

## After the Perfect Storm: Learning From Disruptions in Maine's Materials Management System

BRIEANNE BERRY, CINDY ISENHOUR, JEAN MACRAE, ERIN VICTOR, TRAVIS BLACKMER, JARED ENTWISTLE, LINDA SILKA, MICHAEL HAEDICKE, SUSANNE LEE, AND DEBORAH SABER

University of Maine, Orono, ME, USA

Email: brieanne.berry@maine.edu

**ABSTRACT** Recent disruptions in waste management, including the COVID-19 pandemic and China's decision to limit waste imports from the United States, have shocked materials management systems across the United States. In Maine, these disruptions have been exacerbated by significant disturbances in the state's waste management infrastructure. These shocks, emerging on multiple scales, combine to strongly impact Maine's communities. Drawing on interviews with stakeholders involved in waste hauling, processing, outreach and education, as well as state and municipal government. Our paper explores how participants are leveraging these experiences to envision a more resilient materials management system for the state. However, as this case study illustrates, the complexity of materials management systems means that there is no single solution for ongoing, emergent, and unforeseen disruptions. Our research identifies tensions related to how to define system boundaries, the respective roles of the government and markets, issues of scale, and the dual need for both centralized and distributed solutions. Our exploration of materials management disruptions in Maine demonstrates the complexity of building and managing systems that attempt to balance the social, economic and ecological dimensions of materials management systems.

**KEYWORDS** materials management, waste, waste management, United States, recycling

### INTRODUCTION

In the early months of 2020, the world was gripped by the COVID-19 pandemic, reeling from the disruptions it brought. But for Maine, where this case study takes place, the pandemic was just the latest in a series of challenges for the state's materials management system. Materials management systems include the people, organizations, facilities, and institutions responsible for handling (and preventing) waste. These actors have faced challenging decisions about infrastructure investments, instability in global recyclables markets, and changes in international trade policy in addition to the pandemic. These disruptions have made it difficult for materials managers to figure out what to do with waste streams that continue to grow even as the options for processing those materials are constricted.

This case draws on interviews with Maine materials management stakeholders to explore the disruptions to

Maine's materials management system. We ask what we can learn from these disruptions for, if the past is any indicator, there are further disruptions to come. In the following sections, we will describe Maine's materials management system and the challenges the system has experienced over the past decade. We will then explore how stakeholders experienced recent disruptions and how they envision potential solutions. Our work suggests that there are conflicting visions of what a materials management system should look like, and that these visions are underpinned by different value systems. We end by considering emergent policy tools that have the potential to remake materials management systems in Maine and beyond.

While our case focuses on the disruptions experienced by materials management stakeholders in Maine, we note here that many stakeholders framed their responses to these disruptions—and future visions of materials

management in Maine—in terms of sustainability and resilience. We recognize that these terms have long and varied histories in the academic literature [1], and distinct definitions. Exploring the epistemological roots of “sustainability” and “resilience” is outside the scope of this paper. Instead, we share our stakeholders’ understandings of these terms in reference to disruptions in Maine’s materials management system.

## CASE EXAMINATION

### Overview of Materials Management

“Materials management” is an important part of society’s production and consumption systems. Traditionally represented linearly (see figure 1), going from resource extraction and processing, to manufacturing, transportation and retail, consumption, and disposal, this system consumes water, energy, and nonrenewable resources and emits pollution at each stage. If the system is *circularized* by recapturing materials for reuse (recovery and reuse in the same form) or recycling (recovery and reprocessing to raw material form), materials, energy, and water inputs can be reduced, and pollution can be minimized [2]. Circular systems also reduce the rate of resource depletion and support a hierarchy of reduction, reuse, and recycling of materials in that order.

### Conditions in Maine

Maine is the northeasternmost state in the United States, with a population that is more rural and elderly, on average, than other states [3]. With a well-documented culture of reuse [4], many Mainers pride themselves on a waste-not mentality that contributes to some of the lowest waste generation rates in the country [5]. Maine’s materials management “system” is, in reality, a complex assemblage

of people, organizations, institutions, businesses, and infrastructure that interact to move objects through different pathways depending on their value, location, physical attributes, available markets, and associated policies and regulations.

Many decisions about materials management in Maine are made at the municipal level, where resources and infrastructure vary enormously. Some towns have—or share, through regional cooperatives—a transfer station where residents drop off materials which are collected and stored until there are enough to sell or ship. While transfer stations are common in rural parts of the state, many towns in more populous areas contract with haulers for residential curbside pickup to move waste and recyclables to regional disposal or recycling facilities (see figure 2).

The state hosts numerous food diversion operations, some operated by towns and many more by private businesses. Within the state, there is an array of waste processing infrastructure including three waste-to-energy (WTE) incinerators, eight active landfills, and one innovative materials recovery facility with recyclables, fiber and energy recovery which was closed at the time of our writing. Hazardous and biomedical wastes must be exported from the state. While materials management systems are intended to prioritize management strategies based on “delivering the best environmental outcome” [6], in practice, decisions about how best to manage materials are influenced by costs, power, politics, infrastructure, and emergent local and global events that shape ideas about risks and the various benefits of diverse strategies.

### Maine’s Materials Management Disruptions

There is a long history of leadership on materials management in Maine (see figure 3 for timeline). The state’s

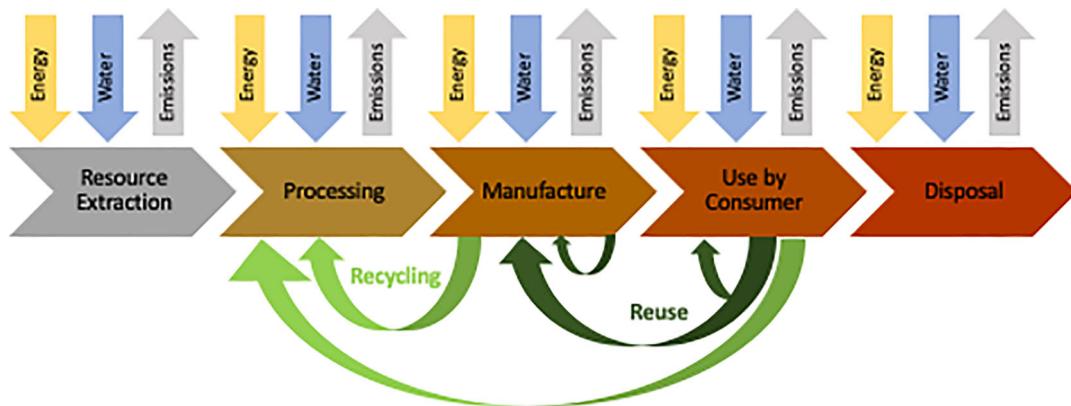


FIGURE 1. Materials flow through the production and consumption system.

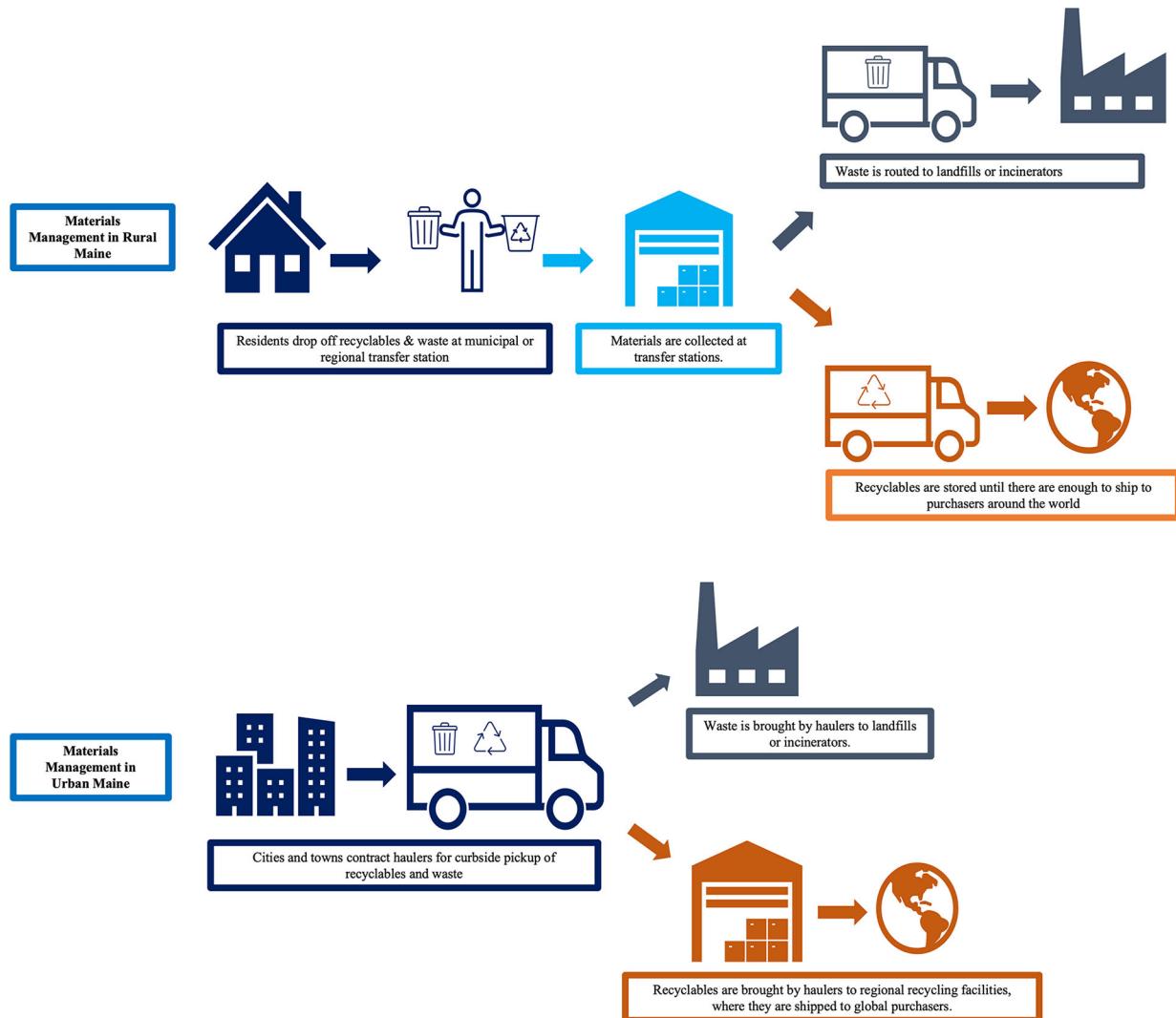


FIGURE 2. Materials management systems in rural and urban Maine.

expansive bottle bill was one of the first in the country [7], and Maine was the first in the nation to implement extended producer responsibility for electronic waste [8], a policy that holds producers responsible for end-of-life management for the electronic goods they produce. Maine was also the first in the nation to pass legislation to create an extended producer responsibility system for packaging [9], and recently rolled out a statewide ban on plastic bags [10]. Yet, despite significant advances and steps toward progressive, meaningful action on materials management, Maine has been roiled by a series of events that call into question the resilience of its system (see figure 3).

The disruptions described here are not an all-inclusive accounting of threats to materials management systems in Maine, but they do provide a sense of recent issues faced

by Maine's waste managers, painting a picture of a system in constant flux.

Yet, if the challenges are diverse, so are perspectives on how to best respond to these challenges. This paper draws on 6 years of stakeholder-engaged work by our interdisciplinary team as well as a series of interviews with 14 individuals involved in materials management systems in Maine. Our sample of participants while not representative of the state's materials management system as a whole, was drawn from municipal officials, waste haulers and processors, as well as representatives from state and local government. This range of perspectives allows us to gather insights into the impacts of disruptions in Maine's materials management system across scale and inclusive of varying perspectives.

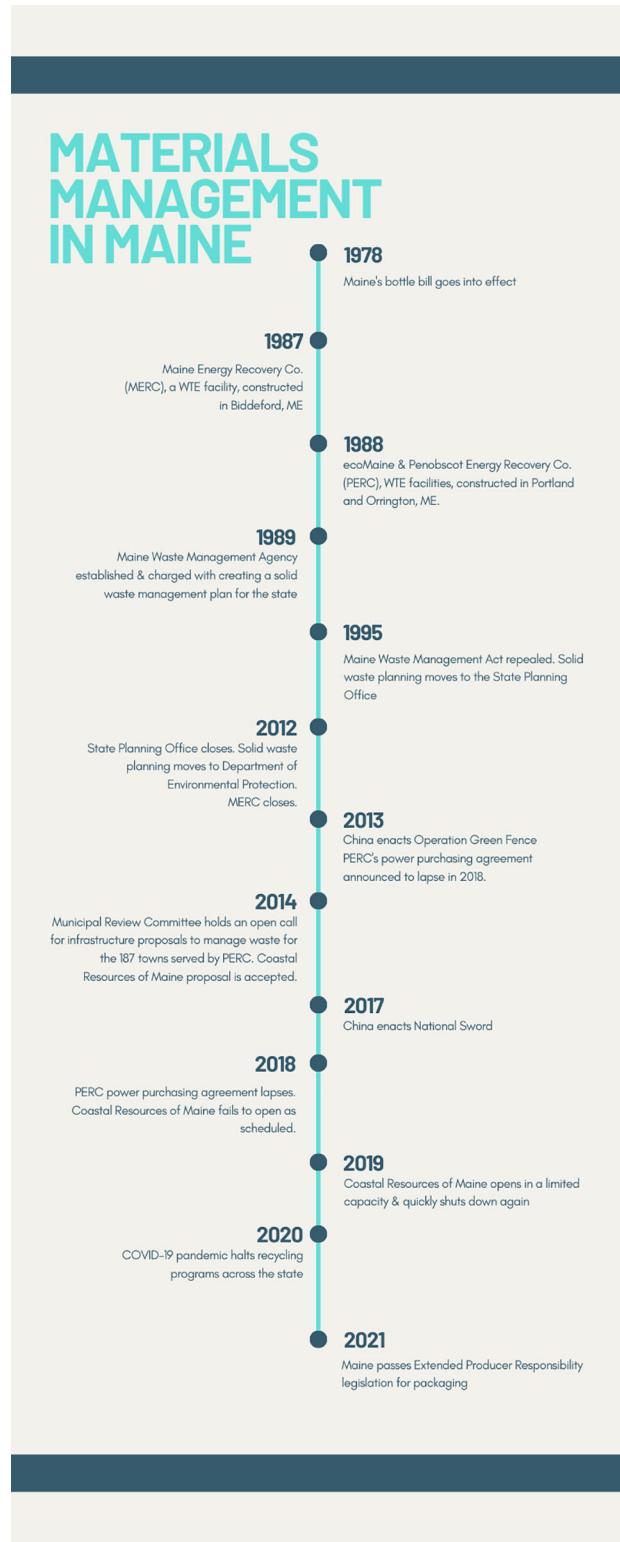


FIGURE 3. Timeline of materials management in Maine.

Interviews lasted approximately 1 h, were conducted via Zoom, and were recorded with the permission of participants (IRB#20210119). Our discussions with these

key actors in Maine's materials management system focused on exploring the impact of recent disruptions, the state of Maine's current materials management system, and what a future might look like for materials management systems in Maine.

**DISRUPTION: UNSETTLED INFRASTRUCTURE.** In 2013, Maine's materials management infrastructure experienced significant upheaval. A long-standing power purchasing agreement was scheduled to elapse in 2018, which had previously made the Penobscot Energy Recovery Company (PERC), a WTE incineration facility, the most economical option for managing waste for 187 Maine communities. PERC received favorable rates for the electricity generated from incinerating waste, which allowed for lower waste processing fees for municipalities. With the impending end of this agreement, however, the cost for municipalities to use this facility was set to increase substantially. Given these projections, the 187 communities that sent their waste to the incinerator sought to develop an alternative that would allow them to meet their needs, support waste reduction, reuse, and recycling, and keep costs affordable.

The communities held an open call for infrastructure proposals in 2014, which led to dozens of submissions. After review, the communities settled on the development of what was eventually named the Coastal Resources of Maine facility, which would use novel processes to sort recyclables, recover fibers, and create energy from paper and organic materials through a proprietary process. While this approach had been used in a small test facility in the United States, and had been reviewed and vetted by experts in pulp and paper engineering fields, the technology had not been deployed at scale [11]. Importantly, Coastal Resources of Maine encouraged municipalities to shift to a “one bin all-in” system, where waste and recyclables were mixed together in the same bin rather than being source-separated. Coastal Resources of Maine offered a service that would separate these materials and find the best use for them without requiring source separation. This represented a significant change for most municipalities, whose residents had been accustomed to separating recyclables from waste—a behavior that had taken time and effort to teach and practice successfully.

Coastal Resources of Maine was intended to open in 2018, however, a number of factors, including construction delays, financial issues, legal disputes, weather, and

technical and political obstacles, significantly delayed its opening [12]. As one stakeholder described to us “it had 2 years of delays, whether it be the construction—they switched contractors during it—whether it be the permitting or whatever it was . . . they went through 2 years of delays, which they hemorrhaged their funds.” When the facility did not open as planned in 2018, municipalities that had contracted to send their waste to this new plant instead had to send their materials to an emergency bypass location—a landfill located 65 miles away from the new facility. When the facility finally opened in a limited capacity in 2019, over a year late, it quickly shuttered again due to financial and technical issues [13]. Unable to raise the funds needed to operate at scale, the facility was put up for sale, again leaving its member communities to utilize the bypass landfill [14].

These disruptions put stress on communities, haulers, and various waste disposal sites as materials managers scrambled to find economically and environmentally viable solutions to deal with the unexpected waste stream. The future of the facility remains uncertain, as a recent effort by another operator to purchase the plant fell through [15]. While some stakeholders we spoke with were supportive of the innovative technology, they also made it clear that good technology alone couldn’t make the plant run. One stakeholder told us, somewhat ruefully, “there’s a new organization coming in [ . . . ] And hearing their background, it’s a little concerning because they haven’t operated a commercial facility. So I think there’s still a lot of speculation as to—are they really going to be able to make it work? [ . . . ] Is somebody else really going to be able to step in and secure that disposal facility for the [ . . . ] communities that are set to go there?”

While disruptions in local waste infrastructure have significantly impacted Maine’s materials management system, materials managers have also been confronted with massive changes in the global market for recyclables.

**DISRUPTION: SHIFTING GLOBAL MARKETS.** From 1995 until very recently, China led global waste imports [16], accounting for nearly half of all waste imports globally, and over 70% of plastics imports by volume [17].

Imported waste products were recycled to be used as feedstock for production processes. Dramatic growth in global waste exports [18] since the early 1990’s, in combination with the problem of recyclables “contaminated” by trash [17], led China to limit waste imports through

increasingly strict regulations. In 2013 China enacted Operation Green Fence (OGF), with a goal of enforcing its existing policies related to imports of hazardous waste materials. OGF was announced and implemented in February 2013, and “waste exporters learned of the intervention on the day it was launched,” [19] taking global markets by surprise. OGF lasted 10 months, ending in November 2013. Operation Green Fence strictly enforced existing laws that limited the allowable contamination of recyclable imports. Given China’s significant role in the international waste trade, OGF had widespread impacts on global recycling markets [16–18].

The disruptions from Operation Green Fence served as a prelude to further upheavals as China further restricted imports of waste and recyclables in 2017 through a policy known as National Sword. The National Sword policy banned the import of a broad range of materials from all sources, including mixed paper and mixed plastics [20]. The policy also significantly reduced allowable contamination in recyclables, from 1.5% to .5% and imposed tariffs on specific recyclable products originating from the United States [20]. As a result of National Sword, China reduced its import of mixed plastic waste by over 90%, and of mixed paper waste by over 50% [21], causing “dire” impacts at the local scale in the United States, where recycling and waste programs are typically managed [22]. Indeed, one of our stakeholders told us that “as soon as the National Sword came along—I mean the bottom fell out” of recycling markets. As recycling facilities scrambled to meet the .5% contamination threshold or find new markets for their recyclable materials, many program managers saw their recycling programs go from income generators to expensive line items not accounted for in the town budget. These market changes required municipalities to make difficult choices about the sustainability of their recycling efforts. One municipal official told our team that “we are paying 344 times what we normally would pay to dispose of recycling. So our costs have gone up considerably. The number of materials we are accepting has also gone down. We know that this is likely not a temporary change either.”

As shifting Chinese policies have diverted materials to new markets, other countries have also begun to alter their policies on waste imports. For example, in 2020, South Korea placed restrictions on waste paper and PET bottle imports due at least in part to increasing rates of

contamination [23]. Like the rollout of Operation Green Fence, these recent changes in South Korean policy were made with little advance notice, presenting planning and logistical issues for global flows of recyclable materials. Global market disruptions are continuing to affect municipal materials management in Maine, as described by one of our stakeholders: “The single stream recycling really worked great for years until China stopped accepting the material and National Sword dropped and then all the other countries decided it was time to also follow suit. So that had a big ripple effect on every part of the recycling markets.”

Even as materials managers in Maine sought to deal with challenges associated with global market changes and infrastructural uncertainty, new disruptions continued to emerge, including the COVID-19 pandemic, which had nearly immediate impacts on materials management in Maine.

**DISRUPTION: COVID-19 AND EMERGENT THREATS.** The recent history of challenges to Maine’s materials management system suggests that uncertainty and upheaval are characteristics rather than accidents in the system. This idea is supported by recent disruptions due to the COVID-19 pandemic, which injected further uncertainty into an already precarious system. As one stakeholder noted with some frustration, “I’m trying to be an optimist!—It’s a little bit discouraging because there is so much unknown between where we’ve been, where we’re going, COVID impacts . . . So I’m not trying to be a pessimist, but there’s just this sense of holy cow, what next? What’s the next shoe that’s going to drop?” The pandemic stressed systems in multiple ways: in many locales, COVID-19 infections among workers created labor shortages [24], while budget shortfalls related to the pandemic (combined with rising costs for recycling and materials management) meant that many municipalities chose to cut services deemed optional, like recycling programs [25]. As one of our stakeholders describes, in the early days of the pandemic “there was a lot of fear about handling and [ . . . ] a lot of transfer stations shut down their programs for a period [ . . . ] And I wouldn’t be surprised if some still are [shut down].” Another stakeholder confirmed this fear, telling us that “for a while, a lot of towns said we’re not going to recycle because we’re scared of the virus.” These challenges were exacerbated by rising and shifting waste streams, as social distancing, personal

protective equipment, and online ordering became de facto strategies for risk reduction among large population groups [26].

#### **REIMAGINING MATERIALS MANAGEMENT SYSTEMS.**

The materials management professionals and municipal representatives we spoke to often referred to this confluence of disruptions as “a perfect storm” that created serious problems in materials management systems. As municipalities decided to abandon unprofitable and increasingly expensive recycling programs, and as COVID-19 created a boom in the disposal of single use packaging, discussions about what Maine’s materials management system should look like and how to achieve those visions were suddenly of greater interest.

In what follows, we draw on interviews with materials management stakeholders who occupy a variety of positions in the overall system. While our interviewees are not necessarily representative of the whole materials management community in Maine, our conversations help to illustrate tensions in the ways that people prioritize materials management goals. These tensions are underlined by different conceptualizations of system boundaries and value propositions that depend, in part, on an individual’s position and experiences in Maine’s materials management system. To help illustrate these positions and tensions that emerged through the interviews, we construct three materials management typologies<sup>1</sup> that maximize difference [27].

#### **Centralized Planning and Systems Thinking**

James is the city manager for a small town in mid-coast Maine. He came to the town after having held several other positions in municipal and town management. While the duties of a town manager are extremely varied, James told us that waste is an ever-present and perpetual problem. In his 20+ years in municipal management, he has seen several major challenges to Maine’s waste management systems but thinks things are particularly bad at the moment. He said, “personally, I think that materials management in Maine is sort of at a crisis point . . . primarily because the options are dwindling . . . and the fallback becomes the least tenable alternative, which is landfilling.” In addition to disruptions tied to

<sup>1</sup> The three “ideal type” respondents featured here are composites of several participants. Due to the small size of our sample, we use this strategy, mixing the personal details of multiple participants, as well as pseudonyms to ensure participant confidentiality.

international markets and COVID-19, James felt strongly that the state's contract with the operator of the state landfill provided too much power to the operator and created perverse incentives for waste reduction. Once state subsidies for the PERC incinerator expired and communities split on where to send their waste, some facilities didn't have enough waste to support their operations and began importing waste from Massachusetts and as far away as Ireland to continue to fire their boilers or make payroll at the landfill. "It's like crisis management at its worst," said James. With recycling so expensive and the failure of the Coastal Resource of Maine facility, all the options were "so expensive that they're not affordable"—except for landfilling, which was, according to James, artificially cheap due to the management contract at the state landfill. When Coastal Resources of Maine failed, the next best option for James' town was to have their recyclables incinerated (which, during the pandemic, the state counted as recycling). For James and many other municipal managers, costs determine their actions, regardless of their support for environmental protection or concerns about local jobs at waste processing facilities.

In James' assessment, the problem stemmed from a lack of planning and systems thinking. James reflected, "we really should have thought this over a lot more before we said the free market can package anything any way it wants to . . . we'll just take care of it for you." When asked to reenvision materials management in Maine, James argued that an improved system would be affordable for the municipalities and would be well planned and coordinated so as to support Maine's waste hierarchy. James reflected, "I think that a system would include strong product stewardship. I think it may include some sort of subsidy for the more expensive processing methods that are better for us environmentally. That gets us up the hierarchy of it. And I know that—subsidy?—that's terrible, but in essence we are subsidizing the landfills."

The recent problems in Maine, James argued, presented the perfect opportunity to look at the whole materials management system. Rather than individual pieces that "are not well coordinated," James argued that there needed to be a systematic effort to assemble those pieces into a working system. That solution, however, would take significant state intervention, investment, and considerable political will. Without those interventions, James argued, "it's not going to happen."

#### Good Data and Collaborative Infrastructure

Gwen has been involved in Maine's waste management landscape for most of her professional life, working in a variety of positions at landfill operations, waste transportation, and now in the management of a processing facility. She argues that the simplest solutions are always the most resilient. They can really "take a beating and come back and still do what it was meant to do." In the case of waste management in Maine, Gwen feels the most resilient option is landfilling. Ironically, according to Gwen, as you move up the hierarchy, the complexity makes the process less resilient. She observed, "a couple of things happen when you tend to go up the hierarchy, and that is the level of complexity increases and usually the costs associated with the technology or the result for each rung increases." When costs increase, it is difficult to compete with the low price of a landfill. But just because landfilling is a resilient processing solution, Gwen argued, that doesn't necessarily mean it is the most desirable. Our interview with Gwen focused on the importance of building a system that includes options for all types of waste, is distributed, and can support the waste management hierarchy.

Having been involved in some significant turbulence in waste processing contracts at her facility, Gwen reflected that operations and maintenance at recovery facilities require steady flows of waste to keep the operation viable. She tells us, "we have run into times where we haven't had enough material and we haven't had material in the quantities that were at the prices needed to support this operation. That's really one of our big challenges, is to make enough money to keep this thing going." The pain of having to lay off staff, cut hours, and completely redesign already existing processing equipment seemed apparent in Gwen's voice as she talked about how different waste management operations are often in direct competition. Part of the problem, in Gwen's perspective, is the competitive environment. She imagines a more resilient system built on cooperative agreements, where one process can fill in for another and provide redundancy in the system.

She told us that building a robust system meant not just looking at the various processes but the system as a whole. She said, "part of a resilient system isn't only just all individual components but it's the entire infrastructure itself. So if you have a contraction in one part of the infrastructure, say recycling, the wrong reaction is to

say, ‘well, the hell with it, let’s just do away with our recycling programs.’ Really, the way [...] to go forward is to say, let’s keep those systems in place so that long learned behavior—and it took a while for people to learn how to do that—you don’t have to go through all that all over again so that the system is ready to jump start whenever you replace the batteries.”

For Gwen, the most important consideration for improving resilience was establishing a distributed and coordinated infrastructure that could “move the material to its highest use.” She argued that all facilities have their place because not all forms of waste can be recycled or incinerated. But to get there, Gwen argued, two things are necessary: good data about the whole system and policy support. She advocated for data collection to understand more about the waste being generated. With this information, there is a greater chance to prevent waste and ensure that recovered materials are processed as high up the hierarchy as possible. She argued that we need to better understand materials markets and waste generation patterns—“how these supply chains and systems actually work rather than how we want them to work.” Gwen concluded, “In the long run any systemic change which would actually bring truly more meaningful material into play, higher up in the hierarchy, would require policies that have a little bit of teeth in them to try to get them there.”

#### Local Self-Reliance and Innovative Systems

Mark works for an organization that provides a wide array of waste-related services from environmental education and market analysis to assistance with regulatory requirements. He works with many people throughout the state and is acutely aware of the unique challenges associated with materials management in different communities. Mark commented, in particular, on the dramatic impact of China’s policies restricting US exports of recyclables and the need for local solutions. He said, “I think the China thing was the biggest thing. I think we need to instead invest in local infrastructure. We need to forget about China and all of that. Who is the end user? How much volume can we supply and [...] what can we get in grants and finances so that we can put them next door to us or within striking distance so we can eliminate all that, the guy in the middle, the transportation? And then what does that do for the carbon footprint and all that type of thing too?” Indeed, Mark was not the only participant to

suggest colocating businesses that produce or process waste products next to those that can take the materials as inputs for new production.

Localized self-sufficiency was a common theme in interviews. As with Mark, many folks argued that highly unstable global markets will continuously insert risk into materials management systems. For these folks, the idea of creating local infrastructure to reuse discarded materials had the potential to keep valuable resources in circulation locally. Another participant echoed Mark saying, “I love the idea of being able to think of what we currently characterize as waste as a resource. And what do you do with that resource? How do you best manage that? Can we use our local talent to figure out something creative to do with it? So let’s do it here rather than having to ship it somewhere and have them create the product out of what we have.”

For Mark, the development of local capacity and processing resources at the local level required innovation and creative thinking. He said, “Thinking outside the box. That’s what these towns need to do... Innovation and creativity. That’s it. And that’s [...] the only way Maine’s resiliency is going to happen [...] You have to have—you’ve got to be thinking outside the box. We talk about resilience—somebody has got to be willing to take a chance and to invest in new technologies and new ways of doing things. And we can’t just keep waiting for somebody else to do it. You know, we’ve got to step up.”

Mark’s experience working with local communities led him to believe that there was unlikely to be a single solution that would fix Maine’s materials management system. Instead, localized grassroots efforts and entrepreneurship are required. This is in part because Maine is characterized by more densely populated communities on the southern coast and very sparsely populated western mountains and northern agricultural communities. The solutions that work in one area, he argued, are not likely to work in all. He told us, “when I think about resiliency—I think less about just passing regulatory efforts at the state level and more about trying to build the capacity and the resources at the local level.”

**TENSIONS AND TRADE-OFFS FOR THE FUTURE.** It seems clear that Mark, James, and Gwen—along with our other participants—agree that Maine’s current materials management system is far from ideal. It is also clear that there are multiple ways of envisioning a future system by those

who occupy and are so familiar with Maine's waste landscape. James's frustration with being unable to find the money to do the right thing at the municipal level led him to advocate for stronger state investment and intervention. Gwen's experience competing for trash led her to think about how we could build cooperative and complimentary waste management data systems and infrastructural capacity. Mark's experience working with municipalities across the state left him skeptical of both international markets and one-size-fits-all solutions. For Mark, an improved system would be local and based on grassroots creativity and entrepreneurship.

In part, these tensions depend on the *geographical* and *temporal boundaries* one sets. Some seemed to talk about the short-term operations of a particular facility, or even the infrastructure as a whole. As Gwen said, "A landfill is simple. You put it in the ground and the belief is, you know, at least at that point in time that that's the end of it." Others used broader time scales to think about the system's sustainability. Those participants were more likely to imagine solutions linked to supporting the waste hierarchy by reducing waste generation in the first place and trying to ensure that Maine's systems make the best use of all materials. Others seemed to impose geographical boundaries on their thinking, imagining how Maine's system could create local solutions for materials reuse and separate itself from dependence on global markets, while supporting local livelihoods. Still others argued that this local approach was not tenable in a global marketplace that empowers producers to package products how they like and consumers to choose freely. From this perspective, the boundaries of systems must be drawn wider not more narrowly. For example, one participant pointed to factors that can't be controlled locally. He said, "we keep looking at this from the back end of this animal. The consumer end is the front end where all of this stuff comes in. And changing the appetite of the animal might—make an outcome on what comes out the back."

Not only do geographical and temporal boundaries influence how one thinks about building a system to withstand disruptions but so do *underlying value propositions* tied to social, economic and environmental priorities. Some respondents clearly felt that nothing would work unless systems were economically viable. Indeed, many facilities and municipalities are forced to simply focus on the reality of keeping their operations afloat.

This can create competition that is reliant on growing waste streams—in opposition to environmental goals. When municipalities see no other choice but to go with the lowest cost option, the focus on economic terms alone can distract them from solutions that might also have the potential to create good local jobs or to process materials in ways that contribute to environmental health. As one participant argued "a landfill really only requires like two, three, four people [...] But when you look at recycling systems, you need a lot more people to make that operation go [...] So it's more resilient for jobs. It helps have more job security. And, you know, there's only so many certainties in life. And I think waste is one of them. We're always going to have to deal with it somehow. But the ways we do choose to deal with it could be made more sustainable and more resilient for sure [...] it can't always be about the value; we need to look at the right solution."

For some participants, "the right" solutions were linked to environmental values, ensuring that materials were utilized to their fullest potential, and that pollution is reduced. One participant remarked, "So for me a resilient system would be [...] high quality processing mills appear again in the state with the mind towards environment and in protecting water."

Contrasting system boundaries and value propositions in participant conceptualizations of resilience certainly led to some tensions that became increasingly apparent as we analyzed the interview transcripts. Most notable were tensions between local solutions and ensuring that solutions operated at a scale capable of addressing larger systemic issues. Some participants rejected "one-size-fits-all" state level policies, arguing that oftentimes, "one size doesn't even fit one," and instead advocated locally appropriate solutions to improve community development and self-sufficiency. Others rejected that approach arguing that unless state or federal policies intervene there is very little that can be done to reduce the flow of waste into the state or ensure that it is processed so that value recovered can be maximized. One town manager argued that until producers are required to ensure that the materials in their products and packaging can be recovered, it is unlikely to happen. He said, "producers aren't just going to voluntarily do this stuff [...] I really think that states are going to struggle until we get a national - a national policy that's going to work better [...] I think it takes legislation, it's going to take more than just a local effort."

## CONCLUSION

The major disruptions to Maine's materials management system over the last decade provide an important backdrop to recent policy shifts in the state in the past year. The disruptions explored here highlight how uncertainty is a characteristic of the complex, dynamic system of how materials move in and out of Maine—rather than a series of external accidents happening to an otherwise perfectly functioning system. Faced with infrastructure challenges, unpredictable global markets, and inconsistent materials management capacity, Maine has felt first-hand the difficulties of managing materials at the end of their lifespans rather than moving upstream to manage materials when they are produced. An important lesson learned from these disruptions is that placing full responsibility for managing materials on the consumer can prevent environmental goals from being met, especially for Maine's small and remote communities.

We heard from our stakeholders that pushing materials management upstream—toward policies and programs that reduce the amount of waste generated and help redesign products to be easily recyclable—would result in greater efficiencies and potential for greater investment in recovery. Shifting to managing materials at the “front end of the animal,” “where all of this stuff comes in,” as one of our stakeholders put it, “might—make an outcome on what comes out the back.” Indeed, the “front end of the animal” is where emergent policies in Maine are situated. For example, in 2021 Maine became the first state in the United States of America to pass extended producer responsibility (EPR) legislation for packaging [11]. This legislation holds producers accountable for the packaging waste they create [28]. It both provides incentives for producers to reduce and redesign packaging as well as providing much-needed funding for municipalities to invest in improvements to their own recycling programs. While our case study suggests that no single piece of legislation can solve all of the issues we identified, we see this policy movement as an important step.

The disruptions faced in Maine and elsewhere have clearly illuminated the fault lines in how we currently manage materials. Recognizing the plurality of visions for the future and learning from past challenges will be critical to creating more sustainable and equitable systems in the future.

## CASE STUDY QUESTIONS

- What can we learn from the history of disruptions to Maine's materials management system? Do you see any common threads between the three disruptions outlined in this case study?
- Imagine you are working with stakeholders to envision a materials management system in Maine. What characteristics would that system need to have to address the concerns and priorities of “Mark,” “James,” and “Gwen?”
- How do the stakeholders in this case study discuss environmental, economic, and social trade-offs of materials management systems?
- What other policies can you find that shift the burden of materials management upstream? What are some of the benefits and trade-offs of these approaches?

## AUTHOR CONTRIBUTIONS

All authors contributed equally to data generation, analysis, and writing.

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