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The Tragedy of the Nurdles: Governing Global Externalities

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Abstract: Nurdles have been referred to by some as a global environmental disaster. However, relative to the controversies surrounding industrial fracking practices, such as public health and safety associated with extraction of shale gas (as well as shale oil), the problems with nurdles are not as widely known. In this article, we highlight that fracking and nurdles are interrelated: fracking processes are a major source of the raw materials used to produce nurdles, which are tiny plastic pellets polluting our waters. Our contention is that a key question for analysis of fracking is how to regulate the externalities associated with downstream products produced in the fracking process. This article takes insights from Elinor Ostrom and scholars of the Bloomington School of Political Economy—such as polycentricity, diversity of collective action problems (CAPs), coproduction, and institutional diversity—to analyze nurdles pollution as a global commons problem. Nurdles generate widespread, large-scale negative externalities that are difficult to contain and address within a fixed geographical boundary governed by a static jurisdictional authority. Using the case of the Royal Dutch Shell cracker plant in Beaver County, Pennsylvania, we show that nurdles present complex and nested challenges that require coproduction, with citizen monitoring playing an essential role in mitigating negative externalities. We demonstrate the efficacy of applying polycentric approaches toward addressing CAPs associated with nurdles.

Keywords: nurdles; fracking; tragedy of the commons; polycentricity; Ostrom

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1. Introduction

Global plastic production has increased dramatically since the 1950s, from about 2 million metric tons to around 200 million metric tons in 2022. Nurdles are the building block of this increase in plastic production. These glittery plastic beads have also been called the biggest environmental disaster you have never heard of [1]. Nurdles spill whenever they are manufactured and are transported around the world in cargo ships. They are polluting the world's oceans, inland water, and our bodies since we eat the animals that consume these plastics.

Nurdle production has also increased as fracking commenced. Simply put, fracking produces a great deal of ethane that supplies the raw material to produce nurdles. To keep up with our increasing demand for plastic products, the production of nurdles has also risen exponentially, facilitated, in large part, by increased fracking in the United States. Trillions of nurdles are produced each year from natural gas or oil, which are then used in the production of everyday plastics. These small polyethylene microplastics are produced in ethane crackers from ethane gas. From the crackers, nurdles are shipped to other facilities where they are turned into thousands of plastic products that we use every day.

In this paper, we focus on the global regulation of nurdles in the case of an American community, specifically the strengths and limits of monocentric versus polycentric approaches to deal with the nurdles problem. Informed by Elinor Ostrom's research on the global commons, we argue that polycentric regulation is more appropriate for nurdles and that existing polycentric arrangements provide a workable framework to regulate nurdles.

Nurdles are a complex problem. Such problems are characterized by high uncertainty and severity, and the 'elements that make up a greater whole' interact in unpredictable ways, making it unfeasible to be analyzed in a linear fashion [2]. Nurdles are essentially everywhere: in inland water sources, the oceans, and our bodies, as we increasingly consume plastics through our consumption of fish that ingest these plastics. The sources are often challenging to identify, and control of nurdles is a major challenge to improving the sustainability of plastics production. Hence, although the pervasiveness of the nurdles problem leads many to advocate for a large-scale, often centralized, solution designed and implemented by national or supranational governments. We contend that such propositions are myopic. They fail to adequately consider the importance of institutional diversity and coproduction in crafting sustainable solutions to the nurdles crisis.

Our analysis builds on the recent advancements in the literature on the polycentric approach to governing complex global externalities, following the foundational works by Elinor Ostrom and the scholars of the Bloomington School of Political Economy [3,4]. Paniagua and Rayamajhee [5] highlight three key features of complex global externalities: these global externalities involve an exceptionally large number of individuals, organizations, and authorities at multiple scales; identification of the causes of the externalities is challenging because problems are nested in multiple interconnected layers; and discerning appropriate solutions is difficult—even infeasible if the intended beneficiaries of the solutions do not participate in crafting the solutions. We show that these features present insurmountable challenges to monocentric policy design and implementation. We argue that a polycentric approach is more suitable for understanding and addressing such problems as they are less susceptible to epistemological and incentive-incompatibility challenges.

We provide support for the case for polycentric systems to manage nurdles by documenting the features of nurdles, specifically that they share features of complex externalities best suited to such approaches. We show this primarily with a case study of the experiences of the Royal Dutch Shell cracker plant, which is the first ethylene cracker in Appalachia. The plant, which opened in 2022, is expected to produce up to 100 rail cars a day of nurdles. Our case study relies on an analytical narrative using newspaper articles, environmental agency reports, and other primary sources. Our desk research approach involved searching for any relevant data on nurdles in Pennsylvania as well as in the United States, as well as through reviews of research to better understand the extent to which nurdles are considered in academic and government publications dealing with shale gas production. Our methodological choice is motivated by the fact that no reliable quantitative data on nurdles is available to date. The only quantitative data on nurdles pollution that exist for public use are provided by Nurdle Patrol, but we cannot rely on them for two reasons: available data are biased due to higher reporting in areas with higher citizen science participants, and available data do not allow us to analyze institutions. As Skarbek [6] notes, the use of case studies and analytical narratives is suitable, and, in many cases, the only appropriate method. Given these data challenges, relying solely on them would necessarily preclude us from studying many important and urgent topics. This is certainly the case for the topic we aim to investigate in this essay.

Our analysis shows that nurdles are archetypal large-scale, complex externalities that defy geographical boundaries and political jurisdictions. We argue that there are several challenges with a singular, monocentric authority to regulate nurdles: it lacks the necessary external feedback and error-correcting mechanisms, competitive pressures, accountability measures, and, more importantly, adequate incentives to adapt to evolving circumstances. In addition, because nurdle challenges are closely related to fracking, (as nurdles are a downstream product of fracking), externalities from these two processes interact, exacerbating epistemological hurdles for a monocentric authority.

Our emphasis on fracking and nurdles complements Holahan and Arnold's [7] institutional theory of hydraulic fracturing and extends it to the analysis of nurdle externalities. According to their theory, shale gas development differs from conventional oil and gas production because the collective action problems associated with them interact with

different technologies and geological conditions, thereby posing fundamentally different externality challenges. Thus, they require different kinds of institutional solutions. Holahan and Arnold's [7] theory, which accounts for the geological and institutional characteristics of fracking, suggests that environmental risks associated with fracking appear large and consequential relative to conventional drilling because of the lack of effective institutions specifically evolved to address fracking. Specifically, their focus is on groundwater contamination from shale gas drilling. Our analysis expands on their perspective and shows that the nurdle problem presents an even bigger challenge relative to fracking.

Moreover, we show that complexity does not mean that the solutions should be more monocentric. In the United States, the epicenter of the boom in shale gas production, regulation of shale gas falls primarily under the jurisdictions of state governments, and, in some cases, states may even delegate it to local governments [8,9]. An emerging body of literature explores the extent to which the federal system in the United States has led to a "fractured" regulatory regime and exacerbated the environmental costs of fracking [10–12]. Some contend that the large scale of the associated costs of fracking provides economic justification for consolidating all governing authority to the federal level, in particular, under the purview of the Environmental Protection Agency [8]. Another contested issue pertains to the overall economic viability of fracking—that is, if fracking should even be allowed, as some states and local governments have considered implementing bans on fracking. Our Ostromian theoretical framework, combined with evidence from the Dutch Shell Cracker Plant, highlights that among imperfect alternatives, polycentric regulation of nurdles may offers better promise than monocentric regulation.

The remainder of the article is structured as follows. Section 2 describes the commons problem associated with governing nurdles. We discuss whether nurdles pollution can be illustrated through the lens of the Tragedy of the Commons. Section 3 develops a conceptual framework to analyze the nurdles problem by borrowing insights from Elinor Ostrom and the Bloomington school scholars. We selected this perspective because it addresses challenges related to the governance of commons, including global commons, and because it offers a framework to compare monocentric theories of regulation with the polycentric perspective articulated by Ostrom and her colleagues. In Section 4, we discuss fracking, cracking, and nurdles. We focus on the relationship between the three to illustrate the origins, consequences, and extent of nurdles pollution and its complex nature. Section 5 characterizes nurdles as a complex global externality. Section 6 uses the case of the Dutch Shell cracker plant in Beaver County, Pennsylvania, to illustrate that nurdles present complex and nested challenges that require a regulatory framework that enables a coproductive role of citizens that, we argue, would be challenging to replicate in a monocentric regulatory regime. The final section concludes.

2. The Tragedy of Nurdles?

Global environmental challenges, such as climate change, are frequently described using the analogy of the "tragedy of the commons" [13]. This analogy is motivated by the apparent disjoint between collective objectives and individual incentives that characterize many such challenges. However, as Elinor Ostrom and scholars of the Bloomington School have shown, such comparisons presume that participants are helplessly trapped in situations that they are unable to get out of [14,15]. Often, this presumption leads scholars and policymakers to make a case for external intervention to design and implement centralized solutions. In this section, we argue that the tragedy of the commons is a misleading and even counterproductive analogy to refer to the nurdle problems, as it oversimplifies the complexities and nestedness characteristic of externalities associated with nurdles.

The tragedy of the commons thinking is motivated by the idea that self-interested individuals will overuse, overexploit, and pollute resources and environmental commons absent coercive regulations, likely imposed by external authorities [16]. It can be thought of as a social dilemma situation in which individual rationality comes into conflict with

what is optimal for the group [17]. When property rights are not clearly defined due to geographic, technological, institutional, and other reasons, free riding can occur; a self-interested herder, given the opportunity to benefit from the inputs of her fellow herders, will do so and contribute minimally toward to the maintenance and preservation of the commonly owned pasture [16]. Similarly, in a collective action problem situation, where one's share of benefits does not depend on their level of inputs, they may choose not to contribute, particularly if the group size is large and their contributions (or lack thereof) are not likely to be noticed [18,19]. Thus, in the absence of coercion and mechanisms of monitoring and sanctioning, the extent to which rational individuals succumb to their own interest determines the size of the deadweight loss from free riding.

With respect to global environmental problems, there are countless free-riding opportunities for all parties concerned, and the benefits and costs of any mitigation measures are dispersed in complex ways. One individual's marginal contribution is unlikely to have a discernable effect in either mitigating the problem or in encouraging others to contribute to a solution. Thus, even if individuals have some interest in avoiding the tragedy, they may decide not to contribute to such efforts. This logic, when applied to global environmental resources, dictates that independent human action will result in the depletion of natural resources and the destruction of the global environment, especially as the population increases [20,21].

Elinor Ostrom provides an alternative perspective that recognizes the perils of the tragedy of commons view to conceptualize and address large-scale environmental problems such as global climate change [22]. Ostrom and scholars of the Bloomington school argue that global problems such as climate change and pandemics are collective action problems arranged at multiple, nested, and/or overlapping scales. They argue that the nestedness of associated externalities and the diversity of institutional conditions across jurisdictions are important considerations that can only be sufficiently accounted for using the polycentric approach [23]. Within the polycentric framework, the roles of self-governing individuals, subnational governments, small and large private and public organizations, businesses, civil society, and innumerous parties become critical both in developing our understanding of the complexities of the challenges and in crafting institutional solutions amenable to diverse interests and values. Viewed this way, individuals are not disinterested agents trapped in their social dilemmas. Instead, they devise numerous technological and institutional mechanisms to address different aspects of the global problem in their own ways. These contributions, when combined and coordinated, cumulatively contribute significantly to addressing global externalities. In analyzing natural resource commons such as fisheries or forests, Ostrom [24] argued that self-governance and communal management of shared resources can be effective in staving off tragedies of the resource commons. Self-governance does not by itself ensure the successful preservation of the resource system, but it is essential. Resource systems can be effectively self-governed by the users themselves, who take on various de facto and de jure roles—such as appropriators, claimants, proprietors, managers, and owners—and often operate beyond the purview of markets and states [14].

Relative to global externalities associated with climate change and pandemics, most common pool resource (CPR) systems that Ostrom and her colleagues examined presented localized challenges, sometimes involving multiple jurisdictions but rarely spanning many countries. Greenhouse gas emissions, on the other hand, have externalities that cannot be confined by national boundaries or any political jurisdictions. Moreover, the number of individuals responsible for and affected by climate change is in billions. Thus, these concerns have led some to conclude that large-scale externalities require global governance to manage them centrally through regulatory or other mechanisms. However, such proposals assume away many complexities of externalities and the institutional contexts within which they materialize. As Ostrom argues, even though climate change poses global challenges, decisions and actions taken by small- and medium-scale actors such as households, private businesses, local governments, and civil society are equally, if not more, important to miti-

gating greenhouse gas emissions [22]. Moreover, actors at various levels interact with one another in myriad ways, competing in some arenas and cooperating in others, generating complex sets of incentives and affecting greenhouse gas emissions and mitigation. Thus, any proposed solutions that ignore the incentives and actions facing actors across all levels are unlikely to succeed and may even produce counterproductive outcomes.

An important implication of the above analysis is that commons governance requires inputs and "buy-in" from participants [25]. This holds true not only for common pool resource management, but also for the governance of global environmental externalities, climatic disasters, and pandemics [26–28]. Thus, although a narrow set of externalities may require some centralization, it comes at a steep cost of an increased probability of reducing citizen input [29]. External governance is costly, both in terms of the associated cost of designing and implementing policies and with respect to its opportunity costs. In many instances, when the economic benefits of cooperation or the costs of noncooperation are large enough, self-governing institutions can emerge and evolve to address the demand for governance. This can occur even in unexpected settings such as prisons and pirate ships [30,31]. When formal governance mechanisms impose prohibitive costs or do not account for the "buy-in" aspect, self-governance becomes less likely or takes on violent and undesired forms [32].

The commons problem associated with nurdles is straightforward. Consumers of plastics and plastic products can enjoy a vast range of goods and services at low costs because cracker plants produce trillions of nurdles at low average costs. Consumers can do so without having to pay for the environmental costs, such as the harmful effects on marine ecosystems. Because an individual consumer's marginal reduction in plastic consumption has negligible impact on the net harm to the ecosystem, they have very little incentive to curtail plastic use. On the other hand, the high costs of monitoring nurdle spills and leakages result in a moral hazard problem for producers and transportation companies. With a few notable exceptions, such as major cargo spills from the X-Press Pearl accident in 2021, it is nearly impossible to identify the origins of nurdles once they enter the ocean. Each member of the nurdles supply chain has the incentive to underinvest in preventative measures and rely on other members to take necessary actions. Similarly, because nurdles travel great distances extending political jurisdictions and even national boundaries, governments have incentives to stay complacent and rely on other governments to pay for initial coordination efforts, which can be costly. Thus, multiple commons problems exist for consumers, producers, and governments. However, the more pertinent question is: does the nurdles commons problem amount to a tragedy? In this essay, we contend that whether the nurdles commons presents a tragedy depends on the approach we adopt to address it. Specifically, viewed from the lens of monocentric policymaking, nurdles commons is indeed a tragedy. However, polycentric thinking and policymaking offer an opportunity to avoid the tragedy by allowing us to address it at multiple levels and scales.

3. A Conceptual Framework for Analyzing Complex Global Externalities

3.1. What to Do about Externalities

The conventional view on externalities is that they represent aberrations from the norm, and thus need correcting. When private and social costs diverge, there is either an oversupply or undersupply because the external costs, by definition, are not incorporated in market prices. To remedy that, an external authority must intervene through taxes, regulation, or other forms of coercion. Where positive externalities are present, subsidies are called for; where negative externalities exist, taxes are necessary. The government, it is assumed, remedies the discrepancy by transferring the taxes to the party affected by negative externalities and subsidies to the producer that generates uncompensated positive externalities. This perspective is attributed to Arthur Pigou, and externalities perceived to be solvable using this approach are referred to as Pigouvian externalities.

Coase [33] presents an alternative perspective based on the theory of transaction costs. For Coase, the mere presence of externalities is not an adequate justification for external intervention. He argued that individuals can contract to resolve these externalities provided property rights are clearly defined and transaction costs are sufficiently low. Another important insight from Coase is that externalities have a reciprocal nature. If firm A's activities harm firm B, stopping A from conducting its activities ends up harming A. Thus, Coase argued that the economically efficient solution must consider the relative marginal values of both A and B's outputs. A blanket ban will result in inefficient levels of output. Thus, Coase argues that A and B could (and do) engage in negotiations to resolve the problem in mutually acceptable terms. Coase emphasized that all institutional choices to address externalities—including the choice to rely on the central government—incur transaction costs. These costs include information costs, costs of organizing, negotiation costs, and costs of designing policies and implementing them. Thus, proposals for an institutional solution of any type must be based on comparative institutional analyses that weigh the full set of costs and benefits of all institutional choices.

3.2. Ostrom and the Governance of Complex Global Externalities

Much like Coase, Elinor Ostrom was also a proponent of comparative institutional analysis as a better methodological approach for studying collective action problems. Ostrom contended that scholarly discussions on the topic tend to presume only two forms of institutions to overcome collective challenges—markets and states. In doing so, they ignore a vast diversity of institutions that did not fit within the narrow purview of formal markets or states. She argued that a policy analyst studying social dilemmas should consider the entire array of existing and feasible institutions, including but not limited to markets and states. Her analysis is especially relevant to the governance of complex large-scale externalities that do not obey strict political boundaries. Such externalities are intractable for a monocentric authority operating at a fixed governance level. Moreover, they may incur insurmountable transaction costs making Coasean solutions infeasible.

Ostrom offers a way out of the social dilemma [22]. She argues that what are commonly presented as large-scale externalities solvable only by the political authority at the highest level are, in fact, nested externalities. Externalities are said to be nested when decisions and actions taken within one decision-making unit affects other units organized at different scales [22]. Greenhouse gas (GHG) emissions provide a good illustration. Although GHG is often presented as a global commons problem, a number of actors at all levels are responsible for it. The actions taken by individuals, families, schools and universities, private firms, corporations, local governments, states, and nations affect GHGs released into the atmosphere. Thus, efforts to reduce GHG emissions must overcome not one but multiple linked collective action problems organized at multiple scales. Scaling up the problem to a global level to impose a singular solution, such as a blanket ban, may seem convenient, but they are guaranteed to fail for several reasons. Such solutions are unlikely to be received positively by constituents residing in many jurisdictions. Because decisions affecting GHG emissions are many, they are near impossible to monitor and sanction without the "buy-in" of participants at all levels. However, because the nodes of authorities are dispersed, solutions to such problems are likely to emerge at different levels. Ostrom proposed a polycentric approach, where multiple actors and organizations with overlapping jurisdictions compete and/or cooperate to offer diverse solutions to overcome a given collective action problem, as a viable route to overcoming such nested problems.

Externalities associated with nurdles share some of the same features of climate change and pandemics that have been used to characterize them as nested global externalities. Paniagua and Rayamajhee [5] define complex global externalities by the following features: (1) the externality involves an exceptionally large number of individuals at multiple scales; (2) identification of the causes of the externalities is challenging; and (3) discerning appropriate regulations is difficult. Scenarios characterized by the above features can be described as involving large transaction costs. Transaction costs are high because the number of parties

involved in decisions that affect outcomes is large. As the number of individuals rises, so do various forms of transaction costs: costs of information-sharing, setting agendas, organizing meetings, conducting elections, and so on. One way to minimize the costs of organization is by delegating decision-making authority to a higher authority. However, this leads to significant tradeoffs. Decisions made by a singular authority without adequate consultation or reasonable consensus increase the rate of noncompliance. Noncompliance is particularly costly if they have cascading effects, such as in the case of pandemics. Solutions that are viewed as coercive can lead to resentment and defiance, which is difficult to overcome once institutional trust is depleted. Instead, the nested externalities approach unbundles the singular collective action problem into multiple interlinked problems that can be addressed at different levels. The advantage of this approach is that it places less emphasis on scaling up the problem and relies heavily on citizen coproduction, while still allowing for limited scaling up depending on the specific features of the given externality.

Polycentric approaches are more effective at overcoming nested externalities challenges because they do not rely on a single authority. They harness markets, state capacity, and coproductive efforts of nongovernmental and nonmarket actors without requiring them to consolidate efforts. By allowing simultaneous policy experimentations at different jurisdictions and encouraging simultaneous technological experimentations in the private, nongovernmental sphere, polycentric approaches increase the chances for workable solutions to emerge. Moreover, because citizens have opportunities to devise imperfect but pragmatic solutions, they are more likely to trust each other and cooperate for collective action. They are also more likely to develop effective mechanisms of mutual monitoring and sanctioning necessary to prevent freeriding and solve collective action problems.

4. Fracking, Cracking, and Nurdles

4.1. Fracking

Here, we briefly introduce fracking, cracking, and the nurdles problem. Fracking is a process for extracting natural gas and oil from shale formations. The first commercially viable techniques were developed in the 1990s in Texas, USA [34]. Though drillers had known of natural gas deposits in shale formations for decades, they were notoriously challenging to extract [35]. A breakthrough came from drillers experimenting on an area known as the Wildcatter's Graveyard on one of the Texas shale plays. These entrepreneurial drillers were able to figure out how to make the water used in fracking slick enough so it did not clog up the machines used to inject water into the shale formations. This required the use of chemicals. This was a source of significant concern because many of the chemicals used would remain in the ground after the oil or gas was extracted from the shale, resulting in groundwater contamination.

The concern with groundwater is one of many negative externalities associated with the extraction of shale. Other documented externalities include environmental pollution in the extraction process [36,37], crime [38], risky sexual behavior [39], traffic accidents as a consequence of more trucking activity in areas with fracking [40], and declining housing values near wells [41] (For an extensive review of these externalities, see Piano and Murtazashvili [42,43]). There are also numerous positive externalities associated with shale gas development, including an increase in economic activities and associated benefits such as job growth and investment in public infrastructure [44]. As manufacturers switch to shale gas and rely less on coal and fossil fuels, it leads to a decrease in pollution [45]. Increased tax revenue from shale development can result in a decrease in property taxes and an increase in local educational spending [46]. Given these costs and benefits, the economically relevant questions for shale gas development are whether benefits outweigh the costs, and if they do, what the magnitudes of costs and benefits are.

Our view is that many conflicts over shale gas development are due to differences in its perceived costs and benefits across communities. This is different from the concerns raised about the "fractured" regulatory regime governing hydraulic fracking, but the two views are not inconsistent with each other. The Energy Policy Act of 2005 grants jurisdiction

over the oil and gas industry to individual states. So, a significant variation exists in the regulatory approaches adopted by different states. Naturally, this can be a potential source of interstate conflict. However, the conclusion that "unfracturing" the regulatory regime by scaling up regulations to the federal level resolves conflicts assumes away the heterogeneity in perceived benefits and costs, which are the sources of conflicts in the first place. Given the varying cost–benefit calculus across local-level jurisdictions, homogenizing the problem and imposing uniform regulations can further exacerbate tensions in many cases. This is not to say that problems should not be scaled up at all—instead, what problems should be scaled up (or down) and to what level depends on the specific attributes of the externalities and the institutions that exist to address them. There is a precarious tradeoff between disallowing conflict altogether by scaling up the problem and allowing states to devise conflict resolution mechanisms compatible with their own cost–benefit considerations.

4.2. Cracking

Fracking is followed by cracking. Ethane was previously an unusable byproduct of the natural gas extraction process. Innovations of "cracking" technologies made it possible to convert it to plastic. During the natural gas extraction process, ethane is isolated and transferred to petrochemical facilities, usually through pipelines. It is then split or cracked—hence the term 'cracking'—to form ethylene, a colorless hydrocarbon that is used to produce polyethylene, the most common form of plastic. The success of hydraulic fracturing and horizontal drilling resulted in vast quantities of inputs for plastic production. Thus, the fracking boom simultaneously triggered a plastic boom.

Every year, cracker plants produce millions of tons of polyethylene that are shipped to factories all over the world to make plastic products such as grocery bags, food packaging, keyboards, syringes, bottles, and toys. The Shell Pennsylvania Petrochemicals Complex (the Shell cracker plant) in Potter Township, Pennsylvania, alone is estimated to produce 1.6 million tons of plastic pellets—commonly referred to as nurdles—each year once in operation. We will delve more into the Shell cracker plant later.

4.3. Nurdles Pollution

Nurdles are the basic building blocks of all plastic products we consume. Every year, cracker plants produce trillions of nurdles, which are then shipped to factories to produce a vast range of plastic products. However, a small fraction of these nurdles, which still amount to a vast number because of the sheer volume of production, escape their production processes and make their way into our waters and land. These pellets can slip into cracker plant drains, spill out of cargo containers while being transported, or leak from storage facilities and distribution centers. Major accidental spills, such as the one that occurred on the Sri Lankan coast in 2021, can release thousands of metric tons into our oceans. Systematic data on nurdles are not available, but unofficial estimates suggest that about 200,000 metric tons of these plastic pellets infiltrate our water systems annually [1].

While valuable as inputs in the production of plastic products, nurdles in our waters are harmful to hundreds of fish species, other aquatic animals, and potentially to humans who eat fish [47,48]. We do not yet fully understand the scope of health hazards directly associated with nurdles. However, indirect evidence involving plastics suggests that they may cause suffocation, malnutrition, reduced mobility, and death for many marine wildlife species [49]. Nurdles have also been found to block the digestive tracts of fish and cause starvation.

5. Nurdles as a Complex Global Externality

5.1. A Large Number of Parties Contribute to the Problem

Although the full range of impacts of nurdles on human health is not well-understood, their effects on marine life alone have already presented a truly global-scale challenge. As one Guardian piece stated, "nurdles are everywhere" [50]. Fidra, a Scottish environmental group, found that nurdle pollution existed in 28 of the 32 countries they surveyed

(https://www.fidra.org.uk/about-us/our-impact/ (accessed on 20 January 2023)). Nurdles from the same spillage can travel from the Sri Lankan coast to the beaches of Corpus Christi, Texas, but discerning or proving their origins remains infeasible [51]. When the X-Press Pearl container ship caught fire and sank near the Sri Lankan coast in May 2021, 1680 tons of these pre-production plastic pellets were released into the ocean. The United Nations Environmental Programme (UNEP) called it the "worst maritime disaster" in Sri Lanka's history [52]. Following the disaster, billions of nurdles have been found in the coastlines of Sri Lanka, Malaysia, and Somalia. With that said, it is not an easy task to identify the exact source of nurdles; residual nurdles from all stages of plastic production processes ultimately find their way to the ocean [51].

Moreover, plastic producers and shippers are not solely responsible for the nurdles problem. The problem exists, in large part, due to increasing global consumer demand for plastic products [47]. Despite efforts by environmental activists to disincentivize plastic consumption, plastics are widely popular. They are ubiquitous in modern lives, and this is unlikely to change anytime soon. In theory, if consumer demand for plastics plummeted, cracker plants would go out of business. Even marginal reductions in consumer demand would lead to a decrease in the supply of nurdles.

A potential supply-side solution would be to restrict cracker plants from producing nurdles. However, given the increasing demand for plastic products, this will likely move cracker jobs abroad, potentially in countries with less strict environmental protection laws, and further increase the chances of them being released when shipped around the world. Spills will happen, regardless of the magnitudes of their private and social costs. Increasing marginal costs of spills and leakages through harsher penalties can potentially reduce spillover risks, but it would not eliminate the risks entirely. For instance, no restriction, penalty, or tax could have prevented the X-Press Pearl disaster. Moreover, they do nothing to address the problem associated with billions of nurdles that have already infiltrated our oceans. It is also unclear what the substitution effects of such restrictions would be. Given the rising demand for plastics, manufacturers will find ways to produce them, possibly using methods that have worse health and environmental effects.

Nurdle pollution is also driven by demands for jobs. For example, the state of Pennsylvania offered USD 1.6 billion in tax incentives to the Shell cracker plant to move to Beaver County because it would bring thousands of jobs and revitalize the local economy [53]. This incentive played a major role in Shell's decision to move to Pennsylvania and not to neighboring Ohio or West Virginia. Thus, citizens and their elected representatives, who weigh the costs of benefits of nurdles production, make decisions that affect the production of nurdles. The point is not to implicate citizens and their representatives but to highlight that different communities weigh the costs and benefits of the production of nurdles differently. These differential calculations limit the ability of a one-size-fits-all policy.

5.2. Complex Feedback Loops

The nurdles problem does not exist in a vacuum. It is part of a complex network of interconnected industries and consumers. Natural gas producers supply inputs to produce nurdles, but they are not the only suppliers. Nurdles and the use of plastics predate the rise of shale production in the United States. Prior to the shale revolution (and to an extent, even afterward), nurdles were produced using conventional oil, gas, and coal, all of which are associated with more harmful environmental and health impacts. Nurdle producers (cracker plants) are a small part of a vast network of industries that either produces plastic products or relies on plastics to produce final goods. Virtually every industry falls into one of these two categories. All nonindustrial organizations, including public and nonprofit organizations, the service sector, and voluntary, civic, and professional associations, are inadvertent contributors to the nurdles problem. Since individuals and families are the ultimate beneficiaries of all products and services, they, too, contribute to the problem. Governmental actors at all levels, including those who faithfully represent their constituencies and those who appease special interest groups and lobbyists, also play

crucial roles in mitigating or exacerbating the nurdles problem. Thus, decisions and actions taken by each participant in this complex nurdles network affects the costs and benefits for the rest of the network members.

5.3. Diversity of Regulatory Responses

There are no obvious regulatory solutions to the nurdles problem. Every regulatory solution comes with steep tradeoffs and potential repercussions spanning different sectors of the economy. For example, an outright ban on fracking imposed by the Federal Government has the potential to hurt residents of Beaver County, Pennsylvania, who rely on cracker plant jobs for their livelihood. A uniform policy solution is likely to lead to widespread public resentment and outcry in certain communities. Moreover, there are significant uncertainties surrounding the regulation of nurdles because we lack sufficient understanding of their effects on environmental and human health, and we do not know what policies would be effective in mitigating nurdle pollution. Thus, there is a dire need for policy experimentation to determine the relative efficacies of different policy approaches. Polycentric approaches provide the most viable pathways for constructive experimentation.

Furthermore, policy uncertainties are not limited to nurdles but pervade the governance of fracking broadly. Fracking policies vary tremendously across jurisdictions, in part because they affect the benefit-cost calculus of different jurisdictions differently. Variation in geographic features affects the profitability of fracking and cracking. For instance, proximity to groundwater determines their economic viability, so jurisdictions that stand to benefit from their proximity to groundwater may hold more favorable views than coastal counties with a vibrant tourism industry. Similarly, their effects on seismic activity are severe in Oklahoma but less severe in Pennsylvania [54]. Other factors, such as the level of urbanization, land use, environmental conditions, and economic factors, can influence their cost–benefit calculus. Given these differences, any policy, including outright bans, taxation, or production caps, is likely to result in separate groups of winners and losers.

Another crucial challenge in regulating nurdles pollution is to identify the relevant governmental level at which to design and implement policies. Nurdles travel freely in open waters, violating state and national borders. This has led to concerted efforts in the U.S. Congress to pass the Break Free From Plastic Pollution Act, which aims to regulate the discharge of nurdles into storm drains, waterways, or sewers. However, the political consensus at the national level is time-consuming, costly, and seems unlikely. Even if consensus is possible, it will likely result in implementation challenges, given differences in the valuation of the economic benefits of nurdles and the costs of nurdles pollution. Globalizing the problem similarly elevates decision-making and implementation challenges.

6. Polycentric Regulation of Nurdles

6.1. The Dutch Shell Cracker Plant in Beaver County, Pennsylvania

In this section, we focus on the Royal Dutch Shell cracker plant located in Potter Township of Beaver County, Pennsylvania. Potter is a small town with around 500 residents, just 30 miles northwest of Pittsburgh. Shell's new ethane cracker plant sits at the southern shore of the Ohio River and occupies 386 acres along the riverbanks. It is the first cracker plant to open in the Appalachian region of the United States. Like many Rust Belt communities in the region, Potter County was dealing with declining extractive industries. In particular, the community was grappling with the consequences of the closure of the Horsehead Corporation zinc smelting plant. The closure of the smelting plant was a major blow to the local economy, as it provided many jobs and contributed to the local economy. Thus, Shell's decision to establish the cracker plant in Potter was viewed favorably by many, despite the associated environmental risks.

Less than a year since it began its operation in November 2022, the plant has garnered both applause and fury [55]. The Marcellus Shale Coalition described the plant's inaugural day as a "historic day for Pennsylvania" [56], touting more than six thousand jobs it brought to the area. Citing many economic benefits, the state of Pennsylvania offered Shell

an estimated tax break of USD 1.6 billion. On the other hand, two environmental groups have already filed a notice of intent to sue the plant owners and operators for violations of the state's air pollution laws [55].

In addition to the USD 1.6 billion subsidy, Shell was attracted to Beaver County because of its proximity to the Marcellus and Utica formations, which would provide low-cost ethane to produce plastics. The plant uses roughly 100,000 barrels of ethane per day to produce 1.6 metric tons of polyethylene per year. The location also offers a strategic advantage because more than 70 percent of North American polyethylene buyers are located within a 700-mile radius of Potter [57].

6.2. Regulation at Multiple Scales

Regulatory authority over the Royal Dutch cracker plant in Potter is shared between the township, state, and federal governments. The Pennsylvania Department of Environmental Protection (PADEP) is the state's chief monitoring authority charged with regulatory oversight over the Shell cracker plant's operations. PADEP does so based on the national Ambient Air Quality Standards that are set by the Environmental Protection Agency (EPA). The EPA is the nation's federal agency tasked with all matters relating to environmental protection. PADEP is responsible for daily monitoring of plant emissions, reporting all emergencies and malfunctions, and testing and calibrating pollution monitoring equipment using a third party. PADEP's focus has been on air quality. It seems to have been actively fulfilling its duties, evidenced by a notice of violation it issued against the plant in December 2022, a month after the plant began its operation.

Potter Township has limited planning and regulatory capacity to deal with the challenges brought by the multi-billion-dollar plant in town. Despite sizable investment in the town, the township lacks adequate tax revenues to effectively regulate a large firm that forms the backbone of its local economy. However, what the township lacks in regulatory capacity and resources, it counters with commitment and coordination efforts. The township has set its own regulatory agenda based on its own valuation of the costs and benefits of the plant's operations. It has prioritized increasing local revenues, enhancing governance capacity, and holding Shell accountable to the community it is a part of. The township's top priority has been to balance the economic needs of its community with potential environmental and health risks from plastic production that may extend to neighboring communities. To that end, the township has already initiated cost-sharing measures with neighboring communities. The Potter Township Board of Supervisors incorporated community engagement as a core part of their strategic planning to tackle some of the environmental challenges that come from having a large-scale plant in town. They frequently conduct hazardous waste collection events, and recycling efforts and organize public meetings to gather feedback. They have also made concerted efforts to enhance cross-municipal relations [58].

Analysis of the regulatory landscape pertaining to the management of environmental problems in Potter—and Pennsylvania broadly—reveals to us the following features of polycentric governance: (a) there exists a significant disagreement of the valuation of costs and benefits of large-scale investment projects; (b) different levels of governing authorities share overlapping jurisdictions over environmental protection matters; (c) each level of authority contributes to mitigating environmental challenges by bringing in different knowledge and strengths, and (d) communities develop inter-municipal relations and coordinate their efforts to manage shared resources and address mutual challenges. Although the above analysis does not only relate to nurdles, it also shows that complex, large-scale challenges cannot be aggregated into a singular level and addressed by imposing a lump-sum policy for all constituencies. The residents of Potter and similar cracker plant towns regularly engage in policy experimentation and develop horizontal and vertical relationships based on shared interests to address multi-layered challenges. Over time, similar coordination efforts and successes could emerge from these experimentations that may help us avoid the tragedy of the nurdles.

6.3. Coproduction of Solutions

One important feature of the nurdles problem is that its solutions require coproduction. The notion of coproduction describes a situation where public goods cannot be provided by the state or any unitary authority alone. Inputs from the intended beneficiaries of the goods are necessary ingredients for the production, provision, and maintenance of the goods [59,60]. The concept has been used to describe the role of citizens and civil society in overcoming collective action problems related to post-disaster recovery and pandemic governance [27].

Consider the challenge of monitoring nurdles. Nurdles are tiny plastic pellets that can easily escape one's attention because of their color and size. Unless one is actively looking to find them, people can confuse them for pebbles or large chunks of sand. For a central governing authority to effectively monitor nurdles from spills or leakages would require a large, well-staffed department with branches scattered all around the globe. Even if a financially unconstrained nurdle police force exists to collect nurdles, finding them is just one of the many monitoring challenges. Effective monitoring requires developing methods and technologies to identify their sources and coordinating across jurisdictions to punish violations.

There are ample examples of citizen input in overcoming monitoring challenges. Oceanographer Mark Benfield has been researching nurdles for a long time, mostly on the Mississippi River. He uses a spectrometer to determine their chemical composition and track their origins. This has been possible because of cooperative efforts from various partner organizations and individuals. Voluntary advocacy groups such as the Concerned Ohio River Residents (CORR) and Eyes on Shell have emerged to raise funds, improve our scientific understanding, and raise public awareness regarding the effects of petrochemicals (https://www.concernedohioriverresidents.org/ (accessed on 1 February 2023)). Researcher and activist Jace Tunnell founded the Nurdle Patrol citizen science project, which recruits hundreds of volunteer citizen scientists to count nurdles on their local beaches and submit their data to a group of scientists who analyze them to better understand the scale of the problem. Nurdle Patrol has partnered with over 200 different organizations, including private and public universities, environmental groups, state and federal agencies, and private foundations, to raise funds and public awareness [61].

All the above efforts from private individuals and organizations show that, although the state or federal environmental protection agencies may have a crucial role to play in managing nurdles externalities, they are limited in their ability to do so without appropriate vehicles for inputs from citizens. The coproductive nature of the global externalities problem and of its solutions means that any program or policy that disregards or crowds out private entrepreneurship and citizen participation will likely exacerbate the problem.

7. Conclusions

Complex global externalities often lead to calls for centralized, global solutions. In this article, we have argued that such calls tend to overestimate the effectiveness and benefits of global governance and underestimate the costs of large-scale coordination. An emerging literature on the polycentric governance of global externalities takes these costs of coordination seriously. It provides a viable policy path that permits (or even encourages) the possibility of large-scale coordination but does not rely on them. This literature presents global externalities as an array of nested externalities problems that are organized at different levels and are interlinked with complex feedback loops. In line with this emerging literature, we argued throughout the essay that the nurdles pollution problem can be better understood and addressed more effectively using the polycentric approach. We show that the nurdles problem is similar to global externalities such as greenhouse gas emissions (GHGs) and pandemics, where global governance is extremely costly and even infeasible, given the evolving nature of externalities, technological changes, and shifting boundaries.

We showed that the nurdles problem shares the same set of defining features of a complex global externality: a large number of parties contributes to the problem, complex feedback loops across different levels exist, there is a great diversity of responses by actors at different levels, and the nature of externality evolves in a manner that makes governance at a static political level challenging. These factors make it extremely difficult to design and implement a uniform solution to the problem. Thus, we make a case for a polycentric approach that does not offer an explicit, readily implementable solution but provides a framework to consider a wide diversity of institutions interacting in complex causal pathways to generate different sets of incentives for actors interacting at different levels. Although our approach does not rule out the necessity and/or possibility of a large-scale solution, it acknowledges the difficulties of coming up with a solution and does not presume that such a solution, even if feasible, would magically eliminate the problem. Finally, using the case of the Dutch Shell Cracker plant, we illustrate the role of citizens in coproducing solutions and the ways in which multiple organizations contribute to crafting solutions. Since many other communities have welcomed cracker plants, there are many opportunities to extend the case study presented here to understand the extent to which citizens can respond to the challenge posed by nurdles as well as ways in which government regulations at multiple scales can enhance and complement citizens' efforts to address complex externalities.

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