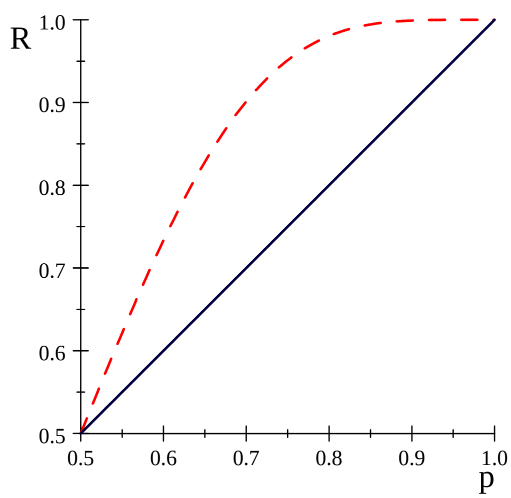

Figure 2.2: Expected returns of decisions under centralization (dashed line) versus decentralization (solid line) with $N = 9$ and $G = 1$.

With respect to risk, however, there are two countervailing effects. On the one hand centralized decisions are more tightly clustered around the right decision than decentralized ones, to the effect that the variance tends to be lower under centralization. On the other hand, the outcome is the same for all regions in centralized decisionmaking while may vary under decentralization, realizing a spreading of the risk, which in turn makes for lower variance under decentralization. Which of these two effects prevails depends on N and p.

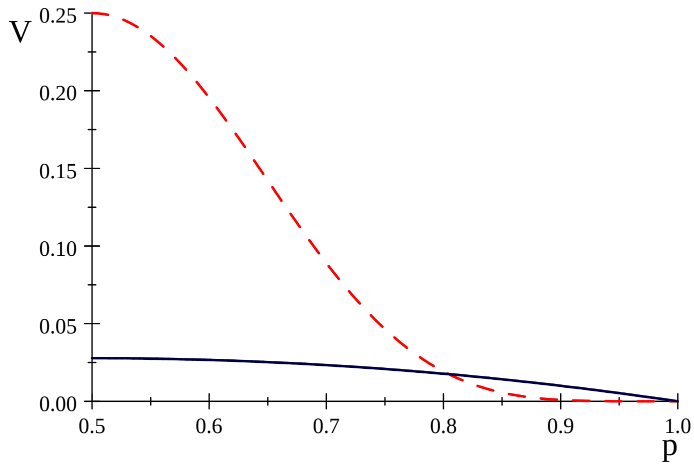

Figure 2.2: Variance of decisions under centralization (dashed line) versus decentralization (solid line) with $N = 9$ and $G = 1$.

Figure 2.2 depicts the variance of decisions when there are 9 experts. With decentralization the variance is hill-shaped, while centralized decisionmaking yields a bell-shaped function (in the appendix we show that this is true for any N). The figure only depicts the halves of those functions that apply to our setting ($p > \frac{1}{2}$). There is a level of expertise $\hat{p}$ at which the curves cross ($\hat{p}$ is about 0.8 in the figure). When the available expertise is poor ($p < \hat{p}$), decentralization attains a lower variance; in contrast, with advanced expertise ($p > \hat{p}$) centralization performs better. This result suggests that decentralization is a substitute for lack of expertise in terms of reducing the riskiness of decisions. Is it so also with respect to N?

When N increases, the variance of decentralized decisions decreases because there are more regions and hence spreading risk is easier; the variance of centralized decisions also decreases because the accuracy $P_N(p)$ of decisions increases. Thus both curves move downwards and to the left, crossing at a point $\hat{p}' < \hat{p}$. Thus, centralization becomes desirable for a broader range of expertise, suggesting that decentralization is also a substitute for lack of experts as it is for lack of expertise.

We can now draw some implications for social welfare and the choice between centralization and decentralization. When the available expertise is advanced centralization is to be preferred as it yields more accurate and less risky decisions. With poor expertise, decisions under centralization, although more accurate, are also more risky than under decentralization. The choice then depends on how much "weight" is given to riskiness. In turn, this depends not only on the risk aversion index, which obviously makes decentralization more desirable, but also on the stakes of the decisionmaking process, G, which appear as a simple term in the expected return but are squared in the calculus of the variance. Hence, when the stakes are larger–that is, when the right decision is very valuable or, conversely, the wrong decision is very harmful–decentralization is again more desirable. Finally, the number of available experts influences this balance by lowering the threshold of expertise above which centralization dominates, thus undermining the scope of decentralization. The following proposition (proven in the appendix) summarizes these results.

Proposition 1 *With independent risks, if $p > \hat{p}$ centralization is optimal. If $p < \hat{p}$ centralization is optimal for a low degree of risk-aversion α or small stakes G; otherwise decentralization is optimal. The threshold $\hat{p}$ decreases in the number of experts N.*

2.3 Decentralization with interdependent risks

Although some risks might be independent, other risks are not. A bad decision taken in a region might well affect neighboring regions or even the entire planet. It is not superfluous to stress once more that, although we are analyzing the case of interdependency, this only refers to outcomes and not to decisions, which we still assume to be taken independently in each region. There are various ways in which interdependencies could play a role in this analysis, but there is something all formulations will have in common. When the outcomes are more dependent on each other, the advantage of decentralization in terms of risk-diversification tends to fade away.

To show that decentralization may still play a role, let us take an extreme scenario in which the decisions taken by different agencies are aggregated to produce a unique global outcome that applies to all regions; that is, the risk-diversification advantage is completely lost. Let us define interdependency as meaning that if $r \in \{1, 2, ..., N\}$ regions take the right decision, this converts in a good outcome for the entire planet irrespective of what decisions other regions took. The number r measures how much impact on the global outcome a local decision has.

Using terminology borrowed from reliability theory,[13] the problem is one of determining the reliability of an r-out-of-N system: the system works if at least r components work. The probability that the system works, that is, the probability that at least r regions take the right decision is thus given by:

$$Q_1(p, r) = \sum_{i=r}^{N} \binom{N}{i} p^i (1-p)^{N-i} \tag{1}$$

Accordingly, expected return and variance with interdependent risks are as follows:[14]

[13] LIT

[14] The formulations in the text follow from simplifying the following expressions: $R_N = \sum_{j=1}^{N} P_1(p) \frac{G}{N}$ and $V_N = \sum_{j=1}^{N} \left[P_1(p) \left(\frac{G}{N} - \frac{R_N}{N} \right)^2 + (1 - P_1(p)) \left(0 - \frac{R_N}{N} \right)^2 \right]$.

$$\begin{aligned} R_N &= Q_1(p,r)\,G \\ V_N &= Q_1(p,r)\,(1-Q_1(p,r))\,G^2 \end{aligned}$$

Note that in this case there is no advantage in diversifying risk as the outcome is either good or bad for all regions. Accordingly, the problem is purely to maximize the likelihood of a good outcome. We will examine three stereotypical cases.

2.3.1 Best-shot risks

We start by considering $r = 1$. In this case, taking the right decision in any of the regions means that the outcome will be good for the whole planet, irrespective of whether other regions have also taken the right decision. This is a 1-out-of-N (a series) system and can alternatively be interpreted as an any-vote system, in which if any of the local committees votes for the right outcome, that outcome will be chosen globally. Simplifying (1), the formula governing this type of risks can be written as 1 minus the probability that all regions take the bad decision:

$$Q_1(p,1) = 1-(1-p)^N > P_N(p) \tag{2}$$

The probability of success in best-shot risks is larger with decentralization than with centralization. There are two forces at work. Although decentralization triggers a negative effect, as its accuracy is less than that of a centralized agency, the likelihood that *all* regions take the bad decision is small and turns out to be less than the probability that the centralized agency takes the wrong decision. Thus the likelihood of a good outcome can be improved by decentralizing decisionmaking, as (2) shows.

2.3.2 Majority risks

Here we have $r = \frac{N+1}{2}$. The situation described corresponds to a risk that can be avoided if there are more right decisions than wrong ones. This is an $\frac{N+1}{2}$-out-of-N system and (1) becomes:

$$Q_1\left(p, \frac{N+1}{2}\right) = \sum_{i=\frac{N+1}{2}}^{N} \binom{N}{i} p^i (1-p)^{N-i} = P_N(p)$$

The probability of success in majority risks is the same whether decisions are centralized or decentralized. This is due to the fact that decisions by regional agencies in a decentralized system are aggregated in the same way as the votes of individual experts in a centralized agency.

2.3.3 Weakest-link risks

Finally, consider $r = N$. A wrong decision in any of the regions entails a bad outcome for the whole planet. This is an N-out-of-N (a parallel) system that is analogous to a unanimity voting rule, where any local committee can veto the good outcome. Simplifying (1), the formula governing this type of risks can be written as the probability that all regions take the good decision:

$$Q_1(p, N) = p^N < P_N(p)$$

Here increasing decentralization has two negative effects. On the one hand, a regional agency is less accurate than a centralized one; on the other hand, for the outcome to be good all agencies have to take the right decision, which further lowers the chance that the outcome will be good. The combined effect is that the likelihood of success decreases with decentralization.

2.3.4 Summary of the results for interdependent risks

The result of the decisionmaking process heavily depends on the type of risk. Decentralization has two countervailing effects. On the one hand, it entails a lesser degree of accuracy in each on the regions, thus potentially reducing the expected return to the decision. On the other hand, it makes it more likely that at least some regions will adopt the good decision. Whether one effect dominates the other depends on the proportion r of regions that need to take a good decision for the global outcome to be good. The following proposition follows directly from the previous analysis.

Proposition 2 *With best-shot risks, decentralization is optimal; with majority risks, decentralization and centralization yield the same level of social welfare; finally, with weakest-link risks, centralization is optimal.*

2.4 The political economy of decentralization

Discussing problems of global risk as we do rises the question of whether people care about global risks or are only focused on risks that materialize in their vicinity. This problem can be equivalently framed in terms of whether people can move or not. Let us first note that our definitions of expected returns and variance of decisions given by R_i and V_i refer to the global level, which is what people will care for if they can move. Let us also note that if risks are interdependent there is little to be said about the distinction between the global and the local level. However, if risks are independent and individuals cannot move, they will only look at what happens at the local level. With centralization, in each region we have the following expected return and variance:

$$\begin{aligned} R_1^L &= P_N(p)\frac{G}{N} \\ V_1^L &= P_N(p)\left(1 - P_N(p)\right)\left(\frac{G}{N}\right)^2 \end{aligned}$$

With decentralization, instead, we will have:

$$R_N^L = p\frac{G}{N}$$
$$V_N^L = p(1-p)\left(\frac{G}{N}\right)^2$$

There are two remarkable changes. First of all the stakes of the decision making process are $\frac{G}{N}$ instead of G, but this is true both for centralized and for decentralized decisionmaking and is easily understood with reference to the fact that now only the local effects of policies count. More importantly, the risk-spreading term $\frac{1}{N}$ has disappeared from the calculus of the variance under decentralization. This is a straightforward consequence of the fact that if the focus is local and a local decision is wrong, a right decision in a different region does not help. Comparing, we have $R_1^L > R_N^L$ and $V_1^L < V_N^L$, which bring to light an interesting contrast between a world with nomadic individuals and an opposite world with settled ones. In a nomadic world, our previous analysis applies and centralization and decentralization have their own roles, depending on the available expertise and the number of experts. In a settled world, instead, centralization always yields higher expected returns and lower variance, irrespective of other considerations. This is simply because it yields a higher probability that the committee is correct. This implies that, although by aggregating preferences and risks decentralization turns out to be advantageous, people unanimously prefer centralization. The interesting contrast is that mobile individuals or individuals who care about global problems–think of the survival of whales qua species–might prefer a decentralized decisionmaking process while, under similar circumstances, settled individuals or individuals who only care about local issues–whether whale survive in their own region–will favor centralization. This apparent paradox is easily explained by noting that, under the circumstances emphasized in our analysis, global risk reduction is best attained by decentralization.

3 The optimal level of governance

In the preceding sections we have sought the optimal level of governance in a dichotomous way, only allowing for complete centralization or complete decentralization. In this section we extend the analysis to intermediate levels of governance in between these two extremes. We thus employ a more general framework, which encompasses the two cases studied so far. The planet is partitioned in k regions of equal size, so that in each region decisions are independently taken by a local agency composed of $n = \frac{N}{k}$ experts. If $k = 1$, decisions are taken by one centralized agency. As k grows towards N we have an increasing degree of decentralization; the limit case of $k = N$ corresponds to complete decentralization studied above.

3.1 Independent risks

With independent risks, the probability that a local agency takes the good decision is $P_{\frac{N}{k}}(p)$, which decreases in k: the more decentralization is implemented, the lower the probability that local agencies will implement the right decision. With independent risks, expected return and variance for a level of decentralization k are readily calculated as follows:

$$\begin{aligned} R_k &= P_{\frac{N}{k}}(p)\, G \\ V_k &= \frac{1}{k} P_{\frac{N}{k}}(p) \left(1 - P_{\frac{N}{k}}(p)\right) G^2 \end{aligned} \tag{3}$$

From the expressions above it is easy to notice that the return to a decision R_k decreases with decentralization k, while the effect of decentralization on the variance could go either way.

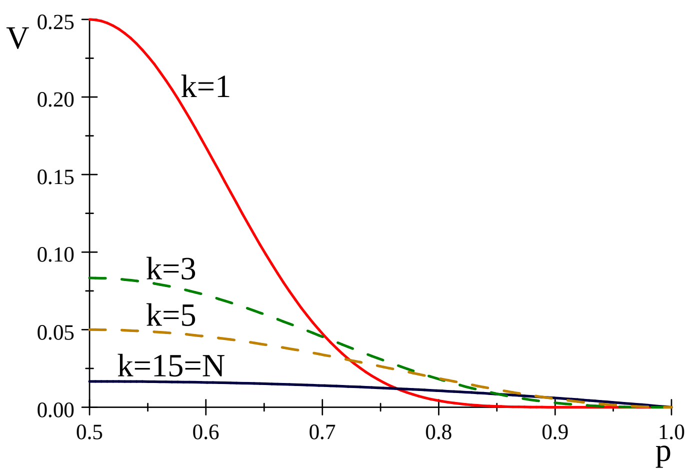

Figure 3.1: Variance of decisions under different levels of decentralization with $N = 15$, $G = 1$.

Figure 3.1 depicts the results of simulations run for $N = 15$. The upper and the lower lines (looking at the left of the graph) depict the two cases already studied of centralization ($k = 1$) and complete decentralization ($k = N = 15$). The intermediate dashed lines correspond to two intermediate levels of decentralization. The upper of the two describes a situation in which $k = 3$ agencies of 5 members each work independently and take decisions that apply to $\frac{1}{3}$ of the world. The lower line describes a more decentralized level of governance, where the planet is divided in 5 regions and each of the regional agencies operates with 3 experts. The graph shows that the variance of decisions is lower either with centralization or with complete decentralization, the discriminant being again a level of expertise $\hat{p}$ defined as above, which decreases in N. With poor expertise ($p < \hat{p}$) complete decentralization yields lower variance that any other level of decentralization; to the contrary, with advanced expertise ($p > \hat{p}$) centralization yields lower variance than any level of decentralization.

This result brings the problem back to the dichotomous framework only partially. In fact, if $p > \hat{p}$, taking decisions at a central level yields both less risk and greater accuracy, thus centralization is preferable. If $p < \hat{p}$, however, there is a trade-off to be addressed. While decentralization progressively lowers accuracy it also yields better risk spreading, thus some level of decentralization might be optimal, but not necessarily complete decentralization. The graph suggests that when $p < \hat{p}$ the variance of decisions decreases in k. Thus, decreasing decentralization k towards centralized decisionmaking yields greater expected returns at the cost of greater risk.

The optimal balance between risk and expected returns is dictated by the parameters of the model. The optimal degree of decentralization k^* increases in the degree of risk-aversion α and in the stakes of the decision G, as they give more weight to a reduction of risk as opposed to the reduction in expected returns. In contrast k^* decreases in the number of experts N and in their expertise p, as both of this variables make centralization more efficient in spreading risk. The following proposition (proven in the appendix) summarizes these results

Proposition 3 *With independent risks, if $p > \hat{p}$ the optimal level of governance is $k^* = 1$ (centralization). If $p < \hat{p}$ the optimal level of governance k^* increases towards decentralization in the degree of risk aversion α and the stakes G, and decreases towards centralization in the number of experts N and in the expertise p.*

3.2 Interdependent risks

With interdependent risks, allowing for intermediate levels of decentralization does not change the results obtained in the dichotomous case, since, as we shall see, either centralization or complete decentralization are optimal. The probability of a good outcome in the case of k agencies is

$$Q_k(p,r) = \sum_{i=r}^{k} \binom{N}{i} P_{\frac{N}{k}}(p)^i \left(1 - P_{\frac{N}{k}}(p)\right)^{k-i} \tag{4}$$

With best-shot risks, (4) becomes

$$Q_k(p,1) = 1 - \left(1 - P_{\frac{N}{k}}(p)\right)^k$$

The level of k that maximizes $Q_k(p,1)$ is $k^* = N$, complete decentralization. This is the case if $1-\left(1 - P_{\frac{N}{k}}(p)\right)^k < 1-\left(1 - P_{\frac{N}{N}}(p)\right)^N$. By letting $n = \frac{N}{k}$ and rearranging the previous inequality can be reduced to $(1 - P_n(p)) > (1-p)^n$, which is always satisfied by virtue of (2). Thus, even when intermediate levels of decentralization are feasible, it remains optimal to decentralize governance completely. With majority risks, (4) becomes

$$Q_k\left(p, \frac{k+1}{2}\right) = \sum_{i=\frac{k+1}{2}}^{k} \binom{k}{i} P_{\frac{N}{k}}(p)^i \left(1 - P_{\frac{N}{k}}(p)\right)^{k-i} \tag{5}$$

Note that $Q_k\left(p, \frac{\frac{N}{k}+1}{2}\right)$ in (5) can be written as $P_k\left(P_{\frac{N}{k}}(p)\right)$, that is it is the same as the probability that a committee of k members takes the right decision, where the probability that each member of the committee votes for the right decision is given by $P_{\frac{N}{k}}(p)$. This is in turn the probability that a committee of $\frac{N}{k}$ experts takes the right decision, given a probability p that each expert takes the right decision. From the perspective of calculating the probability that a good outcome results, majority risks are analogous to an indirect majority system. It is well known (Berg, 1997, p. 564) that

$$P_{nk}(p) > P_k(P_n(p)) \tag{6}$$

The inequality in (6) suggests that one (direct majority) committee of nk members has a larger probability to take the right decision that a two-step procedure in which first k different committees of n members decide independently and then they each send a delegate to a an assembly of the k delegates, who vote again and take the final decision. Applying this result to our setting implies $Q_k\left(p, \frac{\frac{N}{k}+1}{2}\right) < Q_1\left(p, \frac{N+1}{2}\right) = P_N(p)$, that is any intermediate level of decentralization achieves a lower probability of a good outcome than complete decentralization and centralization. With weakest-link risks, (4) becomes

$$Q_k(p, k) = P_{\frac{N}{k}}(p)^k$$

It is easy to see that by reducing k to 1 the former probability improves, suggesting that centralization fares better than any level of decentralization. These results can be summed up as follows:

Proposition 4 *With best-shot risks, the optimal level of governance is $k^* = N$ (complete decentralization); with majority risks, the (equally) optimal levels of governance are $k^* = N$ (complete decentralization) and $k^* = 1$ (centralization); finally, with weakest-link risks, the optimal level of governance is $k^* = 1$ (centralization).*

4 Decisions over a standard

In this section, we extend the basic model in order to allow for decisions that do not concern binary choices, such as the adoption or the rejection of a certain policy, but rather continuous choices, such as the setting of standards. To capture the idea that there is a "right" value for the standard, we assume that the return $r(s)$ to a standard s is a single-picked, symmetric, and continuously differentiable function, having a unique maximum at s^*. This implies that, if the standard is set too low or too high, the return decreases.

As we have postulated for approval decisions, even experts have some difficulty singling out the optimal level of the standard. They make errors in estimating the optimal value of the standard and their errors are normally distributed according to $f(e)$ with mean 0 and variance σ^2. Thus, an expert's assessment is $s = s^* + e$ and is also normally distributed according to $f(s^* + e)$, with mean s^* and variance σ^2. Since the distribution is the same for all experts, our previous assumption that the experts have homogeneous expertise carries over to this setting. The quality of the information available to the experts, formerly denoted by p, is now represented by the variance of the assessments distribution σ^2. A smaller variance means that the experts will more accurately assess the optimal value, which is conceptually the same as a grater p in the previous model. Experts err, but they are unbiased since on average they correctly estimate the optimal standard at s^*; moreover, errors on either side are equally likely since the median is also s^*, that is, both the likelihood that an expert assesses the optimal standard at $s > s^*$ and the likelihood that he assesses it at $s < s^*$ are equal to 50%.

When the experts gather in a committee, each of them proposes his preferred value and then they vote on the alternative proposals until a proposal is found that defeats all of the others in pair-wise comparisons. It is reasonable to assume that the experts' preference orderings are single-picked at their assessed value, as they plausibly dislike outcomes that are away to the left or to the right from what they think is the best choice. It follows from the median voter theorem (Black, 1948; Downs, 1957)[15] that the median proposal will prevail.

This situation is analogous to a random sampling from the assessments' distribution $f(s)$, with samples of size n (the size of the committee), each observation representing an expert's assessment of the optimal value of the standard. We are interested in the sample medians. Let z denote the sample median and $g_n(z)$ its density function; it is known (Cramer, 1946, p. 369) that the sample median z (the committee decision) is asymptotically normal with mean s^* and variance $v = \frac{\sigma^2 \pi}{2n}$.[16]

The above formulation has the interesting property that it replicates the same characteristics as the model of approval decisions; thus, the model of committee decisions over standards can be seen as an extension of the CJT to continuous choices. Firstly, we have $v < \sigma^2$, for $n > 1$; thus, in expectation, the committee's decision is more accurate than an individual's decision as the variance of the committee decision is lower than the variance of the individual experts' assessments. Secondly, because v increases in σ^2 and decreases in n, the accuracy of the committee decision increases in the available expertise and in the

[15] See Enelow and Hinich (1984) for a formal model and Congleton (2004) for a recent survey article.

[16] It might well be the case that the errors distribution is bounded to the left or to the right. For example a standard might be by nature a positive number. In this case, the normal approximation might not be the best choice and the formal analysis would change. For errors distributions other than normal the sample median is asymptotically normal with mean equal to the population median and variance $v = \frac{1}{4f(s^*)^2 n}$ (Cramer 1946, p. 369). Chu (1955) shows that convergence to the normal distribution is particularly "rapid" as n increases.

number of experts, as in the approval decisions case. With independent risks, the expected return and the variance of decisions with a level of decentralization k can be calculated as follows:

$$R_k = \int_{-\infty}^{+\infty} g_{\frac{N}{k}}(z)\, r(z)\, dz$$
$$V_k = \frac{1}{k}\int_{-\infty}^{+\infty} g_{\frac{N}{k}}(z)\left(r(z) - R_k\right)^2 dz$$

The expected return is decreasing in k. This is easy to see by noticing that the accuracy (variance) of the agency's decisions is $v = \frac{\sigma^2 \pi k}{2N}$ and increases in k. Thus, lower values of $r(z)$, which are further away from the maximum value, receive more weight and the expected return of the decision decreases. By similar arguments, the expected return R_k increases in the available expertise (decreases in σ^2) and also increases in the number of experts N.

As we have noted for approval decisions, increasing k has two effects on the riskiness of the global outcome: on the one hand, it reduces the accuracy of the decision, thereby making decisions that are far away from the expected return more likely. On the other hand, it increases the spread of such risks. Which one of these two effects dominates depends on the other parameters of the model. As we have observed for approval decisions, centralization is always optimal if the riskiness of decisions increases in k. In this case, in fact, centralizing decisionmaking achieves both a reduction of risk and an increase in the expected return. In contrast, for values of the parameters σ^2 and N for which the riskiness of decisions decreases in k, some level of decentralization might be optimal in order to reduce risk at the price of lower returns. In this case, the optimal level of decentralization k^* is increasing in σ^2 and decreasing in N. In fact, both of these changes make the return to a decision increase and its riskiness decrease, thereby substituting for some degree of decentralization.

Analysis of interdependent risks to be added___.

5 Implications and discussion

The model developed in this paper provides general insights on the optimal level of decisionmaking in the field of risk law, by re-conceptualizing decisions about the level of governance as risk management strategies. Our analysis has general applicability for the policy question about the optimal level of governance both at a global level (e.g. Codex Alimentarius Commission) and in the context of federal states–e.g. the United States and Switzerland–or regional areas–e.g. the European Union, the North American Free Trade Agreement (NAFTA)and the Association of Southeast Asian Nations (ASEAN). It goes without saying that each case would have to be studied in relation to its specific characteristics and the applicability of the model assessed accordingly. Before translating the results of the model into policy implications, it is therefore important to pay attention to some of the restrictive assumptions we made and further discuss how these assumptions may affect the policy relevance of our results.

5.1 Role of experts in decisionmaking about risks

The first assumption in need of qualification is the idea that decisions are delegated to a group of experts. While such an assumption does not dramatically depart from reality, it overlooks important dimensions underlying the process of risk regulation; most notably, the fact that the determination of a product's safety cannot simply be reduced to a scientific question. To establish whether a certain substance is safe, an assessment of its potential risks by scientists is necessary. Yet, this risk assessment does not generally tell whether a substance is safe; it only indicates that a certain relationship exits between, for instance, exposure and probability of becoming ill. To establish that the substance is safe one should decide what the 'acceptable level' for society of being exposed to a certain risk is. What is, for instance, the acceptable probability of dying by car accident? In other words, the vexed questions of 'how safe is safe enough?' can be answered only by combining technical knowledge about risks with knowledge about people's perceptions of risk (Slovic, Fishoff and Lichtenstein, 1980).

Several studies have shown that people find risks more or less acceptable on the basis of various factors; for instance, if people perceive a risk as equitably spread among the population or voluntarily undertaken they find it more acceptable than otherwise (Slovic, 1987 and 1991). For this reason, in many countries a phase of risk assessment, where factual data about the risks of a substance are gathered and assessed by scientists, is complemented by a risk management phase where a political decision taking into account people's preferences is performed (Ruckelshaus, 1985).

The fact that decisions about risks need to be based both on technical information about the probability distribution that a certain harm will occur and on knowledge about people preferences may have various implications for the policy relevance of the model. On the one hand, one can argue that, in spite of the outlined complexities, the model retains a great deal of practical relevance because the role of expert committees in risk regulation remains a prominent one. Moreover, the expert committee can be seen as a proxy for resources devoted to the decisionmaking process. In this case, few adjustments would be necessary. On the other hand, our initial assumptions could be considerably refined, leading to somewhat different conclusions, as discussed in the next subsection.

5.2 Local knowledge

One could consider that there might be some inherent informational advantage in going local. If this is true, the expertise would increase with decentralized decisionmaking; in other words, p would become endogenous to the model. Let us consider two plausible instances. The first is that local decisionmakers might better know the preferences of their constituencies. The main point is that what is considered an acceptable risk by one constituency may not be considered so by another. Second, even with homogenous preferences, local conditions or exposure to risk may vary. To illustrate, take two different standards commonly used by regulatory food agencies: the acceptable daily intakes (ADI) and the maximum residue levels (MRLs) of potentially harmful compounds present in food. The optimal ADI may differ across regions because preferences concerning acceptable risks vary; with the same preferences, the optimal ADI standards should in theory be the same. In contrast, optimal MRLs might vary even with homogeneous preferences, because of local variations in food consumption behavior. Local experts are likely to better evaluate both local preferences and local conditions, such as exposure to risks, which translates into an increase in p when decentralizing. Ceteris paribus, decentralization becomes more desirable.

5.3 Scientific uncertainty and scientific progress

Our model is based on the assumption that experts, notwithstanding a margin of scientific uncertainty,[17] are able to evaluate the risk potentials of dangerous substances/activities in a more accurate way than the layperson. However, not all technologies are equally understood. We have distinguished cases of advanced expertise from cases of poor expertise, where p is close to 50%, a situation that may be referred to as radical scientific uncertainty. In the latter set of cases, the difference between centralization and decentralization in terms of accuracy of decisions is minimal, while the decentralization gains in risk diversification are quite large, unequivocally casting a vote in favor of decentralization.

These results could be read as a new interpretative canon for the much-contested precautionary principle.[18] Within this framework, we suggest that the precautionary principle can be read as requiring decentralization in cases of radical scientific uncertainty. One could argue that in these cases to have expert committees would be pointless. However, such line of argumentation would be misleading. In fact, in order to be aware of the degree of scientific uncertainty, we need experts. Moreover, the time dimension should also be considered, since experts through time could revert a situation of poor expertise to one of advanced expertise.

But what trend can we generally expect in the process of centralization or decentralization as a resul of scientific progress? Should we observe more or less decentralization as time passes, society develops, and the state of the art of scientific knowledge improves? In the preceding analysis, we have taken the expertise p as given; here, we consider that it might change over time and speculate on its consequences. We have already noticed that centralization becomes more desirable when p increases. Thus, progress should bring about a more centralized decisionmaking process.

However, there might be another important issue coming into play. Scientific development pushes the technological boundary further away from known techniques, posing new, previously unknown risks, such as nanotechnologies. New

[17] The term uncertainty has been variously defined in the literature.
LIT.

[18] LIT.

questions might therefore arise and to answer them society might have to rely on experts with possibly very preliminary knowledge (small p). In contrast to the previous considerations, these conditions make decentralization more desirable. The overall effect might be one of smooth transition from decentralized to centralized decisionmaking: One might expect new issues characterized by small p being tackled at a local level. As more information on the effects of such decisions becomes available, one can expect such issues to be gradually attracted towards more centralized levels of governance. At the same time new problems arise which might follow the same path from local to central agencies.

5.4 Investments in research

Investments in research alter the pace of scientific progress referred above–pausibly accelerating it–but they might also increase the number of available experts N. Whether the latter pays out or not depends on the costs of such investments in relation to the benefits they yield in terms of greater social welfare. For our purposes, another issue if of more direct interest. In the analysis we have noticed that, with more experts available, centralization becomes more desirable. Thus, One could expect that investing in research might bring about a more centralized decisionmaking process. Likewise, one could expect rich areas of the world to rely on centralization more than poorer areas, where investments in research are less prominent.

5.5 Strategic voting

To be added_ _ _

5.6 Mutual influence among experts and among agencies

To be added_ _ _

6 An application of the model: the case of global risk law

A global risk authority does not exist, nor does a global environmental organization; though for the creation of the latter some proposals have been advanced (Esty, 2000). Notwithstanding this apparent lack of central governance, several decisions in the field of risk law are taken at the global level. For instance the decisions of the Codex Alimentarius Commission (hereafter the Codex Commission) about the safety of various foodstuffs might be seen as an example of central governance of risk law. The Codex Commission is an inter-governmental body created in 1963 by the Food and Agricultural Organization of the United Nations (FAO) and by the World Health Organization (WHO) to develop food safety standards and guidelines in relation to food safety; most notably, these standards and guidelines are based on the opinions of experts committees. While the standards set up by Codex are not formally binding, they might become indirectly so because of their linkage with the World Trade Organization (WTO). The law of the WTO and the standards set by the Codex Commission are related by virtue of the Sanitary and Phytosanitary Agreement (SPS Agreement), which is one of the multilateral agreements constituting the body of WTO law.

The SPS Agreement deals with regulatory measures that could constitute barriers to trade, and in order to minimize such barriers, it encourages WTO Members to harmonize SPS measures. The harmonization goal and its relation to the work of the Codex Commission clearly emerges from the sixth preambular paragraph of the SPS Agreement, where we read: "Desiring to further the use of *harmonized* sanitary and phytosanitary measures between Members, on the basis of international standards, guidelines and recommendations developed by the relevant international organizations, including the Codex Alimentarius Commission . . . " (emphasis added); likewise, Article 3 paragraphs 1 of the SPS Agreement provides that "(1) [t]o harmonize sanitary and phytosanitary measures . . . Members shall base their sanitary or phytosanitary measures on international standards, guidelines or recommendations, where they exist; . . . ." These rules, as embodied in the SPS Agreement, could generate a process of indirect harmonization of risk law among WTO Members.

At this point, it should be emphasized that WTO law is a rather influential branch of international law, not the least because of its well-functioning dispute settlement and enforcement mechanism. Thus, while the standards immediately relevant for the SPS Agreement, as the ones set by the Codex Commission, are usually not binding "WTO rules may transubstantiate voluntary standards into mandatory ones" (Charnovitz, 2005, p. 30). For these reasons, the SPS Agreement is likely to influence Members' risk policy and most probably not marginally so. In other words, an indirect centralization of risk law may take place through the WTO law system read in conjunction with the work of the Codex Commission.

While the possibility of centralization of certain risk laws through Codex coupled with WTO law is plausible, the current system is much more complex. The SPS Agreement contains several provisions that leave WTO Members relatively free in setting their own risk policies (e.g. Article 3.3 SPS Agreement). The interpretation of the SPS Agreement given by the WTO judiciary organs is also not conclusive and has left many loopholes (Pauwelyn, 1999; Quick and Bluthner, 1999; Arcuri, 2005). This means that in practice the level of (de-)centralization of risk law at the international level is still somewhat unclear and in this respect a better understanding of the possible rationales underlying this process may be helpful to rethink the current system.

Our analysis has shed light on the circumstances under which a higher degree of harmonization might be desirable and on those under which different Members policies would be superior and it could thus become one criterion for policymakers to (re-)shape the existing regime; it could also provide some feedback for the WTO judiciary on whether a more or less deferential attitude in matters pertaining to risk law is justified from an economic perspective.

The model has shown that the desirability of (de-)centralization depends to a great extent on the typology of risks and therefore we suggest that also in a global framework such risk characteristics are to be taken into account. More specifically, we have shown that for independent risks the level of expertise, the degree of risk aversion, and the stakes of the decision determine the desirability of (de-)centralization. We risks are interdependent, centralization is most desirable for weakest-link risks, whereas for best-shot risks decentralization is to be preferred. As illustrated in the previous section, decentralization would have additional advantages if preferences in different jurisdictions are heterogeneous, if exposure to risks would varies, and when the degree of uncertainty increases. One could argue that the latter is partly reflected in Article 5.7 of the SPS Agreement, which leaves the highest degree of freedom to members in cases of insufficient scientific evidence.

Whether risks are independent or interdependent, however, is neither a criterion explicitly endorsed by the SPS Agreement; nor has it been an issue taken into account by the WTO panels or Appellate Body. We argue that taking into account these issues would render the outlined process of indirect global risk governance more rational. One could counter-argue that, since the WTO is not an organization aiming at global risk governance, it is rather legitimate to ignore such issues. While pertinent, such an argument would be misleading. In fact, harmonization ambitions in the area of risks law are explicitly embodied in the SPS Agreement and therefore it is crucial to understand the effects of global harmonization of risk regulations on global welfare.

Understanding and taking seriously into account these effects would not only conform to an economic logic but would also be consistent with a legal one. In fact, Article 31 of the 1969 Vienna Convention on the law of Treaties, which embodies customary rules of interpretation of public international law provides that a treaty shall be interpreted, inter alia, "in the light of its object and purpose." In this context it may be worth recalling that the general goals of WTO law, include the achievement of better "standards of living ... allowing for the optimal use of the world's resources", as explicitly stated in the first preambular paragraph of the Agreement establishing the WTO. In the light of these brief considerations, we can conclude that taking into account the welfare effects of centralized or decentralized decisionmaking would not only be desirable from an economic perspective but would also comply with a legal logic.

Having clarified this point, we should emphasize that it would be beyond the scope of this article to appraise whether the WTO, in conjunction with other intergovernmental bodies such as Codex, is the best forum to address issues of global risk law. We simply analyze the current regime as it is; in this context, we suggest that insights generated by the model can significantly improve the rationality of the existing regime. More specifically, the types of risks analyzed in this article could become a new guideline for the policymaker and judges for deciding the level of optimal harmonization of global risk law. This is not to say that this should become the only criterion to be followed; more modestly, we argue that this could become an additional criterion to assess the benefits and costs of harmonization of risk law at the global level; a criterion so far not developed by theory and, perhaps also for this reason, neglected by policymakers and judges.

7 Conclusions

This analysis has cast light on the circumstances under which, in decisionmaking concerning risks, centralization is superior to decentralization and vice versa. Previous literature in this area has paid no attention to this issue. We argue for a re-conceptualization of choice of the optimal level of governance as risk management strategies and show that it can significantly enrich the analytical grid used so far to analyze these and similar problems.

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8 Appendix

First note the following results that will be used in the following. According to a well-known formula (Mood, 1950, p. 235):

$$\begin{aligned} P_n(p) &= \sum_{i=\frac{n+1}{2}}^{n} \binom{n}{i} p^i (1-p)^{n-i} \qquad (7) \\ &= n \binom{n-1}{\frac{n-1}{2}} \int_0^p x^{\frac{n-1}{2}} (1-x)^{\frac{n-1}{2}} \, dx \end{aligned}$$

Moreover, (Boland, 1989, p. 181):

$$1 - P_n(p) = P_n(1-p) \qquad (8)$$

Lemma 5 *There exist a level of expertise $\hat{p}$ such that, if $p < \hat{p}$, the variance of a decision is less under complete decentralization than under centralization ($V_1 > V_N$), while, if $p > \hat{p}$, the opposite is true ($V_1 < V_N$). Finally, $\hat{p}$ decreases in N.*

Proof. Let

$$\hat{p} = p : N P_N(p) (1 - P_N(p)) = p(1-p)$$

and

$$\Psi_N^1 \equiv \frac{P_N(p)(1 - P_N(p))}{\frac{1}{N} p(1-p)}$$

note that $V_1 > V_N$ iff $\Psi_N^1 > 1$ and $V_1 < V_N$ iff $\Psi_N^1 < 1$. It is easy to see that $\frac{1}{N} p(1-p)$ a strictly concave function of $p \in \left(\frac{1}{2}, 1\right)$, decreasing at an increasing rate. Using (7) we can write $P_N(p)(1 - P_N(p))$ as:

$$N^2 \binom{N-1}{\frac{N-1}{2}}^2 \int_0^p x^{\frac{N-1}{2}} (1-x)^{\frac{N-1}{2}} \, dx \int_p^1 x^{\frac{N-1}{2}} (1-x)^{\frac{N-1}{2}} \, dx$$

from which we can calculate its first derivative:

$$D' = (1 - 2P_N(p)) N \binom{N-1}{\frac{N-1}{2}} p^{\frac{N-1}{2}} (1-p)^{\frac{N-1}{2}} < 0$$

and its second derivative:

$$D'' = \frac{N}{2} \binom{N-1}{\frac{N-1}{2}} p^{\frac{N-3}{2}} (1-p)^{\frac{N-3}{2}} (\zeta - \theta)$$

where:

$$\begin{aligned}\zeta &= (2p-1)(2P_N(p)-1)(N-1)\\ \theta &= 4N\binom{N-1}{\frac{N-1}{2}}p^{\frac{N+1}{2}}(1-p)^{\frac{N+1}{2}}\end{aligned}$$

Note that $sign\left(D^{''}\right) = sign(\zeta-\theta)$; since ζ is zero at $p=\frac{1}{2}$ and increases in p, while θ decreases in p and is zero at $p=1$, $D^{''}$ changes sign from negative to positive as p increases. Thus $P_N(p)(1-P_N(p))$ has an inverted-S shape (half of a bell) as in figure 2.2. Now note that $\lim_{p\downarrow\frac{1}{2}}\Psi_N^1 = N > 1$, while, using l'Hospital's rule,

$$\lim_{p\uparrow 1}\Psi_N^1 = N\frac{\lim_{p\uparrow 1} D^{'}}{\lim_{p\uparrow 1}\left[\frac{\partial}{\partial p}(p(1-p))\right]} = \frac{0}{-1} < 1$$

Thus there exists a $\hat{p}$ at which $\Psi_N^1 = 1$ and the curves cross. They cannot cross more than once as this would imply $D^{''}$ changing sign more than once. Finally, $\hat{p}$ decreases in N since both curves shift to the left as N increases. ■

Proof of proposition 1. Social welfare under centralization and decentralization can be compared as follows:

$$\begin{aligned}\Delta W &= R_1 - R_N - \alpha(V_1 - V_N)\\ &= [P_N(p)-p]G - \alpha\left[P_N(p)(1-P_N(p)) - \frac{1}{N}p(1-p)\right]G^2\end{aligned}$$

Centralization is desirable if $\Delta W > 0$. First note that $R_1 > R_N$ ($P_N(p) > p$) for $\frac{1}{2} < p < 1$, hence the first term is positive. From lemma 5, the second term is positive if $p < \hat{p}$ and negative if $p > \hat{p}$. Thus if $p > \hat{p}$, $\Delta W > 0$ (centralization is desirable) for any value of the other parameters, notably α and G. If $p < \hat{p}$, $\Delta W > 0$ (centralization is desirable) for $\alpha G < \varphi = \frac{NP_N(p)-p}{NP_N(p)(1-P_N(p))-p(1-p)}$ and negative (decentralization is desirable) otherwise. ■

Proof of (2). The inequality in (2) holds iff:

$$(1-p)^N < 1 - P_N(p)$$

Using (8), we can write:

$$\begin{aligned}1-P_N(p) &= P_N(1-p)\\ &= (1-p)^N + \sum_{i=\frac{N+1}{2}}^{N-1}\binom{N}{i}p^{N-i}(1-p)^i > (1-p)^N\end{aligned}$$

Thus, we have $1-P_N(p) > (1-p)^N$. ■

Lemma 6 *When intermediate levels of decentralizations are allowed, if $p < \hat{p}$, then the variance of a decision V_k is minimized by complete decentralization ($k^* = N$); conversely, if $p > \hat{p}$, then the variance of a decision V_k is minimized by centralization ($k^* = 1$).*

Proof. Let us first define a set of feasible values for k. Let $\mathbf{T} = \{t_1, ..., t_T\}$ be a set of T prime numbers and $\mathbf{T}_n$ and $\mathbf{T}_k$ be subsets of $\mathbf{T}$ such that $\mathbf{T}_n \cup \mathbf{T}_k = \mathbf{T}$ and $\mathbf{T}_n \cap \mathbf{T}_k = \varnothing$. Let $N = \prod_i t_i \in \mathbf{T}$, $n = \prod_i t_i \in \mathbf{T}_n$ if $\mathbf{T}_n \neq \varnothing$ ($n = 1$ otherwise), and $k = \prod_i t_i \in \mathbf{T}_k$ if $\mathbf{T}_k \neq \varnothing$ ($k = 1$ otherwise). Note that $nk = N$. Let us first show than any two variance functions cross once and only once. Let

$$\Psi_h^k \equiv \frac{\frac{1}{k} P_{\frac{N}{k}}(p)\left(1 - P_{\frac{N}{k}}(p)\right)}{\frac{1}{h} P_{\frac{N}{h}}(p)\left(1 - P_{\frac{N}{h}}(p)\right)} \tag{9}$$

where $h > k$. It follows from lemma 5 that both the numerator and the denominator are decreasing functions with an inverted-S shape: they first decrease at an increasing rate and then at a decreasing rate. Note also that $\lim_{p\downarrow\frac{1}{2}} \Psi_h^k = \frac{h}{k} > 1$, and, $\lim_{p\downarrow 1} \Psi_h^k = 0 < 1$. The latter results by using again l'Hospital's rule

$$\begin{aligned}
\lim_{p\downarrow 1} \Psi_h^k &= \lim_{p\downarrow 1} \frac{\partial}{\partial p} \Psi_h^k \\
&= \left(\frac{h}{k}\right)^2 \frac{\left(1 - 2P_{\frac{N}{k}}(p)\right)}{\left(1 - 2P_{\frac{N}{h}}(p)\right)} \binom{\frac{N}{k} - 1}{\frac{\frac{N}{k}-1}{2}} \binom{\frac{N}{h} - 1}{\frac{\frac{N}{h}-1}{2}}^{-1} p^{\frac{hN-kN}{2hk}} (1-p)^{\frac{hN-kN}{2hk}} = 0
\end{aligned}$$

Thus Ψ_k^h is greater than 1 for p close to $\frac{1}{2}$ and less than 1 for p close to 1. The curves cross when $\Psi_k^h = 1$ and they cross only once as the sign of their second derivative changes only once.

To prove the first part of the lemma, let

$$\Psi_N^k \equiv \frac{\frac{1}{k} P_{\frac{N}{k}}(p)\left(1 - P_{\frac{N}{k}}(p)\right)}{\frac{1}{N} p(1-p)} = n \frac{P_n(p)(1 - P_n(p))}{p(1-p)} \tag{10}$$

and note that V_k is minimized by $k^* = N$ iff $\Psi_N^k > 1$, for any $k < N$. From lemma 5 we know that $\hat{p}$ decreases in N; since $n < N$, we have $\Psi_N^k > 1$ if $p < \hat{p}$ and hence decentralization is optimal ($k^* = N$).

To prove the second part of the lemma, let

$$\Psi_k^1 \equiv \frac{P_N(p)(1 - P_N(p))}{\frac{1}{k} P_{\frac{N}{k}}(p)\left(1 - P_{\frac{N}{k}}(p)\right)} = k \frac{P_{nk}(p)(1 - P_{nk}(p))}{P_n(p)(1 - P_n(p))}$$

and note that V_k is minimized by $k^* = 1$ iff $\Psi_k^1 < 1$, for any $k > 1$. At $p = \hat{p}$, we have $nkP_{nk}(\hat{p})(1 - P_{nk}(\hat{p})) = \hat{p}(1 - \hat{p})$; thus, we can write $\Psi_k^1 = \frac{1}{n} \frac{\hat{p}(1-\hat{p})}{P_n(\hat{p})(1-P_n(\hat{p}))} < 1$, where the inequality follows again from lemma 5. It follows that $\Psi_k^1 < 1$ if $p > \hat{p}$ and hence centralization is optimal ($k^* = 1$). ■

Lemma 7 *If $p < \hat{p}$, the variance of a decision V_k decreases in k.*

Proof. Using (9) and (10), note V_k decreases in k iff $\Psi_h^k > 1$. Finally, note that $\Psi_h^k > \Psi_N^k > 1$. ■

Lemma 8 *If $p < \hat{p}$, the variance of a decision V_k decreases in p and N.*

Proof. Note that V_k decreases in p and N iff $\frac{1}{k} P_{\frac{N}{k}}(p) \left(1 - P_{\frac{N}{k}}(p)\right)$ decreases in p and N, which follows trivially from the fact that $P_{\frac{N}{k}}(p)$ is greater than $\frac{1}{2}$ and increases in p and N. ■

Proof of proposition 4. It follows from lemma 6 that, if $p > \hat{p}$, centralization is optimal ($k^* = 1$) for any levels of the parameters, since it yields both greater expected returns and lower variance than any other level of k. If $p < \hat{p}$, instead, centralization maximizes the expected return, while complete decentralization minimizes the variance. We know from (3) that the expected return R_k decreases in k and from lemma 7 that also the variance V_k decreases in k. Thus by decreasing or decreasing k we have greater expected returns at the price of greater risk and, vice versa, by increasing k we have lower risk at the price of lower expected returns. The socially optimal level of k depends on the weight society put on R_k and V_k. With large risk aversion α or stakes G more weight is put on V_k and hence k^* increases in α and G. Finally, from lemma 8 we know that for any level of k the variance of a decision V_k decreases in p and N. it follows that when p or N increases, the same expected return corresponds to lower variance and hence k can be further increased to attain greater expected returns at lower costs in terms of increased variance. Thus, k^* increases in p and N. ■